UNIVERSIDAD DE NAVARRA

ESCUELA SUPERIOR DE INGENIEROS

Crisis Management Toolbox: the Relevant Role of Critical Infrastructures and their Dependencies

DISSERTATION

submitted for the Degree of Doctor of Philosophy by

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Donostia-San Sebastián, November 2014

To my parents and husband.

Agradecimientos

Medité mucho el tomar la decisión de realizar la tesis doctoral por el reto que suponía. Hoy viendo hasta donde he llegado y lo que he vivido durante estos años, reconozco lo mucho que me ha aportado ya que gracias a este reto he crecido personal y profesionalmente. Pero el mérito no es sólo mío. No hubiera podido conseguirlo sin la ayuda de muchas personas a las que quiero. Por ello, mediante estas líneas deseo agradecer a todos aquellos que de una forma u otra me han apoyado, acompañándome en el camino.

En primer lugar, agradezco a Tecnun y a la Universidad de Navarra la confianza depositada en mí al ofrecerme la oportunidad de realizar esta tesis doctoral, habiéndome permitido que me sintiera cada día, durante estos años, como en casa.

A mis compañeros del Departamento de Organización, gracias por crear un ambiente de trabajo tan agradable y por su buena disposición a ayudarme. Compañeros de quienes he aprendido mucho y con los que también me he divertido en las múltiples actividades y comidas. Muy especialmente, deseo agradecer a mis directores, Josune y Sarri, por su tiempo, su apoyo y sus consejos. Sin ellos, no hubiera podido llegar hasta aquí. Gracias de corazón.

Mi agradecimiento a todas las personas tanto de instituciones públicas como de organizaciones privadas que han colaborado en el desarrollo de este trabajo de investigación.

Por supuesto mi profundo agradecimiento a mis padres, Luis e Isabel, y a mi marido, Iñigo. Por estar ahí en los buenos momentos pero sobre todo en los complicados, en los que he necesitado que me escucharan y que me animaran. Por cómo me queréis os quiero tanto.

Gracias también a mi maravillosa familia e inigualables amigos. Y no me olvido de "las chicas" con las que he podido contar día a día para lo profesional y lo personal, grandes amigas hoy y siempre.

A todos, muchas gracias.

Ana Laugé Eizaguirre

Acknowledgments

I meditated a lot on doing the doctoral thesis due to the challenge involved. Today, seeing what I have accomplished and what I have lived during these years, I realise how much doing the doctoral thesis has given me and how, thanks to this challenge, I have grown personally and professionally. But merit is not only mine. I could not have done it without the help of many people I love. Therefore, through these lines I would like to thank all those who, in one way or another, have supported me on the way.

First of all, I thank Tecnun and University of Navarra for the trust they put in me giving me the opportunity to do this thesis. Over the years, every day, they allowed me to feel at home.

To my colleagues in the Management Department, thank you for creating a pleasant working environment and for your willingness to help. Colleagues from whom I have learned a lot and with whom I also had fun in several activities and meals. Most especially, I want to thank my supervisors, Josune and Sarri, for their time, support and advice. Without them I would not have achieved it. Thank you from the bottom of my heart.

My thanks to all the people from public institutions and private organisations that collaborated in the development of this research.

Of course my profound thanks to my parents, Luis and Isabel, and to my husband, Iñigo. For being there in good moments but especially in complicated ones, when I needed someone who listened and encouraged me. The way you love me makes me love you so much.

Thanks also to my wonderful family and unmatched friends. And I do not forget "the girls" with whom I could count every day professionally and personally, great friends today and always.

To all of you, thank you very much.

Ana Laugé Eizaguirre

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Abstract

Critical Infrastructures (CIs) such as Energy, Information and Communication Technologies, Transport, etc. have become critical for society since in the last decades society's dependency on the proper performance of CIs has increased. Recent crises such as Haitian and Japanese earthquakes (in 2010 and 2011 respectively) or Sandy hurricane (2012) have made evident this dependency. These crises have severely affected CIs and therefore, impacts on society have been aggravated. Consequently, effort on how to reduce future crises impacts with special focus on CIs and their dependencies has to be made.

The main objective of crisis management is to decrease crisis impacts. Thus, in order to reduce impacts crisis managers must identify the possible impacts that can occur, how these impacts can be assessed, the causes that generate impacts and their evolution over time. The consequences that crises lead to affect society in different ways and even if some impacts are unavoidable through a proper crisis management these impacts can at least be reduced. Moreover, impacts origins have evolved as the criticality of CIs has increased. As a result of the increased dependency on CIs, a failure in any CI entails important disturbances for society.

Moreover, CIs are dependent among each other and consequently when a CI fails it can affect other CIs through cascading effects. As a result, CIs have a relevant role in impact generation when a crisis strikes.

In light of this situation, research on how to lessen the impacts of crises must be performed. Therefore, this research aims to reduce future crises impacts. The use of the Crisis Management Toolbox which is focused on the Relevant Role of Critical Infrastructures and their Dependencies (the CriMaCID toolbox) will help crisis managers and CI managers improving future crisis management increasing their awareness about impacts and their causes. Consequently, geographic area's and CIs' resilience will also be improved.

In order to develop and to validate this research the collaboration of experts such as crisis managers and CI managers has been essential. Moreover, different research methods such as literature review, multiple case studies analysis, survey, simulation and interviews have been applied.

1 Introduction

In this chapter a general overview of the thesis is presented. Firstly, the problem under analysis concerning crisis impacts and their evolution is explained. Secondly, the chapter presents the aims of this research in order to lessen future crisis impacts through the development of a toolbox. This toolbox provides a holistic and dynamic perspective of the impacts that can be generated by a crisis with a special focus on Critical Infrastructures (CIs) due to their relevance for society's welfare. Finally, an overview of the structure of the chapters of this thesis is presented.

1.1 Overview

The history of humanity includes repeated episodes of suffering through overcoming crises. Crises such as Haitian earthquake (2010), the Eyjafjallajökull volcano eruption (2010), Japanese earthquake with the consequent Fukushima nuclear release (2011) or Sandy hurricane (2012) are examples of how current society can suffer the impact of a crisis. How many people were killed or injured? How prolonged power cuts were? How long did society and organisations suffer the consequences? Is society still aware in any way due to these crises?

The impacts that may result as a consequence of a crisis can be very different and last for short or long term depending on the triggering event that caused them but also on the way these crises are managed. The impacts generated by a triggering event can evolve differently depending on the previously deployed prevention and preparation policies and based on crisis managers learning from past crises. For example, even if the triggering event of Haitian and Japanese earthquakes is similar their consequences and evolution over time is different based on for example, their preparation. Then, consequences can be aggravated and prolonged as occurred after the Haitian earthquake. Japanese crisis impacts were reduced due to the buildings construction policies but also due to managers' and society's preparation to face these crises.

Another issue to consider is that, nowadays, welfare of society is completely dependent on the proper functioning of Critical Infrastructures (CIs) and a failure even being brief can have consequences and decrease welfare level. CIs do not work on isolation but connected to other CIs conforming complex and interconnected systems (Katina et al. 2014) (Figure 1.1). This makes failures to spread through cascading effects from one CI to others (Setola et al. 2009). Examples of cascading effects were evident in crises such as Japanese earthquake or the Eyjafjallajökull volcano eruption where sectors such as Transport or Food were affected. Therefore, CIs and their dependencies must be analysed jointly and with the collaboration of multidisciplinary agents to improve future crisis management.

Figure 1.1 Example of CIs dependencies

Consequently, this research has developed a toolbox in order to helps crisis managers and CI managers to improve future crisis management through the analysis of impacts and focusing on the role of CIs and their dependencies.

1.2 Crises impact assessment

One important aspect of crisis management consists of the assessment of generated impacts, learn from previous mistakes, and identify best practices to improve current crisis management. Therefore, a comprehensive assessment of the potential crisis impacts has to be conducted so that crisis managers are aware of the consequences and can improve their preparation to better respond when a crisis occurs.

A suitable impact analysis helps improving the way these impacts should be avoided or managed and makes possible the learning about the consequences of a crisis. In order to carry out an efficient crisis management, through the development of preventive measures and response programs, impacts should be identified. Impact analysis also helps to mitigate the harshness or can even avoid impacts in face of future crises (National Research Council 1999).

Furthermore, a proper assessment of crisis impacts helps assessing the efficiency of prevention and preparedness measures implemented to prevent or reduce the impact of such crises. Actually, impact analysis can help improving crisis management throughout the overall crisis lifecycle from prevention to recovery.

However, current impact assessment methodologies still have some limitations. For example, these methodologies do not analyse how impacts evolve. Though, impacts evolution over time analysis is needed to know how impacts interact. That is how direct impacts create indirect ones. Through cascading effects new impacts can be generated or the existing ones can be aggravated. Also, impacts transcend to other sectors or even international borders.

It is necessary to include holistic analysis with an overall perspective of all impacts that a crisis can lead to, as usually indirect impacts are not monitored as they cannot be easily quantified. However, these impacts analysis is relevant as they can be prolonged for months or years (Lequeux and Ciavola 2011, Pfurtscheller et al. 2011).

Moreover, current impact assessment methodologies do not identify same impacts categories and sectors, and also indicators included in each sector vary (Logar and van den Bergh 2011).

In light of this situation, there is still a need of developing a holistic impact analysis including a categorisation which makes possible to answer to the identified gaps and barriers.

1.3 Critical Infrastructures role

When analysing crises that have received most attention from the general public in recent years, we find a clear common aspect: they have significantly affected CIs, thus aggravating and prolonging crises' impacts (Chang et al. 2007). Moreover, failures in CIs have become more common in the last years (ICS-CERT 2011, 2013). As a consequence, recent crises have significantly increased people's concern about CIs vulnerabilities given that the welfare of society is dependent on CIs proper functioning (Zimmerman 2005, Collier and Lakoff 2008, Croope and McNeil 2011).

Additionally, the complexity of CI systems and their dependencies increase the difficulty of crisis management (Dudenhoeffer et al. 2006, Zimmerman 2009). CIs dependencies are an important issue to focus on when managing crises as dependencies can make impacts to evolve in an unexpected way. It is necessary that crisis managers and CI managers understand existing CIs dependencies and their evolution over time in order to effectively manage crises and to identify current crisis management gaps (Peerenboom et al. 2002, Rinaldi 2004, Pederson et al. 2006, Oliva et al. 2011). Thus, including a dynamic perspective on this problem analysis is important (Eusgeld et al. 2011). This means that cause and effect relations are analysed in order to know how impacts evolve over time. Currently, impact assessment does not take into account evolution over time and estimations only focus on a final quantification. Though, as some impacts can generate new ones or aggravate the existing impacts this dynamic analysis is necessary to improve crisis management.

However, even though research has been performed analysing CIs system complexity, the study of CIs dependencies is still an immature and a growing research field (Rinaldi et al. 2001, Dunn and Wigert 2004, Bologna 2006, Sarriegi et al. 2008, Eusgeld et al. 2011).

Despite the fact that detailed information of individual CIs and their elements can be obtained, the understanding of dependencies between different CIs is limited.

Being aware of the different effects a CI can suffer depending on the time of affection allows managers to implement policies in order to minimise future failures or to lessen the impacts caused by a crisis (Fioriti et al. 2010).

Consequently, considering the analysis of current impacts assessment methodologies and the relevant role of CIs, tools to help crisis managers and CI managers assessing impacts, CIs dependencies consequences and their evolution over time are still needed.

1.4 Research objectives

The aim of this PhD thesis is to develop a toolbox to assist crisis managers and CI managers to improve their management through the analysis of crises impacts with special focus on CIs and their dependencies. The developed toolbox improves crisis management and helps reducing future crises impacts through the increase of managers' awareness which consequently will help to improve a geographic area's and particular CIs resilience level.

Resilience is defined as the ability of a system to reduce the probability of failure, to reduce impacts and to reduce the time needed to recover (Bruneau et al. 2003) not only from expected triggering events abut also from any shocks or unexpected triggering events (Labaka et al. 2013). Thus, to improve resilience a precise impact analysis is needed in order to develop preventive measures, preparation activities and response and recovery programs.

The developed toolbox will help improving crisis management and consequently geographic area's and CIs' resilience will be increased through: 1) impact indicators identification and categorisation, 2) identifying the most critical CIs and evidences that dependencies lead to, 3) improving CIs dependencies analysis to reduce probability of failure and improving management, and 4) helping to understand crises complex behaviour.

Through this research a toolbox called "Crisis Management toolbox: the relevant role of Critical Infrastructures and their Dependencies" has been developed (from now on the toolbox will be referred as "CriMaCID toolbox"). The toolbox will be applicable for crises caused by a triggering event such as natural disasters, man-made disasters, accidents or attacks but not for crises such as economic crises or social value crises. The toolbox aims to reduce future crises impacts through detailed analysis and identifying their causes. The toolbox will help understanding the different impacts that a crisis generates, how impacts evolve over time and how the existing CIs dependencies cascade and prolong those impacts.

To achieve the main objective of this PhD the following steps have been carried out. First of all, crises impacts assessment handbooks, methodologies and research projects have been analysed to identify standards or analogous categories and indicators for impact assessment. Then, current methodologies' difficulties and gaps when these methodologies are used in real crises have been identified. The following research questions related to impacts assessment have been defined:

- RQ1.1. Is there any impact assessment standard? Do different impact assessment methodologies provide analogous indicators or methodologies?
- RQ1.2. Which are the current methodologies' difficulties or gaps?
- RQ1.3. Do impact assessments analyse how impacts evolve over time? What is the cause and effect relation among impacts? Can some impacts generate others?

After identifying the main gaps and observing the important role that CIs have on impacts generation, the need to analyse the role of CIs has been identified. When CIs are damaged by a crisis, impacts spread through cascading effects to dependent CIs and other sectors aggravating and prolonging impacts. Therefore, special focus on CIs and their dependencies including a dynamic perspective through evolution over time analysis has to be taken in order to improve crisis management. CIs related research questions are:

- RQ2.1. What is the role of CIs on impacts generation?
- RQ2.2. Are all CIs equally critical? Which are the CIs that generate more impacts? And which are the CIs that suffer more from others failure?
- RQ2.3. How can CIs dependencies be identified? Is dependency a one-dimensional concept?
- RQ2.4. What are the generated impacts when a CI fails?

1.5 Content

The content of this research is distributed in several chapters. See below a summary of each chapter:

- *Chapter 2: State of the art*
  A literature review analysis have been performed to analyse handbooks and methodologies related to impact assessment in order to identify the currently used impact categories and indicators but also gaps and difficulties. One of these gaps is that current methodologies do not make special focus on the relevant role that CIs have on impact generation due to existing dependencies. Therefore, CIs characteristics and their dependencies are also analysed in this research.
- *Chapter 3: Research Methodology*
  In this chapter the methodology followed during the research is explained.
- *Chapter 4: The CriMaCID toolbox*
  The CriMaCID toolbox is explained in this chapter. The CriMaCID toolbox is made up of four tools: 1) *Impact indicators framework*, 2) *CIs dependency-influence cluster*, 3) *CI dependency radar* and, 4) *Simulation model*.
- *Chapter 5: Validation of the CriMaCID toolbox*
  This section presents the validation process of the CriMaCID toolbox. The validation process has been carried out with the collaboration of several crisis managers and CI managers.
- *Chapter 6: Conclusions, Limitations and Future Research*
  Main conclusions of the research and the CriMaCID toolbox are explained through this chapter. In addition, future research related to the CriMaCID toolbox is commented.

2 State of the Art

This chapter presents the state of the art analysis. Literature review regarding crisis management, impact assessment and the role of CIs is performed. From this review the research gaps of this PhD thesis have been gathered.

One of the issues that should be improved about crisis management is the assessment of impacts. An appropriate impact assessment improves the learning about the consequences of a crisis in order to identify the essential needs for future crisis management. Furthermore, being society highly dependent on the proper performance of CIs, especial focus has to be made on analysing impacts of CIs. Therefore, this research provides a toolbox to improve crisis management, increasing managers' awareness that leads to an improvement of geographic area's and particular CIs' resilience level which will consequently reduce future crises impacts.

2.1 Introduction

Managing crises is an uninterrupted process. Before the crisis peak strikes, managers must concentrate on developing preventive measures, training activities and response programs as during crisis peak time there is no opportunity to design them. But, crisis managers cannot make decisions about how to prevent or respond to a crisis being unaware of their consequences. Therefore, in order efficiently manage crises, a proper estimation of impacts which helps to mitigate the harshness or can even avoid impacts in face of future crises must be performed.

Consequently, in this chapter a review of current crisis management is made. Nonetheless, crisis management is not an easy task due to, for example, the occurrence of unexpected triggering events or lack of resources for an efficient preparation or a suitable response.

Secondly, the analysis of crises impacts is carried out. During a crisis different impacts are generated and its estimation has to be included into crisis management process. If managers are not aware of the potential consequences of a crisis (for example on the performance of CIs) the generated impacts could be more severe. As it has been mentioned before, the occurrence of non-assessed consequences difficults crisis management. Therefore, crisis managers need to be aware about existing dependencies among several sectors which spread cascading effects from one to another. Furthermore, these cascading effects can transcend international borders affecting more than one country. For example, during the last decade there have been several international large scale power cuts such as the 2003 black-outs in North America (U.S.-Canada Power System Outage Task Force 2004) and Italy (CRE and AEEG 2004, UCTE 2004) as well as the 2006 black-out in Europe which spread to Morocco (UCTE 2007, Johnson 2008).

Therefore, the case of CIs needs special analysis as they are critical for society's welfare. If a crisis affects CIs performance, cascading effects generated due to CIs dependencies spread impacts and therefore, crisis impacts will be prolonged and aggravated. For that reason, as a third issue, the role of CIs on impact generation is analysed. CIs and their dependencies further complicate crisis management. Consequently, if crisis managers do not have all the information about CIs dependencies, they could not be aware of how a failure in one CI can affect others. Then, the identification of all dependencies among CIs is a must in crisis management.

2.2 Crisis management

As Coombs states a crisis does not just happen it evolves (Coombs 2007). A crisis does not start when the triggering event occurs; there is a long process before the crisis peak and also after. In order to successfully manage and overcome a crisis, it is important to be aware of the crisis lifecycle (long term evolution of crises) as there is an incubation period that begins much earlier than the triggering event (Roux-Dufort 2007).

Crisis management should not only rely on the steps and actions carried out when a triggering event occurs. It must be a learning process instead. Failing to understand the characteristics of crisis lifecycle's phases can result in ineffective response when managing crises. Thus, there is a need of a holistic overview when managing crises in order to adopt not only reactive, but also proactive measures that can minimise or even avoid crises and their associated impacts (Nudell and Antokol 1988, King 2007, Jaques 2007).

Several authors have defined different lifecycle phases for crisis management (Turoff et al. 2009) (see Table 2.1). The lifecycle is usually divided into three to six phases as explained below:

Three phases' crisis lifecycle

In general, the three phases are defined by several authors (Smith 1990, Richardson 1994, Coombs 2007) as the period before the critical event, the crisis peak and then, the period after the peak.

Smith (1990) defines the three phases of the crisis lifecycle focusing on organisation leaders' role. 1) Crisis management is the time before the critical event occurrence and refers to the policies and culture of organisational leaders in order to prevent the crisis. Then, 2) the operational period when dealing with the crisis and finally, 3) crisis of legitimation in the post crisis phase.

Additionally, Richardson (1994) defines similar phases but labels each phase differently: 1) precrisis or disaster phase focusing on prevention activities, 2) crisis impact or rescue phase when the triggering event occurs and 3) recovery or demise when restoration activities must be carried on.

Coombs (2007) labelled the three stages as precrisis, crisis event and postcrisis. 1) Precrisis is the incubation period where a series of warning signals come out before the crisis event. 2) Crisis event is a sequence of events in an unstable or crucial time in which a decisive change occurs. And finally, 3) postcrisis is the period in which the safety level is restored and learning and continuity mechanisms are initiated in face of future crises.

Four phases' crisis lifecycle

Other authors define a four stages' crisis lifecycle (Fink 1986, Myers 1993, Alexander 2002, Drennan and McConnell 2007, Crandall and Spillan 2009).

Fink's (1986) model is one of the first to consider a crisis as an extended event. He divides a crisis in four stages: 1) emergent clues or hints of a potential crisis, 2) crisis breakout, 3) the effects of the crisis and the efforts to get through it and 4) finding signals that make stakeholders sure that the crisis is over.

Myer (1993) includes these four phases into crisis lifecycle: 1) normal operations to avoid or minimise future crises, 2) emergency response when a crisis occurs, 3) interim processing until the normal activity can resume and finally 4) restoration phase when the normal activity is recovered.

Drenann and McConnell (2007) define same four phases as 1) mitigation to minimise or avoid a crisis occurrence, 2) preparedness in order to train people to improve response, 3) response after the triggering event and 4) recovery to a normal situation.

Crandall and Spillan (2009) define a slightly different four phases: 1) landscape survey refers to the identification of vulnerabilities, 2) strategic planning for preparation activities, 3) crisis management as the response to the event and, 4) organisational learning, in order to improve future management.

Five phases' crisis lifecycle

There is also a five stages' lifecycle model used by Mitroff (1994). This model identifies the following stages: 1) signal detection and actions to prevent them, 2) risk factors' detection and reduction, 3) crisis damage's containment, 4) recovery phase and, 5) crisis management's reviewing and critiquing to learn from it.

Six phases' crisis lifecycle

Finally, the six stages approach is defined by Van de Walle and Turoff (Van de Walle and Turoff 2008) and comprises: 1) preparedness including analysis of threats, planning, and evaluation, 2) training for further phases, 3) mitigation of threats and signals, 4) detection of the crisis, 5) response and, 6) recovery as the normalisation of the situation.

Fink (1986)	Smith (1990)	Myers (1993)	Richardson (1994)	Mitroff (1994)	Alexander (2002)	Drenann & McConnell (2007)	Coombs (2007)	Van de Walle & Turoff (2008)	Crandall, Parnell & Spillan (2009)
Crisis indicators	Crisis of management	Normal Operations	Precrisis / Disaster phase	Signal detection and prevention	Mitigation		Precrisis	Preparedness	Landscape survey
								Training	
				Risk detection and reduction	Preparedness			Mitigation	Strategic Planning
								Detection	
Crisis breakout	Operational crisis	Emergency response	Crisis impact / Rescue phase	Damage containment	Response		Crisis peak	Response	Crisis management
		Interim Processing							
Response	Crisis of legitimation	Restoration	Recovery / Demise phase	Recovery	Recovery		Postcrisis	Recovery	Organisational learning
Recovery				Learning					

Table 2.1 Crisis lifecycle's phases according to different authors. Table adapted from Crandall et al. (2013)

This research will be focused on the four phases' lifecycle proposal (Alexander 2002, Drennan and McConnell 2007), which comprises prevention, preparedness, response and recovery phases. In Figure 2.1 the impact of a crisis in the different crisis lifecycle phases is represented.

During the prevention period, organisations work to identify the risks to which they are exposed, carrying out measures to avoid or minimise future crises. Management activities involve signal detection and crisis prevention. Crisis managers should detect warning signs, collect information about them and analyse this information. Additionally, managers should prevent detected signals to turn into a crisis or, at least should lessen the risk level of the crisis. Afterwards, crisis managers must be prepared before a crisis triggers. This involves developing the crisis management plan and updating it, selecting and training the crisis management team, conducting exercises to test the crisis management plan and team, identifying vulnerabilities and structuring communications. Then, the crisis managers are engaged in preparing to respond quickly and appropriately to any crisis.

Figure 2.1 Impact through crisis lifecycle

Later, when the triggering event of the crisis occurs, respond and deal with the crisis to reduce impacts is the main goal of crisis managers. Crisis managers have to run procedures during the crisis peak until it is considered to be resolved. When a crisis is going on, managers must respond quickly, accurately and consistently. This phase concerns the acknowledgement of the crisis and the crisis response. Managers must identify the crisis and how imapcts are evolving in order to make the best decisions at each moment. According to the crisis' type, the managers must follow procedures or management plans so as to lessen the immediate consequences and side effects of the crisis.

After the response phase, a recovery period starts in which the aim is to regain the level of welfare before the triggering event. Crisis managers have to put in place actions to recover from the crisis. This phase consists of corrective actions to solve the problems created by the crisis and to restore the safety level. This phase usually takes longer because consequences from a crisis are extensive and hard to solve. Once the crisis is over, it is important to investigate it, so as to understand why it happened and how to avoid or mitigate from happening again. Managers should analyse the procedures and study made mistakes to learn from them (Crichton et al. 2009). Finally, crisis managers must start preparing for the next crisis management and the cycle starts again.

2.3 Impacts assessment

One important aspect of crisis management consists of the assessment of impacts. Therefore, to assist crisis management, a comprehensive assessment of the potential impacts that may result as a consequence of a crisis has to be conducted. Crisis managers have to be aware of the consequences in order to improve their preparation and to better respond when a crisis occurs leading to an improvement of the resilience. However, the analysis of crises impacts results complicated due to crises complexity which relies on the interaction of multiple issues that lead to extensive impacts such as loss of life, displacements of populations, widespread damage to societies, and economies and the need for large-scale and multi-faceted humanitarian assistance.

A suitable impact assessment improves the way those impacts should be managed and fosters the learning about the consequences of a crisis in order to identify the essential needs for improving future crisis management. Through an efficient crisis management, the development of preventive measures and response programs can help to mitigate the harshness of crises impacts and may even prevent future crises (National Research Council 1999).

Actually, impact assessment can help improving crisis management throughout the overall crisis lifecycle (Figure 2.2).

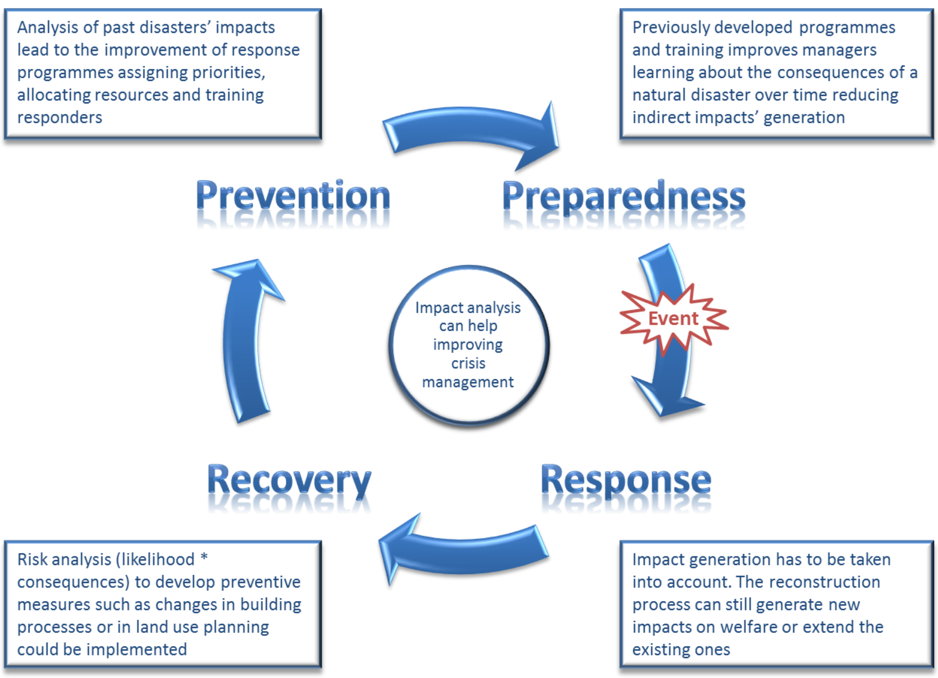

Figure 2.2 Influence of impact assessment on crisis management lifecycle

During prevention phase, impact assessment will be useful for risk analysis which relies on the likelihood of a triggering event and its consequences. Through a more accurate risk analysis, preventive measures such as changes in building processes or in land use planning could be implemented. In the preparation phase, the assessment of past crises impacts leads to the improvement of response programmes assigning priorities, allocating resources and training responders. Furthermore, in the response phase all previously developed programmes and training facilitate learning about the consequences of a crisis. Finally, in the recovery phase new impacts on society's welfare level can still be generated and the existing ones can be extended. Therefore, a holistic impact assessment has to be carried out in order to improve preventive measures and response and recovery programs.

2.3.1 Impact assessment methodologies

A review and analysis of the dimensions that are currently used in the literature for the classification and assessment of impacts has been conducted (Laugé et al. 2012). We have chosen to analyse crises such as natural disasters as this type of crises have great impacts and comprise all kind of impacts occurring in several sectors.

For this purpose, classifications used by international agencies such as National Research Council (1999), SCARM (2000), Bureau of Transport Economics (2001), FEMA (2002), Pelling, Özerdem et al. (2002), U.S. General Accounting Office (2002), Calderón Patier, Fernández-Ardavín Martínez et al. (2003), ECLAC (2003), Benson, Twigg (2004), Middelmann (2007), Rose (2009), Hallegatte, Przyluski (2010), Australian Government (2011) and the ones used in some research projects funded by the European Union (EUMASS 2011, DOMINO 2011) have been analysed. These classifications are further explained in the following sections. Approximations based on mathematical models which are merely focused in the determination of the economic impacts of crises are out of the scope of this research since our focus is not an economic quantification of impacts (Dixon et al. 1982, Adams et al. 2002, Horridge et al. 2003).

From the study of these methodologies, two different classification types for the assessment of crisis impacts are inferred. The first type classifies impact according to their nature differentiating between tangible versus intangible and direct versus indirect impacts. The second classification distinguishes impacts based on the affected sector.

2.3.2 Impact categories based on their nature

Tangible impacts are the impacts that can be measured in monetary terms, such as destruction of vehicles, buildings or infrastructures, the changes in income or increasing of costs. Thus, their estimation, for example in euros, results much easier. On the other hand, intangible impacts cannot be translated to monetary terms as there is no systematic or agreed method available to measure them (Bureau of Transport Economics 2001, Hallegatte and Przyluski 2010, Middelmann 2007).

Therefore intangible impacts are more difficult to estimate. Examples of intangible impacts are deaths, injured people, human suffering, cultural artefacts, losses of memorabilia and psychological effects. Both tangible and intangible impacts can also be positive such as income increase in not affected industry or development of community and solidarity. Despite the importance of intangible impacts, the difficulty for an objective measurement hinders their use when assessing impacts after a crisis (Bureau of Transport Economics 2001).

Furthermore, it is useful to distinguish between the physical destruction caused by the triggering event of a crisis (direct impacts) and the consequences of such destruction (indirect impacts) (Figure 2.3). Direct impacts represent the partial or complete physical destruction caused by the triggering event to human beings, buildings, infrastructure, vehicles, capital and on stock. On the other hand, indirect impacts are consequence of direct impacts caused by the hazard. Indirect impacts are more difficult to evaluate (National Research Council 1999) as months or years are needed to properly estimate them (Lequeux and Ciavola 2011, Pfurtscheller et al. 2011). Examples of indirect impacts are changes in income or flows of goods and services that will not be produced and that may extend throughout the rehabilitation and reconstruction periods and increase the unemployment rate (Calderón Patier et al. 2003, National Research Council 1999). Indirect impacts can also be positive, generating benefits to society such as increasing income of the construction sector due to reconstruction activities (Xie et al. 2013).

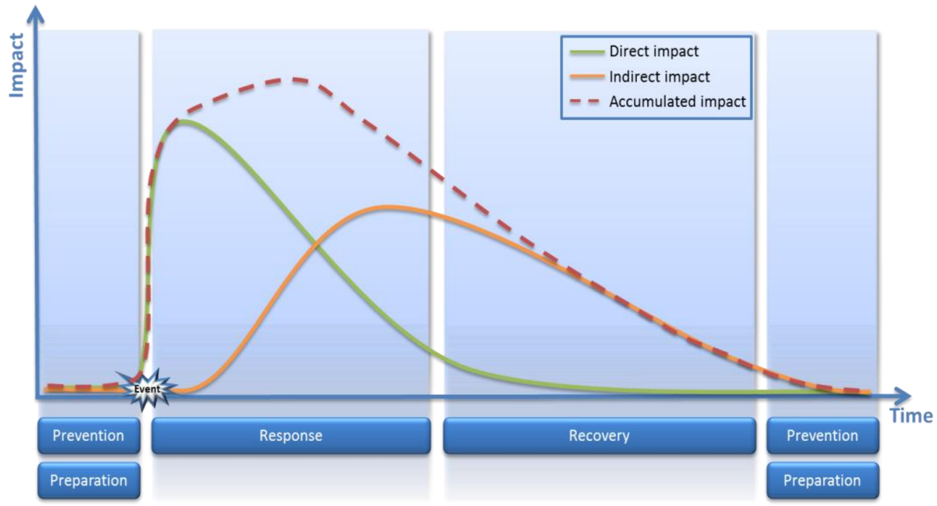

Figure 2.3 Direct, indirect and accumulated impact through crisis lifecycle

According to some reports on natural disasters, indirect impacts represent between the 25% and the 40% of the direct impacts (Bureau of Transport Economics 2001). However, other reports highlight that this proportion varies depending on the size of the crisis, the greater the triggering event the greater the proportion of indirect impacts (Gordon and Richardson 1995, Toyoda 1997). Therefore, there is not an established amount of indirect impacts generated by direct impacts.

The Table 2.2 shows the categorisation of impacts developed by Middelman (2007) which was based on the categorisations made up by Smith et al. (1995) and SCARM (2000).

		Impact	
		Direct	Indirect
Measurement	Tangible	- Internal content (buildings content) - External content (vehicles, ships, etc.) - Structural (buildings and infrastructure)	- Businesses productive or revenue losses - Non provision of public services - Costs associated to emergency assistance
	Intangible	- Deaths and injured - Loss of cultural elements and memorabilia	- Disturbances to society - Health problems caused by stress - Society's loss of trust - Investors' loss of trust

Table 2.2 Impact categories based on Middelmann (2007)

If a road is damaged by an earthquake, the destruction of the road is classified as a direct tangible impact. Also, if there were injured people at the time of the destruction of the road they would be considered as a direct intangible impact. However, an indirect tangible impact could be the economic losses of the companies which might have accessibility problems to receive row materials or deliver finished goods. Furthermore, the delays and troubles suffered by neighbours when reaching their workplaces are considered indirect intangible impacts.

There is another method for impacts classification similar to the previous one. This relies on dividing impacts into refundable and non-refundable impacts (National Research Council 1999). Refundable impacts include damages that are covered by insurance companies or those from whose expenses local or state governments are responsible for. By contrast, the non-refundable impacts are the ones to which affected people are facing as neither companies nor governments take care of them.

2.3.3 Impact categories depending on the affected sector

The second classification distinguishes impacts based on the affected sector such as social, economic, environmental, or infrastructures, also including macroeconomic or overall effects.

The Economic Commission for Latin America and the Caribbean (ECLAC) has developed a set of guidelines that provides criteria for assessing crises impacts (ECLAC 2003). It is based on internationally accepted standard methodology to assess the socio-economic and environmental effects of both natural and man-made disasters. The handbook prepared by ECLAC focuses on the conceptual and methodological aspects of assessing the damage caused to the population, including the effects on living conditions, environmental impact and loss of production of goods and services and, temporary effects on key macroeconomic variables. ECLAC divides impacts into the following sectors: Social (affected population, housing, education, culture and health), Infrastructure (energy, water and sanitation, and transport and communications), Economic (agriculture, trade and industry, and tourism) and Overall effects (environment, impact on women, damage overview, macroeconomic effects, and employment and income).

On the other hand, HAZUS (FEMA 2002) is a software to estimate the impact of natural disasters developed by the Federal Emergency Management Agency (FEMA) of the United States, whose first version was released in 1997. HAZUS assesses physical, economic and social sectors' impact but excludes the environmental impact. Casualties caused by secondary effects, such as heart attacks or injuries while rescuing trapped victims, are neither included.

Both the ECLAC and HAZUS are the most internationally accepted methodologies for disasters' impact assessment. However, several organisations have developed other classifications which are also taken into account in this research and are explained below.

National Research Council of the United States (National Research Council 1999) assesses and classifies impacts of natural disasters by sectors: Property (structures, contents and vehicles), Agriculture (crops and livestock), People (injuries, deaths and health effects), Infrastructure (transport and services among others) and Businesses productivity.

The Industry and Resources Department of South Australia has developed a report on the different impacts that may arise as consequence of an incident at oil companies (PIRSA 2000). This classification divides impacts into: Environmental (soil, emissions, surface water and groundwater, etc.), Social (infrastructure, health etc.) and Economic (welfare, employment, GDP etc.).

The report edited by the Australian Agency for International Development is focused on assessing the economic impact of natural disasters in the Pacific (Mckenzie et al. 2005). In this case the report recommends classifying impacts in the following areas: Social (housing, education and health), Infrastructure (energy, water and transport) and Economic (tourism and agriculture). To this classification the agency adds a fourth category called cross-sectoral impacts, which are impacts affecting various sectors such as environmental impacts, psychosocial and government.

The Australian Government developed in 2007 a book entitled "Natural Hazards in Australia: Identifying Risk Analysis Requirements" (Middelmann 2007). The second chapter is based on the assessment of the impacts of natural disasters and the following classification of impacts is determined: Physical (infrastructure, discharges, emissions etc.), Social (death, injury, psychological harm, loss of income etc.) and Economic (production disruption, power outages, cost of emergency operations etc.).

Furthermore, there are several projects funded by the European Union which are focused on the assessment of the impacts of different crises. In this research we have analysed EUMASS and DOMINOS projects which have been recently completed. EUMASS project aims at developing a unified solution for risk analysis in the subway. In this case the impact assessment is classified into: Infrastructure, People (wounded and dead) and Service (transportation service disruption) (EUMASS 2011). Furthermore, the DOMINO project assesses the impacts caused by the malfunctioning of either energy or transport infrastructures. DOMINO's aim is to assess the Economic, Human (dead and injured) and Public effects paying special attention to cascading effects, also called domino effects (DOMINO 2011).

Consequently, there is not an agreed terminology nor for impact sectors designation nor for the indicators included in each sector. The following table (Table 2.3) shows a comparison of the impact assessment methodologies analysed based on their sectors classification. There are some sectors that even being focused on similar aspects are not assessing exactly the same. For example, "Social", "People" and "Human" could seem to be the same but the names are referred to different issues and indicators, including or excluding infrastructure or only referring to deaths or injured in other cases. Something similar occurs with the other sectors.

<table>
<tr><th></th><th>National Research Council (1999)</th><th>PIRSA (2000)</th><th>FEMA (2002)</th><th>ECLAC (2003)</th><th>International Development Agency (2005)</th><th>Natural Hazards (2007)</th><th>EUMASS (2011)</th><th>DOMINO (2011)</th></tr>
<tr><td rowspan="8">Sectors</td><td>People</td><td rowspan="3">Social</td><td rowspan="2">Social</td><td rowspan="2">Social</td><td rowspan="2">Social</td><td rowspan="2">Social</td><td>People</td><td>Human</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td>Infrastructure</td><td rowspan="2">Physical</td><td rowspan="2">Infrastructure</td><td rowspan="2">Infrastructure</td><td rowspan="2">Physical</td><td rowspan="2">Infrastructure</td><td rowspan="3">Public effects</td></tr>
<tr><td>Property</td><td></td></tr>
<tr><td rowspan="2"></td><td>Environment</td><td rowspan="2"></td><td rowspan="2">Inter-sector</td><td rowspan="2">Transversal</td><td rowspan="2"></td><td></td></tr>
<tr><td></td><td rowspan="2">Service</td><td></td></tr>
<tr><td>Productive</td><td rowspan="2">Economic</td><td rowspan="2">Economic</td><td rowspan="2">Economic</td><td rowspan="2">Economic</td><td rowspan="2">Economic</td><td rowspan="2">Economic</td></tr>
<tr><td>Agriculture</td><td></td></tr>
</table>

Table 2.3 Impact classification by sectors

2.3.4 Impact assessment barriers and limitations

Apart from using impact assessment as a record of the consequences of a crisis, the assessment should be also used as a learning tool for crisis managers in order to improve future crisis management. Then, after completing the analysis of the methodologies currently used for impact assessment several barriers and limitations have been identified.

It is likely that crises have a greater long-term impact on quality of life, livelihoods, economic and environmental conditions than what is currently being assessed. Usually impact assessment is carried out immediately after the triggering event to prioritise relief and rehabilitation needs. This involves the accomplishment of the assessment in situations of great stress for those managing the crisis. Therefore, generally, the assessment focuses only on quantifying direct physical damage in infrastructures and assessing the number of deaths and injuries. Indirect impacts, such as the effects on the productive capacity of the affected geographic area, are rarely monitored as months or years are needed to properly assess them (Lequeux and Ciavola 2011, Pfurtscheller et al. 2011). That is why the official assessments of impacts do not convey the whole story of how crises affect people and their environment (Logar and van den Bergh 2011). Furthermore, as discussed previously some impacts are difficult to quantify and despite the importance of such impacts, the difficulty for an objective measurement hinders its integration in assessing the impacts after a crisis (Bureau of Transport Economics 2001). Thus, the assessment of impacts that is currently developed today is often incomplete and inaccurate (Mckenzie et al. 2005).

A current challenge in assessing the impacts of a crisis is to decide what has to be included. For example, if an earthquake destroys a road there is no doubt about including the reconstruction of this road among the impacts. But sometimes other issues such as economic losses of businesses that are accessed by this road, their customers and suppliers' losses and the discomfort caused to those who need to use longer alternate routes with a consequent increase in fuel consumption are not included.

Therefore, adopting a holistic perspective when assessing impacts, would allow observing all impacts generated including also the ones that in many cases are excluded, such as the indirect impact mentioned previously.

Furthermore, the lack of consistency among methodologies concerning the definition of various concepts is another barrier when assessing impacts (Logar and van den Bergh 2011). Each organisation uses similar terms in which they group different kind of impacts in a sector, so that the results of these assessments cannot be directly compared but they need a deep analysis of what each sector comprises.

In addition, the cause and effect among impacts should be included in assessments in order to allow crisis managers understand how some impacts generate new ones. If managers are aware of how impacts evolve and their associated cascading effects, they could identify and properly manage critical elements that could generate new impacts or aggravate the existing ones. Then, impact assessment must consider impacts evolution over time as with this kind of information crisis managers could learn how direct impacts evolve over time creating indirect ones in order to improve mitigation, preparation, response and recovery activities.

Finally, as it has been previously mentioned, society is highly dependent on the correct performance of CIs. CIs create a system of interconnected infrastructures that play an important role in impact generation. Therefore, if one or more CIs result to be damaged important consequences will be generated affecting the whole society. However, despite CIs' criticality, current impact assessment methodologies do not make special focus on them. For that reason, it is necessary to deeply analyse CIs and their dependencies in order to lessen the consequences in case any CI fails. Furthermore, CIs and their dependencies must be well known by crisis managers to improve their management over all phases of crisis lifecycle.

Therefore, the detection of currently existing barriers and limitations highlights the need of developing a holistic impact assessment which comprises all kind of impacts generated with special attention on CIs due to their important role on impact generation. A categorization by nature and by sector has been established in order to facilitate a coherent impact assessment to different crisis manager organizations. This impact assessment also includes evolution over time analysis through the differentiation between direct and indirect impacts. This helps increasing awareness to improve direct impacts management in order to lessen indirect ones.

2.4 Critical Infrastructures

The dependency of society on the proper peformance of CIs has been highlighted in recent crises. CIs set up interconnected systems and consequently a failure in one CI can spread to other dependent CIs or sectors. This represents a further complication in crisis management, increasing the impact of crises and seriously affecting the welfare of society.

As the Council Directive 2008/114/EC of the European Union states, "critical infrastructure means an asset, system or part thereof located in Member States which is essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people, and the disruption or destruction of which would have a significant impact on a Member State as a result of the failure to maintain those functions" (The Council of the European Union 2008). This definition of CIs highlights the important role that CIs have on society's welfare. Therefore, current society is highly dependent on CIs (Dudenhoeffer et al. 2006, Min et al. 2007, Sarriegi et al. 2008, Oliva et al. 2010, Katina et al. 2014). This dependency causes serious problems when a failure affects one or more CIs (Min et al. 2007, Boin and McConnell 2007, Sarriegi et al. 2008).

The CIs included in this research correspond to the list from the Green paper on the European Programme for Critical Infrastructure Protection (Commission of the European Communities 2005), which considers the following eleven sectors as critical (Table 2.4):

Sector	Product or Service
Energy	- Oil and gas production, refining, treatment and storage, including pipelines - Electricity generation - Transmission of electricity, gas and oil - Distribution of electricity, gas and oil
Information and Communication Technologies	- Information system and network protection - Instrumentation automation and control systems (SCADA…) - Internet - Provision of fixed telecommunications - Provision of mobile telecommunications - Radio communication and navigation - Satellite communication - Broadcasting
Water	- Provision of drinking water - Control of water quality - Stemming and control of water quantity
Food	- Provision of food and safeguarding food safety and security
Health	- Medical and hospital care - Medicines, serums, vaccines and pharmaceuticals - Bio-laboratories and bio-agents
Financial	- Payment services/payment structures (private) - Government financial assignment
Public & Legal Order and Safety	- Maintaining public & legal order, safety and security - Administration of justice and detention
Civil Administration	- Government functions - Armed forces - Civil administration services - Emergency services - Postal and courier services
Transport	- Road transport - Rail transport - Air traffic - Inland waterways transport - Ocean and short-sea shipping
Chemical and Nuclear Industry	- Production and storage/processing of chemical and nuclear substances - Pipelines of dangerous goods (chemical substances)
Space and Research	- Space - Research

Table 2.4 Critical Infrastructures list (Commission of the European Communities 2005)

2.4.1 The Role of CIs in crises

The history of humanity has gone through suffering and overcoming several crises. But, what makes people remember the occurrence of a crisis years later? Why have crises such as Hurricane Sandy, the Haitian and Japanese earthquakes and the eruption of the Eyjafjallajökull volcano had such a great impact on society?

The answer to these questions relies on the magnitude of crises effects on CIs. Analysing crises that have received most attention from the general public in recent years, there is a clear common aspect: they have significantly affected CIs aggravating and prolonging crises impacts (Chang et al. 2007). Recent crises have significantly increased people's concern about the vulnerabilities of CIs given that the welfare of society is dependent on CIs proper performance (Collier and Lakoff 2008, Croope and McNeil 2011). Thus, special focus must be given to CIs and their dependencies for effectively manage crises (Rinaldi 2004, Pederson et al. 2006, Streips and Simpson 2007, Min et al. 2007, Boin and McConnell 2007, Oliva et al. 2011).

The criticality of CIs becomes evident when any of them fails. This failure can occur due to different crises such as a natural disaster, an accident or a terrorist attack. These are the situations where CI managers, governments and society realise about the importance of the proper performance of CIs.

2.4.2 CIs characteristics

CIs constitute connected and dependent systems (Chang et al. 2007, Stapelberg 2008) as each CI needs the outcome from others to continue with its normal activity. However, even if CIs dependencies are unavoidable, this fact makes CIs more vulnerable as dependencies increase their risk of failure (Rinaldi et al. 2001, Bologna 2006, Zimmerman 2009). These dependencies can make failures spread from one to another disrupting society's welfare (President's Comission on Critical Infrastructure Protection 1997, Rinaldi et al. 2001, Sarriegi et al. 2008). Consequently, CIs systems and their dependencies increase the difficulty of crisis management (Dudenhoeffer et al. 2006, Zimmerman 2009).

Researchers in CI protection use the term "cascading effects" to refer to the fact that one triggering event affecting one CI can subsequently impact others (Rinaldi et al. 2001, Rinaldi 2004, Min et al. 2007, Dudenhoeffer et al. 2006, Peerenboom and Fisher 2007, Duenas-Osorio and Vemuru 2009, Stapelberg 2008, Setola et al. 2009, Theoharidou et al. 2010, Deshmukh et al. 2011). This is usually referred as indirect impacts in the literature related to crisis impacts assessment. Cascading effects occur due to the existing dependencies among infrastructures. For example, Hurricane Katrina's direct impacts affected electricity and transport, among other infrastructures, and these effects spread to the water, telecommunications and gas distribution systems (Rahman 2005). Thus, understanding such CIs system dependencies supposes a great challenge (Rinaldi et al. 2001).

It has to be pointed that in the scientific literature most of authors use the concept "CIs interdependencies" for every dependency among CIs, without distinguishing between interdependency and dependency concepts. Dependency is a linkage or connection between two infrastructures, through which the state of one infrastructure influences or is correlated to the state of another (Rinaldi et al. 2001). On the other hand, interdependency is a bidirectional relationship between two infrastructures through which the state of each infrastructure influences or is correlated to the state of the other. More generally, two infrastructures are interdependent when each one is dependent on the other (Rinaldi et al. 2001). For example, if two CIs (A and B) are interdependent, there will be a bidirectional effect as A will rely on B and vice versa (Figure 2.4a). However, if A and B are dependent the effect will be unidirectional, for example A will be dependent on B but B will not be affected by A (Figure 2.4b).

In this research the focus is made on studying CIs dependencies. However, through this research interdependencies among two CIs can be deduced if a bidirectional dependency exists.

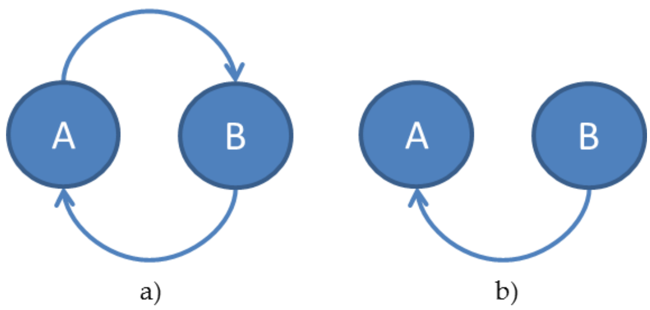

Figure 2.4 Interdependency (a) vs. Dependency (b) concepts

Moreover, CI managers tend to be aware of first order dependencies (direct dependencies) of their CI on other CIs and they know the vulnerabilities these dependencies lead to. However, even though detailed information of individual CIs and their elements can be obtained, the understanding of CIs dependencies is limited because CIs systems complicates the ability of managers to be aware about higher order dependencies (Setola et al. 2008). Higher order dependencies of a CI are dependencies of the CIs it is directly dependent on. For example, if A is dependent on B and B is dependent on C, A will have first order dependency on B and a higher order dependency on C (Figure 2.5). Furthermore, a bidirectional analysis is needed in order to know, apart from CIs dependencies, the influence of any CI on others in order to anticipate how a failure in one CI can spread to others. For example, thinking about a hospital that suffers a blackout. Even if the hospital is well prepared and has its own power generators to deliver energy to all areas, the blackout can affect train service and if the blackout is prolonged it can difficult some doctors or nurses getting to the hospital. Therefore, even if the hospital is not directly dependent on Energy it is indirectly dependent through a direct dependency on Transport.

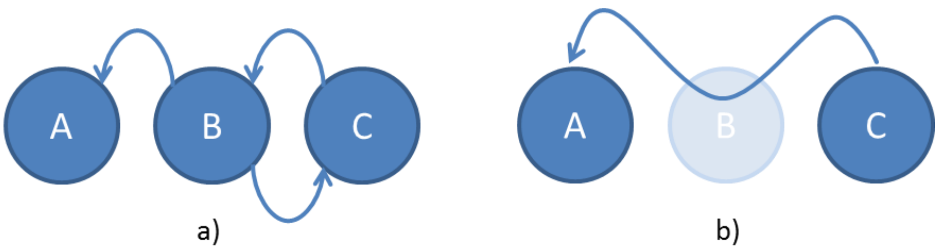

Figure 2.5 First order dependencies (a) and second order dependency (b) among CIs

Consequently, tools to understand the criticality of CIs and their dependencies are needed in order to help crisis managers assess crises impacts. Simulation seems to be an appropriate technique to study holistic CIs dependencies due to the need of including evolution over time and decision making in order to improve crisis management (Sarriegi et al. 2008, Sarriegi et al. 2009). Furthermore, CIs modelling must have a holistic perspective including social, environmental or economic aspects to help in crisis management. However, due to the explained difficulties and particularly due to CIs dependencies overall impact assessment results a difficult task (Setola et al. 2009).

Even if CIs dependencies are unavoidable for their proper performance, this also makes CIs more vulnerable as dependencies increase their risk of failure (Rinaldi et al. 2001, Bologna 2006, Zimmerman 2009) CIs dependencies can be produced by different causes (Dudenhoeffer et al. 2006). The commonly used classification is the one developed by Rinaldi which differentiates among physical, cyber, geographic and logical dependencies (Rinaldi et al. 2001). A Physical dependency occurs when two CIs are dependent on the output from the other CI. The Cyber dependency relies on the information sent and received among CIs. Geographic dependency arises when two CIs are close one to the other so as that a failure in a CI or in the area where is located can affect the other CI. A Logical dependency is when a CI depends on the state of another not by a physical, cyber or geographic dependency, but for example due to policy, legal, or regulatory issues.

Other authors have adapted Rinaldi's classification. For example a similar classification is the one developed by Dudenhoeffer where the names of the categories have been changed to: Physical, Informational, Geospatial and Policy (Dudenhoeffer et al. 2006). Furthermore, in 2009 De Porcellini et al. included a fifth category called Social dependency when disorder is spread due to human activity (De Porcellinis et al. 2009).

2.4.3 CIs dependencies analysis

The study of CIs dependencies is an immature and a growing research field (Rinaldi et al. 2001, Dunn and Wigert 2004, Bologna 2006, Sarriegi et al. 2008, Eusgeld et al. 2011). CIs dependencies can make a short disruption in a CI cause great and long term effects in society (Conrad et al. 2006). In cases where CIs dependencies are cross-border, impacts can also spread to another country creating international effects (The Council of the European Union 2008, Sarriegi et al. 2009). Even though detailed information of individual CIs and their elements can be obtained, the understanding of dependencies between different CIs is limited and often, experts are not completely aware of them (Sarriegi et al. 2008, Setola et al. 2008, Oliva et al. 2010).

Furthermore, the quantification of CIs dependencies can help improving security in order to reduce service disruptions (Zimmerman and Restrepo 2006). Identifying the consequences of a CI failure can improve the detection of CIs affection, the geographic area affected and the economic losses in the occurrence of a crisis (Rinaldi 2004).

The study of CIs dependencies is a complicated task. Therefore, usually when analysing CIs dependencies the focus is made on the analysis of individual or few CIs and do not provide the whole picture of CIs as a system (Schmitz 2003, Rinaldi 2004, Dudenhoeffer et al. 2006, Abele-Wigert and Dunn 2006, Eusgeld et al. 2008, Sarriegi et al. 2008). Therefore, analysing dependencies among all CIs could lead to an improvement of crisis management (Rinaldi et al. 2001, Dudenhoeffer et al. 2006).

However, several researches have been conducted analysing few CIs dependencies (Rinaldi et al. 2001, Schmitz 2003, Rinaldi 2004, Dunn and Wigert 2004, Panzieri et al. 2004, Dudenhoeffer et al. 2006, Zimmerman and Restrepo 2006, Sarriegi et al. 2008, Eusgeld et al. 2008, IRRIIS 2009, CRUTIAL 2009, Bloomfield et al. 2010, Theoharidou et al. 2010, CSIRO 2011) but a holistic analysis including all CIs has to be performed in order to help CI managers having a holistic perspective to improve their management (Dudenhoeffer et al. 2006, Rinaldi et al. 2001). There are some researches (Bush et al. 2005, ANL 2008, Drabble et al. 2009) that analyse and model all the CIs listed by the Department of Homeland Security of the USA (Moteff and Parfomak 2004) but these researches are restricted, usually for military use (Yusta et al. 2011), and little or no information can be obtained about the process of CIs dependencies' measuring. Therefore, holistic research on CIs dependencies available for crisis managers and CI managers is needed.

Furthermore, these researches do not analyse how dependencies and their consequences evolve. However, including evolution over time and long term perspective is needed (Eusgeld et al. 2011) to be able to take into account CIs dependencies evolution over time as effects from one CI to others can spread differently due to time delays. This can complicate the understanding of causes and effects, affecting decisions or policies for crisis management (Sarriegi et al. 2008). For instance, the effect that any CI would have in another infrastructure would not be the same if the CI would be down for few hours or for some days.

2.4.4 CIs dependencies modelling

Several authors have highlighted the importance of the analysis, modelling and simulation of CIs and their dependencies for national and international security (Robinson et al. 1998, Department of Homeland Security 2009, Pederson et al. 2006, Sarriegi et al. 2008, Setola et al. 2008, Oliva et al. 2011). Modelling and simulation of CIs can help crisis management from prevention until response phases (Dudenhoeffer et al. 2006). Furthermore, the criticality of CIs for society makes analysis and modelling of system behaviour a very relevant task (Min et al. 2007).

CIs dependencies modelling is not an easy task and several difficulties have been identified. One of the most important difficulty is the data gathering process (Rinaldi 2004, Beyer and Flentge 2006, Min et al. 2007, Stapelberg 2008, Eusgeld et al. 2011, Oliva et al. 2011) as the relevant information is not easily available due to confidentiality or security issues. Furthermore, there is not an agreed or standard methodology for CIs modelling (Beyer and Flentge 2006, Pederson et al. 2006, Eusgeld et al. 2008). Finding the appropriate level of abstraction for CIs modelling is also a hard task as at a very low level too many details are required (Oliva et al. 2010, Bloomfield et al. 2009) and a too high level could not be appropriate for all systems or could not give significant results (Beyer and Flentge 2006). Furthermore, agents from different expertise have different points of view and information of the same CIs system and therefore, multidisciplinary agents' participation is needed (Peerenboom 2001, Beyer and Flentge 2006, Sarriegi et al. 2008, Sarriegi et al. 2009). Moreover, CI managers are usually aware of the CIs they directly depend (first order dependency) but they do not really know about the effects of higher order dependencies (Setola et al. 2009). Additionally, some of CIs dependencies can be easily identified but others can produce unforeseen effects (Pederson et al. 2006, Beyer and Flentge 2006, Stapelberg 2008).

Efforts have been made by several organisations to analyse and model CIs and their dependencies (Farina et al. 2013). There are several modelling methodologies that have been used for CIs modelling. Examples of these methodologies are: aggregate supply and demand tools, dynamic simulations, agent based models, physics based models, population mobility models, input-output models, effect based operations models, game theory models, risk models, operations research models or high level architecture models (Rinaldi 2004, Stapelberg 2008, Eusgeld et al. 2011). Reviewing several international projects and researches about CIs dependencies modelling agent based, input output and dynamic simulation models have been identified as the most used and recommended methodologies (Peerenboom and Fisher 2007, Setola et al. 2009, Theoharidou et al. 2010, Eusgeld et al. 2011, Kotzanikolaou et al. 2013). These methodologies are explained below.

Agent based models have been widely used for CIs modelling (Pederson et al. 2006, Casalicchio et al. 2007, Stapelberg 2008). Agent based models can represent complex systems behaviour through the analysis of agents interactions. It is appropriate mostly when the focus of the study is based on the complex interactions among agents and with the environment when geographic location is relevant. However, agents based models communication is complicated and it is not the proper modeling when focusing on analysing behavior over time, variability and the interactions among variables (Sveen et al. 2008, Sarriegi et al. 2008, Sarriegi et al. 2009).

Input output models (Leontief 1951) have been also applied to CIs modelling (Haimes et al. 2005, Setola et al. 2009, Oliva et al. 2012). Input output models rely on the flow of resources allowing to obtain an economic perspective (Sarriegi et al. 2008, Sarriegi et al. 2009). However, they are mostly focused on economy, being heavily dependent on reliable data and imply equilibrium conditions. Furthermore, equilibrium conditions are not useful when analysing dynamics of systems produced for example, due to crises disruptions. However, it would be useful to know the affection of economic sectors (Dauelsberg and Outkin 2005, Kujawski 2006, Sveen et al. 2008).

Dynamic simulation such as System Dynamics methodology (Forrester 1961, Sterman 2000) which includes long term perspective and impact evolution over time has also been proposed by several authors as a proper tool for CIs modelling (Zimmerman 2004, Rinaldi 2004, Bush et al. 2005, Zimmerman and Restrepo 2006, Pederson et al. 2006, Min et al. 2007, Sarriegi et al. 2008, LeClaire et al. 2009, Stapelberg 2008). It is based on feedback interactions which is analogous to CIs dependencies. Furthermore, System Dynamics focuses on the behaviour that the interaction of variables leads to and not only on isolated events (Forrester 1961, Sterman 2000, Maani and Cavana 2007). This high aggregation level allows the analysis of crises as evolutionary processes where the activities carried out on pre and post-crisis stages have significant influence during the whole crisis lifecycle. Moreover, System Dynamics can model socio technical systems including not only technical details but also human and organisational aspects (Sarriegi et al. 2008, Sveen et al. 2008, Sarriegi et al. 2009). This means the inclusion of not only quantitative variables (hard variables), but also aspects that, although usually they cannot be empirically measured (soft variables), are known to be critical for decision making as they may have significant side effects during a crisis that can even influence the crisis duration (Lindell and Prater 2003). Moreover, the development of System Dynamics models is made with the cooperation of experts increasing their confidence on the model and helping them to better understand the problem under analysis (Sarriegi et al. 2009).

2.5 Contribution of this research

This research aims to develop the CriMaCID toolbox in order to improve future crisis management. This research is focused on crisis impacts and how a correct assessment of impacts can facilitate crisis managers learning in order to improve management of future crises.

Current impact assessment can be complemented with a holistic analysis including an overall perspective of the generated impacts. Usually, these methodologies focus only in quantifying deaths, injured people and economic impact. However, there is much more to focus on, such as CIs affection and important effects on society's welfare. Then, the important role of CIs is not recognised. Furthermore, there is not an agreed terminology nor for impact sectors designation nor for the indicators included in each sector (Logar and van den Bergh 2011). The CriMaCID toolbox allows having a holistic perspective. Through the real cases analysis and the literature review the CriMaCID toolbox proposed an impact categorisation distinguishing direct from indirect impacts and tangible from intangible ones. The CriMaCID toolbox includes also a specific focus on CIs impacts and dependencies analysis.

Moreover, these methodologies focus on quantifying final accumulated impact and do not analyse how impacts evolve over time generating new ones or aggravating the existing impacts. This is a worthy point when learning from past crisis management. Analysing past crises impacts evolution could help in decision making for mitigation and preparation in order to know what should be improved before. In addition, in the response and recovery phases it would help to make decision about resources deployment in order to minimise consequences. The CriMaCID toolbox allows an evolutionary analysis through the identification of the impacts (direct impacts) that can generate others (indirect impacts). This issue increases crisis managers' awareness about the direct impacts that should be better managed to reduce the generation or aggravation of indirect ones.

Additionally, previous methodologies can be complemented with special attention on CIs. The developed CriMaCID toolbox research makes special focus on CIs as the four tools of the CriMaCID toolbox pay special emphasis on CIs analysis.

CIs do not work on isolation (Katina et al. 2014) so holistic analysis of the CIs and their dependencies is needed. However, most of the research focuses on one or few CIs due to the complexity of including all. The CriMaCID toolbox allows performing the identification of all CIs dependencies of a geographic area (municipal, regional, national, etc.) or even of a particular CI. Moreover, multidisciplinary agents' participation is needed (Peerenboom 2001, Beyer and Flentge 2006, Sarriegi et al. 2008, Sarriegi et al. 2009). The CriMaCID toolbox solves this issue through multidisciplinary experts' participation on the development and validation of the CriMaCID toolbox.

CIs dependencies' effects vary depending on the time a CI fails as impacts increase exponentially from a certain period of time. Then, managers need to be aware about evolution over time. Being aware of the different effects a CI can suffer depending on the time of affection allows managers to carry out management policies in order to minimise future failures or to lessen the impacts caused by a crisis (Fioriti et al. 2010). Then, the tools of the CriMaCID toolbox take into account the different effects of CIs dependencies depending on the failure duration.

The insights gained through modelling a crisis can help developing policies and legal and regulatory issues. Therefore, it is necessary that crisis managers understand existing CIs dependencies in order to effectively manage prevention, preparation, response and recovery phases and to detect current crisis management gaps (Peerenboom et al. 2002, Rinaldi 2004, Pederson et al. 2006, Oliva et al. 2011). Consequently, the CriMaCID toolbox includes simulation. A simulation model has been developed to understand the criticality of CIs, their dependencies interaction and impacts when triggering events strike.

3 Research methodology

This chapter presents the methodology, the development of this research and the different steps carried out.

Knowledge about crisis management resides in experts minds. Therefore, multidisciplinary experts from different organisations and countries have taken part in this research for the development and validation of the CriMaCID toolbox.

Research methods such as literature review, multiple case studies analysis, survey, simulation and interviews have been used to develop and validate the CriMaCID toolbox.

3.1 Introduction

In this research the CriMaCID toolbox has been developed in order to help crisis managers and CI managers to improve their analysis of crises' impacts with special focus on CIs and their dependencies. The CriMaCID toolbox consists of four tools: 1) *Impact indicators framework*, 2) *CIs dependency-influence cluster*, 3) *CI dependency radar*, and 4) *Simulation model*. Each tool has different research methodology requirements and therefore, the approach used for developing the tools consists of the following research methods: literature review, multiple case studies analysis, survey, modelling and interviews.

Before focusing on the research methodology followed for the development and validation of the CriMaCID toolbox first the integration of the four tools has to be explained.

The *Impact indicators framework* has been developed in order to help crisis managers identifying the potential impacts that they should manage. The indicators and their categorization have been gathered from a literature review about crises impacts assessment methodologies. From literature review we identified a limitation in current impact assessment methodologies, there is a need to study CIs role on impacts generation and aggravation due to society's dependency on their proper performance. Therefore, we decided to analyse CIs dependencies through a literature review on this issue. As there was a need of analysing CIs with a holistic perspective the *CIs dependency-influence cluster* tool has been developed. A survey through an online questionnaire has been carried out in order to identify CIs dependencies and their evidences. Subsequently, through the information gathered the dependency and influence level of each type of CI has been identified and the evidences to explain these dependencies have been gathered. Then, taking into account experts comments about the complexity of the concept of dependency, the research has been focused on the identification of the dependency dimensions that help understanding CI dependencies. Therefore, the *CI dependency radar* has been developed. This tool can help CI managers to identify their current dependency level, compare the information with a target defined level and think about policies to achieve this target. Additionally, through simulation the understanding of the complex interactions of variables can be improved. Moreover, unknown scenarios can be simulated. Therefore, a *Simulation model* has been developed to analyse evolution over time of CIs dependencies and the generated impacts in order to increase crisis managers' awareness about the complex interaction of variables.

Figure 3.1 shows the different research methods applied for developing each of the four tools of the CriMaCID toolbox. Furthermore, the results obtained and the publications gathered in each phases are specified.

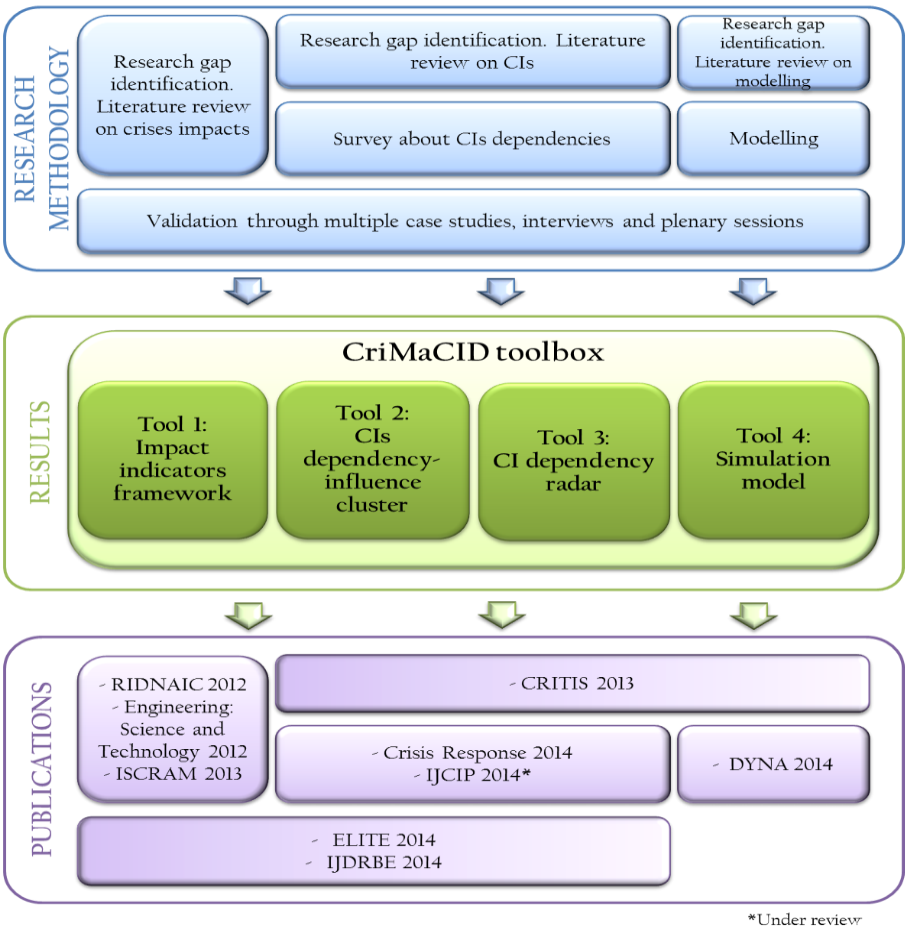

Figure 3.1 Research methodology

In this chapter the different research methods applied for the development and validation of each tool are explained.

3.2 *Impact indicators framework*

The methodology to identify research gaps and to extract the impact indicators of the CriMaCID toolbox has been based on literature review.

The *Impact indicators framework* is composed by 152 impact indicators classified in four sectors distinguishing by their nature in direct or indirect and tangible or intangible impacts.

3.2.1 Research gap and impact indicators identification. Literature review

Currently used impact assessment methodologies have been analysed in order to determine if there were any common categories or indicators and to identify their barriers and limitations.

The aim of the literature review was first to discover what has been done until now in the impact analysis field and to find out the current gaps where more research is still needed.

A review and analysis of the methodologies that are currently used in the literature for the identification, classification and assessment of the impacts of natural disasters has been conducted (Laugé et al. 2012). For this purpose, classifications used by international agencies and organisations from different countries and the ones used in several research projects funded by the European Union were analysed. From this review the different impact categorisations have been proposed. Four different sectors (CIs, social, economic and environmental sectors) to classify impacts have been identified. Additionally, apart from sectors classification, impacts have been also classified as direct versus indirect impacts and tangible versus intangible impacts. These categories have been included into the *Impact indicators framework* tool. Furthermore, the list of impact indicators was developed.

From this review we obtained a list of impact indicators classified by sectors and nature. As a result of this analysis, an important conclusion is that when CIs are damaged crisis consequences are aggravated and prolonged over time. Actually, even if this affection significantly decreases society's welfare level, it does not receive any special attention in impacts assessment methodologies.

3.3 CIs dependency analysis tools: *CIs dependency-influence cluster* and *CI dependency radar*

Special focus has been made based on the important role that CIs play in impacts magnification which requires a deep analysis of CIs and their characteristics. Below the research methods used for the development of the *CIs dependency-influence cluster* and the *CI dependency radar* tools are explained.

3.3.1 Research gap identification. Literature review

Literature about CIs characteristics and several research projects on CIs have been reviewed in order to analyse their role on impacts propagation.

From this analysis we concluded that even though progress has been made on researching about CIs there is still a need of more research about CIs systems and their dependencies (Peerenboom and Fisher 2007, Eusgeld et al. 2008). Even though detailed information of individual CIs and their elements can be obtained, the understanding of dependencies between different CIs is limited and a holistic analysis including all CIs has to be performed. Researches about CIs dependencies do not analysis evolution. However, crisis managers and CI managers have to be aware of the different effects a CI can suffer depending on the time of affection.

Therefore, the focus of this research has been to develop tools to improve the role of CIs and their dependencies on impact generation.

3.3.2 Survey process

The knowledge about CIs dependencies and their effects resides mostly in the minds of CI managers. Therefore, in order to analyse CIs dependencies a survey through an online questionnaire was chosen as research method. The aim of this questionnaire is to help crisis managers finding out the dependency level among CIs and the evidences that create the dependency. The questionnaire allows analysing CIs dependencies asking experts to evaluate how a failed CI can impact on other CIs and how a CI can be affected when other CIs fail.

As Groves (2013) defines "the survey is a systematic method for gathering information from (a sample of) entities for the purpose of constructing quantitative descriptors of the attributes of the larger population of which the entities are members".

A survey consists of a systematic and standardised approach to collect information from a large group of people through questionnaires (PIRSA 2000, Otter and Borja 2001). Four basic tasks compose the core of the survey method:

1. *Sampling:* a representative sample of the population should be selected to complete the questionnaire. This sample should provide unbiased estimates of the characteristics of the chosen population.
2. *Inference:* statistical inference allows the generalisation of sample results to estimate the parameters of the population within calculable margin of errors.
3. *Measurement:* how the questions are asked and the format of the questionnaires allows experts to provide valid and reliable answers.
4. *Analysis:* Data analysis techniques facilitate the analysis of the data and the definition of statistical relationships among the variables.

The collection of the information can be performed using three different means: mail questionnaire, telephone interview or face-to-face interview (Norris 2005). This research used online mail questionnaire to conduct the survey. Online questionnaire is a cheap mean to conduct a survey and very easy to distribute since there are free online tools to develop the survey and the tool offers the possibility to send a URL to each expert. Furthermore, experts can easily access to it with just clicking on it. However, some authors (Pelling et al. 2002) argue that mail-questionnaire presents some pitfalls such as significantly lower response rates or low control regarding the people who can access to the questionnaire. This research has taken into account all these issues and has found a solution in order to avoid these problems by sending personalised emails to experts and sending personal URLs.

Online survey development comprises five phases: planning of the survey, writing the questionnaire, designing the web questionnaire, sending invitations and data collection (Gonzalez-Bañales and Adam 2007).

1. *Planning of the survey*: After reviewing the analysis about CIs and their dependencies we identified the need of determining which CIs were more critical. Therefore, we decided to develop a survey through an online questionnaire in order to identify which CIs were more dependent on or influenced by others.
2. *Writing the questionnaire:* Through the survey we wanted to know the evidences and effects that made a CI dependent on another and the time it will require to recover a normal activity once the failed CI was restored. Furthermore, we asked the effect over a CI if any other would be damaged for a certain period of time in order to study how impacts evolve over time.
3. *Designing the web questionnaire:* a free tool was used to design and implement the online questionnaire (http://www.encuestafacil.com/). The complete survey can be found in Appendix A.
4. *Sending invitations:* The survey was sent to 154 CI organisations and 52 answers were received from 9 different countries and one international organisation. The organisations that took place in the survey can be found in Table 3.1.
5. *Data collection*: We obtained a response rate of 33.8%. Answers were received individually from the organisations and were compiled in Excel sheets in order to analyse all together. Results can be found in Section 4.3.

CI Sector	Organisation	Country
Energy	REE (Spanish Electric Net company)	Spain
	Iberdrola Energy company	Spain
	ABB electric ingenieering	Germany
	ELES Slovenian energy comany	Slovenia
	Ikusi technlogy for infrastructures	Spain
	Matia Fundazioa	Spain
ICT	ICT department of TECNUN	Spain
	Indra Dirección Seguridad de Sistemas	Spain
	New Jersey Institute of Technology	USA
	Basque Government emergency service	Spain
	Univ.Ljubljana	Slovenia
	University at Albany	USA
	EPES service	Spain
Water	Asociación Española Agua y Saneamiento	Spain
	Consorcio de Aguas de Gipuzkoa	Spain
	ICRA (Water research centre)	Spain
Food	García Carrión food comany	Spain
	EROSKI company	Spain
	CNPIC (Spanish National CI Protection centre)	Spain
	BMELV food company	Germany
	BLE food company	Germany
	OKIN food company	Spain
	Humboldt Universität zu Berlin	Germany
	NATRA food company	Spain
	BBK food company	Germany
Health	International Association of Emergency Managers	Europe
	Policlínica Hospital	Spain
	FRK Red Cross centre	Austria
	Riojasalud Health centre	Spain
	CUN (University of Navarra Hospital)	Spain
Financial	Kutxabank	Spain
	BBK bank	Spain
	Caja Rural Navarra bank	Spain
Public and Legal Order and Safety	Police Academy of the Netherlands	Netherlands
	San Sebastian Local Police	Spain
	APTB-Catalonian firefighter service	Spain
Civil Administration	SGSP (The Main School of Fire Service of Warsaw)	Poland
	DYA (Ambulance service)	Spain
	Austrian Federal Ministry of Defence and Sports	Austria
	Spanish emergency and civil protection department	Spain
	Firefighter department of Catalonia	Spain
Transport	Puerto Pasajes	Spain
	Scientist at a Consultant office on modelling/simulation supply	Germany
	Transport cluster of Guipúzcoa	Spain
	Bidelan	Spain
	Puerto Bilbao	Spain
Chemical and Nuclear Industry	Svensk Energi–Swedenergy–AB	Sweden
	Risk Initiative and Statistical Consultancy Unit University of Warwick	UK
	Chemical Industry from Rentería	Spain
Space and Research	CSIC (panish National Research Council)	Spain
	New Jersey Institute of Technology	USA
	Argonnne National Laboratory	USA

Table 3.1 Organisations who answered the survey

Before sending the questionnaire to experts, a pilot test was conducted. Once the questionnaire draft was done, we sent it to six experts from different CIs to get feedback about the clarity, completeness, and appropriateness of the survey introduction, instructions, and questions. As a result of the pilot study, changes were made to the language used in the instructions and to the formulation of some questions.

Organisations related to CIs in different countries of Europe, North America and Asia were contacted by email. The email included an explanation of the research, the aim of the questionnaire and a request for their collaboration.

The online questionnaire is divided in three sections which are explained below. The complete questionnaire can be found in Appendix A.

3.3.2.1 First section of the questionnaire

In the first section of the questionnaire (Figure 3.2) the list of CIs defined by the European Programme for CI Protection (Commission of the European Communities 2005) was included and the experts were asked to choose the CI they worked on, or in the case of researches, the CIs they felt more comfortable answering about. Table 3.2 shows the number and percentage of questionnaires completed by the experts that correspond to each of the eleven CIs considered in this research.

First, we would like to know the CI on which you work or feel most comfortable answering about. We will then refer to this CI as "your" CI. You must select only one CI. If you want to answer to more than one CI, please fulfil one questionnaires for each CI

- ☐ Energy
- ☐ Information and Communication Technologies
- ☐ Water
- ☐ Food
- ☐ Health
- ☐ Financial
- ☐ Public & Legal Order and Safety
- ☐ Civil Administration
- ☐ Transport
- ☐ Chemical and Nuclear Industry
- ☐ Space and Research

Figure 3.2 1st section of the questionnaire: experts' background

CIs	Questionnaires
Energy	6 (11.5%)
ICT	7 (13.4%)
Water	3 (5.8%)
Food	9 (17.3%)
Health	5 (9.6%)
Financial	3 (5.8%)
Public and Legal Order and Safety	3 (5.8%)
Civil Administration	5 (9.6%)
Transport	5 (9.6%)
Chemical and Nuclear Industry	3 (5.8%)
Space and Research	3 (5.8%)
TOTAL	*52 (100%)*

Table 3.2 Number (Percentage) of answers received for each CI

3.3.2.2 Second section of the questionnaire

The second section (Figure 3.3) of the questionnaire aims to perform a qualitative analysis related to better define the evidences that make a CI dependent of another one. This section was focused first on the consequences due to a failure in another CI. Secondly, the aim of this section was also to analyse the time the CI needed to recover once the failed CI started working again. For that reason, experts had to answer about a crisis which did not affect their CI but some other CI. Then, they described the evidences which make their CI dependent on the affected CI indicating the most important dependencies. Furthermore, experts were asked to answer about their recovery time when the affected CI is repaired, in order to know if their recovery is immediate or needs some time.

> Think about a natural disaster that has not affected your CI but others. We would like you to describe the evidences which make your CI dependent on other CIs. Please indicate the most important dependencies (up to 3). Furthermore, when the affected CI is repaired, will your recovery be immediate or delayed?
>
> a) Which are the detailed consequences on your CI if CI X is down for more than 48 hours?
> b) Now thinking about the time for recovery. When CI X is repaired or restored, how much time will you need time to recover your CI normal activity?
>
> ☐ Less than 1h.
> ☐ Less than 6h.
> ☐ More than 6h.
> ☐ Other (Please specify):

Figure 3.3 2nd section of the questionnaire: CI dependencies evidences

Answers to this part of the questionnaire were open; experts could write up to three evidences about how a failure in each of the other ten CIs affect their CI performance.

The answers received for this section were really different. Not only when matching the eleven CI sectors but also when comparing answers from two different CIs of the same sector. We aimed to obtain different evidences from CI sectors and therefore, we decided to choose different CIs from the same CI sector. All answers were collected and analysed in order to identify evidences which could help understanding dependencies among CIs. From this section analysis a template to include the evidences has been created. The results of this question are included in Section 4.3.

On the other hand, experts were asked to define the time needed to recover their normal activity once the failed CI is restored. In this case, experts had to choose different periods of time or propose a different one. Taking into account the different CI organisations and their different preparation in face of other CIs failures, answers were significantly different in each case. For example, the answers received when asking about the time that Energy CI will need to recover its normal activity after a failure of 48 hours in ICT vary from less than one hour to less than six hours. These differences among the answers depend on the CI since each CI can have different redundant equipment, protocols or training policies to face an ICT failure. The time for recovery is particular for each organisation and no specific time to recover normal activity can be identified for each sector of CIs. Consequently, it can be concluded that the differences between CIs of the same sector are significant and this analysis should be made specifically for each sector.

3.3.2.3 Third section of the questionnaire

Through the third section (Figure 3.4) the experts were asked to answer about the extent of the effects on their own CI if any other CI failed completely. The proposed scenario was focused on a complete failure of a CI, where the CI cannot deliver any service to others. We wanted managers to think in a similar scenario and therefore, we chose a total failure scenario. A scenario of a partial damage of a CI could have led managers to imagine very different situations. Therefore, we asked experts to rate their dependency on the rest of CIs when other CIs cannot deliver any service during different periods of time. The aim was to know the magnitude of the effects on each CI depending on the time another CI was not working at all. For that reason, experts were asked to answer about their CI dependency on the other 10 CIs in different periods of total failure, from less than two hours to more than one week. The answers had to be given related to a specific scale from "0-No effect" to "5-Very high effect". The scale was a measure of the effects that CI could suffer due to a direct dependency on another CI if this CI fails for a certain period of time. The full scale is explained in Figure 3.4.

Think about the degree of effects on your CI if any other CI fails due to its dependency on the failed CI. Which effect would your CI have if the following CIs are down for less than 2h, less than 6h, less than 12h, less than 24h, more than 24h or more than 1 week? We would like you to answer considering this scale:

Scale	Definition
0	No effect: My CI can operate as usual
1	Very low effect: My CI can operate deploying few extra resources
2	Low effect: My CI can operate deploying huge amount of extra resources
3	Medium effect: My CI can only deliver critical services deploying few extra resources
4	High effect: My CI can only deliver critical services deploying huge amount of extra resources
5	Very high effect: My CI cannot continue operating

Figure 3.4 3rd section of the questionnaire: effects of CI dependencies

The results obtained through the online questionnaire can be found in Appendix B. Table 3.3 is included as an example of these results and it shows CIs dependencies if other CIs are not working to any extent for less than two hours. The data included in this table has been calculated as the average of the answers given by experts for each CI.

The first row of Table 3.3 shows the effects of being without Energy for a period of time of less than two hours. On the other hand, the first column of Table 3.3 represents how a failure in the other CIs would affect Energy if the failure lasts less than two hours. Same explanation of rows and columns is valid for the other tables only varying the failure timeframe.

Effect on / Failed CI	Energy	ICT	Water	Food	Health	Financial	Order & Safety	Civil Admin.	Transport	Chemical & Nuclear	Space & Research
Energy		0,86	1,33	2,89	1,40	2,67	1,67	0,40	2,40	4,67	1,33
ICT	2,67		1,00	1,67	2,20	2,33	2,67	1,40	2,40	2,67	1,00
Water	0,83	0,57		1,56	1,20	0,00	1,00	0,60	0,20	1,00	0,67
Food	0,00	0,14	0,00		0,60	0,00	0,33	0,20	0,00	0,33	0,33
Health	0,50	0,14	0,00	0,78		0,00	1,67	0,60	0,00	0,33	0,00
Financial	0,17	0,71	0,00	1,22	0,20		0,33	0,00	0,60	1,33	0,00
Order & Safety	0,83	0,43	0,33	1,00	1,00	1,67		1,40	0,80	1,00	0,00
Civil Admin.	0,33	0,86	0,00	0,38	1,00	0,33	1,00		0,20	1,00	0,00
Transport	1,17	1,00	0,00	1,11	1,40	1,00	2,00	0,60		0,00	0,00
Chemical & Nuclear	1,50	0,29	0,00	0,22	0,40	0,00	2,00	1,40	0,20		0,00
Space & Research	0,17	0,57	0,00	0,00	0,00	0,00	0,00	0,00	0,20	0,00	

Table 3.3 CIs dependencies if other CIs are down less than two hours

For example, as it can be seen in Table 3.3, experts have quantified the dependency of Energy on ICT with a value of 2.67, if ICT is not working less than two hours. This means that Energy CI will have to deploy extra resources in order to keep communications ongoing at least to deliver critical services. However, focusing on the dependency of ICT on Energy, if Energy is not working, for a period of time of less than two hours, experts considered that ICT could work as usual only deploying few extra resources (i.e. switching on power generators).

Furthermore, through this research higher order dependencies can be identified in the different periods of time. An example of higher order dependencies is the higher order dependency of Civil Administration CI on Financial CI. Figure 3.5a shows first order dependencies among these CIs. The Financial failure will directly affect Transport CI (first order dependency). For example, a failure in payment services could lead to problems to Transport CI if customers cannot buy tickets. However, Civil Administration CI will not be affected as it is not directly dependent on Financial CI. Then, taking into account that Transport CI has failed, this failure will affect Civil Administration CI as it has a first order dependency on Transport CI. For example, administration workers could have problems to go to work. As a result, even if Civil Administration CI is not directly dependent on Financial CI, it will be affected through a second order dependency (Figure 3.5b). Therefore, being aware not only about direct dependencies but also higher order ones is essential for CI managers in order to properly manage them and to prevent or minimise future crises.

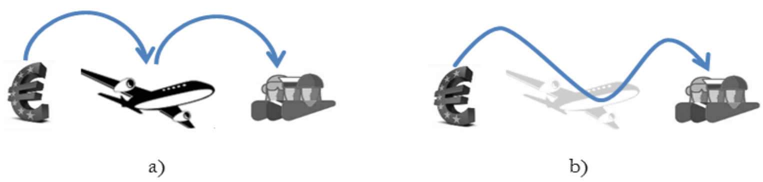

Figure 3.5 Example of first (a) and second (b) order dependencies among CIs

The different periods of failure analysed through the questionnaire showed that depending on the time a CI does not work, the effect on the rest of CIs will be different. It is obvious that bigger the time a CI is not working the higher the effects on the rest of CIs. However, an important issue that CI managers need to know is that there is a time period from what the effects of dependencies become significant. Usually, CIs suffer short duration triggering events but even if managers do not consider longer triggering events or unexpected ones so likely, preparation and response to face them have to be improved as consequences increase exponentially.

The gathered data from the online questionnaire allows clustering CIs depending on their dependency or influence level on others. Then, the process to apply this tool is the following. Crisis managers will have to identify the influence or dependency level of each CI based on the results of the questionnaire and the evidences that these dependencies lead to. Therefore, the process of clustering CIs will be performed by crisis managers. Firstly, they will have to identify the CIs of their geographic area (municipal, regional, national, etc.). Secondly, crisis managers will have to send to CI managers the questionnaire. Thirdly, once having gathered the information crisis managers will be able to define CIs dependency and influence on others.

Additionally, when carrying out the questionnaire experts commented about the complexity of identifying dependencies even focused on a single CI and the difficulty to understand and manage these dependencies. Consequently, we focused our research in analysing which dimensions could be identified to determine CIs dependencies. Taking into account experts comments and literature review five dimension to determine CIs dependencies were identified. In order to facilitate the understanding of CIs dependencies, a radar like tool has been developed: the *CI dependency radar* (Figure 3.6).

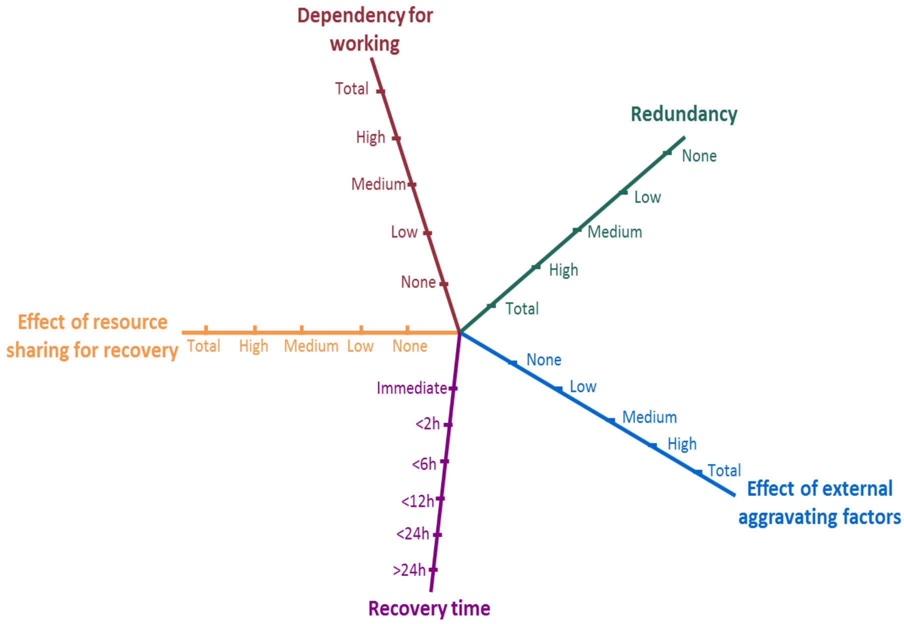

Figure 3.6 CI dependency radar

3.4 *Simulation model*

Simulation is an appropriate technique to study CIs dependencies due to its complexity and the need to include the system's dynamics through the analysis of variables' evolution over time (Sarriegi et al. 2008, Sarriegi et al. 2009). Therefore, the CriMaCID toolbox includes a *Simulation model* in order to show how it can help to better understand the complex performance of the problem under analysis. Moreover, the *Simulation model* developed in this research helps learning from crises that have not occurred yet and therefore the learning cannot be based only on past experiences. The *Simulation model* analyses the cause and effect relationships among CIs and their dependencies and simulates the way dependencies and associated impacts evolve over time.

System Dynamic (SD) simulation methodology has been chosen due to modelling aggregation level and focusing on the needs of the end users to better understand the interaction among variables. The developed SD *Simulation model* allows running different scenarios in order to obtain a broad visualisation of the problem. When designing and implementing those scenarios and policies on the *Simulation model*, different behaviours are obtained. The scope of the *Simulation model* does not concentrate on the technical details of CIs, but rather try to embrace the big picture of CIs dependencies and their associated impacts.

In the *Simulation model* we have included data gathered through the meetings with CI managers and from the survey. Other needed data have been estimated, based on the few real data available. Furthermore, the aggregation level is high but it still allows including enough detail about CIs performance, their dependencies and the effects of carrying out recovery policies.

Taking into account the *CIs dependency-influence cluster* we decided to choose one CI from each cluster to include in the *Simulation model*. However, finally we decided not to include Space and Research CI in the model for two reasons. First reason is that Space and Research is the most independent CI and therefore, if the *Simulation model* wants to analyse the relationship among impacts its role will not be very relevant. And the second reason is based on the previous work by Macaulay (2009) where he also decided to exclude this CI from his research after comparing the CIs listed by the United States of America, Canada and the European Commission. In his work Macaulay explains that even the CIs are called differently the three lists include the same CIs except for Space and Research as only the European Commission considers it as a CI.

Crisis managers can use the developed *Simulation model* for training, as it enables the integration of knowledge from all involved managers. Some of the simulated behaviour are not straightforward to predict, as there are time delays involved between causes and effects and between actions and reactions. The analysis of the generated behaviours allows crisis managers to obtain an overall perspective for a better understanding of crises, as they can observe how their decisions affect crises' evolution and the generated impacts. The scenarios and policies are degrees of freedom that can be modified in the *Simulation model* to obtain different behaviours that enable observing the impacts of each policy in the overall system in addition to understanding the causes of undesirable and unpredicted dynamics.

3.5 Validation process

Once the CriMaCID toolbox was developed its usefulness had to be confirmed. For that reason, a validation process was carried out through case studies, interviews and plenary sessions with the collaboration of several Basque CIs organisations. Detailed information about the validation process can be found in Chapter 5.

The case study is defined as "an empirical inquiry that investigates a contemporary phenomenon within its real-life context, when the boundaries between phenomenon and context are not clearly evident, and in which multiple sources of evidence are used" (National Center for PTSD 2010). This research method is considered a robust method particularly when a holistic, in-depth investigation is required (FORA 2009). Although case study has mostly been used in the exploratory phase to develop research ideas and questions, it is also very suitable to theory testing or refinement (Taylor and Kent 2007, MaRS 2010). The case study methodology is a versatile research method, that can be used both with exploratory purposes but also to construct, extend or test a theory (Rowley 2002, Yin 1994). Case study also helps in raising more confidence (National Research Council 1999).

To ensure the validity and reliability of the study Yin (2006) outlined four logical tests which help gaining more confidence in the obtained results:

- *Construct validity:* this refers that obtained data should be reliable and adequate for our research. Gathering information from multiple sources such as interviews, internal documents, and observations ensures the reliability and correctness of the data.

- *Internal validity:* this refers to the data analysis where the researcher defines some relationships and patterns and compares with the expected ones.
- *External validity:* this refers to if obtained results from the study can be generalised to other cases or not.
- *Reliability:* this refers to the reliability level of the study, that is, if the same study was conducted, following the same procedures, the same results should be obtained.

Firstly, the validation of the *Impact indicators framework* was performed through multiple case studies based on past crises. Reports from several crises such as floods, hurricanes, earthquakes, volcanic ash clouds, and accidents such as nuclear radiations or oil spills were reviewed in order to assure the holistic perspective of the *Impact indicators framework* (Table 3.4).

Crisis type	Triggering event	Crisis name	Year
Natural disaster	Flood	Bilbao floods	1983
Accident	Nuclear accident	Chernobyl nuclear accident	1986
Accident	Oil spill	Prestige oil spill	2002
Natural disaster	Hurricane	Katrina hurricane	2005
Natural disaster	Earthquake	Haitian earthquake	2010
Natural disaster	Volcanic ash cloud	Eyjafjallajökull volcanic ash cloud	2010
Natural disaster	Hurricane	Sandy hurricane	2012

Table 3.4 Analysed crises through the multiple case studies

Afterwards, interviews with crisis managers and CI managers were carried out. The aim of the interviews was to validate the CriMaCID toolbox obtaining information about the already implemented tools regarding impact indicators and CIs and their dependencies analysis and confirming the usefulness of the toolbox.

The validation process was focused on those CIs that were found in the survey as the most influential ones. These CIs are the ones that can suffer more impacts from their dependencies on others. Therefore, these CIs should be the more interested in knowing tools that could help them understanding these dependencies. These three CIs are Food, Health and Public and Legal Order and Safety. Some CIs included in Civil Administration CI were also included in the validation process since some services' proper working, such as ambulances or fight fighters, are related to the police service which is included into Public and Legal Order and Safety CI.

The aim of the process of validation with CI managers was to present and discuss the assumptions made during the CriMaCID toolbox development in order to analyse the usefulness of the developed tools for their CIs. Sixteen CI organisations of the Basque Country took part. In Section 5.2.2 a list with the sixteen organisations interviewed is included.

Additionally three plenary sessions were carried out. The first plenary session was organised in February 2014 in Donostia-San Sebastian. To this session civil protection services and emergency services were invited and eight participants from a total of five organisations took part (see Section 5.2.3 for a complete list of participants).

The second session held on May 2014 was part of the Conference of Risk and Emergency Management organised by the city council of Donostia-San Sebastian. 400 participants belonging to civil protection organisations, emergency services, research centres CI managers and industries participated in this conference.

Finally, a plenary session with crisis managers and CI organisations was arranged. The structure of this session was similar to the structure followed during interviews but after this session a questionnaire was given to participants in order to obtain information about their opinions regarding the

CriMaCID toolbox. In this plenary session fifteen participants from thirteen organisations took part. Section 5.2.3 includes a list of the organisations.

3.6 Conclusions

The research methodology for the development and validation of the CriMaCID toolbox has been explained based on the tools that have been developed during this thesis.

For the development and validation of each tool different research methods have been used. The research methods applied are literature review, multiple case studies analysis, survey, simulation and interviews.

The collaboration of crisis managers and CI managers has been crucial for the development and validation of the CriMaCID toolbox. Therefore, some of the research methods have been focused on gathering knowledge which mainly resides in experts minds.

4 The CriMaCID toolbox

In this chapter, the CriMaCID toolbox is presented. The CriMaCID toolbox consists of four tools: 1) Impact indicators framework, 2) CIs dependency-influence cluster, 3) CI dependency radar and 4) Simulation model. The objective of the CriMaCID toolbox is to support crisis managers and CI managers to reduce future crisis impacts. Crisis impacts, in addition to being a record of consequences, can be used by crisis managers to analyse behaviour over time when applying different policies and to identify CIs dependencies. Therefore, this toolbox aims to help crisis managers and CI managers to reduce future crisis impacts by implementing new policies or improving existing ones consequently increasing resilience level.

4.1 Introduction

The aim of the CriMaCID toolbox is to provide tools to crisis managers and CI managers in order to allow them reducing future crisis impacts through better managing future crises. The CriMaCID toolbox allows crisis managers to have a holistic and dynamic perspective of crisis impacts in order to increase their awareness about the impacts a crisis can generate on a geographic area (municipal, regional, national, etc.) or on a particular CI. Then, crisis managers and CI managers can improve their management through the development and implementation of prevention, preparation, response and recovery policies.

The distinguishing and valuable features of the CriMaCID toolbox, comparing it with current impact assessment methodologies, are the holistic analysis of impacts and CIs dependencies, together with the dynamic perspective.

The CriMaCID toolbox allows having a holistic perspective as it includes a complete study of the impacts that could be generated by a crisis, focusing on the ones affecting CIs. Then, the CriMaCID toolbox categorises impacts based on their nature and sector. Moreover, being CIs crucial for societies' welfare a holistic analysis of CIs dependencies that could lead to CIs disruptions has been carried out. The developed research makes special focus on CIs and their dependencies as the four tools include or are focused on CIs analysis. The toolbox allows performing the identification of CIs dependencies in a geographic area or even of a single CI.

The dynamic perspective of the CriMaCID toolbox allows increasing managers' awareness about impacts behaviour over time. Due to cause and effect relationships as long as direct impacts persist, there will be more indirect impacts generated. Then, identifying direct impacts and properly managing their consequences the generation or aggravation of indirect ones can be reduced. It is therefore recommended to take into account relationships among impacts and evolution over time. The study of these relations is crucial for a correct crisis management because impacts can still be generated years after the occurrence of the triggering event. Then, the CriMaCID toolbox takes into account the different effects of CIs dependencies depending on the failure duration. Besides, the CriMaCID toolbox includes simulation to help understanding how dependencies can make impacts to cascade. The model can be used by crisis managers and CI managers as an analysis and training tool to increase their awareness about systems complexity and to test the effectiveness of the implementation of prevention, preparation, response and recovery policies.

The CriMaCID toolbox provides a holistic and dynamic perspective (see Figure 4.1) by means of four tools:

1. *Impact indicators framework* comprises 152 impact indicators classified by their nature and the affected sector. The aim of this tool is to provide a holistic perspective including different indicators of impacts that crises could generate. The tool increases the awareness of crisis managers in order to carry out policies to avoid impacts occurrence or at least diminish them.
2. *CIs dependency-influence cluster* allows crisis managers and CI managers to be aware of the most influential or dependent CIs in a geographic area. The objectives are: 1) to improve preparation of crisis managers and CI managers against failures of the most influential CIs and, as consequence, 2) to increase the resilience of the most dependent CIs to minimise future impacts.
3. *CI dependency radar* is focused on the analysis of a single CI and its dependencies. This tool helps a CI manager to make an analysis of its specific dependencies on the rest of CIs. In this case, the tool has to be applied in each CI in order obtain a graphical representation of their level of dependency in different periods of failure on other CIs.
4. *Simulation model* allows crisis managers and CI managers to better understand the interaction of the multiple variables that interact during a crisis. A *Simulation model* has been developed focused on analysing the influence and dependencies of the CIs included

within a geographic area and the impacts when damaged by a triggering event.

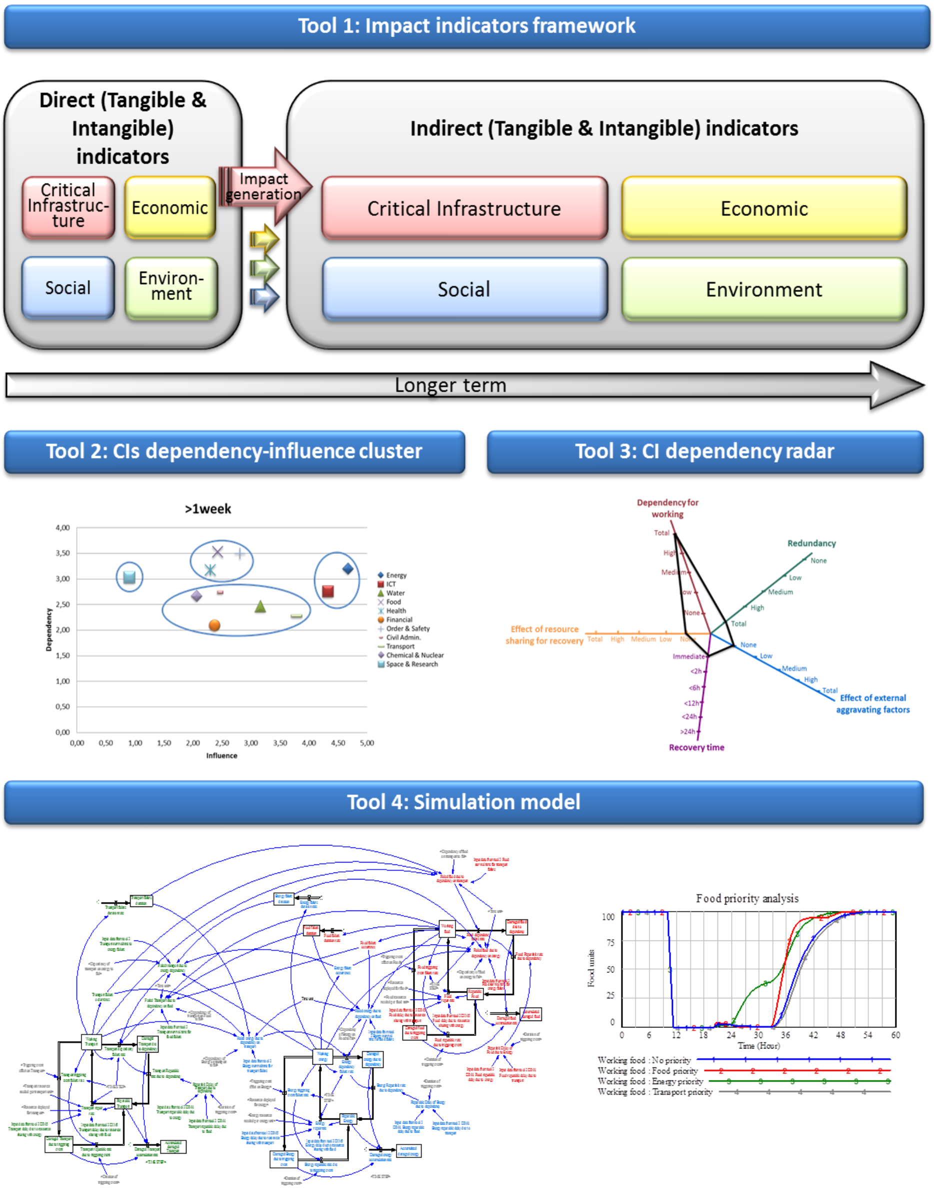

Figure 4.1 The CriMaCID toolbox

Moreover, the tools of the CriMaCID toolbox have been developed taking into account that the analysis of impact assessment can be performed using different approaches (Table 4.1). When the focus is made on improving crisis management of a geographic area a more aggregated approach of which are the most influential or dependent CIs will be required instead of focusing on particularities of each CI. However, if the analysis is focused on one specific CI a more detailed study of its dependencies on other CIs will be required. In this case, there are several issues that have to be taken into account such as the level of affection and the time needed to recovery among others. Therefore, depending on the purpose of the analysis, the chosen tool will be different. In the CriMaCID toolbox two different units of analysis have been considered: geographic area or single CI. Each unit of analysis allows satisfying the specific needs of crisis managers at different levels (civil protection, emergency services and other authorities) and also the needs of single CIs. The first unit of analysis refers to a geographic area unit of analysis where crisis managers are the target end users. The second unit of analysis is valuable for single CIs where CI managers will be the end users.

Tool	Unit of analysis
Impact indicators framework	Geographic area
CIs dependency-influence cluster	Geographic area
CI dependency radar	Single CI
Simulation model	Geographic area

Table 4.1 Unit of analysis of each tool

In the following sections of this chapter each tool of the CriMaCID toolbox is explained. The structure of the following sections aims to first describe the tool, then explain how the tool is used and finally, provide examples of how they have been applied through this research.

4.2 1st tool: *Impact indicators framework*

The review of existing impact assessment methodologies carried out in Section 2.3 points out that there is a need of developing a holistic impact assessment which comprises all kind of impacts generated with special attention on CIs, due to their important role on impact generation. These methodologies do not pay special attention on CIs even if CIs proper performance is essential for society's welfare. Crisis managers and CI managers need to be aware of the importance of CIs when managing a crisis and how dependencies make impacts spread from one CI to others or to different sectors.

4.2.1 *Impact indicators framework* description

The *Impact indicators framework* classifies impacts according to their nature and sector (Figure 4.2). The included sectors have been defined based on the impacts assessment methodologies analysed in Section 2.3. The *Impact indicators framework* classifies impacts by sectors including: Economic, Social, Environmental and CIs. In addition, impacts have been classified according to their nature, differentiating direct impacts from indirect ones and also tangible from intangible. In the developed example, in each sector several indicators have been listed comprising a total of 152 impact indicators.

Direct impacts occur after the triggering event whereas indirect impacts, being consequence of the direct ones, spread over a longer time. Hence, as the time goes by, indirect impacts' assessment becomes more and more difficult.

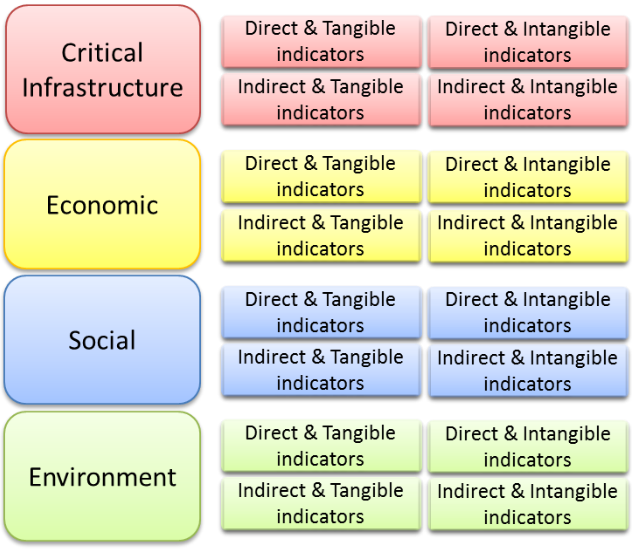

Figure 4.2 Impact indicators' sectors and categories

Additionally, in each sector different families have been identified in order to help identifying the indicators corresponding to each one. Following the sectors and families of the *Impact indicators framework* tool are explained.

The *Impact indicators framework* does not include impact indicators related to macroeconomic effects (for example GDP). Macroeconomic indicators are gathered through the aggregation of several indicators already included in the *Impact indicators framework*. Therefore, including macroeconomic indicators could entail double counting. Finally, the indicators have been defined at an aggregated level and therefore, specific indicators such as impact on special groups (for example women or children) have not been included as separate indicators but aggregated.

4.2.1.1 CIs sector

This sector comprises the impacts suffered by CIs. The included CIs correspond to the indicative list of the Green paper on the European Programme for CI Protection (Commission of the European Communities

2005) which considers the following infrastructures as critical: Energy, Information and Communication Technologies (ICT), Water, Food, Health, Financial, Public & Legal Order and Safety, Civil Administration, Transport, Chemical and Nuclear Industry, and Space and Research.

The direct impacts' indicators included into this sector correspond to the physical damage suffered by infrastructure, equipment and supplies each of the eleven CIs. On the other hand, indirect impacts' indicators are referred to the problems of access to providers' services and to changes in CIs costs.

4.2.1.2 Economic sector

This sector excludes businesses already included in CI sector. Into the economic sector we have included impacts over primary (production of raw material and basic foods), secondary (trade and industry) and tertiary (services) sectors.

Direct economic impacts are related to the physical damage and losses on each of the three sectors whereas indirect impacts are related to changes in operational costs, productivity and income.

4.2.1.3 Social sector

Social impacts are the effects of crises over population, culture, education, and property. Direct impacts are related to damaged infrastructure, equipment and supplies but also to injured or death people. Indirect impacts include cultural, educational and property associated costs but also effects on people health, welfare level decrease associated to CIs low performance and humanitarian help.

4.2.1.4 Environmental sector

The environmental sector includes impacts on soil, air, surface or ground water, fauna and flora, sensitive areas and natural resources impacts. Environmental direct and indirect families are similar; the differences rely on the cause. The direct impacts are generated by the triggering event while indirect ones are generated as consequence of the direct impacts.

4.2.2 *Impact indicators framework* use

The *Impact indicators framework* has been developed with a holistic perspective, including all types of impacts that can be considered after a crisis. Then, the *Impact indicators framework* is designed to be used by crisis managers (civil protection, emergency services and other authorities) of a specific geographic area. In each geographic area crisis managers should particularise the *Impact indicators framework* in order to be aware about the different types of impacts their geographic area can suffer. Based on their experience crisis managers should be able to detect the impact indicators that could occur as consequence of a crisis in their geographic area. Then, they should analyse how these indicators have been assessed in the past. Through this analysis areas of improvement can be identified.

The example of this tool that has been developed through this research focuses on crisis managers needs but *Impact indicators framework* could also be adapted to be valuable for particular CIs, focusing on the specific impacts that a CI could suffer.

4.2.3 *Impact indicators framework* example

In following sections each sector and the corresponding impact indicators classified by direct versus indirect and tangible versus intangible are explained. Tangible impact indicators could be translated to an economic value so the unit to measure them would be euros, dollars, etc. However, intangible impacts cannot be economically measured in an easy way and therefore; no units to measure them are given.

4.2.3.1 CIs sector

The direct impacts' indicators included into this sector correspond to the physical damage suffered by each CI (Table 4.2). A total of 24 indicators have been identified. All CIs sectors' direct impacts are tangible impacts as a monetary value can be assigned:

- Damage to infrastructure: amount of resources required to rehabilitate, reconstruct, repair or replace damaged buildings, installations and infrastructure physically damaged by the triggering event.
- Damage to equipment and supplies: cost of repair or replacement of tools, machinery, materials and goods damaged by the triggering event.

On the other hand, indirect impacts' indicators are referred to the increase in operating costs or loss of income for each CI (Table 4.3). 33 indirect indicators have been listed. All CIs sectors' indirect impacts are tangible impacts as a monetary value can be assigned except for "Inadequate providers' services":

- Increase in operating costs: additional amount of resources required to continue with the normal activity.
- Costs of demolition and debris removal: cost of the activities needed to demolish damaged infrastructure including the cost to take away the rubble in order to clean out the area.
- Inadequate providers' services: disturbances suffered by a CI due to the low performance of their providers, including other CIs.

	Critical Infrastructure	Family	Tangible vs Intangible	Indicator
Direct impact	Energy	Damage to energy infr., eq. and supp.	T	Damage to energy infrastructure e.g. electricity plants, distribution systems, fuel depots
			T	Damage to equipment and supplies
	ICT	Damage to communication infr., eq. and supp.	T	Damage to communication infrastructure e.g. transceiver facilities for cellular phones
			T	Damage to equipment and supplies
	Water	Damage to water infr., eq. and supp.	T	Damage to water infrastructure
			T	Damage to equipment and supplies
			T	Loss of water sources
	Food	Damage to food infr., eq. and supp.	T	Damage to food infrastructure, farm land...
			T	Damage to machinery and equipment
			T	Loss of stock (livestock, inputs, harvested products) and crops ready for harvest
	Health	Damage to health infr., eq. and supp.	T	Damage to hospitals and health centres
			T	Damage to medical and nonmedical equipment and supplies
	Financial	Damage to financial infr., eq. and supp.	T	Damage to financial infrastructure
			T	Damage to equipment and supplies
	Public & Legal Order and Safety	Damage to legal infr., eq. and supp.	T	Damage to legal infrastructure
			T	Damage to equipment and supplies
	Civil Administration	Damage to civil administration infr., eq. and supp.	T	Damage to civil administration infrastructures
			T	Damage to equipment and supplies
	Transport	Damage to transport infr., eq. and supp.	T	Damage to transport infrastructure e.g. roads, bridges, railroads, airports, wharfs
			T	Damage to public and private vehicles e.g. cars, aircraft, boats
	Chemical and Nuclear Industry	Damage to chemical and nuclear infr., eq. and supp.	T	Damage to chemical and nuclear industry infrastructure
			T	Damage to equipment and supplies
	Space & Research	Damage to Space and Research infr., eq. and supp.	T	Damage to space and research infrastructure
			T	Damage to equipment and supplies

Table 4.2 Direct impact indicators in CI sector ("T" means Tangible impacts while "I" means Intangible)

	Critical Infrastructure	Family	Tangible vs Intangible	Indicator
Indirect impact	Energy	Changes in energy costs	T	Increase in energy operating costs
			T	Cost of demolition and debris removal
			I	Inadequate access to providers' services
	ICT	Changes in communication costs	T	Increase in communications operating costs
			T	Cost of demolition and debris removal
			I	Inadequate access to providers' services
	Water	Changes in water costs	T	Increase in water operating costs
			T	Cost of demolition and debris removal
			I	Inadequate access to providers' services
	Food	Changes in food costs	T	Increase in food operating costs
			T	Cost of demolition and debris removal
			I	Inadequate access to providers' services
	Health	Changes in health costs a	T	Increase in health operating costs
			T	Cost of demolition and debris removal
			I	Inadequate access to providers' services
	Financial	Changes in financial costs	T	Increase in financial operating costs
			T	Cost of demolition and debris removal
			I	Inadequate access to providers' services
	Public & Legal Order and Safety	Changes in legal costs	T	Increase in legal operating costs
			T	Cost of demolition and debris removal
			I	Inadequate access to providers' services
	Civil Administration	Changes in civil administration costs	T	Increase in administration operating costs
			T	Cost of demolition and debris removal
			I	Inadequate access to providers' services
	Transport	Changes in transport costs	T	Increase in transport operating costs
			T	Cost of demolition and debris removal
			I	Inadequate access to providers' services
	Chemical and Nuclear Industry	Changes in chemical and nuclear costs	T	Increase in chemical and nuclear industry operating costs
			T	Cost of demolition and debris removal
			I	Inadequate access to providers' services
	Space & Research	Changes in Space and Research costs	T	Increase in space and research operating costs
			T	Cost of demolition and debris removal
			I	Inadequate access to providers' services

Table 4.3 Indirect impact indicators in CI sector

4.2.3.2 Economic sector

Direct economic impacts are related to the physical damage on each of the three sectors (Table 4.4). 10 indicators have been identified. All Economic sectors' direct impacts are tangible impacts as a monetary value can be assigned:

- Damage to infrastructure: amount of resources required to rehabilitate, reconstruct, repair or replace damaged buildings, installations and infrastructure physically damaged by the triggering event.
- Damage to equipment and supplies: cost of repair or replacement of tools, machinery, materials and goods damaged by the triggering event.
- Loss of stock: raw materials, products under production process and finished goods that have been damaged by the triggering event.

	Economic sector	Family	Tangible vs Intangible	Indicator
Direct impact	Primary	Primary sector damage and losses	T	Damage to infrastructure
			T	Damage to equipment and supplies
			T	Loss of stock
	Secondary	Trade and industry damage and losses	T	Damage to industrial infrastructure e.g. buildings (excluding the ones included into CIs)
			T	Damage to equipment and supplies (excluding the ones included into CIs)
			T	Loss of stock (processed goods, raw materials)
			T	Damage to public facilities for commerce and trade
	Tertiary	Service sector damage and losses	T	Damage to infrastructure (excluding the ones included into CIs)
			T	Damage to equipment and supplies (excluding the ones included into CIs)
			T	Loss of stock

Table 4.4 Direct impact indicators in economic sector

Furthermore, indirect impact examples are unemployment and loss of income or increase in operating costs among others (Table 4.5). 19 indirect indicators are included. All Economic sectors' indirect impacts are tangible impacts as a monetary value can be assigned, except for "Inadequate providers' services", "Unemployment" and "Employment created in reconstruction". In this sector positive indirect impacts can be identified such as "Income increase in surrounding not affected activities" and "Employment created in reconstruction":

- Increase in operating costs: additional amount of resources required to continue with the normal activity.
- Loss of income: the effects of the crisis on businesses and CIs can reduce the production or service delivery capacity. Also, due to the effects on the geographic area, the demand of products and services can also be lowered.
- Cost of demolition and debris removal: cost of the activities needed to demolish damaged infrastructure including the cost to take away the rubble in order to clean out the area.
- Income increase in surrounding not affected activities: The activities not affected by the crisis can notice an increase in the demand of their products and services due to the reduction of productivity of the affected activities.
- Inadequate providers' services: disturbances suffered by businesses due to the low performance of providers' including other CIs.
- Unemployment: Physical damages on businesses and a possible reduction of demand can force businesses to fire workers, increasing unemployment rate.
- Employment created in reconstruction: for the reconstruction of the affected area employees are needed and therefore new employment can be created.

	Economic sector	Family	Tangible vs Intangible	Indicator
Indirect impact	**Primary**	Primary sector operating costs, productivity and income	T	Increase in operating costs
			T	Loss of income
			T	Cost of demolition and debris removal
			T	Income increase in surrounding not affected activities
			I	Inadequate access to providers' services
			I	Unemployment
	Secondary	Industrial operating costs, productivity and income	T	Increase in industrial operating costs
			T	Loss of income (due to reduced production and loss of demand)
			T	Cost of demolition and debris removal
			T	Income increase in surrounding not affected activities
			I	Inadequate access to providers' services
			I	Unemployment
	Tertiary	Service sector operating costs, productivity and income	T	Increase in operating costs
			T	Loss of income
			T	Cost of demolition and debris removal
			T	Income increase in surrounding not affected activities
			I	Employment created in reconstruction
			I	Inadequate access to providers' services
			I	Unemployment

Table 4.5 Indirect direct impact indicators in economic sector

4.2.3.3 Social sector

Social impacts are effects of crises over population, culture, education, and property, including direct impacts such as physical destruction or affected people (Table 4.6) whereas indirect impacts are related to people displacement, secondary health effects, demographic changes, insecurity or humanitarian aid (Table 4.7). In social sector 9 direct and 28 indirect indicators are included:

- Cultural direct and tangible impact indicators are related to the resources needed to rehabilitate, reconstruct, repair or replace damaged cultural buildings, works of art, archaeological findings and archives. Furthermore, there is an intangible indicator that includes the loss of irreparable or irreplaceable works of art, archaeological findings and archives. As indirect and tangible indicators we have defined the increase in cultural services operating costs, and the required investment to demolish and to remove debris.
- Educational direct and tangible indicators are related to the resources needed to rehabilitate, re-construct, repair or replace damaged educational buildings and installations, equipment and supplies whereas indirect and tangible ones involve increase in operating costs and demolition and debris removal costs.
- Property direct and tangible indicators include the resources needed to rehabilitate, reconstruct, repair or replace damaged infrastructure and contents. On the other hand, indirect and tangible indicators are related to the costs associated to relocating people, maintaining shelters and demolition and debris removal. Additionally, indirect and intangible impacts are related to the people who have been displaced or who live in temporary shelters.
- People related direct and intangible indicators are number of deaths and injured people due to the triggering event. Furthermore, indirect indicators related to people are subdivided in three groups:
    - Affected people after crisis comprises intangible indicators for injured and death people and their psychological effects as

consequence of direct impacts as well as costs associated with treatments.

- Effects on people caused by low performance of CIs are intangible indicators such as the effects on daily lives that people suffer due to an inadequate CIs' services.
- Humanitarian help tangible indicators are related to economic aid from international countries and NGOs.

	Social sector	Family	Tangible vs Intangible	Indicator
Direct impact	Culture	Damage to cultural infrastructure and contents	T	Damage to cultural infrastructure
			T	Damage to contents (Works of art, Archaeological findings and Archives)
			I	Damage to Works of art, Archaeological findings and Archives which are irreparable or irreplaceable
	Education	Damage to education infrastructure, equipment and supplies	T	Damage to educational buildings and installations e.g. schools, libraries…
			T	Damage to educational equipment and supplies
	Property	Damage to property	T	Damage to infrastructure
			T	Damage to contents
	People	Affected people during crisis	I	Deaths during crisis
			I	Injured during crisis

Table 4.6 Direct impact indicators in social sector

	Social sector	Family	Tangible vs Intangible	Indicator
Indirect impact	**Culture**	Cultural service	T	Increase in cultural services operating costs
			T	Costs of demolition and debris removal
	Education	Education service	T	Increase in educational operating costs
			T	Cost of demolition and debris removal
	Property	Property and contents effects	I	Displaced people
			I	People in temporary shelters
			T	Cost of temporary shelters during reconstruction period
			T	Costs of relocating people
			T	Cost of demolition and debris removal
	People	Affected people after crisis	I	Deaths after crisis
			I	Injured after crisis
			I	Psychological effects, stress and sadness
			I	Greater public recognition of hazard risk
			T	Affected people's associated costs (treatments…)
		Effects on people caused by low performance of Critical Infrastructures	I	Power outage disturbances
			I	Communications disturbances
			I	Nutrition problems
			I	Inadequate health service effects
			I	Inadequate Financial service effects
			I	Increase of insecurity
			I	Inadequate administration service effects
			I	Transportation problems
			I	Chemical and nuclear effects on people
			I	Inadequate Space and research service effects
			I	Increase in future quality of service due to new technologies
		Humanitarian help	T	International help (volunteers, NGOs, …)
			T	Community response costs
			T	Increase of local/state/federal funds for reconstruction or mitigation

Table 4.7 Indirect impact indicators in Social sector

4.2.3.4 Environmental sector

The environmental sector includes impacts on soil contamination, soil movements, air emissions, surface or ground water contamination, fauna, flora, sensitive areas and natural resources impacts.

Environmental direct (Table 4.8) and indirect (Table 4.9) indicators are similar; the differences rely on the cause. As explained before direct impacts are the ones caused by the triggering event itself while indirect ones are the consequence of whichever direct impact. 18 direct and 11 indirect indicators have been identified. Therefore, some indicators are repeated as they can be both direct and indirect impacts. However, some indicators are only direct if they are consequence of only the triggering event or indirect if they can only be caused as consequence of direct ones:

- Soil tangible indicators are related to contamination, earthworks and movements and changes to visual attributes of area whereas the tangible indicator refers to the cost of rehabilitating the affected land.
- Air intangible indicators concern air emissions and the tangible indicator is related to the cost to depurate the air.
- Surface and Ground Water intangible indicators entail contamination and altering drainage patterns. However, the cost to depurate or rehabilitate the water and drainage is a tangible indicator.
- Intangible indicators for Fauna & Flora involve disturbances to animal, flora, vegetation species and their habitats. The cost to build up these species and habitats is a tangible indicator.
- Sensitive Areas include intangible indicators related to damages on national parks, world heritage areas and natural resources as well as the required invest to rehabilitate them which is a tangible indicator.

	Environmental sector	Family	Tangible vs Intangible	Indicator
Direct impact	Soil	Soil	I	Earthworks/movements
			I	Contamination (eg. spills)
			I	Changes to visual attributes of area
			T	Cost to rehabilitate land
	Air	Air	I	Air emissions
			T	Cost to depurate the air
	Surface & Ground Water	Water and drainage	I	Water contamination
			I	Altering drainage patterns
			T	Cost to depurate or rehabilitate water drainages
	Fauna & Flora	Species and habitats	I	Disturbance to species
			I	Disturbance to habitats
			I	Disturbing native flora species
			I	Clearing extensive areas of native vegetation
			T	Cost of programs to build up population
	Sensitive Areas	Natural resources and attractions	I	Disturbance to National Parks
			I	Disturbance to World Heritage Areas
			I	Natural resources destruction
			T	Cost to rehabilitate natural resources and attractions

Table 4.8 Direct impact indicators in environmental sector

	Environmental sector	Family	Tangible vs Intangible	Indicator
Indirect impact	Soil	Soil	I	Erosion around collapsed area
			I	Contamination (eg spills)
			I	Fertile soil from volcanic eruption
	Air	Air	I	Air emissions
	Surface & Ground Water	Water and drainage	I	Water contamination
	Fauna & Flora	Species and habitats	I	Disturbance to species
			I	Disturbance to habitats
			I	Disturbing native flora species
	Sensitive Areas	Natural resources and attractions	I	Disturbance to National Parks
			I	Disturbance to World Heritage Areas
			I	Natural resources destruction

Table 4.9 Indirect impact indicators in environmental sector

4.3 2nd tool: *CIs dependency-influence cluster*

CIs as well as any other organisations and even the whole society need other CIs to perform correctly and this makes them dependent. Dependencies among CIs make a failure in a CI to spread from that CI to others. Therefore, if a CI fails, through cascading effects, the consequences will be extended to dependent CIs. As a result, CI managers must understand the complexity of CIs system and be aware of the dependencies and influences each CI has on others.

4.3.1 *CIs dependency-influence cluster* description

The *CIs dependency-influence cluster* tool comprises three different activities: the survey, the clustering of CIs and the gathered evidences.

The questionnaire developed in this research (see Section 3.3) helps crisis managers to perform a holistic, dynamic and quantitative analysis of CIs dependencies taking into account different failure timeframes. Analysing failures of different duration helps being aware of the different scenarios that could occur and makes managers to think about the consequences each scenario could have in order to realise about their preparation for such scenarios. The aim of the questionnaire is to help crisis managers of a geographic area (civil protection, emergency services and other authorities) to identify which CIs are the most critical ones, those where a failure could affect more CIs and consequently the society.

Thanks to the data gathered through the questionnaire the influence and dependency CIs have on others in a geographic area can be determined. Once having identified which CIs are more influential or more dependent, crisis managers and CI managers will better understand the complexity of the system constituted by the complete network of CIs. Crisis managers have to be aware of the most dependent CIs, which are the ones that could suffer more from any other CI failure, in order to carry out the necessary policies to increase these CIs resilience against failures in others. Moreover, the most influential CIs have to be identified in order to be aware of which CIs can affect more severely to others and to develop policies to improve prevention and response, leading to an increase of the resilience level against future crises. Analysing the results for different failure timeframes, CI managers and crisis managers can identify common aspects among CIs, based on their influence or dependency level, in order to apply similar policies and be better prepared in face of future crises. Then, these policies can then be implemented as legislation or as recommendation to be implemented in other CIs.

Additionally, from the online questionnaire information regarding the evidences that make CIs dependent is also gathered. These evidences can help understanding the effects of dependencies and sharing this information can make managers to be aware about issues that they could have not considered before. Therefore, to facilitate the collection of evidences a template has been developed. Table 4.10 shows the template to include the dependency evidences.

Failed CI	Evidence
Energy	
ICT	
Water	
Food	
Health	
Financial	
Public & Legal Order and Safety	
Civil Administration	
Transport	
Chemical & Nuclear Industry	
Space & Research	

Table 4.10 Template to include CI dependencies evidences

4.3.2 *CIs dependency-influence cluster* use

The *CIs dependency-influence cluster* tool has to be particularised for each geographic area under analysis. The CIs included in each cluster can differ depending on the country or geographic area that is being analysed.

The crisis managers of a geographic area (civil protection, emergency services and other authorities) should identify the existing CIs in the area. Then, the questionnaire has to be sent to CI managers. After having collected the data from CI managers, the identification of the influence and dependency level of each CI has to be made.

Finally, the real evidences about dependencies gathered should be shared by crisis managers and CI managers in order to improve preparation to face them. CI managers can work jointly with similar CIs to share information about the evidences being a good way to share knowledge and learn from others.

4.3.3 *CIs dependency-influence cluster* example

In our research, through the online questionnaire explained in Section 3.3, the level of dependency among CIs was asked to a 52 CI managers from different countries. In our example we have not focused the analysis in a specific geographic area as, considering the low rate of answers when carrying out online questionnaires, we could not have received enough answers from CIs of a specific geographic area. Therefore, we decided to send the questionnaire to several CIs in Europe and USA in order to get enough answers to make CIs dependency and influence analysis.

From experts comments it was gathered that the concept of dependent infrastructure can have different meanings depending on the context in which it is used and particularly it can have a different meaning in the context of a critical situation. According to the answers and comments from the experts, we obtained the following conclusions. The first one is that even if CI managers contemplate a possible blackout there are other scenarios related to a failure in any other CI such as a financial system failure or a strike in transport services which they have not considered.

CI managers also pointed out the lack of tools to facilitate the analysis of CIs dependencies. And thanks to this tool their awareness about the dependencies effects and evidences increases which could lead to an improvement of their management and to an increase of their resilience level.

Another conclusion after carrying out the online questionnaire is that some CIs are more critical than others as the consequences when these CIs fail are more significant or affect more CIs. Furthermore, some CIs are more dependent than others. Based on the influence and dependency answers obtained from the online questionnaire, graphs for the analysed periods of failure were drawn. Analysing the graphs, we concluded that CIs can be clustered depending on their dependency or influence level on others. The identification of the clusters of CIs was made by visualizing the aggrupation of CIs. Figure 4.3 to Figure 4.5 include three failure timeframes as examples of the dependency and influence of each CI (all graphs can be found in Appendix B). The vertical axis represents the dependency level whereas the horizontal axis shows the influence, according to the defined scale (Table 4.11).

Scale	Definition
0	No effect: My CI can operate as usual
1	Very low effect: My CI can operate deploying few extra resources
2	Low effect: My CI can operate deploying huge amount of extra resources
3	Medium effect: My CI can only deliver critical services deploying few extra resources
4	High effect: My CI can only deliver critical services deploying huge amount of extra resources
5	Very high effect: My CI cannot continue operating

Table 4.11 Scale defined to determine the effects on a CI due to a failure occurred on another CI

Figure 4.3 show the best scenario were the failure lasts less than two hours. Figure 4.4 shows an intermediate failure scenario (less than twenty four hours. Finally, Figure 4.5 represents the worst scenario (failure of more than one week).

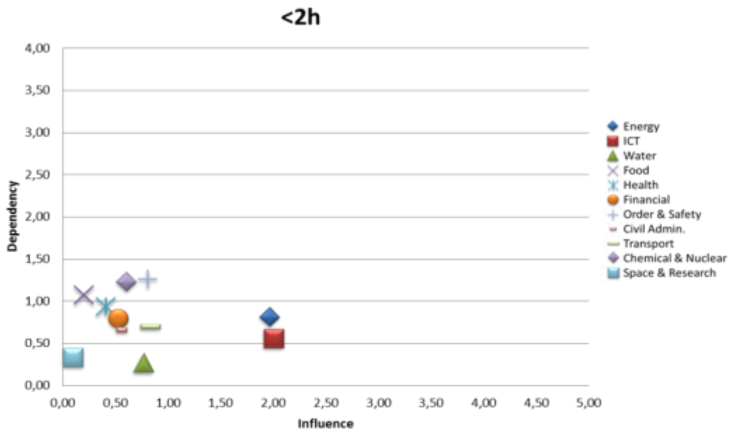

Figure 4.3 CIs Dependency versus Influence graphs where CIs are down less than two hours

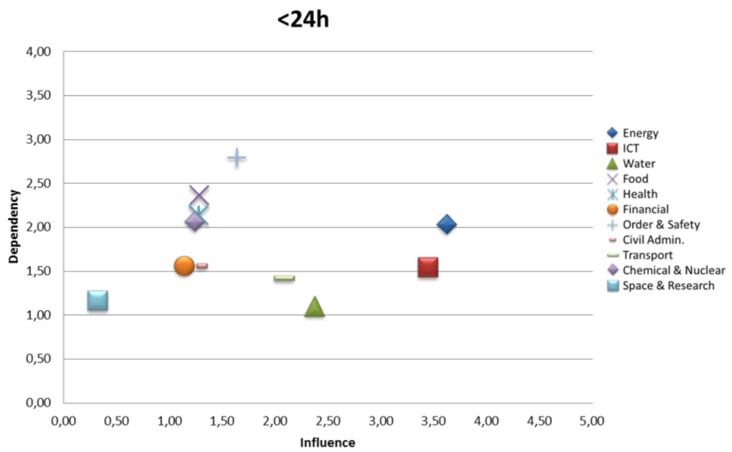

Figure 4.4 CIs Dependency versus Influence graphs where CIs are down less than twenty four hours

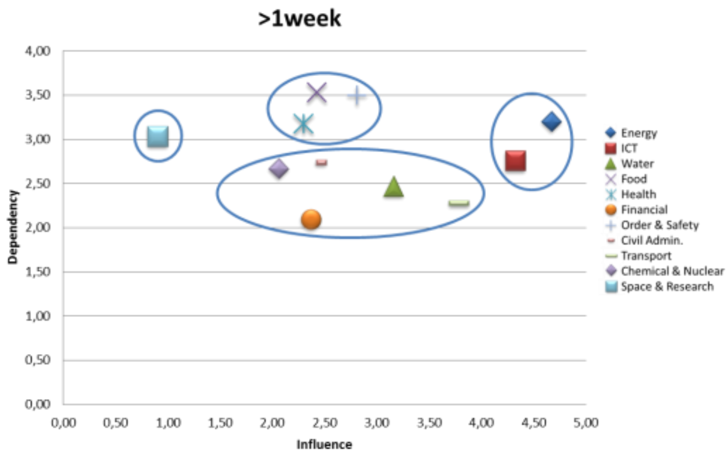

Figure 4.5 CIs Dependency versus Influence graphs where CIs are down more than one week

As result of the data gathered from the online questionnaire and the drawn graphs, four clusters of CIs have been identified (clusters are shown inFigure 4.5): very dependent CIs, very influential CIs, low dependent CIs and low influential CIs.

- The first cluster includes CIs which are the most dependent ones. These CIs are: Health, Food and Public and Legal Oder and Safety CIs. In this case preventive measures have to be carried in order to lessen their dependency of other CIs on them or even the effects that the dependency leads to.
- The second cluster contains the CIs which are the most influential ones: ICT and Energy. CI managers of all the CIs must be aware of their high dependency on ICT and Energy in order to carry out policies to minimise it.
- The third cluster comprises the CIs which have low dependency on others, including: Finance, Water, Transport, Civil Administration, Chemical and Nuclear Industry.

- The last cluster comprises the CIs which do not significantly influence others. In this cluster we include Space and Research CI.

Taking into account the different failure timeframes, Energy and ICT are considered the most influential CIs whereas Space and Research CI is the least. This means that crisis managers and CI managers should be aware of a CI dependency on Energy and ICT. Then, CI managers should identify the consequences these dependencies lead to, in order to carry out policies to reduce their dependency or minimize their consequences. For example, the deployment of own power generators could minimise the dependency of a CI on Energy at least for few hours on their critical services. Moreover, CI managers should design alternative control and communication strategies if ICT fails.

On the other hand, this research shows that the most or least dependent CIs vary depending on the analysed failure timeframe. Analysing different failure timeframes allows improving preparation both for minor failures and for more significant ones such as natural disasters or attacks. In our study, for the shorter period of failure (less than two hours) the most dependent CI is Public and Legal Order and Safety while for the higher period of failure (more than one week) Health is the most dependent CI. The most dependent CIs are the ones that suffer more when other CIs fail. Therefore, these CI managers must be aware of these dependencies and the effects they lead to in order to carry out policies to avoid or lessen the consequences. Furthermore, Water and Financial are the least dependent CIs for the periods of less than two hours and for more than one week respectively.

Through the online questionnaire and meetings with CI managers evidences of dependencies for the eleven CIs were gathered. Table 4.12 shows examples of evidences if Energy CI fails more than 48 hours. A number of evidences for each of the other CIs have also been gathered (see Appendix B).

Failed CI	Evidence
Energy	• Manual procedures must be implemented since automatic ones cannot be performed • Production activities must be stopped • Lighting system does not work • Alert systems can stop working • Inability to transport and distribute water as pumping does not work • Inability to preserve food's cold chain • Hospital protocols do not allow to do surgery and patients who require vital support need to be transfer to other hospitals • Airports should be closed • Cooling system for chemical or nuclear activity will not work, activity will have to stop

Table 4.12 Examples of dependency evidences on Energy

4.4 3rd tool: *CI dependency radar*

After the analysis of the comments received through the online questionnaire, it has been identified that dependency is a complex concept to think about. Also, Macaulay (2009) and Setola (2010) also point out that there is a need of developing metrics or representations in order to analyse CI dependencies. Therefore, it is necessary to identify the different characteristics of CIs dependencies on each other in order to properly analyse CIs system complexity. Through this research a tool to facilitate the understanding of CIs dependencies has been developed: the *CI dependency radar*. The tool is based on the identification of dimensions to determine the dependency of a CI on the others.

4.4.1 *CI dependency radar* description

In order to analyse the dependency of a CI on another CI two different scenarios have been analysed. First of all, "1st order crises" were analysed, that are crises caused by triggering events that affect only one CI. For example, a 1st order crisis can be a storm which floods a hospital. Secondly, scenarios where more CIs are affected are defined as "n order crisis", in our example "2nd order crisis" were analysed. This distinction is needed in order to analyse how resources shared during the crisis resolution can slow down the recovery of a CI.

From this research five dimensions to study dependencies among CIs have been identified and included into the *CI dependency radar* tool, to help defining the level of dependency of a single CI on others. To facilitate the comprehension of the level of dependency between each pair of CIs the dimensions have been graphically represented as a radar diagram. When these dimensions are analysed together they facilitate the assessment of the dependencies between two given CIs. The dependency dimensions refer to how a CI can make another CI fail but also to how the first CI can contribute or difficult the second CI's recovery. Furthermore, external issues are included such as public anxiety or needed resources. The five dimensions of the *CI dependency radar* tool are related to: 1) Dependency for working, 2) Redundancy, 3) Effect of external aggravating factors, 4) Recovery time and, 5) Effect of resources sharing for recovery.

These dimensions have been classified in failure and recovery dimensions (Figure 4.6). Failure dimensions (Dependency for working, Redundancy and Effect of external aggravating factors) refer to how the failure propagates from one damaged CI to another. For analysing these dimensions the scenario is that some other CI has been damaged by the triggering event and the analysed CI has been affected due to its dependency on the damaged CI.

Recovery dimensions (Recovery time and Effect of resources sharing for recovery) refer to how recovery time of a CI can be affected by the recovery of other CIs. In recovery dimensions the difference between "1st order crisis" and "n order crisis" has to be made. For the 5th dimension the scenario has to be changed to a "n order crisis".

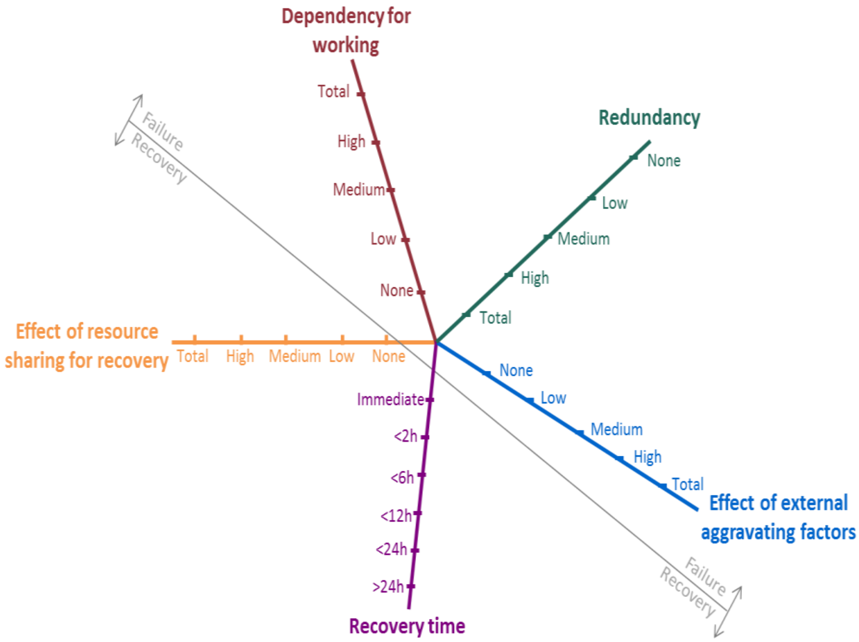

Figure 4.6 CI dependency radar

The *CI dependency radar* dimensions are the following:

a) 1st Dimension: Dependency for working

This dimension analyses how a complete failure in one CI can affect another CI without any alternative supply to deliver service.

The defined scale comprises the following levels of affection:

- None: The affected CI can work as usual
- Low: The affected CI can deliver services with a performance level of 80%
- Medium: The affected CI can deliver services with a performance level of 50%
- High: The affected CI can deliver services with a performance level of 20%

- Total: The affected CI cannot continue working

b) 2nd Dimension: Redundancy

Some infrastructures, being aware of the effects that their dependencies could have on them ("dependency for working" dimension), arrange alternative sources in order to provide them critical services when any CI fails. In this case, the effects that a total CIs failure could have on them may be avoided or minimised.

The scale defined for this dimension is:

- Total: The affected CI has alternatives to completely substitute the failed CI
- High: The affected CI has alternatives to partially substitute the failed CI but the performance level will be close to the 80%
- Medium: The affected CI has alternatives to partially substitute the failed CI but the performance level will be close to the 50%
- Low: The CI affected has alternatives to partially substitute the failed CI but the performance level will be close to the 20%
- None: There is no redundancy or alternative to substitute the failed CI

c) 3rd Dimension: Effect of external aggravating factors

During a complete failure of a CI external aggravating factors such as social anxiety, public disorder etc. can occur. These factors can affect the analysed CI workers for example preventing them to go to work as usual. Then, the level of performance of the analysed CI can be lowered. The answer of this dimension refers to the decrease of the CI performance due to external factors.

- None: The performance level of the affected CI will not decrease
- Low: The performance level of the affected CI will decrease an additional 10%

- Medium: The performance level of the affected CI will decrease an additional 30%
- High: The performance level of the affected CI will decrease an additional 60%
- Total: The affected CI cannot continue working

d) 4th Dimension: Recovery time

Once the damaged CI has been recovered the dependent CI can also start working as usual. However, the recovery of a normal performance can be immediate or delayed as sometimes some protocols must be followed before starting the activity again. For example, airports security protocols require time to be implemented and therefore the airport cannot immediately recover a normal performance until these security protocols are implemented.

For that reason, the defined scale is:

- Immediate: The affected CI can start working as usual immediately
- Less than 2 hours: The affected CI requires up to 2 hours to carry out needed procedures
- Less than 6 hours: The affected CI requires up to 6 hours to carry out needed procedures
- Less than 12 hours: The affected CI requires up to 12 hours to carry out needed procedures
- Less than 24 hours: The affected CI requires up to 24 hours to carry out needed procedures
- More than 24 hours (indicate the time needed): The affected CI will need_____ (hours) to carry out needed procedures

e) 5th Dimension: Effect of resources sharing for recovery

A "2^{nd} order crisis" has been analysed where the two analysed CIs fail. Taking into account that both CIs fail, resources (technical, human…) for their recovery will be needed. The problem arises when some resources have to be shared in order to repair both CIs and as a consequence, this situation can increase their recovery time. For example, police, fire-fighters or maintenance services are resources usually needed when a crisis occurs and therefore, these resources must be shared by all CIs affected.

The potential increase of time has been included in the scale as follows:

- None: Resources are not shared or the sharing does not slow down the recovery
- Low: Sharing of resources increases the recovery time a 10%
- Medium: Sharing of resources increases the recovery time a 25%
- High: Sharing of resources increases the recovery time a 50%
- Total (indicate increase in percentage): Sharing of resources increases the recovery time a ______ (percentage)

4.4.2 *CI dependency radar* use

CI managers have to analyse each dimension for a single CI and its relation with any other CI. Taking into account that the EPCIP considers eleven infrastructures as critical (Commission of the European Communities 2005) each CI will have to complete *CI dependency radars* for each of the other ten CIs or select the CIs they have more dependency on, taking into account the results obatained from the *CIs dependency-influence cluster* tool.

Moreover, CIs dependencies will vary depending on the time the damaged CI fails. Therefore, CI managers will have to complete *CI dependency radars* thinking about complete damage of one or both CIs lasting different periods of time defined by them. These periods of time are: 1) the moment when the CI performance is affected by the damaged CI and, 2) the moment when CI managers consider that CI impact increases exponentially. Consequently, we recommend performing two *CI dependency radar* analyses in order to determine the dependency level of a CI on another in these two scenarios. Before drawing the *CI dependency radars* timeframes identification has to be made.

Once having drawn *CI dependency radars* CI managers can compare them taking into account that bigger the area of the pentagon, greater the dependency among CIs. Moreover, CI managers can define ideal *CI dependency radar* in order to determine what the target dependency level is. Thus, comparing the real radar with the ideal one CI managers can decide activities or policies that should be implemented in order to achieve the target dependency level.

An example of a CI dependency is shown in Figure 4.7. In spite of being this CI totally dependent on another CI (1^{st} dimension), the proper management and the implemented policies make the redundancy level so high that the CI can completely fulfil their needs (2^{nd} dimension). Moreover, external factors do not affect the CI (3^{rd} dimension), its recovery is immediate once the other CI starts working again (4^{th} dimension) and no resources are shared or the sharing does not delay recovery (5^{th} dimension).

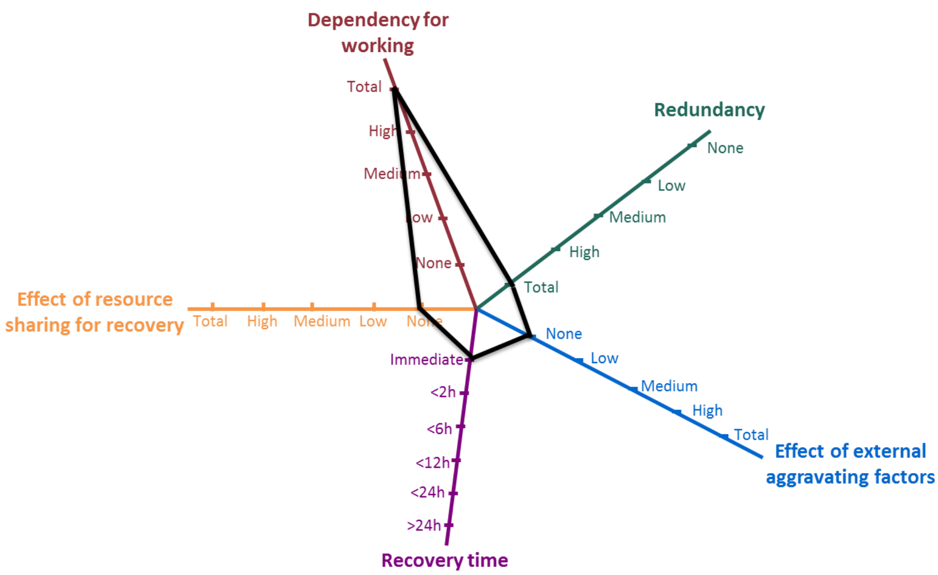

Figure 4.7 Example of a CI dependency radar

4.4.3 *CI dependency radar* examples

Interviews with CI managers were arranged as part of the validation process (see Section 5.2.2). During these interviews, CI managers were asked to make a real analysis of their CI dependency on any other CI using the *CI dependency radar* tool. In this section some examples are shown. CI managers suggested that the tool could help them deciding the investments they should do in order to minimise the effects of CI dependency.

After completing the radars, CI managers should analyse if their dependency level and their consequences are considered problematic. Then, they should identify their target radar in order to compare radars and finally identify what policies they should carry out to achieve the objective.

4.4.3.1 Food *CI dependency radar* on Transport

The first *CI dependency radar* corresponds to a real Food CI organisation and represents its CI dependency on Transport CI (Figure 4.8). In this scenario Food CI managers decided to analyse a failure of 24 hours and a failure of one week. The 24 hour period was chosen since this CI has not redundancy elements if the failure lasts 24 hours but they do have alternatives to try to recover 10% to 20% of their performance level (the redundancy goes from "None" in the radar that represents a failure of 24 hours to "Low" when the failure lasts 1 week). The problem in the first 24 hours is that CI managers are not capable to allocate other transport services. However, if the failure lasted a week managers commented that there are protocols to escort their trucks in scenario of a transport strike or to use alternative routes or transport modalities (trains instead of trucks for example) if roads collapse. Even if this is a special scenario as redundancy is obtained for a longer failure, it can be seen that the radar area is bigger in the one week failure scenario than in the 24 hours scenario.

After applying the tool managers commented on the problems due to resources sharing. In this scenario, the resource that Food CI shares with other

CIs is the police service. The recovery of a normal situation depends highly on police and they are not confident about their availability in case of necessity.

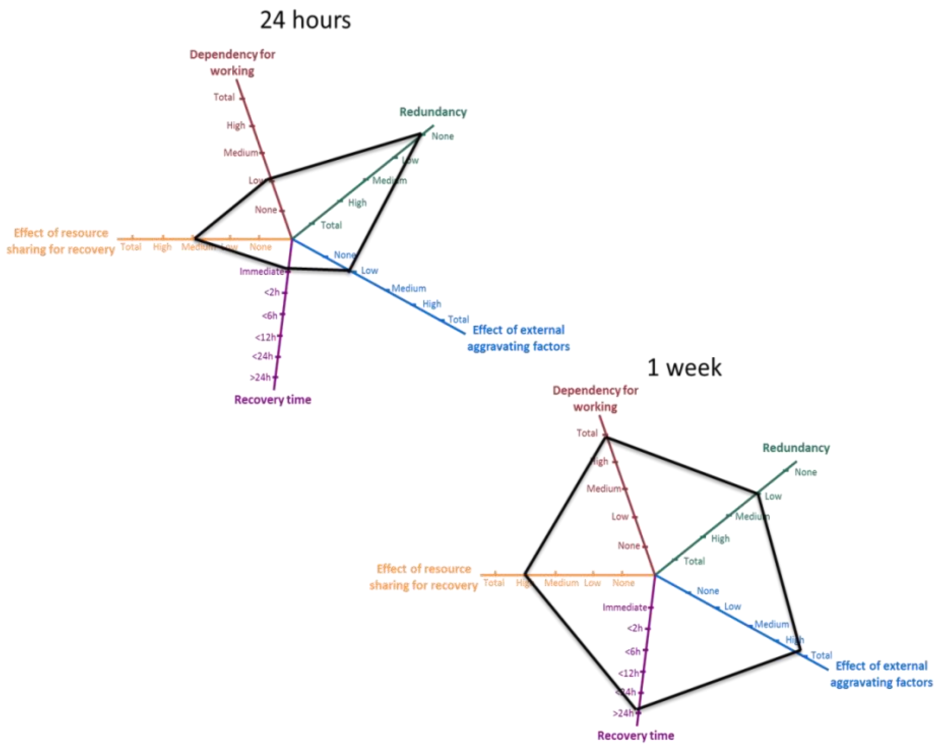

Figure 4.8 CI dependency radars for a failure of 24 hours and 1 week for dependency of Food CI on Transport CI

4.4.3.2 Health *CI dependency radar* on Water

The second example shows a *CI dependency radar* that represents the dependency of a real hospital on Water (Figure 4.9). Hospitals have own water deposits but depending on the size of the hospital water can last few days or a week. In this real scenario, the hospital has water in deposits for 11 days taking into account usual working conditions. Therefore, the manager suggested analysing a failure of 24 hours as, even having the deposits of water, CI performance level will decrease as action protocols determine that surgeries cannot be performed. Moreover, a failure of 12 days is considered as the hospital would not have any water. As it can be seen, not having water for 24 hours leads to a medium dependency. In this scenario, a problem for the hospital would be the people that could go to get water as the hospital could be crowded and it could difficult their activity.

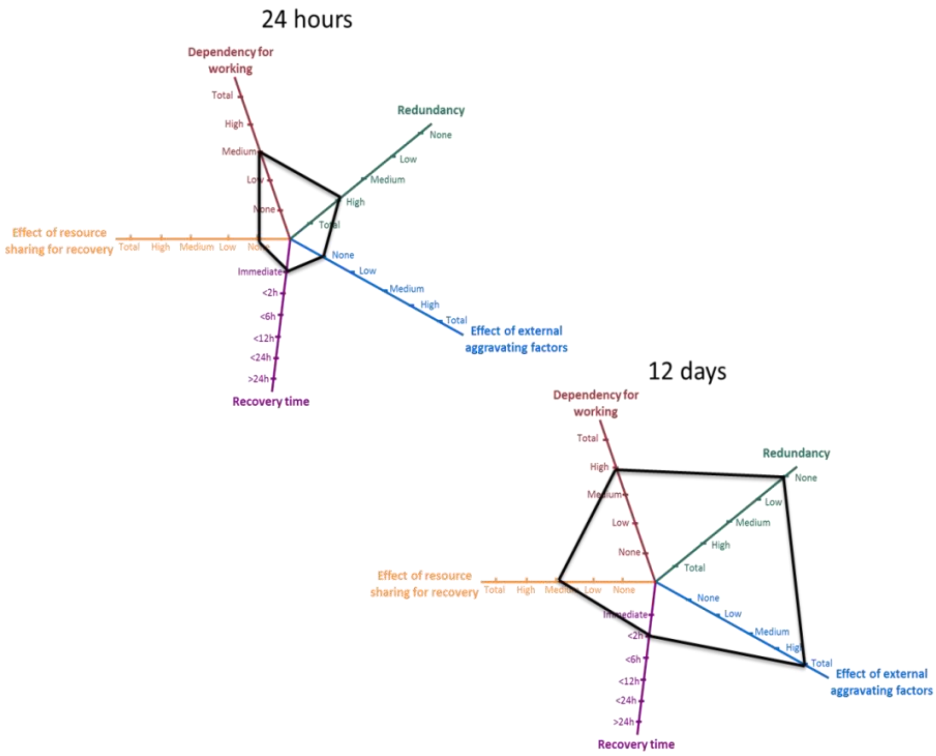

Figure 4.9 CI dependency radars for a failure of 24 hours and 12 days for dependency of Health CI on Water CI

4.4.3.3 Public and Legal Order and Safety *CI dependency radar* on Energy

The third *CI dependency radar* shows Public and Legal Order and Safety CI dependency on Energy CI (Figure 4.10). Almost all interviewed CIs have own power generators but depending on their generators capacity energy will last from one hour to several days. In this scenario, the power generator had autonomy for one week in normal operating conditions. Therefore, the time periods analysed are 24 hours as, even having power generators, performance level will decrease and one week as no generators will be still working. However, even if the failure lasts less than the power generator autonomy, redundancy is not total as not all services are considered critical so no energy is delivered to them.

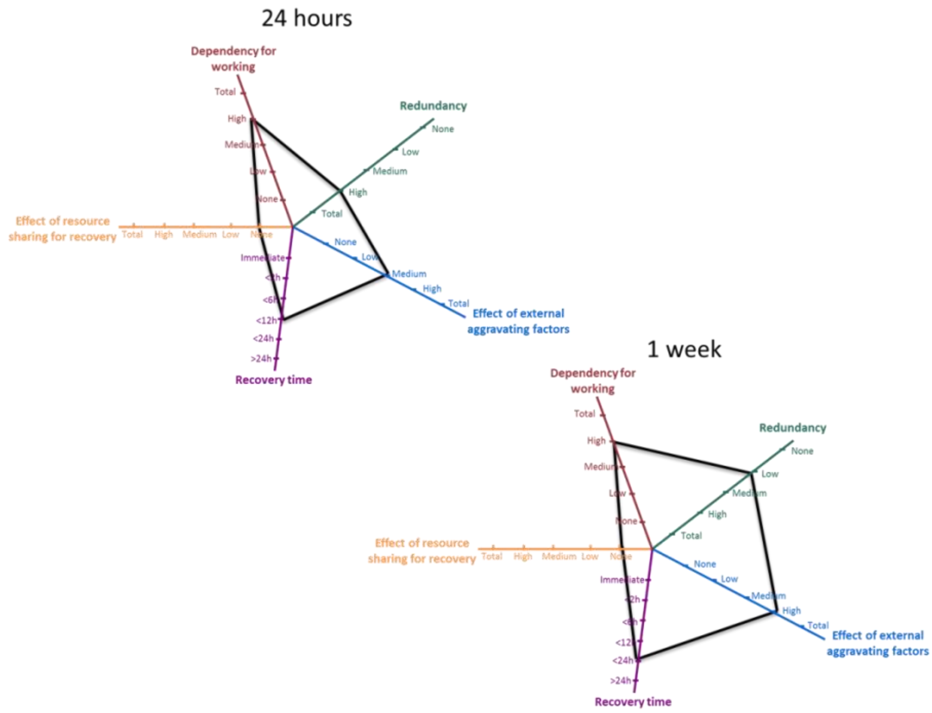

Figure 4.10 CI dependency radars for a failure of 12 hours and 24 hours for dependency of Public and Legal Order and Safety CI on Energy

4.4.3.4 Civil Administration *CI dependency radar* on Health

Finally, the fourth *CI dependency radar* illustrates the Civil Administration CI dependency on Health CI (Figure 4.11). In this example, the time periods analysed are 12 and 24 hours as emergency services are very dependent on Health, even a failure of few hours will affect them considerably and 24 hours without health care service becomes a big issue.

As it can be seen even if the failure lasts for 12 hours their recovery time will also need almost the same time. This long time for recovery is needed since emergency services have to transfer some patients to other hospitals apart from the normal emergencies. Therefore, there are some accumulated emergencies that cannot be solved during health care service failure and which have to be solved once the service has been recovered delaying the recovery of a normal activity. In the scenario of a failure of 24 hours it can be observed that the represented area increases considerably.

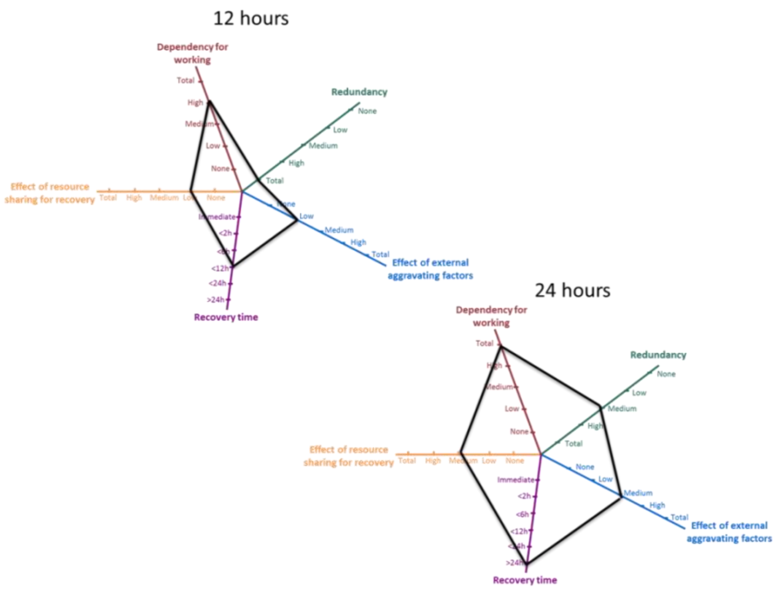

Figure 4.11 Civil Administration CI dependency radars for a failure of 24 hours and 1 week for dependency of Civil Administration CI on Health

4.5 4th tool: *Simulation model*

CIs can suffer minor failures which need effort to be solved, but they cannot be considered as crises. Thankfully, great crises do not usually occur. However, when a crisis strikes the lessons learned from these minor failures might not be useful. Therefore, a *Simulation model* allows analysing crisis situations, even if they have not occurred before. Through *Simulation models* triggering events of different magnitude and several policies implementation can be simulated.

4.5.1 *Simulation model* description

The value added through simulation starts in the development process and continues with *Simulation model*'s use.

The process of developing *Simulation models* needs the involvement of experts. Crisis managers and CI managers have to take part in the development, in order to make explicit their knowledge about the causes and effects of the variables analysed, increasing their awareness about the complex interaction of the variables that are affected when a crisis strikes. Then, *Simulation model* can be used by crisis managers as a training tool to better understand the complexity of CIs dependencies and their impacts through the representation of different scenarios where they have to understand why these behaviours occur. Their participation on the development process also helps them building trust on the *Simulation model*.

The use of the *Simulation model* also enables crisis managers to understand how complex interaction of variables can affect the final behaviour of the system. Then, we have developed a System Dynamics (Forrester 1961, Sterman 2000) *Simulation model* to show how the existing dependencies of CIs can generate or extend the initial impact after a crisis. For example, the model allows analysing how resources can be prioritised based on the dependency or influence level of each CI. Also, triggering events of different duration and crises that have not occurred before could be simulated to make experts analyse variables behaviour over time in such scenarios. This unknown scenarios show the usefulness of simulation and why learning cannot be based only on past experiences. This tool does not aim to develop an absolutely precise model but to show how the development of a *Simulation model* can help increasing crisis managers and CI managers' awareness and knowledge.

Another advantage of *Simulation models* is that models can be used as a communication tool for different stakeholders in order to increase their awareness about the different scenarios and to achieve consensus of variables behaviour over time.

This research includes a dynamic analysis of the effects of a crisis that affects one or more CIs. This analysis illustrates the fact that direct impacts generate subsequent indirect impacts, as a damaged element can affect others due to cascading effects.

4.5.2 *Simulation model* use

The *Simulation model* allows managers to simulate different scenarios with short or long term perspectives and to analyse the effects of carrying out several management policies. Additionally, *Simulation model* on complex systems allows being aware of non-intuitive behaviours that in real crisis situations managers could not be aware of.

The developed *Simulation model* shows how crises effects can spread to different CIs, reducing their performance level, even if they are not directly affected by the triggering event. Furthermore, by analysing crisis evolution over time and how the consequences spread, managers can learn how decision making and the implementation of different policies affect the final crisis impact.

The *Simulation model* developed in this research is focused on three CIs (Energy, Food and Transport) but the model can be broadened in order to represent the most important dependencies among all the CIs or the most influential CIs in a geographic area. The developed *Simulation model* allows calibration to simulate different scenarios and their associated effects.

Furthermore, *Simulation model* represents the effects of CIs dependencies taking into account the dependency dimensions of the *CI dependency radar* (see Section 4.4.1). It allows simulating policies such as the resources deployment and prioritisation policies as impacts can be reduced depending on the way resources are deployed. Then, through the *Simulation model* a better understanding is gained on how the effects, that dependencies lead to, evolve over time.

In light of the obtained results, this *Simulation model* might be a valuable training tool to improve crisis managers and CI managers' comprehension of the complexity of existing dependencies among CIs and their consequent impacts through the understanding of the behaviours that are obtained using different scenarios.

4.5.3 *Simulation model* example

The developed System Dynamics *Simulation model* represents the effect of a crisis on CIs, the consequences of CIs dependencies, and the effect of policies related to resource deployment to repair CIs. The *Simulation model* allows the analysis of how the presence of dependencies between different CIs aggravates and prolongs crisis impacts. Complete information regarding the *Simulation model* structure, SMD-Doc checking tool results, extreme and sensitivity analysis and the equations can be found in Appendix C.

The Simulation model represents a small island in the Atlantic Ocean. A representation of the CIs on the island is shown in Figure 4.12 (lines connecting CIs show dependencies among them). We have included three CIs, one from each cluster identified in Section 4.3.3, excluding the cluster of Space and Research. Consequently, the included CIs are Energy, Food and Transport. Energy is the most influential CI, Food is the more dependent and Transport is not so influential or dependent. The three CIs are interdependent as there is a bidirectional dependency among them. Food CI depends on Energy for production systems and Transport as some food is produced inside the island but other must be supplied from outside. In addition, even if the effect is not immediate, being a shortage of food during some days will have effect on other CIs. The scarcity of food may cause a generalised public anxiety to get food and as consequence, Energy and Transport workers could not be able to continue with their normal activity.

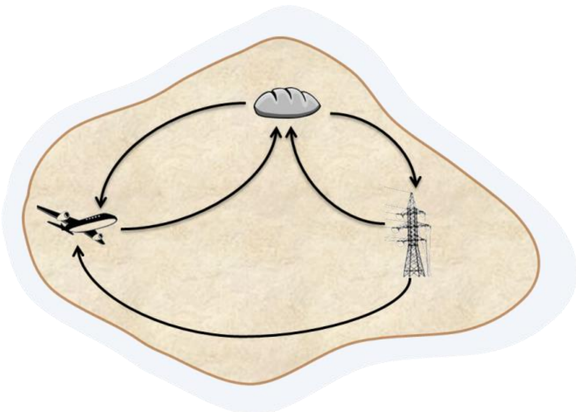

Figure 4.12 Energy is represented with a high voltage tower; a piece of bread corresponds to Food CI and a plane to Transport CI.

4.5.3.1 Structure of the *Simulation model*

The structure of the System Dynamics *Simulation model* is shown from Figure 4.13 to Figure 4.16. The model contains eighteen stocks. Each CI is represented by six stocks and several variables.

The structure of the *Simulation model* for Energy CI is shown in Figure 4.13 (complete model structure is included in Appendix C). The stocks included for Energy CI are: *Working Energy*, *Damaged Energy due to dependency*, *Damaged Energy due to triggering event*, *Reparable Energy*, *Energy failure duration*, and *Accumulated damaged energy*. Stocks (drawn as rectangles) represent the accumulations in a model, whose value depends on the systems behaviour. The *Working Energy* stock represents the percentage of Energy that is working while the *Damaged Energy due to dependency* shows the percentage that has failed due to Energy dependency on Food and Transport CIs. The stock *Damaged Energy due to triggering event* represents the percentage of Energy that has failed due to the triggering event. *Reparable Energy* shows the percentage of energy that can be repaired. Moreover, *Energy failure duration* represents the time that energy has failed and the *Accumulated damaged energy* is a stock that shows the total impact that Energy CI has suffered.

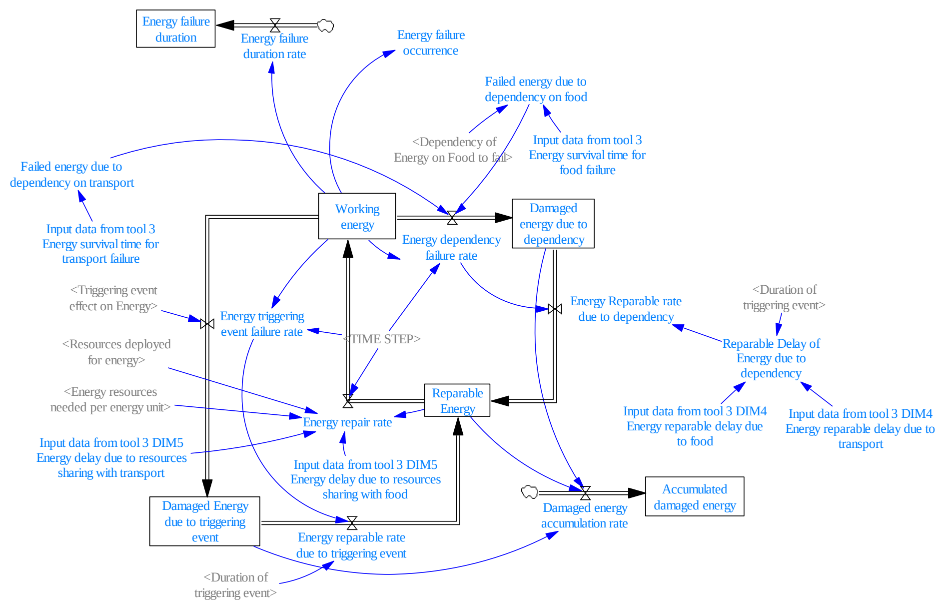

Figure 4.13 Simulation model's structure for Energy CI

Additionally, there are variables and links connecting the stocks in the *Simulation model*. The arrow links symbolise the existing causal influences among the variables that are connected. Behind each variable, equations and data inputs are included. By changing the values of these parameters the model generates different behaviours that can be used for a deeper understanding of the system. Variables to represent the five dimensions of the *CI dependency radar* tool are also included. Energy CI dependency dimensions related to recovery (time to recover and resources sharing) are included in Figure 4.13 and the dimensions of failure (dependency for working, redundancy and external factors) are included in Figure 4.14.

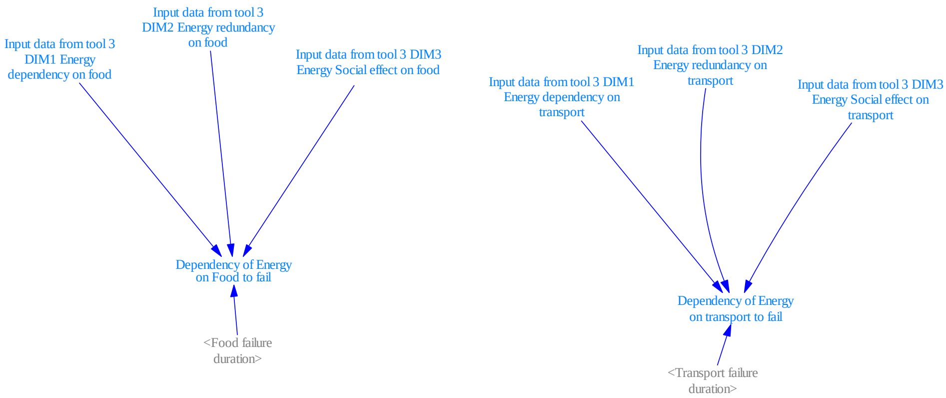

Figure 4.14 Simulation model's structure for Dependency of Energy on Food and Transport CIs

The input variable of the *Simulation model* is *Triggering event* (Figure 4.15) which can affect one or several CIs depending on the simulated scenario. For example, if Energy is damaged by the triggering event, the *Triggering event effect on Energy* variable will influence the *Energy triggering event failure rate* (Figure 4.13). This rate makes some of the *Working Energy* to fail, consequently increasing *Damaged Energy due to triggering event* stock. The percentage of Energy that is at the *Damaged Energy due to triggering event* stock will flow to *Reparable Energy* stock once the triggering event is finished.

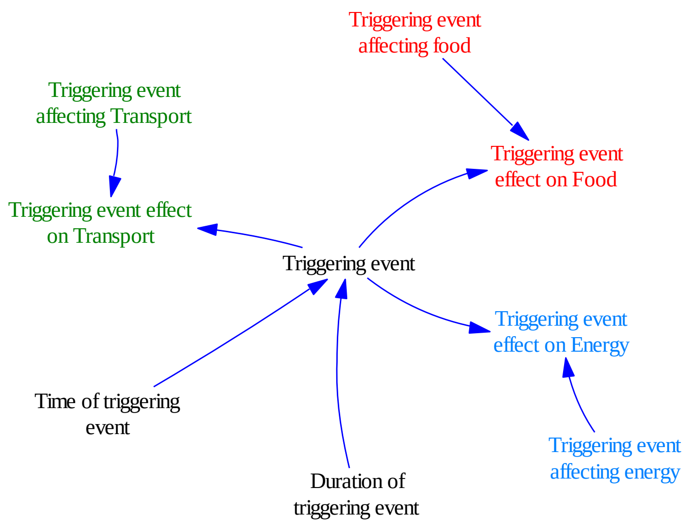

Figure 4.15 Simulation model's structure for Triggering event

Furthermore, if Food or Transport CIs are also damaged, the dependency of Energy on them will also affect Energy CI negatively. This effect will be delayed based on the data gathered from the *CI dependency radar* through *Input data from tool 3 Energy survival time for food failure* variable and/or *Input data from tool 3 Energy survival time for food failure* variable depending on the CI that has been damaged. These variables represent the time that Food and Transport have to fail before affecting Energy CI. Once these CIs have failed for longer than the specified time (in our example 2 hours for Food and 24 hours for Transport) the dependency of Energy on them will activate *Energy dependency failure* rate. Therefore, *Working Energy* stock will decrease and the percentage of *Damaged Energy due to dependency* will increase. This effect on Energy will continue until Food and Transport are restored.

The flow *Energy Reparable rate due to dependency* depends on the data gathered from the *CI dependency radar* through *Input data from tool 3 DIM4 Energy reparable delay due to food* variable and *Input data from tool 3 DIM4 Energy reparable delay due to transport* variable. These variables determine when the percentage of *Damaged*

Energy due to dependency can flow to the *Reparable Energy* stock. Therefore, on the one hand, Energy is damaged by the triggering event and furthermore, by the effect that Food and Transport have on Energy. On the other hand, deployment of resources to repair is what triggers the flow from *Reparable Energy* to *Working Energy*. Thanks to the *Resources deployed for Energy* (Figure 4.16), the Energy system will be repaired, increasing the *Working Energy* stock until the complete Energy system is recovered.

A similar structure is represented for Transport and Food CIs considering their interdependencies among them and with Energy.

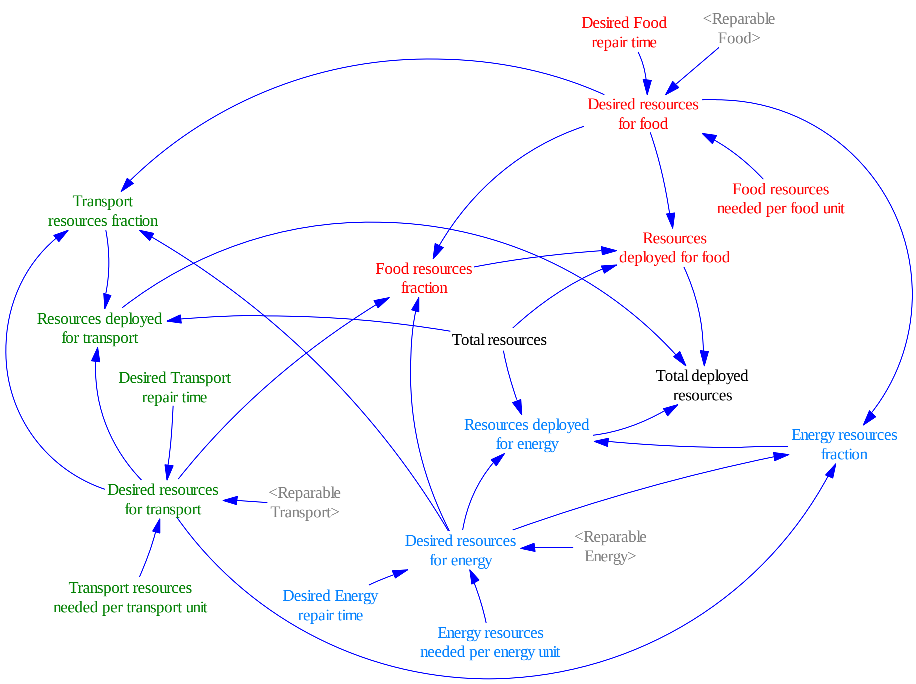

Figure 4.16 Simulation model’s structure for Resources allocation

The *Simulation model* includes 45 variables that can be modified to generate different behaviours. These variables are related to the triggering event, the dependency dimensions and resources allocation.

The triggering event can be modified through “Time of triggering event” and “Duration of triggering event” variables. The variable “Time of triggering event” is the moment when the triggering event starts and the “Duration of triggering event” represents how many hours the triggering event lasts.

For each CI, dependency dimensions variables are included. As an example, the variables related to Energy are explained (Food and Transport variables are similar). The variables related to Energy dependency dimensions are the following:

- The dependency for working of Energy on Food and Transport respectively are represented by “Input data from tool 3 DIM1 Energy dependency on Food” and “Input data from tool 3 DIM1 Energy dependency on Transport” variables (1st dimension of the *CI dependency radar*).
- The redundancy dimension is included through “Input data from tool 3 DIM2 Energy redundancy on Food” and “Input data from tool 3 DIM2 Energy redundancy on Transport” (2nd dimension of the *CI dependency radar*).
- The effect of external factors is represented by “Input data from tool 3 DIM3 Energy social effect on Food” and “Input data from tool 3 DIM3 Energy social effect on Transport” (3rd dimension of the *CI dependency radar*).
- The recovery time is included as “Input data from tool 3 DIM4 Energy reparable delay due to Food” and “Input data from tool 3 DIM4 Energy reparable delay due to Transport” (4th dimension of the *CI dependency radar*).
- The effect of shared resources is included by “Input data from tool 3 DIM5 Energy delay due to resources sharing with Food” and

"Input data from tool 3 DIM5 Energy delay due to resources sharing with Transport" (5th dimension of the *CI dependency radar*).

Apart from the variables related to the five dependency dimensions, the *CI dependency radar* tool allows identifying the time when a CI starts being affected by the failed CI. Therefore, this time is included in the model as "Input data from tool 3 Energy survival time for Food failure" and "Input data from tool 3 Energy survival time for Transport failure" variables.

Moreover, the variables related to resources which are included in the model allows determining the number of available resources ("Total resources"), the resources needed to repair one CI unit ("Energy resources needed per food unit", "Food resources needed per food unit", and "Transport resources needed per food unit") and the desired time in which CIs should be repaired ("Desired Energy repair time", "Desired Food repair time", and "Desired Transport repair time").

4.5.3.2 Behaviour of the *Simulation model*

In this section some of the simulations performed with the *Simulation model* are shown. The first scenario that has been simulated consists of a triggering event that occurs, in hour 10 and lasts for 10 hours. This triggering event has totally damaged Energy, Food and Transport CIs. In this initial scenario resources are equally deployed to restore the three CIs, so no priority is given to repair any of them. Figure 4.17 shows the performance of the three CIs. The scale of the graph represents the percentage of CIs performance, meaning 100% that the CI works properly and 0% that CI does not work at all. Each CI's behaviour is given a number, being 1 for Energy, 2 for Food and 3 for Transport.

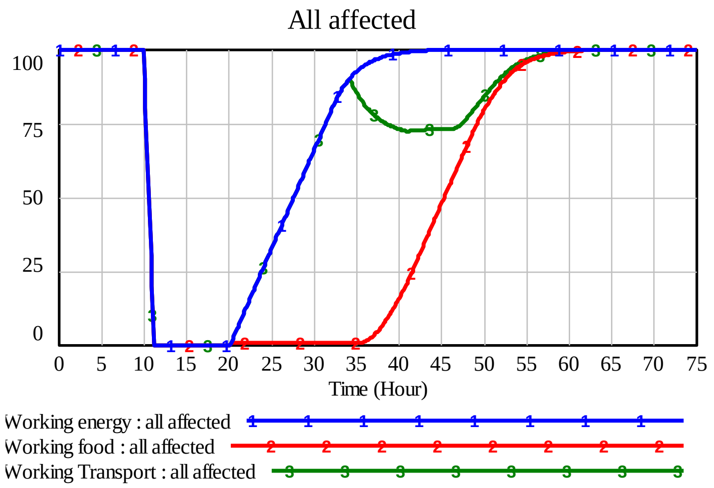

Figure 4.17 Performance of Energy, Transport and Food CIs

In hour 10, the three CIs completely fail due the triggering event that lasts until hour 20 and then the three CIs start to be repaired. In hour 20 Energy and Transport CIs start recovering as they are the less dependent CIs. However, Food needs longer time due to its higher dependency on Energy and Transport. Around hour 35 it can be seen that Transport starts failing again. This occurs due to its dependency in Energy, and in this example Energy has failed a longer time than the one established by experts that is represented by the *Input data from tool 3 Transport survival time for energy failure* (24 hours) variable.

The second simulation is based on the same scenario, when the three CIs are completely damaged by the triggering event and crisis managers have to make decisions about resources deployment policies. The *Simulation model* also allows simulating scenarios where different priorities to allocate resources for recovery are assigned. On the one hand, when no priority to restore any CI has been applied the behaviour is the one shown in the first simulation (Figure 4.17). On the other hand, "Priority to Energy" shows CIs performance when Energy repair has been prioritised in order to achieve a complete restoration of Energy faster (Figure 4.18).

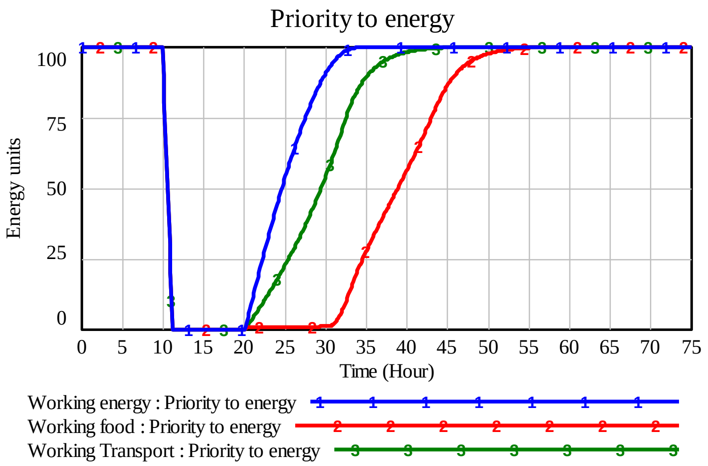

Figure 4.18 Performance of CIs simulating resource deployment priority to recover Energy

The policy of giving priority to restore Energy shows better results since Energy is the most influential CI and its effects on other CIs are high. Therefore, the longer the time Energy is down, the higher its impact on Transport and Food will be as these CIs are dependent on the correct performance of Energy. As a consequence, in “Priority to Energy” scenario the complete recovery of CIs is faster.

To better represent this, we have measured the accumulated impact that each CI suffers through the “impact unit” (i.u.) (Table 4.13). “i.u.” is used to compare the total impact of the three CIs (one “i.u.” is equal to the impact of 1% of a CI which is down for 1 hour). As it can be seen in Table 4.13, the total impact is lower in the “Priority to Energy” scenario. The total impact when prioritizing Energy would be 17% lower for Energy, 18% lower for Food and 15% lower for Transport.

	No priority	Priority to Energy
Energy	1740 i.u.	1450 i.u.
Food	3490 i.u.	2850 i.u.
Transport	2140 i.u.	1870 i.u.

Table 4.13 CIs i.u. when simulating different resource priorities

As crisis managers and CI managers must be prepared before the occurrence of any triggering event to respond more efficiently, the model also allows analysing crisis evolution over time when fewer resources to solve it are allocated. It is logical that having fewer available resources the impacts of a crisis will be higher until a normal situation is recovered. In the following figures two scenarios have been simulated. The scenario where adequate resources are in place to restore CIs is shown in Figure 4.17. Then, Figure 4.19 a shows a scenario where the available resources have been decreased in 20%. The final impact is 25% higher in the second scenario than in the first one even if resources availability has only decreased a 20%. In light of the obtained results, it can be seen that the decrease of resources and the increase of generated impacts are not proportional as the indirect impacts generated will increase due to existing dependencies among CIs.

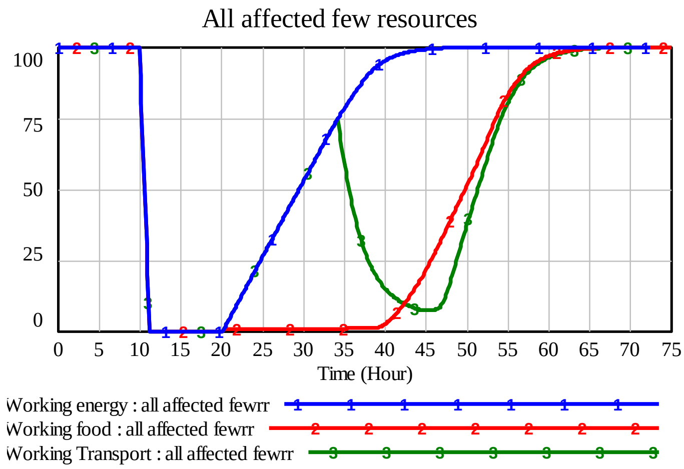

Figure 4.19 CIs totally damaged with resource scarcity

4.6 Conclusions

Through this research the CriMaCID toolbox has been developed. The CriMaCID toolbox aims to improve crisis management through the analysis of crises' impacts with special focus on the analysis of CIs dependencies. The developed CriMaCID toolbox increases crises impacts awareness in order to improve resilience against future crises occurrence.

An I*mpact indicators framework* has been developed where indicators have been classified according to their nature distinguishing direct versus indirect and tangible versus intangible impacts and also according to the affected sector differentiating economic, social, CIs and environmental sectors. The impact indicators framework pays special attention to the role of CIs for impacts generation.

Crises impacts are aggravated and prolonged if CIs are damaged. Therefore, analysing CIs and their dependencies is a relevant task. However, the information regarding this issue was not holistic or dynamic. Moreover, crisis managers and CI managers pointed out the lack of tools to observe CIs dependencies in a clear way. Therefore, through this research, two tools to analyse CIs dependencies have been developed. Depending on the aim of the study the *CIs dependency-influence cluster* or the *CI dependency radar* tools will be applied. These tools will study different failure periods in order to analyse dependencies evolution over time. We propose *CIs dependency-influence cluster* tool that allows analysing CIs of a geographic area through one survey, the CIs dependency and influence identification and to gather evidences about these dependencies. Furthermore, we suggest the use of the *CI dependency radar* tool when analysing the dependencies of a particular CI.

The *simulation model* allows behaviour over time analysis and can be used to increase crisis managers' and CI manager's awareness about impacts assessment and CIs dependencies analysis. The process of *Simulation model* development allows crisis managers and CI managers improving their learning and comprehension of the interaction of variables. Also, the *Simulation model* allows managers to analyse the effect of different triggering events or the implementation of several policies such as giving priority to repair a CI. Furthermore, these policies could lead to a minimisation of the consequences of future crises or even to their avoidance.

The CriMaCID toolbox gives an overview of the impacts that a geographic area can suffer paying special attention to CIs, dependencies and the generated consequences evolution over time increasing CI managers' awareness. Additionally, the CriMaCID toolbox also allows assessing current crisis management strategies' effectiveness and to identify policies that should be implemented. Finally, once having applied the CriMaCID toolbox, crisis managers and CI managers will be in charge of deciding which policies they will apply by comparing the risks to the costs.

5 Validation of the CriMaCID toolbox

This section presents the validation process of the CriMaCID toolbox. The aim of the validation process is to assure that the CriMaCID toolbox provides value improving crisis managers and CI managers' awareness in order to be better prepared against future crises.

The validation process has been carried out with the collaboration of several crisis managers and CI managers. Moreover, the CriMaCID toolbox has been presented in plenary sessions to make crisis managers and CI managers know the toolbox. As a result of these activities, the completeness and usability of the toolbox has been confirmed.

5.1 Introduction

First of all, it is important to define what validation stands for in the context of this research, since validation and verification concepts are often mixed. The following two questions clarify the difference among these two concepts: “Is the model right?” (this defines verification) and “Is the right model?” (this defines validation). A model is developed for a specific purpose or application and its validity refers to the capacity of this model to fulfil this purpose (Sargent 2005). Thus, the required model accuracy depends on the model’s purpose. The validation process can be a costly and very time-consuming activity therefore, evaluations and tests are conducted until sufficient confidence is achieved (Sargent 2005).

The purpose of the validation in this research is to confirm the completeness and usefulness of the CriMaCID toolbox in face of future crisis management and to increase crisis managers and CI managers trust on the developed tools.

The structure of this chapter is the following. Firstly, the methodologies applied for the validation of the CriMaCID toolbox are commented. Secondly, the validation of each tool is explained.

5.2 Validation methodologies

Firstly, case studies based on real past crises were reviewed in order to analyse the *Impact indicators framework.* Afterwards, interviews in CI organisations have been conducted and plenary sessions with crisis managers and multiple CI organisations have been carried out in order to validate the CriMaCID toolbox.

5.2.1 Multiple case studies on past real crises

Multiple case studies of real past crises have been developed to validate the *Impact indicators framework* tool. Reports from several crises have been reviewed in order to validate the *Impact indicators framework*. Reports about floods, hurricanes, earthquakes, volcanic ash clouds, and accidents such as nuclear radiations or oil spills were reviewed.

5.2.2 Interviews with crisis managers and CI managers

The CIs that have been chosen for the validation correspond to Health, Food, and Public and Legal Order and Safety CI sectors. This three CI sectors constitute one of the four clusters identified as a result of the questionnaire about CI dependencies (see Section 4.3.3). Therefore, these three CI sectors have been clustered as the most dependent CIs. This means that these CIs will be the most affected ones if other CIs fail. Consequently, these CIs need to be aware of their dependencies on the rest of CIs and the consequences they lead to in order to deploy resources and carry out the adequate policies to reduce or face these dependencies.

Apart from interviewing Health, Food and Public and Legal Order and Safety CIs, two additional interviews have been performed on Civil Administration CI sector. Civil Administration CI interviews have been included as some organisations related to emergency services work very closely to organisations of Public and Legal Order and Safety CI sector.

As a result, sixteen interviews have been carried out in different CI organisations (Table 5.1):

- Three interviews to organisations related to food supply
- Five interviews to public and private hospitals
- Six interviews to regional and local security and police departments and in a courthouse
- Two interviews to Civil Administration organisations. The first interview was carried out to a fire-fighters department and the second one to an ambulance service

	Organisation
Food	MercaBilbao (food distribution centre) of Vizcaya
	Uvesco (food distribution centre) of the Basque Country
	Eroski (food distribution centre) of the Basque Country
Health	Hospital of Zumarraga
	Hospital of Donostia
	Policlínica (private hospital) of Donostia-San Sebastián
	Hospital of Galdakao
	Hospital of Bidasoa
Public and Legal Order and Safety	Security department of Bilbao
	Civil protection of Donostia-San Sebastián
	Police department of Donostia-San Sebastián
	Ertzaintza (Basque police) station of Iurreta
	Ertzaintza (Basque police) station of Donostia-San Sebastián
	Courthouse of Donostia-San Sebastián
Civil Administration	Fire-fighters of Donostia-San Sebastián
	DYA (ambulance service) of Donostia-San Sebastián

Table 5.1 CI organisations where validation has been performed

The process of validation consisted of interviews with management, security and/or maintenance departments of each organisation. Information about the research and the aim of the interviews was sent in advance to the participants in the interview.

Participants could ask questions and make comments and suggestions at any time during interviews. Different activities were carried out during the interviews. The structure of the interviews was the following.

Firstly, the aim of the research and the research methodology were explained. Then, each of the four developed tools was presented. Once a tool had been explained, questions were posted to participants. The questions aimed to know the opinion of participants about the applicability of the tools on their CIs. Then, tools were applied for their particular CI.

As conclusion of each interview, participants were required about any issue they believe was important and which had not been mentioned. The aim was to identify gaps in order to improve the CriMaCID toolbox or future research issues.

One recommendation of some CI managers after presenting the CriMaCID toolbox was that we should particularise the *Impact indicators framework* for CIs. Concerning the *CIs dependency-influence cluster* tool CI managers commented the importance of data protection issue as CIs would not give information if this is not assured. Regarding dependency evidences, this information will be handled by authorities and the information that CIs will receive will not be referred to any specific CI. Moreover, the idea of comparing the real *CI dependency radar* with the ideal radar values was a suggestion of a CI manager during one of the interviews. Finally, concerning *Simulation model* tool CI managers proposed the development of specific *Simulation models* adapted to their particular CIs.

5.2.3 Plenary sessions with crisis managers and CI managers

The plenary sessions consisted firstly on a presentation of the CriMaCID toolbox. Then, questions about the usability of the toolbox were posed to participants in order to obtain information about the completeness or additional uses of the toolbox.

The first plenary session was organised in February 2014 in Donostia-San Sebastian. To this session civil protection services and emergency services were invited: Eight participants from five organisations took part (Table 5.2). Comments from participants were very positive mostly focused on the usefulness of the tools and their willingness to apply the tools in their organisations. Therefore, after this plenary session face to face interviews with three organisations were arranged. These interviews are included in Table 5.1.

	Organisation
Health	Osakidetza service of Guipuzcoa
Civil Administration	Fire prevention service of Donostia-San Sebastian
	DYA (ambulance service) of Donostia-San Sebastián
	Red Cross emergency department
	Basque government emergency service

Table 5.2 Participants on the first plenary session

The second session held on May 2014 was part of the Conference of Risk and Emergency Management organised by the city council of Donostia-San Sebastian. The police department of Donostia-San Sebastian invited us to present the CriMaCID toolbox in the conference. 400 participants belonging to civil protection organisations, emergency services, research centres CI managers and industries participated in this conference. After presenting the CriMaCID toolbox some participants were interested on the availability of the tools to apply them in their organisations. Afterwards, some participants that showed special interest were contacted to take part in the interviews or in the final plenary session.

The final plenary session took place in Donostia-San Sebastian in October 2014. In this session organisations related to civil protection, emergency services and CI managers took part. Fifteen participants from thirteen organisations attended the session. Table 5.3 includes a list of participant organisations.

	Organisation
Energy	Iberdrola Energy company
Transport	Transport cluster of Guipúzcoa
Food	MercaBilbao (food distribution centre) of Vizcaya
Health	Policlínica (private hospital) of Donostia-San Sebastián
	Hospital of Zumarraga
	Hospital of Donostia
	Hospital of Bidasoa
Public and Legal Order and Safety	Police department of Donostia-San Sebastián
	Ertzaintza (Basque police) station of Iurreta
	Basque security service
Civil Administration	Basque government emergency service
Space & Research	CEIT research centre
	TECNALIA research centre

Table 5.3 Participants on the final plenary session

During plenary sessions the tools of the CriMaCID toolbox generated interesting discussions among crisis managers and CI managers about their usability and how the tools could help them to improve their management. Moreover, some participants required future collaboration in order to apply the CriMaCID toolbox to their CI or in future research projects.

5.3 Validation of the CriMaCID toolbox

In this section the validation of each of the four tools of the CriMaCID toolbox is explained.

5.3.1 Validation of the *Impact indicators framework*

The *Impact indicators framework* is a compilation of impact indicators classified by sector and nature based on international methodologies. Real past crises have been reviewed in order to assure the completeness of the *Impact indicators framework.*

Bilbao (Basque Country, Spain) suffered terrible floods the 26th of August 1983. A heavy rain of 600 litres per square metre flooded almost a hundred of cities and towns of the Basque Country were 37 people died and other five disappeared. Two weeks were needed to completely recover CIs such as water or communications (Ibisate González de Matauco, Askoa et al. 2000).

The Chernobyl nuclear catastrophe took place the 26th of April 1986 when Ukrainian atomic energy plant exploded causing approximately 6000 deaths and 30000 injuries (Manion and Evan 2002). The consequences of this catastrophe are still evident today as people continue suffering side effects. Fortunately, nowadays radiation levels have been reduced because of natural processes and countermeasures. On December 2000, Russian government announced that the Chernobyl nuclear plant was completely closed, almost 15 years after the tragedy (Manion and Evan 2002).

Prestige was an oil tanker which, the 13th of November 2002, sank near the coast of Galicia (Spain). The spill of hundreds of tons of toxic oil affected 2500 kilometres of Spanish, French and Portuguese coasts (García-Mira et al. 2006, Méndez-Martínez 2003). Apart from the evident environmental impact the effects on the affected areas' economy, specially fishing and tourism, was significant (Garcia 2003).

The Katrina hurricane affected the states of Louisiana, Mississippi and Alabama (USA) the 29th of August 2005. The strong winds and heavy storm affected almost 6 million people and killed 1000 people. The worst occurred due to the flooding of New Orleans when levees broke (Gabe et al. 2005).

Haitian earthquake stroke the country the 12th of January 2010 with a magnitude of 7.3 on the Richter scale (Intermon Oxfam 2010). More than

300.000 people lost their lives (Government of the Republic of Haiti 2010). Furthermore, one year later a cholera epidemic killed thousands of people. Nowadays, there are still people living in shelters.

On 20th of March 2010 the first eruption of Eyjafjallajökull volcano took place in Iceland. Subsequently, on April 14, 2010 a second volcanic eruption was accompanied by a huge ash cloud that paralysed air traffic affecting northern Europe. In countries like Ireland and UK airports were closed for more than a week sparking a crisis in the supply of raw materials. UK retailers faced severe shortages of medicines, fruits and vegetables due to airports closure (Hall 2010).

Sandy hurricane made its way from the Caribbean Sea into the Atlantic Ocean and finally entered landfall in southern New Jersey the night of October 29, 2012 (Center for Disaster Management and Risk Reduction Technology (CEDIM) 2012). Sandy left more than 80 deaths, thousands of displaced people and millions without power.

After the review of these past real crises and interviews with crisis managers and CI managers it is noted that there is not any occurred impact that is not already included in the *Impact indicators framework* tool. The analysis of so different crises where diverse impacts have occurred as well as CIs managers experience about suffered impacts allows asserting the completeness of the *Impact indicators framework* tool.

Additionally, the *Impact indicators framework* was validated by the CI organizations that took part in the validation process (Table 5.1). The validation consisted on the agreement of participants about its completeness and usability. Participants agreed that is a hard (or almost impossible) task to be prepared for unknown consequences. The *Impact indicators framework* allows them being aware of any impact their organisation, a specific geographic area or the whole society can suffer.

Participants carefully reviewed the indicators and classification categories and agreed about the holistic view of the tool. Consequently, Public and Legal Order and Safety and Civil Administration participants were grateful about having a complete *Impact indicators framework* that they could particularise for their geographic area. Furthermore, Health and Food CI participants could also appreciate the usefulness of the framework once being chosen the specific impacts they could suffer.

As a result, the *Impact indicators framework* allows having a holistic perspective of all possible crisis impacts. The tool can be used as an input to develop new policies or improve existing ones that help to diminish the impacts identified in the framework.

5.3.2 Validation of *CIs dependency-influence cluster* tool

The values showed in the *CIs dependency-influence cluster* tool were a result from the online questionnaire sent to CI managers from different countries. This tool can help crisis managers and CI managers having a holistic perspective of the dependencies that CIs in a geographic area. This information can be used to identify the CIs that correspond to each cluster and the common policies or activities that could help managing these dependencies or even minimizing them or their effects. Then, this tool has to be particularised to a specific geographic area based on the type of CIs located there.

The methodology used to identify the influence and dependency of CIs was explained to participants in order to know if they agreed on the methodology and with the most or least influential and dependent CIs.

As it occurred with the *Impact indicators framework*, the *CIs cluster* tool has been developed taking into account a geographic area as unit of analysis. This means that Public and Legal Order and Safety and Civil Administration CIs will have to analyse CIs in a specific geographic area through the developed questionnaire. The Public and Legal Order and Safety and Civil Administration CIs need the collaboration of the rest of CIs in order to cluster them. The questionnaire has to be sent to the CIs located in the geographic area in order to identify the specific cluster each CI belongs to.

During the validation process Public and Legal Order and Safety and Civil Administration participants were asked about their current methods to manage

CIs and their dependencies. They explained to us that in Spain the CIs dependencies analysis is still an immature issue. Actually, they have no tools which could facilitate this analysis. Consequently, participants commented that using this *CIs dependency-influence cluster* tool, they could implement common policies or activities to manage them, improving preparation and minimizing future impacts on CIs, and on the whole society.

Moreover, Food and Health CI participants appreciate the need of having a holistic perspective of all CIs in a geographic area, since they usually are aware only of their direct dependencies, but not of their influence on others; since information related to CIs dependencies is not publicly available. As a consequence of the identification of the most or least dependent or influential CIs in a geographic area, crisis managers can carry out policies or activities to better manage them.

5.3.3 Validation of *CI dependency radar* tool

The *CI dependency radar* is a tool that helps CI owners to identify the level of dependency of their CI on others, based on five dimensions and for different failure times. The five dimensions are related to the failure and recovery of CIs. The analysis is made taking into account two scenarios: one where only an external CI is damaged and the CI under analysis is affected due to its dependency, and the second where both the external CI and the own CI have failed due to the triggering event.

Regarding the different periods of time analysed and taking into account participants' comments, our recommendation is the analysis of at least two periods of failure. The first period helps analysing the moment when a failure in a CI starts affecting another CI. The second period of failure corresponds to the moment when the affected CI suffers great impact that affects operability due to its dependency on the failed CI. However, each CI could decide the number of failure periods analysed.

During the validation of the *CI dependency radar* tool, firstly the different scenarios, dimensions and the scales used in each dimension were explained to participants. Then, before applying the tool, participants were asked to identify the two different failure periods to be applied. Then, in each interview the tool was applied for the CIs that CI managers considered more influential for their CI in order to show their level of dependency on other CIs in a graphical representation.

Moreover, when there were people in a validation interview with different responsibilities inside the organisation, they had interesting discussions as their points of view of the same scenario were slightly different. For example, during an interview the general manager of a CI considered that the failure of Public and Legal Order and Safety CI was not critical. However, the security engineer did not agree and he explained that for the security department Public and Legal Order and Safety CI was critical. Therefore, in this case the discussion that the CriMaCID toolbox generated was valuable to increase the awareness about an issue that the general manager did not considered being critical before.

As a result of the validation interviews, we obtained positive comments from participants about the tool as they do not actually know about similar tools they can so easily apply to their CIs. Furthermore, the usability of the tool to include this analysis in their self-protection plan was also positively valued by participants.

5.3.4 Validation of the *Simulation model*

The *Simulation model* has been explained in Section 4.5. After developing the *Simulation model* extreme and sensitivity analyses were performed in order to check if the model performed correctly in different scenarios. Additionally the SDM-Doc tool (Martinez-Moyano 2012) was used to check the model. The SDM-Doc analyses the simulation model and gives information about variables, possible errors or issues that could be improved. For example, the performed analysis identifies that there are no errors in the model. Information regarding the extreme and sensitivity analyses and the outcome from the SDM-Doc tool are included in Appendix C.

Once the *Simulation model* was checked it was presented to participants in the interviews and in the plenary sessions. This *Simulation model* aims to integrate the previous tools by including information gathered from each tool.

The learning process when building models and the different scenarios and policies that could be analysed were explained to participants in order to give them a general idea of the usefulness of the process of developing *Simulation models*. Experts' participation in the process of *Simulation models* development allows participants to increase their awareness about the complexity of the problem. Moreover, some examples of the policies that can be implemented in the *Simulation models* were explained.

In the validation process the model structure was explained to participants. Then, participants were asked to explain and to draw behaviours over time of *Working Energy*, *Working Food* and *Working Transport* stocks. For example, participants were asked to draw the behaviour of these stocks in a specific scenario where the three CIs have been damaged by the triggering event. Four draws are shown in Figure 5.1.

Afterwards, all drawings were shown to participants in order to make explicit the different mental models of each of them and how simulation can help better understanding the complex behaviour of this problem. As it can be seen, the mental model of each participant is different and therefore, through these exercise we showed participants the difficulty of thinking about how a system will perform when so many variables are in place. Moreover, participants commented that they make analyses based on their experience and therefore, they had not thought about such a serious scenario.

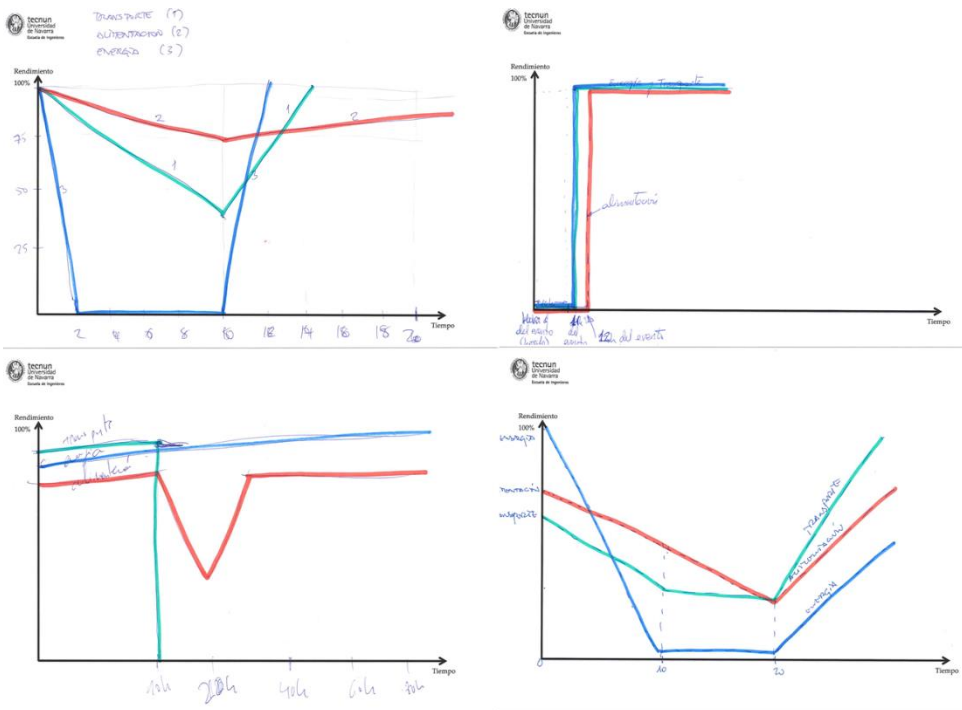

Figure 5.1 Participants behaviour over time drawings (blue line represents Energy CI, green is used for Transport CI and red for Food CI)

Then, different scenarios' simulations were explained in order to show them how simulation can help increasing their understanding of the problem under analysis. Consequently, the simulations were discussed in order to help them to understand the usefulness of the *Simulation model*.

5.4 Conclusions of the validation process

The validation process of the CriMaCID toolbox aimed to determine that the toolbox fulfils the objective of this research. The objective is to develop a toolbox to help crisis managers and CI managers improving their management through the analysis of impacts and with a special focus on CIs dependencies and their effects.

In the final plenary session a questionnaire was given to participants in order to know their opinion about the usability of the CriMaCID toolbox and positive results were obtained. 13 answers were received. The results of the questionnaire are shown in Table 5.4. Being 1 “Totally disagree”, 2 “Disagree”, 3 “Nor agree or disagree”, 4 “Agree”, and 5 “Totally agree”. The complete questionnaire is included in Appendix D.

	Tool 1	Tool 2	Tool 3	Tool 4
1-The tool covers an existing need as problems under analysis are significant	4,08	4,38	4,42	4,67
2-The tool includes the most representative variables of the problem under analysis	4,46	4,23	4,17	4,58
3-The tool offers relevant information of the problem under analysis	4,00	4,46	4,33	4,08
4-The difficulty level for applying the tool to my particular case is adequate	3,85	3,69	3,75	3,58
5-There are similar tools that I can use	3,33	2,75	3,10	2,50
6-I already use a similar tool	2,17	2,08	1,82	1,82
7-Global assessment of the tool regarding value contribution	4,15	4,15	4,33	4,33

Table 5.4 Questionnaire results

Regarding the questionnaire the results were very positive. The first question confirms that crisis managers and CIs managers need tools as the ones developed in the CriMaCID toolbox. The second question assures the completeness of the CriMaCID toolbox as the most representative variables are included. The value added through the toolbox is confirmed by the third question as the majority think that the CriMaCID toolbox offers relevant information of the problem under analysis. Moreover, the difficulty level does not seem to be a barrier for applying the toolbox as it is stated in the fourth question.

When asking about potentially available similar tools, participants confirmed that they do not know similar tools (fifth question) and therefore, they are not applying any other tool (sixth question).

Finally, a last question asking for a global evaluation of each tool value was included. Taking into account participants' assessment it can be said that they considered that the CriMaCID toolbox provides added value and can be useful for crisis managers and CI managers.

Considering the positive comments and the questionnaire results of crisis managers and CI managers during interviews and the sessions the CriMaCID toolbox is useful to increase awareness about crisis impacts analysis, existing dependencies and the effects that these dependencies lead to in order to improve preparation in face of future crises.

However, a limitation of this validation is that we have not completely applied the CriMaCID toolbox in an organisation due to time constraints. Tools have been applied in different CI organisations but the four tools have not been applied in a real particular case. Another issue is that, if we would be able to apply the CriMaCID toolbox, we would have to wait (weeks, month or years) the occurrence of a crisis and then, compare the management and the impacts generated with a previous crisis to see the improvement through the use of the toolbox.

6 Conclusions, Limitations and Future Research

In this chapter main conclusions of the research process to develop the CriMaCID toolbox are presented. Afterwards, limitations of the presented research are commented and finally, future research activities are mentioned.

6.1 Conclusions

In this research the value added of the CriMaCID toolbox has been explained. This toolbox aims to help crisis managers and CI managers to be aware of any impacts that CIs and society could suffer in order to deploy policies that could improve resilience level in face of future crises.

The research questions identified in Section 1.4 have been analysed through this research.

Properly identifying, analysing and assessing the impacts caused by a crisis helps managers to efficiently develop preventive and response programs. The analysed impacts assessment methodologies such as the one developed by FEMA (2002) or the one by ECLAC (2003) are internationally used methodologies (RQ1.1). The problem arises as these methodologies do not make special focus on CIs and their associated impacts. Moreover, there is not an agreed terminology about the indicators included in each sector (RQ1.2). Usually, impact assessment methodologies focus on identifying the final impact but do not analyse impacts evolution over time. However, identifying which impacts (direct impacts) can generate others (indirect impacts) can help improving their management in order to lessen future crises impacts (RQ1.3). The *Impact indicators framework* tool has a holistic perspective including all impacts that society and especially CIs can suffer and categorising indicators based on their nature and affected sector.

Crises can severely affect CIs and due to their dependencies, crisis impacts can spread and prolong over time affecting a whole geographic area and society's welfare (RQ2.1). However, not all CIs are equally critical as some can be more influential while others more dependent (RQ2.2). Therefore, an analysis of CIs dependency and influence level on others is needed and tools to do it have been developed (RQ2.3). Moreover, including a dynamic analysis is needed as, depending on the time a CI does not work, the effect on the rest of CIs will be different. It is obvious that longer the time a CI is not working the higher the effects on the rest of CIs. However, an important issue that CI managers need to be aware of is that there is a time period from what the effects of dependencies become significant. This issue is relevant in order to design proper policies that lead them minimise the effects that dependencies have on their CI. Usually, CIs suffer short duration events but even if managers do not consider longer triggering events so likely, preparation and response to face them have to be improved, as consequences can increase exponentially (RQ2.4). Therefore, the CriMaCID toolbox helps increasing crisis managers and CI managers' awareness about CIs dependencies and their effects through the *CI dependency–influence cluster*, *CI dependency radar* and *Simulation model*.

The CriMaCID toolbox's holistic and dynamic analysis allows crisis managers and CI managers to better understand the complexity of crises. Through the analysis of impact indicators crisis managers can be aware not only about direct impacts but also the indirect ones, and more specifically the ones produced by CIs dependencies. Then, crisis managers and CI managers will be able to design policies in order to minimise impacts, reduce dependencies or prepare response and recovery plans. Furthermore, the dynamic analysis based on the effects of different failure timeframes, will serve as a basis for crisis managers and CI managers to decide which policies and prioritisation activities could be the most efficient to carry out.

6.2 Limitations of this research

The CriMaCID toolbox has some limitations that could difficult its implementation in real geographic areas or in particular CIs.

The *Impact indicators framework* tool could be too wide for crisis managers' use and therefore, crisis managers could be overwhelmed with so many indicators. A possible solution to this issue is that crisis managers could choose only the most relevant indicators.

Crisis managers need the cooperation of all CIs of a geographic area in order to use the *CIs dependency-influence cluster* tool and obtaining their collaboration could not be an easy task. Another relevant issue is that CIs dependency and influence analysis has to be periodically performed as CIs and their dependencies could change based on, for example, new technology on CIs or policies implementation.

Also, the *CI dependency radar* has to be periodically reviewed as values of dependencies dimensions can vary due to applied policies. Additionally, we have analysed the eleven CIs but not the different sectors that each CI comprises. A CI should disaggregate the CIs into sectors and make a different analysis for each of them in case their dependency is different. For example, when analysing a CI dependency on Energy the values of the dependency dimensions for electricity or gas could be different. Therefore, for Energy CI analysis two different *CI dependency radar*s should be performed, one to analyse CI dependency on electricity and the other one for gas dependency analysis.

Finally, the process of developing S*imulation model*s requires the collaboration of experts on simulation, and much time of joint work of these experts with crisis managers or CI managers in order to build the models. Furthermore, S*imulation model*s such as the one presented in this research are not developed to predict what will happen in future crises but to increase managers' awareness about how variables interact generating and prolonging impacts. Crisis managers' or CI managers' learning from simulation can lead to an improvement of future crisis management and to the increase geographic areas' or CIs' resilience level.

Moreover, the CriMaCID toolbox allows having an overview of the impacts that a geographic area can suffer due to a crisis and how CIs and their dependencies can make impacts to spread from one CI to others affecting society's welfare. However, crisis managers and CI managers will have to decide which policies they will apply to improve the current situation analysing the risk reduction versus the cost of implementing policies.

6.3 Future research

This research has developed the CriMaCId toolbox. However, it is necessary to perform an exhaustive implementation of the CriMaCId toolbox in geographic areas and particular CIs. Therefore, future research should be done regarding the CriMaCID toolbox implementation in order to evaluate the usefulness of its implementation.

A future research would be to assess the added value of implementing the *Impact indicators framework* tool in future crises impacts' management.

Considering CI managers' recommendations, another future research line regarding the *Impact indicators framework* is the development of a specific framework focused on each CI of a geographic area.

Additionally, multiple case studies research on identifying policies to lessen dependencies or their effects through the implementation of the *CIs dependency-influence cluster* and the *CI dependency radar* tools can be performed. It could also be analysed if there have been any changes in the implemented policies or if new regulations have been developed after the implementation of the tools.

Research about how engagement of crisis managers and CI managers in the development of *Simulation model*s allows increasing awareness on the problem under analysis can be performed. The aim of this research is to evaluate if awareness of crisis managers and CI managers who have collaborated in the development of *Simulation model*s increases more than the awareness of the experts that only use the model but do not contribute in its development.

Real data obtained from the implementation of the three other tools can be used to redefine the developed *Simulation model* or to build new *Simulation model*s. For example, a *Simulation model* can be focused on a specific CI and its dependencies as suggested by CI managers.

Future research can also be focused on developing a software to facilitate the implementation of the CriMaCID toolbox. As it has been commented previously the toolbox will have to be applied periodically and therefore, this software can also be used to store data and to compare past data with current information.

Research to analyse how information sharing about implemented policies to reduce dependencies or their consequences could improve crisis managers' and CI managers' preparation can be performed. The development of a virtual community of practise could facilitate information sharing.

Finally, dissemination activities to make geographic areas' crisis managers and CI managers know the CriMaCID toolbox have to be arranged. For example, the CriMaCId toolbox could be implemented in the Basque Country. Then, we should arrange meetings with crisis managers and CI managers of the Basque Country to explain them the benefits they could obtain through the implementation of the CriMaCId toolbox.

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Appendix A: Online questionnaire

In this chapter the complete online questionnaire sent to CI operators about CIs dependencies is included.

Critical Infrastructures' Interdependencies

Welcome

Thank you for answering to this questionnaire, your expertise and cooperation are very important for this research!

Answers to the questionnaire and following documents will keep confidential so there will not be any personal information or any relation between experts and answers. Once we receive the questionnaires from all participants we will send you a document with all answers and some new questions regarding your answers.

Critical Infrastructures

The Critical Infrastructures (CIs) included in this research correspond to the list from the green paper on the European Programme for Critical Infrastructure Protection which considers the following infrastructures as critical.

Sector	Product or Service
Energy	- Oil and gas production, refining, treatment and storage, including pipelines - Electricity generation - Transmission of electricity, gas and oil - Distribution of electricity, gas and oil
Information and Communication Technologies	- Information system and network protection - Instrumentation automation and control systems (SCADA…) - Internet - Provision of fixed telecommunications - Provision of mobile telecommunications - Radio communication and navigation - Satellite communication - Broadcasting
Water	- Provision of drinking water - Control of water quality - Stemming and control of water quantity
Food	- Provision of food and safeguarding food safety and security
Health	- Medical and hospital care - Medicines, serums, vaccines and pharmaceuticals - Bio-laboratories and bio-agents
Financial	- Payment services/payment structures (private) - Government financial assignment
Public & Legal Order and Safety	- Maintaining public & legal order, safety and security - Administration of justice and detention
Civil Administration	- Government functions - Armed forces - Civil administration services - Emergency services - Postal and courier services
Transport	- Road transport - Rail transport - Air traffic - Inland waterways transport - Ocean and short-sea shipping
Chemical and Nuclear Industry	- Production and storage/processing of chemical and nuclear substances - Pipelines of dangerous goods (chemical substances)
Space and Research	- Space - Research

Questionnaire

In the following sections we ask you to evaluate the degree of dependency among CIs when a natural disaster occurs. We would like you to think about a natural disaster which has affected a CI making it fail. What will the dependency of your CI be if the failure lasts for different periods of time?

1. **First, we would like to know the CI on which you work or feel most comfortable answering about. We will then refer to this CI as "your" CI. You must select only one CI. If you want to answer to more than one CI, please fulfil one questionnaires for each CI**

- ☐ Energy
- ☐ Information and Communication Technologies
- ☐ Water
- ☐ Food
- ☐ Health
- ☐ Financial
- ☐ Public & Legal Order and Safety
- ☐ Civil Administration
- ☐ Transport
- ☐ Chemical and Nuclear Industry
- ☐ Space and Research

2. **Feel free to make any comments on this section here:**

Note: In the following questions do not fill in answers for your CI. For example, if you are an energy expert fill in answers for the other 10 CIs but leave the Energy gaps blank.

CIs dependencies evidences and recovery time

Think about a natural disaster that has not affected your CI but others. We would like you to describe the evidences which make your CI dependent on other CIs. Please indicate the most important dependencies (up to 3). Furthermore, when the affected CI is repaired, will your recovery be immediate or delayed?

3. Which are the detailed consequences on your CI if Energy is down for more than 48 hours?

Example: An expert on Transport CI thinks that the consequences will be:

1. Local trains will stop as they need electricity to operate

2. Airports must be shut down if there is a power cut as light and security systems would not work

4. Now thinking about the time for recovery. When Energy is repaired or restored, how much time will you need time to recover your CI normal activity?

Example: Following the example posted in Question 3 the answer will be "Other" and the explanation will be "Local trains and lighting will be recovered immediately while airports will need a day to recover their normal functioning due to the need of assuring that security systems work properly"

- ☐ Less than 1h.
- ☐ Less than 6h.
- ☐ More than 6h.
- ☐ Other (Please specify):

5. Which are the detailed consequences on your CI if Information and Communication Technologies is down for more than 48 hours?

6. Now thinking about the time for recovery. When Information and Communication Technologies is repaired or restored, how much time will you need time to recover your CI normal activity?

- ☐ Less than 1h.
- ☐ Less than 6h.
- ☐ More than 6h.
- ☐ Other (Please specify):

7. Which are the detailed consequences on your CI if Water is down for more than 48 hours?

8. Now thinking about the time for recovery. When Water is repaired or restored, how much time will you need time to recover your CI normal activity?

- ☐ Less than 1h.
- ☐ Less than 6h.
- ☐ More than 6h.
- ☐ Other (Please specify):

9. Which are the detailed consequences on your CI if Food is down for more than 48 hours?

10. Now thinking about the time for recovery. When Food is repaired or restored, how much time will you need time to recover your CI normal activity?

- ☐ Less than 1h.
- ☐ Less than 6h.
- ☐ More than 6h.
- ☐ Other (Please specify):

11. Which are the detailed consequences on your CI if Health is down for more than 48 hours?

12. Now thinking about the time for recovery. When Health is repaired or restored, how much time will you need time to recover your CI normal activity?

- ☐ Less than 1h.
- ☐ Less than 6h.
- ☐ More than 6h.
- ☐ Other (Please specify):

13. Which are the detailed consequences on your CI if Financial is down for more than 48 hours?

14. Now thinking about the time for recovery. When Financial is repaired or restored, how much time will you need time to recover your CI normal activity?

- ☐ Less than 1h.
- ☐ Less than 6h.
- ☐ More than 6h.
- ☐ Other (Please specify):

15. Which are the detailed consequences on your CI if Public & Legal Order and Safety is down for more than 48 hours?

16. Now thinking about the time for recovery. When Public & Legal Order and Safety is repaired or restored, how much time will you need time to recover your CI normal activity?

- ☐ Less than 1h.
- ☐ Less than 6h.
- ☐ More than 6h.
- ☐ Other (Please specify):

17. Which are the detailed consequences on your CI if Civil Administration is down for more than 48 hours?

18. Now thinking about the time for recovery. When Civil Administration is repaired or restored, how much time will you need time to recover your CI normal activity?

- ☐ Less than 1h.
- ☐ Less than 6h.
- ☐ More than 6h.
- ☐ Other (Please specify):

19. Which are the detailed consequences on your CI if Transport is down for more than 48 hours?

20. Now thinking about the time for recovery. When Transport is repaired or restored, how much time will you need time to recover your CI normal activity?

- ☐ Less than 1h.
- ☐ Less than 6h.
- ☐ More than 6h.
- ☐ Other (Please specify):

21. Which are the detailed consequences on your CI if Chemical and Nuclear Industry is down for more than 48 hours?

22. Now thinking about the time for recovery. When Chemical and Nuclear Industry is repaired or restored, how much time will you need time to recover your CI normal activity?

- ☐ Less than 1h.
- ☐ Less than 6h.
- ☐ More than 6h.
- ☐ Other (Please specify):

23. Which are the detailed consequences on your CI if Space and Research is down for more than 48 hours?

24. Now thinking about the time for recovery. When Space and Research is repaired or restored, how much time will you need time to recover your CI normal activity?

- ☐ Less than 1h.
- ☐ Less than 6h.
- ☐ More than 6h.
- ☐ Other (Please specify):

25. Feel free to make any comments on this section here:

Critical Infrastructures' dependency degree

Note: In the following questions do not fill in answers for your CI. For example, if you are an energy expert fill in answers for the other 10 CIs but leave the Energy gaps blank.

Think about the degree of effects on your CI if any other CI fails due to its dependency on the failed CI. We would like you to answer to the following questions considering this scale:

0 --> No effect: My CI can operate as usual

1 --> Very low effect: My CI can operate deploying few extra resources

2 --> Low effect: My CI can operate deploying huge amount of extra resources

3 --> Medium effect: My CI can only deliver critical services deploying few extra resources

4 --> High effect: My CI can only deliver critical services deploying huge amount of extra resources

5 --> Very high effect: My CI cannot continue operating

Example: If there is a power cut my CI will suffer no effect for the first 2 hours as we have power generators. Then, it will be low effect if the power cut lasts from 2 to 6 hours as more people would have to work in order to deliver normal service to customers. Then, we will suffer, high effect until hour 12 as only most important services will be delivered. Finally, the processes and services will have to be stopped if the power cut it lasts for more than 12 hours.

Translated to the scale would be:

- 0 for ...less than 2 hours
- 2 for ...less than 6 hours
- 4 for ...less than 12 hours
- 5 for ...less than 24 hours
- 5 for ...more than 24 hours
- 5 for ...more than one week

26. Which effect would your CI have if the following CIs are down for…

	…less than 2 hours	…less than 6 hours	…less than 12 hours	…less than 24 hours	…more than 24 hours	…more than 1 week
Energy						
Information and Communication Technologies						
Water						
Food						
Health						
Financial						
Public & Legal Order and Safety						
Civil Administration						
Transport						
Chemical and Nuclear Industry						
Space and Research						

27. Feel free to make any comments on this section here:

Final comments

28. If you have any other comments write them here.

End of the questionnaire. Thank you very much for your cooperation!

Appendix B: Results of the online questionnaire

This chapter presents the results obtained through the online questionnaire sent to CI managers about CIs dependencies.

B.1 Results of the online questionnaire

Following tables show the results for the different periods of time asked in the survey: less than two hours (Table B.1), less than 6h (Table B.2), less than 12h (Table B.3), less than 24h (Table B.4), more than 24h (Table B.5) and more than one week (Table B.6).

Failed CI \ Effect on	Energy	ICT	Water	Food	Health	Financial	Order & Safety	Civil Admin.	Transport	Chemical & Nuclear	Space & Research
Energy		0,86	1,33	2,89	1,40	2,67	1,67	0,40	2,40	4,67	1,33
ICT	2,67		1,00	1,67	2,20	2,33	2,67	1,40	2,40	2,67	1,00
Water	0,83	0,57		1,56	1,20	0,00	1,00	0,60	0,20	1,00	0,67
Food	0,00	0,14	0,00		0,60	0,00	0,33	0,20	0,00	0,33	0,33
Health	0,50	0,14	0,00	0,78		0,00	1,67	0,60	0,00	0,33	0,00
Financial	0,17	0,71	0,00	1,22	0,20		0,33	0,00	0,60	1,33	0,00
Order & Safety	0,83	0,43	0,33	1,00	1,00	1,67		1,40	0,80	1,00	0,00
Civil Admin.	0,33	0,86	0,00	0,38	1,00	0,33	1,00		0,20	1,00	0,00
Transport	1,17	1,00	0,00	1,11	1,40	1,00	2,00	0,60		0,00	0,00
Chemical & Nuclear	1,50	0,29	0,00	0,22	0,40	0,00	2,00	1,40	0,20		0,00
Space & Research	0,17	0,57	0,00	0,00	0,00	0,00	0,00	0,00	0,20	0,00	

Table B.1 CIs dependencies if other CIs are down less than two hours

Failed CI \ Effect on	Energy	ICT	Water	Food	Health	Financial	Order & Safety	Civil Admin.	Transport	Chemical & Nuclear	Space & Research
Energy		1,86	1,67	3,67	2,60	3,67	2,67	1,00	2,40	4,67	2,00
ICT	2,83		1,33	2,22	2,80	3,67	3,00	1,40	3,00	3,00	1,33
Water	1,17	0,86		2,33	1,80	0,00	2,33	1,00	0,60	2,00	1,67
Food	0,33	0,14	0,00		1,40	0,00	1,67	0,40	0,00	0,67	1,00
Health	0,50	0,57	0,00	1,00		0,00	2,00	1,20	0,00	0,67	0,67
Financial	0,17	0,86	0,00	1,56	0,20		0,33	0,00	0,60	1,33	0,33
Order & Safety	1,50	0,57	0,67	1,56	1,40	2,00		1,40	0,80	1,00	0,33
Civil Admin.	0,50	1,00	0,00	0,50	1,20	0,67	1,00		0,20	1,00	0,67
Transport	1,67	1,14	0,33	1,78	1,80	1,33	2,33	1,20		0,33	0,33
Chemical & Nuclear	1,67	0,43	0,33	0,78	0,60	0,00	2,33	1,40	0,40		0,00
Space & Research	0,17	0,86	0,00	0,00	0,00	0,00	0,00	0,20	0,40	0,00	

Table B.2 CIs dependencies if other CIs are down less than six hours

Failed CI \ Effect on	Energy	ICT	Water	Food	Health	Financial	Order & Safety	Civil Admin.	Transport	Chemical & Nuclear	Space & Research
Energy		2,71	2,33	4,00	3,40	4,00	3,33	1,40	3,00	4,67	2,33
ICT	3,33		2,00	2,89	3,00	3,67	3,67	2,00	3,20	4,00	1,67
Water	1,67	1,86		3,00	2,20	0,33	3,00	2,00	1,00	3,00	1,67
Food	0,50	0,71	0,33		1,80	0,00	2,33	0,60	0,40	1,00	1,00
Health	0,50	1,14	0,00	1,22		0,33	2,67	1,60	0,20	0,67	0,67
Financial	0,83	0,86	0,00	1,89	0,40		0,33	0,00	1,00	1,67	0,33
Order & Safety	2,00	0,86	1,00	1,78	1,60	3,00		2,20	1,00	1,00	0,33
Civil Admin.	0,67	1,71	0,00	0,88	1,80	1,00	1,00		0,60	1,00	1,00
Transport	1,83	1,29	1,00	2,67	2,20	2,00	3,00	1,40		0,67	1,00
Chemical & Nuclear	2,33	0,86	1,00	1,11	1,20	0,00	2,67	1,40	0,60		0,00
Space & Research	0,17	0,86	0,00	0,11	0,00	0,00	0,33	0,40	0,40	0,00	

Table B.3 CIs dependencies if other CIs are down less than twelve hours

Effect on / Failed CI	Energy	ICT	Water	Food	Health	Financial	Order & Safety	Civil Admin.	Transport	Chemical & Nuclear	Space & Research
Energy		3,71	3,00	4,33	4,20	4,00	4,00	2,60	3,00	5,00	2,33
ICT	4,17		2,33	3,56	3,80	4,00	4,33	2,20	3,40	4,67	2,00
Water	2,83	2,14		3,33	2,60	0,33	3,67	2,40	1,40	3,33	1,67
Food	1,50	1,14	0,33		2,40	0,00	3,00	0,80	0,60	1,33	1,67
Health	1,17	1,14	0,67	1,67		0,33	3,67	2,00	0,40	1,00	0,67
Financial	1,83	1,14	0,00	2,33	1,00		1,33	0,00	1,40	2,00	0,67
Order & Safety	2,50	1,14	1,33	2,22	1,60	3,67		2,00	1,40	1,00	0,33
Civil Admin.	1,17	1,71	0,67	1,00	1,80	1,33	1,33		1,60	1,00	1,00
Transport	2,00	1,43	1,33	3,67	2,60	2,00	3,33	1,80		1,33	1,33
Chemical & Nuclear	2,33	0,86	1,33	1,44	1,40	0,00	3,00	1,40	0,60		0,00
Space & Research	0,83	1,00	0,00	0,22	0,00	0,00	0,33	0,40	0,40	0,00	

Table B.4 CIs dependencies if other CIs are down less than twenty-four hours

Effect on / Failed CI	Energy	ICT	Water	Food	Health	Financial	Order & Safety	Civil Admin.	Transport	Chemical & Nuclear	Space & Research
Energy		4,14	3,67	4,56	4,60	4,33	5,00	3,00	4,00	5,00	3,00
ICT	4,33		2,67	4,11	4,00	4,33	4,33	2,80	4,20	5,00	2,67
Water	3,17	2,43		4,00	3,40	0,67	3,67	2,80	2,00	3,67	1,67
Food	2,50	1,57	1,00		3,40	0,00	3,67	1,20	0,60	1,33	1,67
Health	1,83	1,57	0,67	2,22		0,33	4,33	2,80	0,80	1,00	1,33
Financial	2,67	1,43	1,33	3,11	1,80		1,67	0,25	1,40	2,00	1,00
Order & Safety	3,17	1,71	1,67	2,89	2,40	4,00		2,80	1,80	1,33	1,33
Civil Admin.	1,83	2,14	0,67	1,75	2,80	1,33	1,33		1,80	1,67	1,67
Transport	2,83	2,29	2,00	4,33	3,20	2,67	3,67	2,60		1,67	2,00
Chemical & Nuclear	2,67	1,57	2,33	1,89	1,60	0,00	3,33	1,40	0,80		0,33
Space & Research	0,83	1,57	0,33	0,44	0,00	0,00	0,67	0,60	0,60	0,00	

Table B.5 CIs dependencies if other CIs are down more than twenty-four hours

Effect on / Failed CI	Energy	ICT	Water	Food	Health	Financial	Order & Safety	Civil Admin.	Transport	Chemical & Nuclear	Space & Research
Energy		4,57	4,67	5,00	5,00	4,67	5,00	4,20	4,20	5,00	4,33
ICT	4,67		3,67	4,89	4,00	4,67	4,33	3,40	4,60	5,00	4,00
Water	3,50	3,43		4,22	3,80	1,00	3,67	3,00	2,60	3,67	3,00
Food	3,17	2,57	2,00		4,00	0,33	4,00	3,00	0,80	1,33	3,00
Health	3,00	2,00	1,33	3,11		0,67	5,00	3,60	1,20	1,00	2,00
Financial	3,00	2,43	2,00	4,22	2,40		2,00	0,75	2,20	2,67	3,00
Order & Safety	3,67	2,57	2,33	3,56	2,60	4,33		3,40	2,80	2,00	2,67
Civil Admin.	2,50	2,57	1,33	2,50	3,20	1,67	2,00		2,40	2,33	3,67
Transport	3,83	3,00	3,67	4,78	3,80	3,67	4,33	3,40		3,67	3,67
Chemical & Nuclear	3,17	2,14	3,00	2,33	2,40	0,00	3,33	1,80	1,40		1,00
Space & Research	1,50	2,29	0,67	1,00	0,60	0,00	1,33	1,00	0,60	0,00	

Table B.6 CIs dependencies if other CIs are down more than one week

The following graphs represented the average dependency and influence of each CI for different periods of failure: less than two hours (Figure B.), less than six hours (Figure B.2), less than twelve hours (Figure B.3), less than twenty four hours (Figure B.4), more than 24 hours (Figure B.5) and more than one week (Figure B.6).

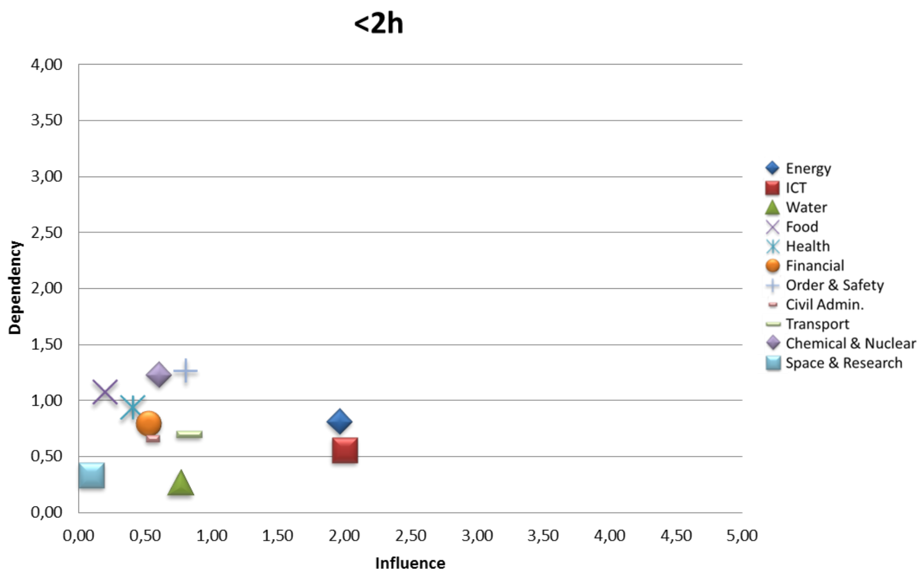


Figure B.1 CIs Dependency vs. Influence in a scenario where CIs are down less than two hours

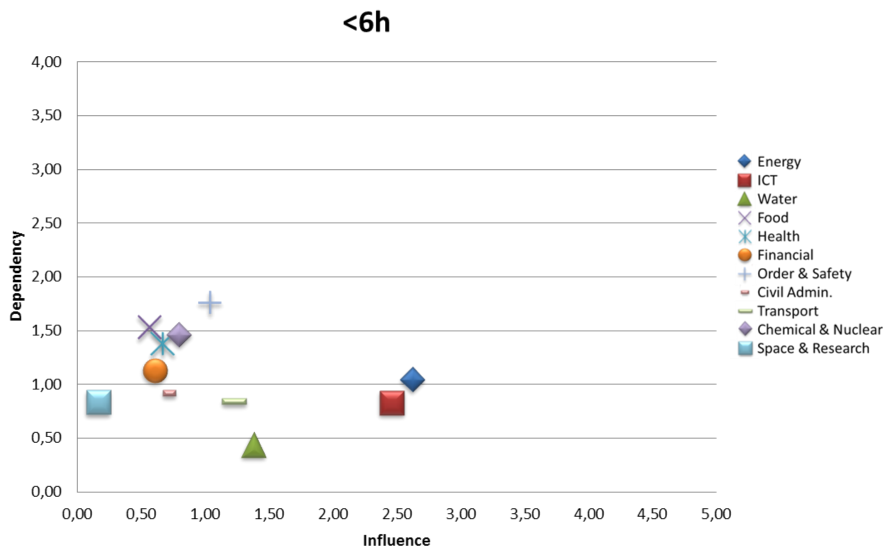


Figure B.2 CIs Dependency vs. Influence in a scenario where CIs are down less than six hours

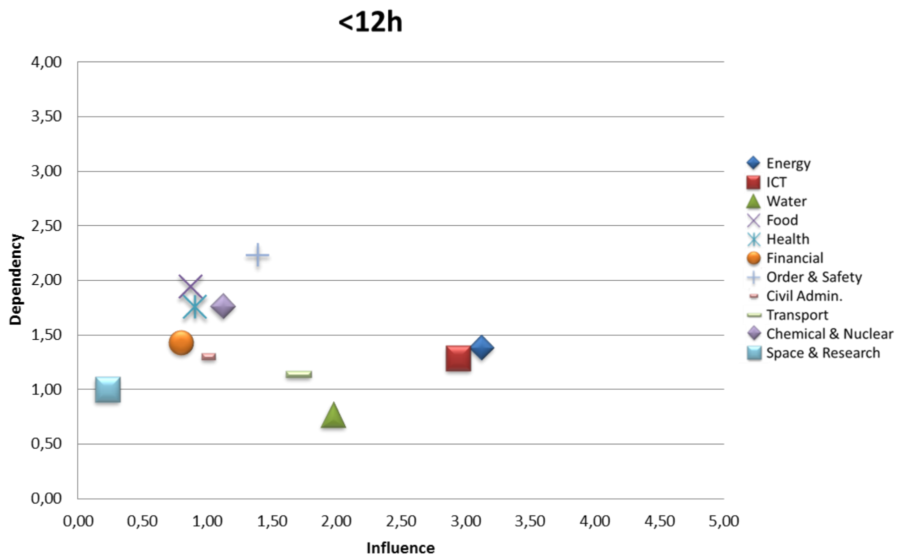


Figure B.3 CIs Dependency vs. Influence in a scenario where CIs are down less than twelve hours

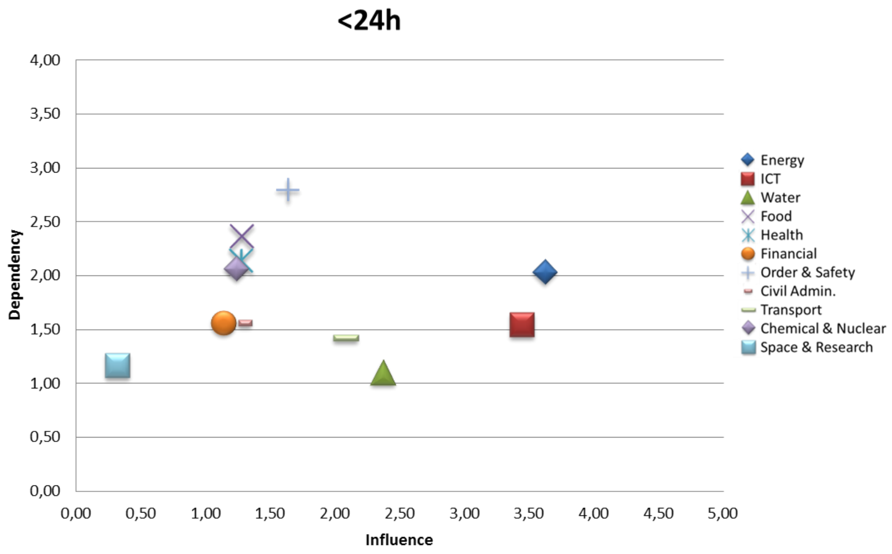


Figure B.4 CIs Dependency vs. Influence in a scenario where CIs are down less than twenty four hours

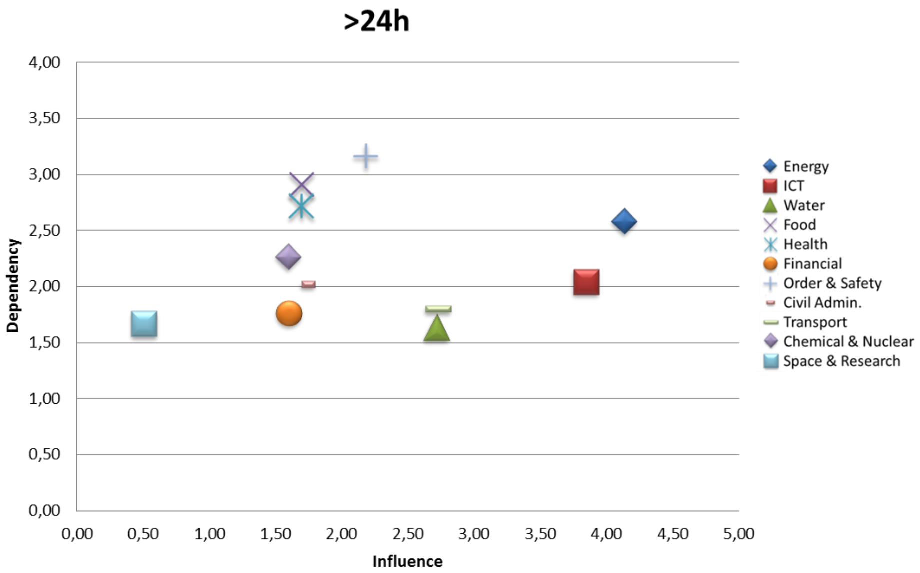


Figure B.5 CIs Dependency vs. Influence in a scenario where CIs are down more than twenty four hours

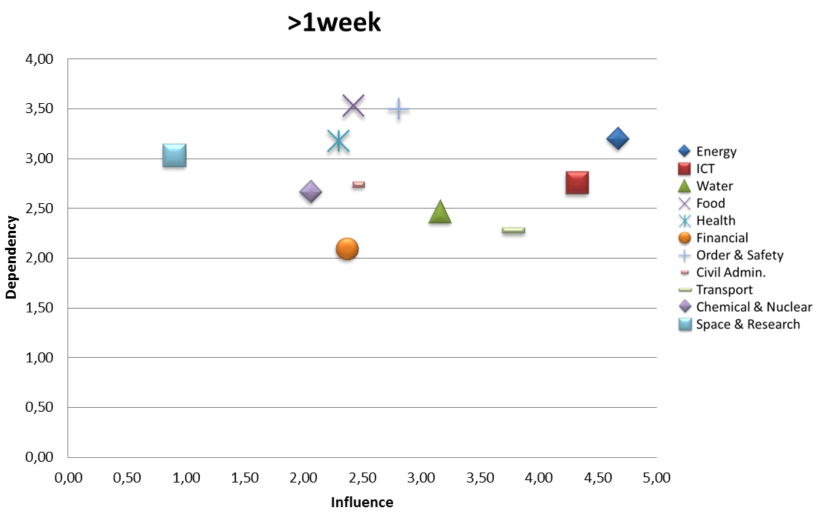


Figure B.6 CIs Dependency vs. Influence in a scenario where CIs are down more than one week

Tables from Table B.7 to Table B.17 show examples of dependencies' evidences gathered through the online questionnaire.

Failed CI	Evidence
Energy	• Manual procedures must be implemented as automatic ones cannot be performed • Production activities must be stopped • Lighting system does not work • Alert systems failure • Inability to transport and distribute water as pumping does not work • Inability to preserve food's cold chain • Hospital protocols do not allow to do surgery and patients who require vital support need to be transfer to other hospitals • Airports should be closed • Cooling system for chemical or nuclear activity will not work, activity will have to stop

Table B.7 Examples of dependency evidences on Energy

Failed CI	Evidence
ICT	• Call phones and related tools are out of operations which slows down operations • No ability to respond to anything except by direct human contact • Logistic infrastructure will not work • Sensors and control systems may not work • Web connected tools are out of operation • Settling and payment systems off

Table B.8 Examples of dependency evidences on ICT

Failed CI	Evidence
Water	• Employees who are not essential must be sent home • Inability to cool facilities will limit operations. • Hygiene for example for food production cannot be assured • Sanitation does not work and this could lead to diseases propagation • Nuclear power plants have to be stopped if the cooling water is not available • Depending on length national emergency services must provide water to population

Table B.9 Examples of dependency evidences on Water

Failed CI	Evidence
Food	• Focus of workers will be on personal matters making work inefficient • Eventually, depending on failure duration, if workers are trying to get food instead of going to work facilities might have to stop production • Depending on failure duration national emergency services must provide food to population

Table B.10 Examples of dependency evidences on Food

Failed CI	Evidence
Health	• No health care services in case of work accidents, food intoxications... • No health centres support in emergency situations • Plan to provide first aid by army • In case nuclear operator considers a safety problem the plant must stop • Depending on duration, diseases can spread becoming pandemics

Table B.11 Examples of dependency evidences on Health

Failed CI	Evidence
Financial	• All banking services are stopped • Customers will have problems to pay the bills if they do not have cash • Organisations cannot pay to suppliers leading to shortage of raw materials to continue with normal productivity • Organisations cannot pay salaries

Table B.12 Examples of dependency evidences on Financial

Failed CI	Evidence
Public & Legal Order and Safety	• Security issues can affect normal operability • Legal and safety processes become hindered • Robberies, pillaging, possible looting in stores, supply shortages,... • Personnel might not come work

Table B.13 Examples of dependency evidences on Public & legal Order & Safety

Failed CI	Evidence
Civil Administration	• Civil administration processes become hindered • No permits, licenses or inspections can be developed • Insecurity due to problems in emergency services • Problems in customs

Table B.14 Examples of dependency evidences on Civil Administration

Failed CI	Evidence
Transport	• Distribution of raw materials of products will not arrive • Workers will have problems to reach their workplace • No equipment replacement • Problems in passengers transport • Emergency services will have problems to attend emergencies or to arrive to their destination

Table B.15 Examples of dependency evidences on Transport

Failed CI	Evidence
Chemical & Nuclear Industry	• If nuclear energy is not available electricity demand cannot be assured • Prices of energy rise • If chemical industry fails for long time there could be shortage of medicines and other products

Table B.16 Examples of dependency evidences on Chemical & Nuclear Industry

Failed CI	Evidence
Space& Research	• Satellite and GPS systems will not work • Research activities will stop and depending on the time no research is performed, problems can arise for example in health care

Table B.17 Examples of dependency evidences on Space& Research

Appendix C: Simulation Model

In this chapter the structure, the SDM-Doc checking tool results, extreme and sensitivity analysis and the equations of the simulation model developed through this research are included.

C.1 Structure of the simulation model

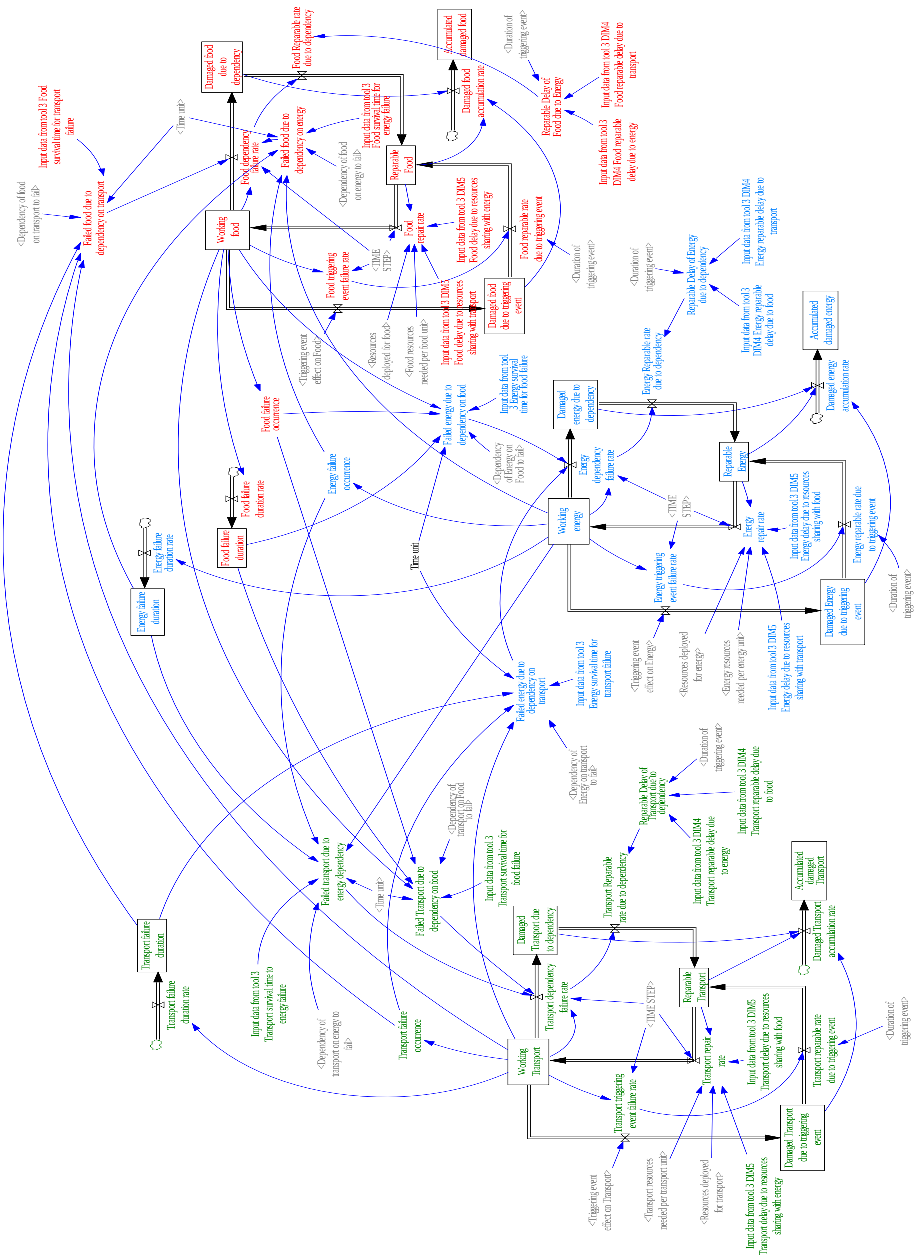


Figure C.1 Simulation model's structure

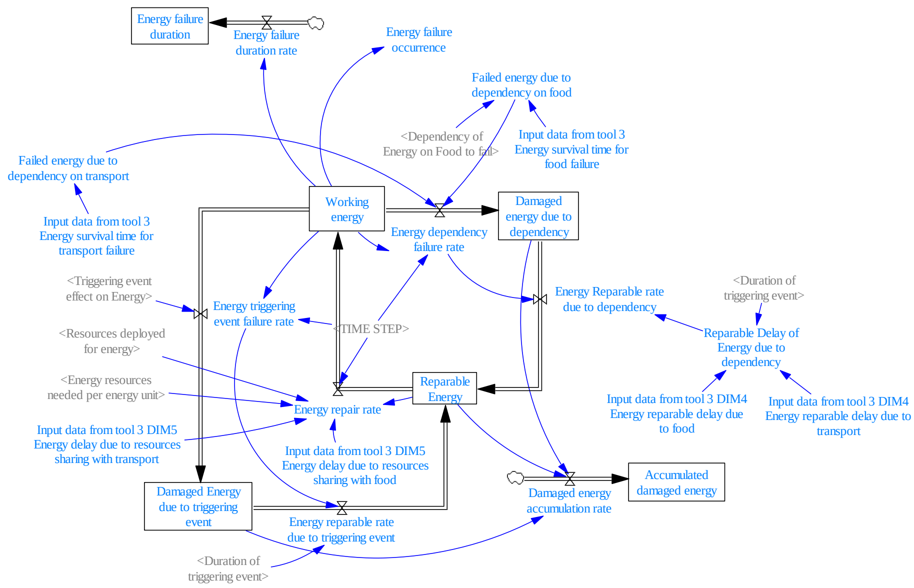


Figure C.2 Simulation model's structure for Energy CI

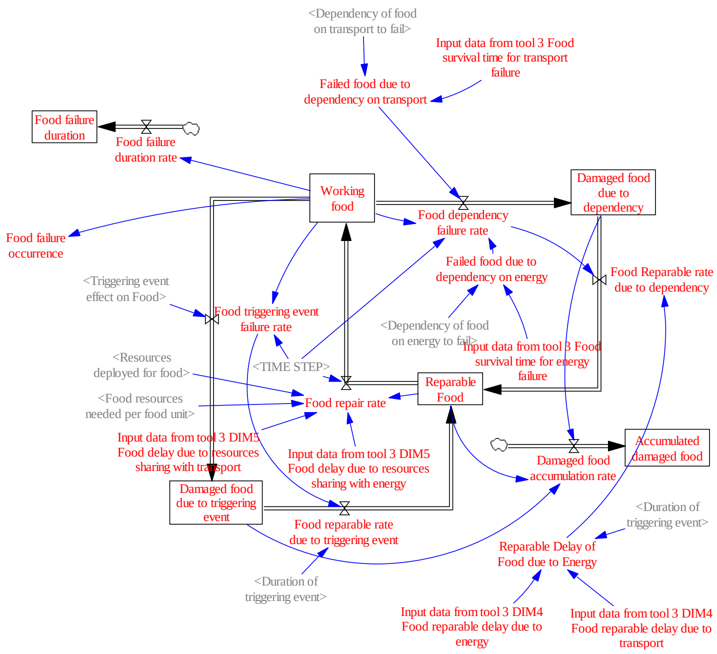


Figure C.3 Simulation model's structure for Food CI

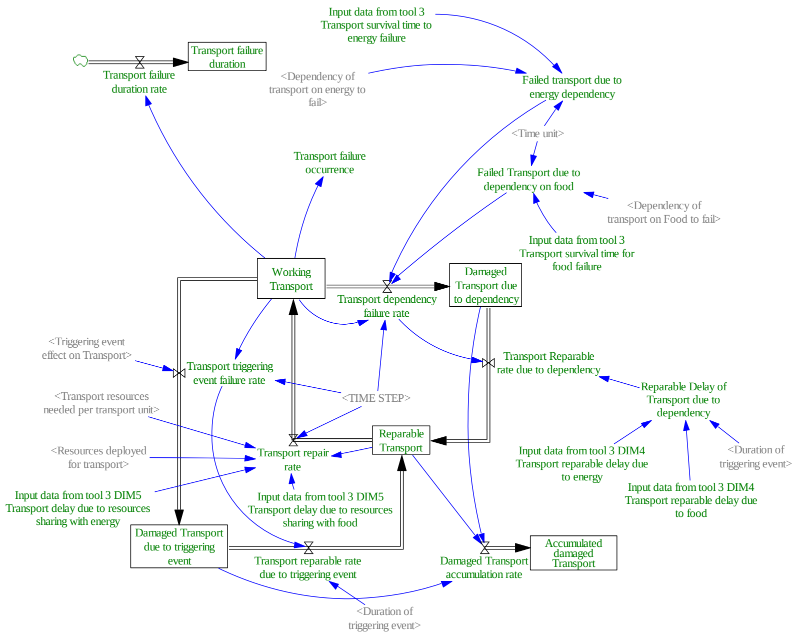


Figure C.4 Simulation model's structure for Transport CI

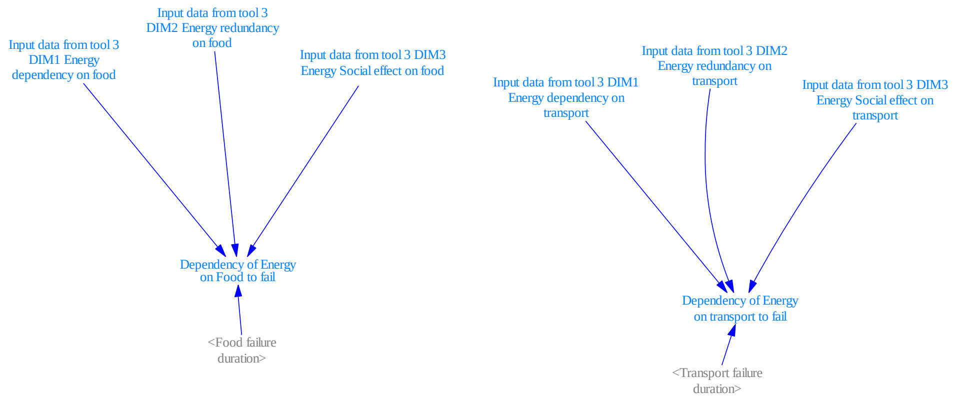


Figure C.5 Simulation model's structure for Dependency of Energy on Food and Transport CIs

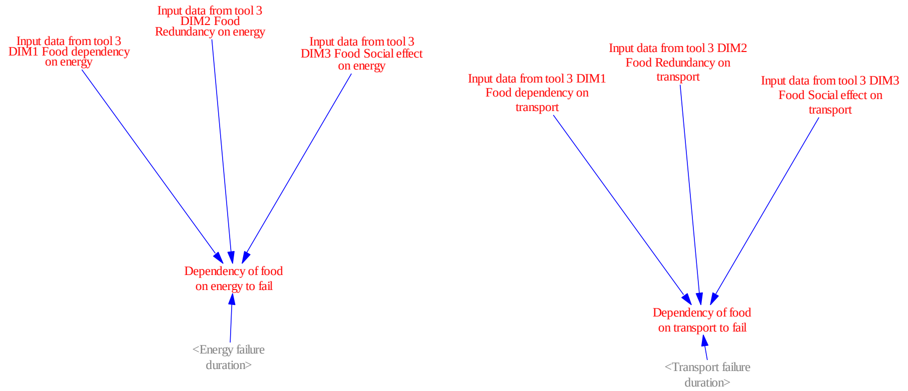


Figure C.6 Simulation model's structure for Dependency of Food on Energy and Transport CIs

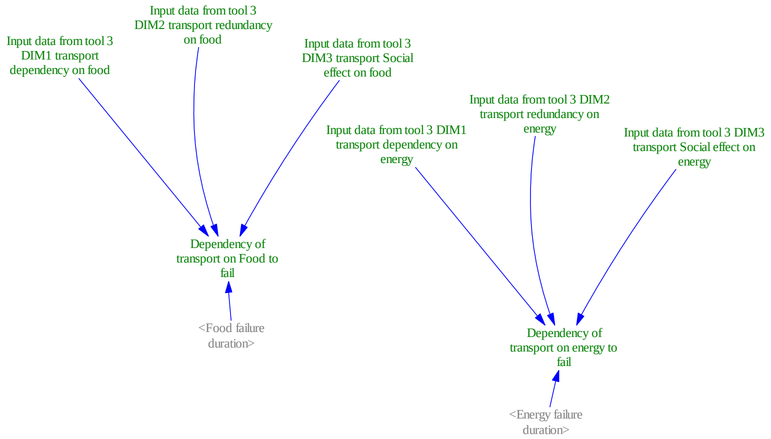


Figure C.7 Simulation model's structure for Dependency of Transport on Energy and Transport CIs

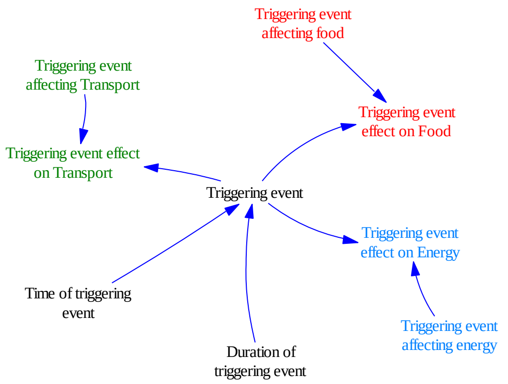


Figure C.8 Simulation model's structure for Triggering event

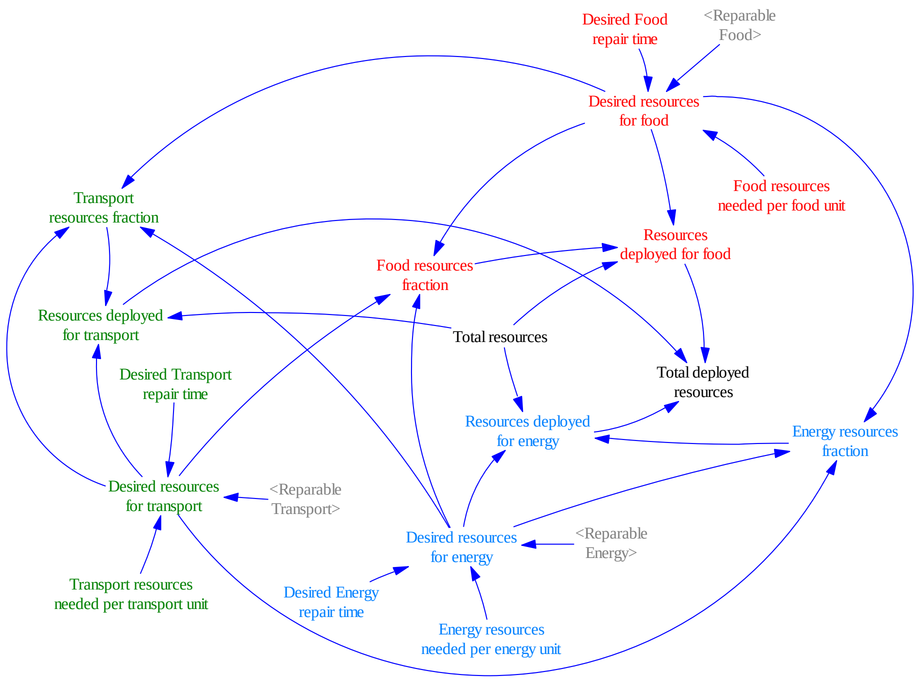


Figure C.9 Simulation model's structure for Resources allocation

C.2 SDM-Doc

The SDM-Doc tool (Martinez-Moyano 2012) has been used to check the model. For example, the tool identifies 4 variables as unused; this means that these variables do not have influence on any other variable. Then, these variables are included in the model as outcomes, only to obtain accumulated graphs.

Documentation of 141008 Clsc

View the 124 variables sorted by type, module, group, variable name, module/group/name, Level Structure, or in a view summary.

Model Assessment Results

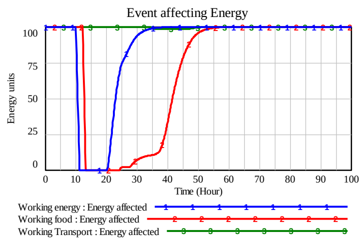
Model Information	Number
Total Number of Variables	124
Total Number of State Variables(Level+Smooth+Delay Variables)	24 (19.4%)
Total Number of Stocks (Stocks in Level+Smooth+Delay Variables) †	21 (16.9%)
Total Number of Macros	0
Variables with Source Information	0
Variables with Dimensionless Units	12 (9.7%)
Function Sensitivity Parameters	0
Data Lookup Tables	0
Time Unit	Hour
Initial Time	0
Final Time	250
Reported Time Interval	TIME STEP
Time Step	0.125
Model Is Fully Formulated	Yes
Modeler-Defined Groups	- No -
VPM File Available	- No -

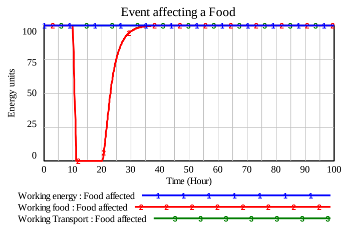
Warnings	Number
Undocumented Equations	0
Equations with Embedded Data(0 and 1 constants ignored)	22 (17.7%)
Equations With Unit Errors or Warnings	Unavailable
Variables Not in Any View	0
Incompletely Defined Subscripted Variables	0
Nonmonotonic Lookup Functions	0
Cascading (Chained) Lookup Functions	0
Non-Zero End Sloped Lookup Functions	0
Equations with "IF THEN ELSE" Functions	21 (16.9%)
Equations with "MIN" or "MAX" Functions	18 (14.5%)
Equations with "STEP", "PULSE", or Related Functions	1 (0.8%)

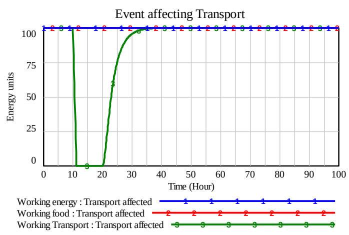
Potential Omissions	Number
Unused Variables	4
Supplementary Variables	0
Supplementary Variables Being Used	0
Complex Variable Formulations (Richardson's Rule = 3)	18
Complex Stock Formulations	0

C.3 Extreme analysis

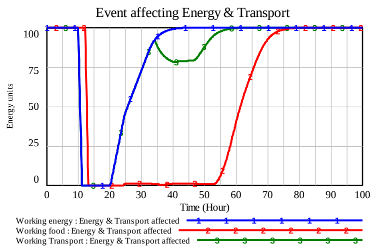
Triggering event affecting one CI

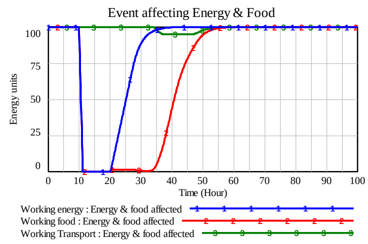


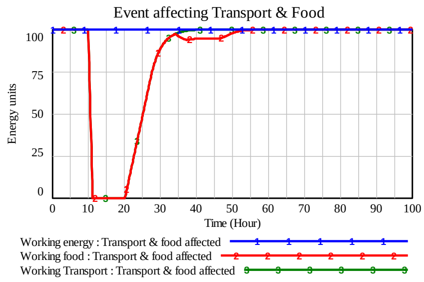




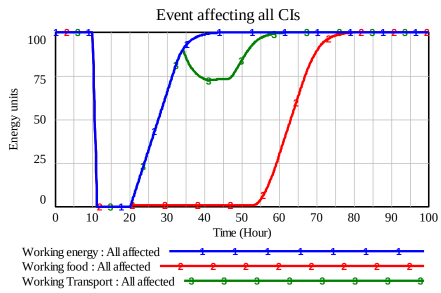
Triggering event affecting two CIs



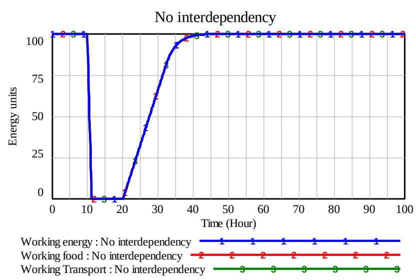


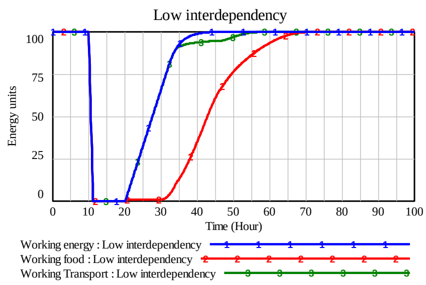


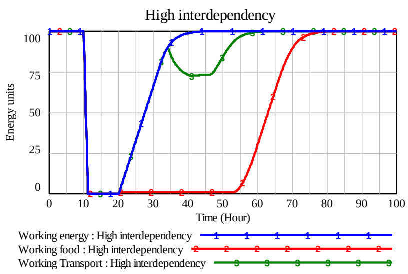
Triggering event affecting three CIs



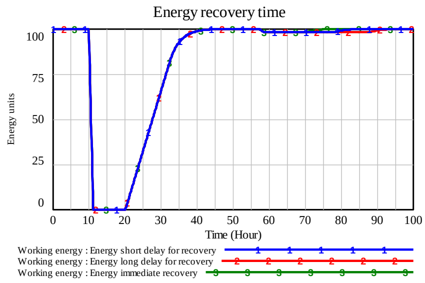
Dimensions 1,2 and 3: Dependency, redundancy and social effect

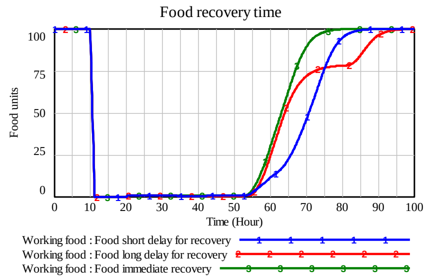


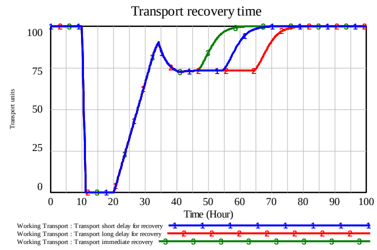




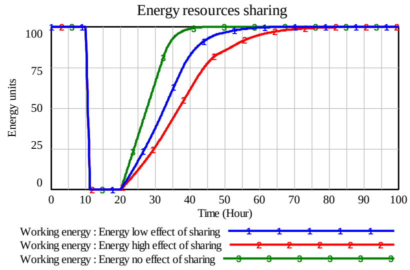
Dimension 4: Recovery time

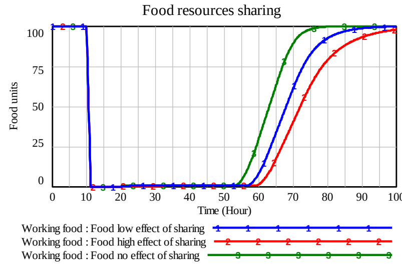


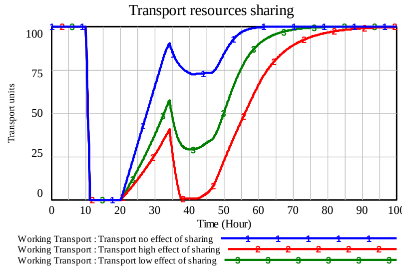




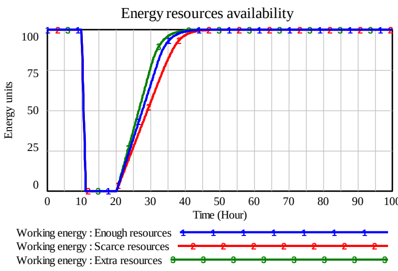
Dimension 5: Resources sharing

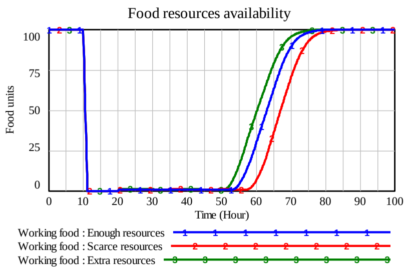


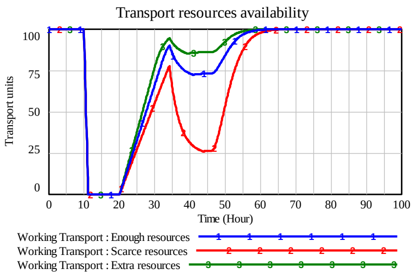




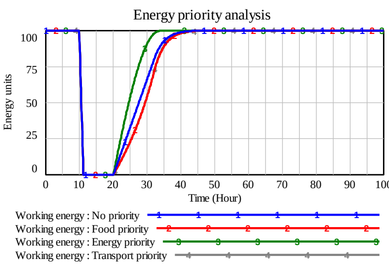
Availability of resources

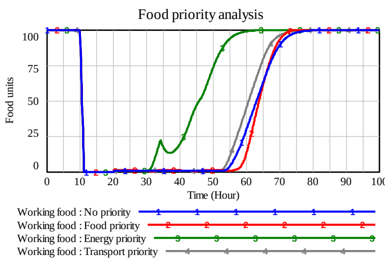


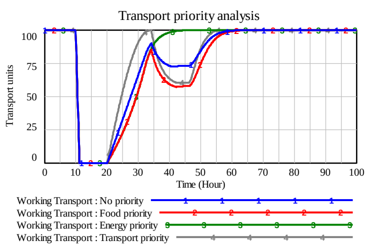




Prioritization

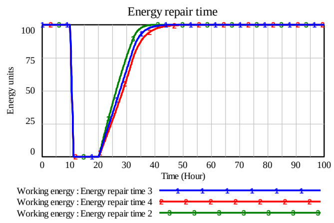




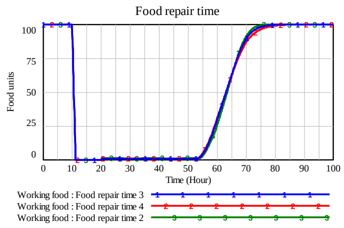


C.4 Sensitivity analysis

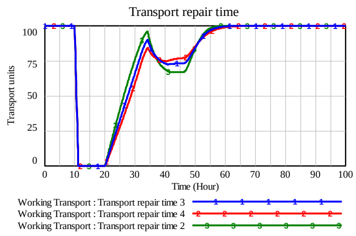
Desired Energy repair time (2,3,4)



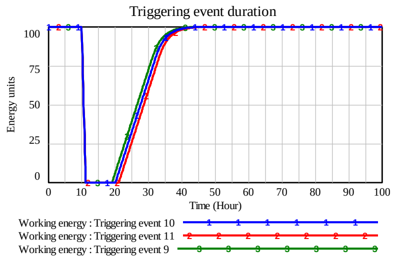
Desired Food repair time = (2,3,4)

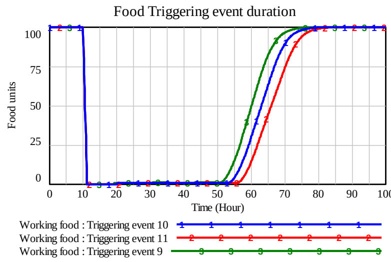


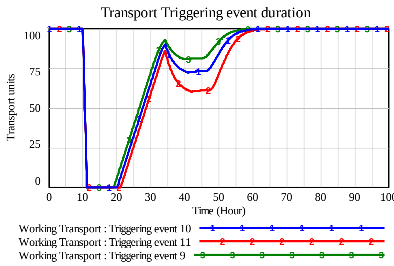
Desired Transport repair time = (2,3,4)



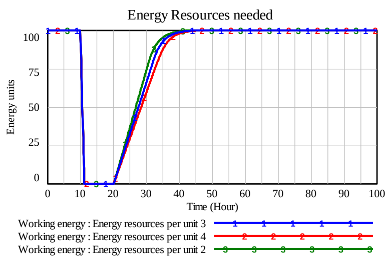
Duration of triggering event= (9,10,11)



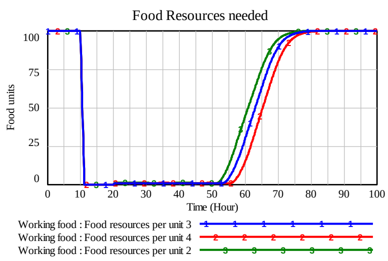




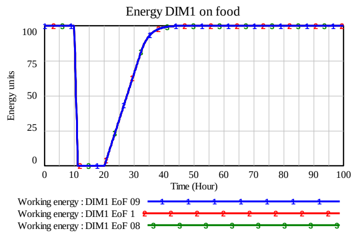
Energy resources needed per energy unit=3



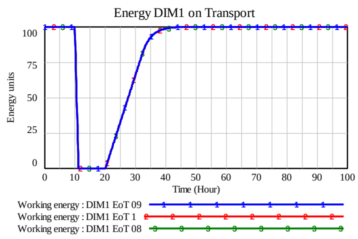
Food resources needed per food unit=3



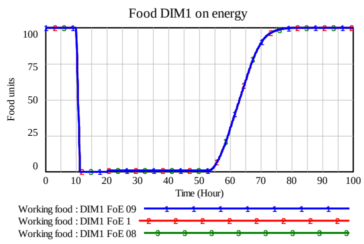
Input data from tool 3 DIM1 Energy dependency on food (0.8,0.9,1)



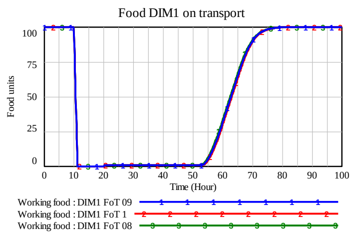
Input data from tool 3 DIM1 Energy dependency on transport (0.8,0.9,1)



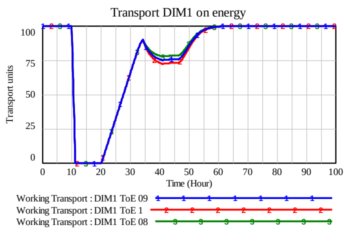
Input data from tool 3 DIM1 Food dependency on energy (0.8,0.9,1)



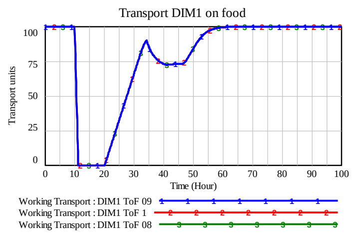
Input data from tool 3 DIM1 Food dependency on transport (0.8,0.9,1)



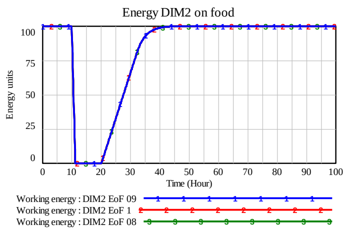
Input data from tool 3 DIM1 transport dependency on energy (0.8,0.9,1)



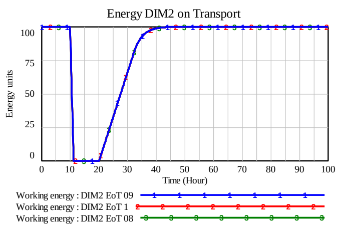
Input data from tool 3 DIM1 transport dependency on food (0.8,0.9,1)



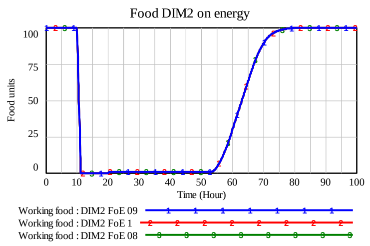
Input data from tool 3 DIM2 Energy redundancy on food (0.8,0.9,1)



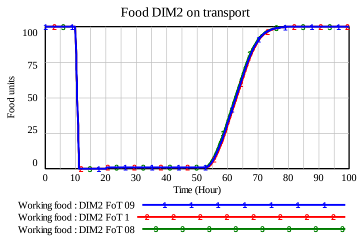
Input data from tool 3 DIM2 Energy redundancy on transport (0.8,0.9,1)



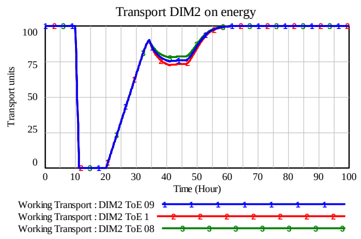
Input data from tool 3 DIM2 Food Redundancy on energy (0.8,0.9,1)



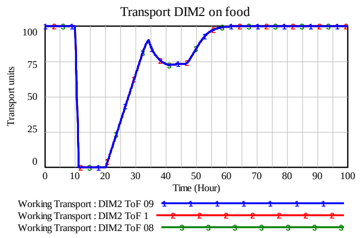
Input data from tool 3 DIM2 Food Redundancy on transport (0.8,0.9,1)



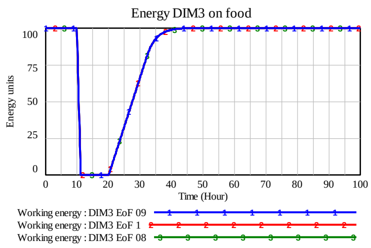
Input data from tool 3 DIM2 transport redundancy on energy (0.8,0.9,1)



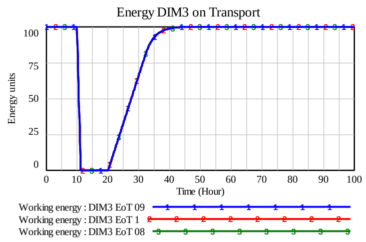
Input data from tool 3 DIM2 transport redundancy on food (0.8,0.9,1)



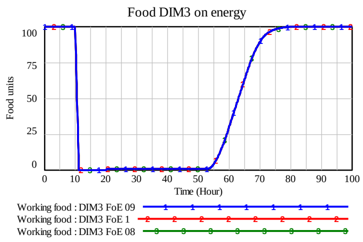
Input data from tool 3 DIM3 Energy Social effect on food (0.8,0.9,1)



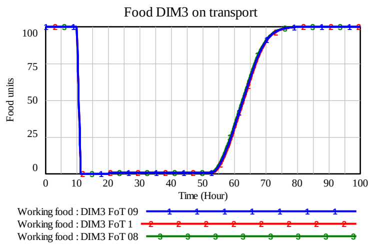
Input data from tool 3 DIM3 Energy Social effect on transport (0.8,0.9,1)



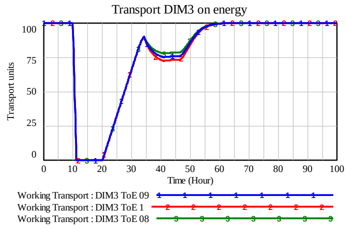
Input data from tool 3 DIM3 Food Social effect on energy (0.8,0.9,1)



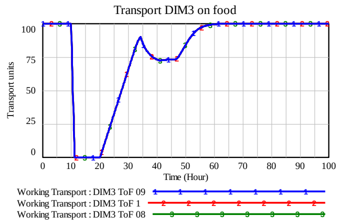
Input data from tool 3 DIM3 Food Social effect on transport (0.8,0.9,1)



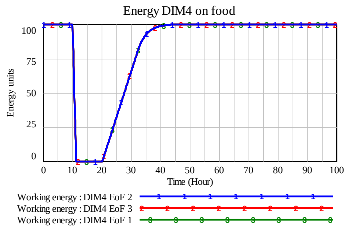
Input data from tool 3 DIM3 transport Social effect on energy (0.8,0.9,1)



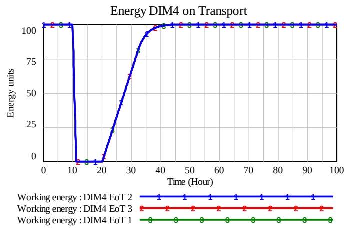
Input data from tool 3 DIM3 transport Social effect on food (0.8,0.9,1)



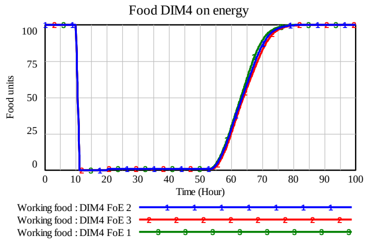
Input data from tool 3 DIM4 Energy reparable delay due to food (1,2,3)



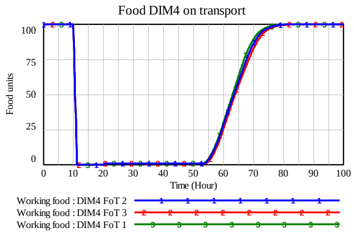
Input data from tool 3 DIM4 Energy reparable delay due to transport (1,2,3)



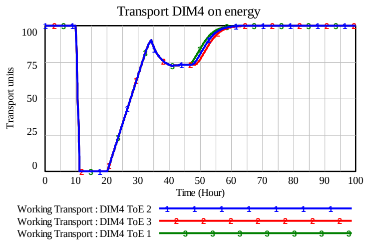
Input data from tool 3 DIM4 Food reparable delay due to energy (1,2,3)



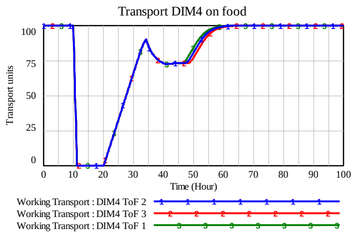
Input data from tool 3 DIM4 Food reparable delay due to transport (1,2,3)



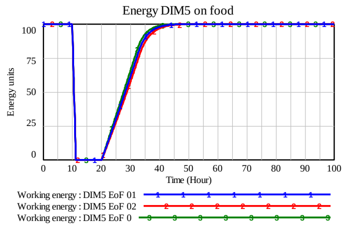
Input data from tool 3 DIM4 Transport reparable delay due to energy (1,2,3)



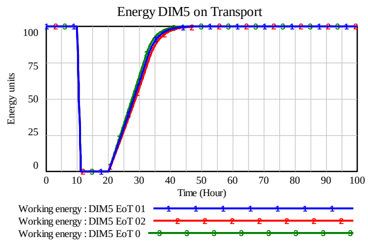
Input data from tool 3 DIM4 Transport reparable delay due to food (1,2,3)



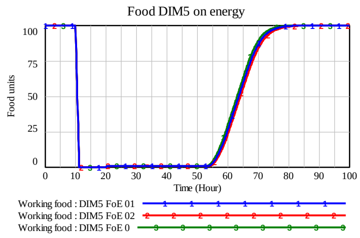
Input data from tool 3 DIM5 Energy delay due to resources sharing with food (0,0.1,0.2)



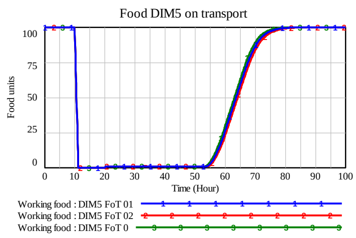
Input data from tool 3 DIM5 Energy delay due to resources sharing with transport (0,0.1,0.2)



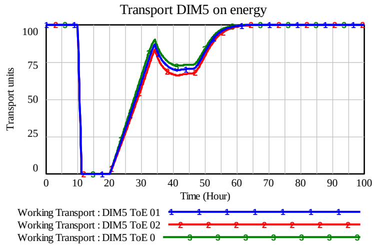
Input data from tool 3 DIM5 Food delay due to resources sharing with energy (0,0.1,0.2)



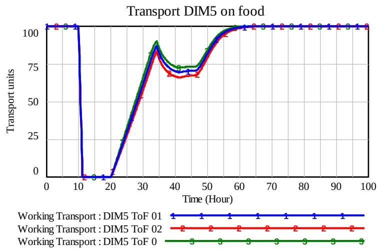
Input data from tool 3 DIM5 Food delay due to resources sharing with transport (0,0.1,0.2)



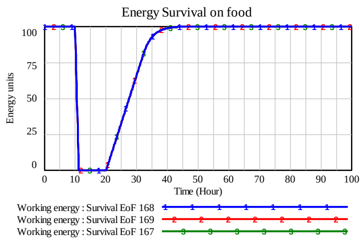
<u>Input data from tool 3 DIM5 Transport delay due to resources sharing with energy (0,0.1,0.2)</u>



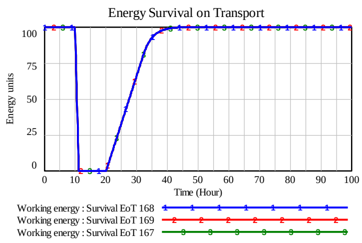
<u>Input data from tool 3 DIM5 Transport delay due to resources sharing with food (0,0.1,0.2)</u>



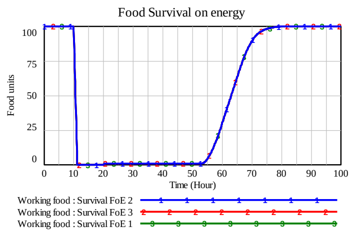
<u>Input data from tool 3 Energy survival time for food failure (167,168,169)</u>



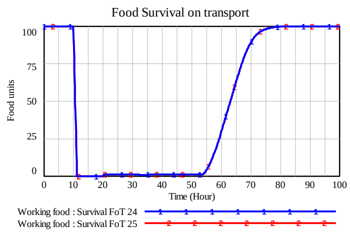
<u>Input data from tool 3 Energy survival time for transport failure (167,168,169)</u>



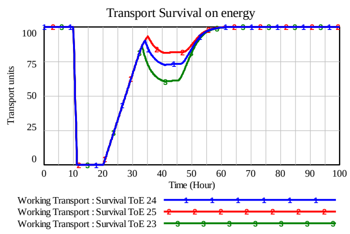
Input data from tool 3 Food survival time for energy failure (1,2,3)



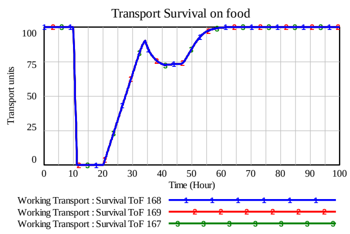
Input data from tool 3 Food survival time for transport failure= (47,48,49)



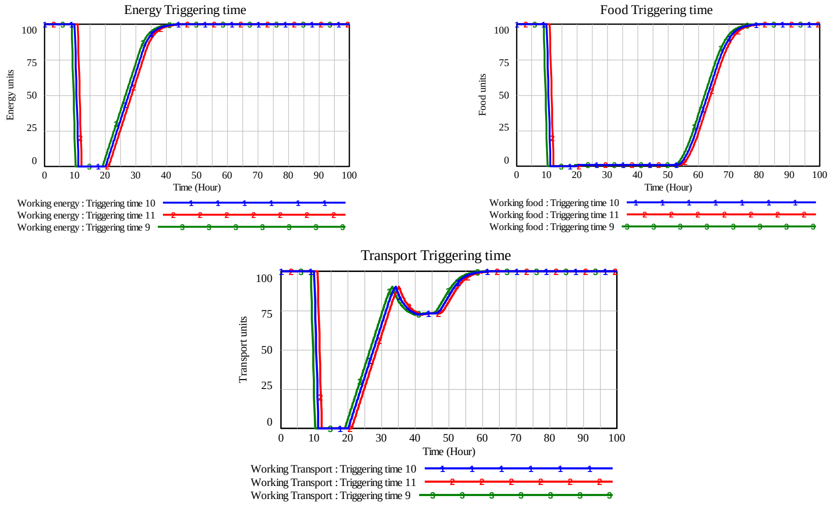
Input data from tool 3 Transport survival time for food failure (167,168,169)



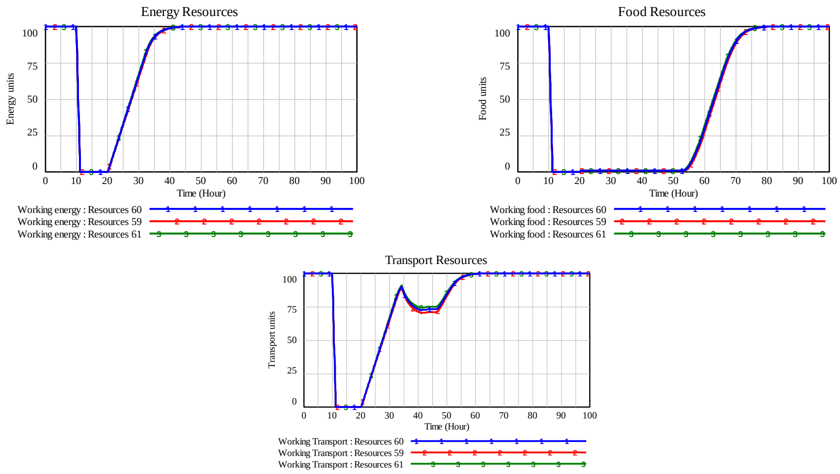
Input data from tool 3 Transport survival time to energy failure (23,24,25)



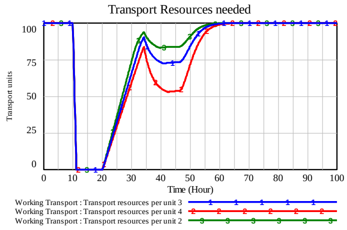
Time of triggering event (9,10,11)



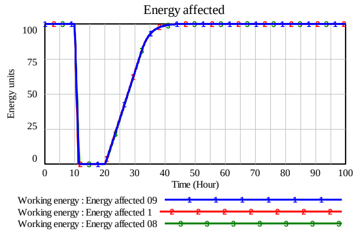
Total resources (59,60,61)



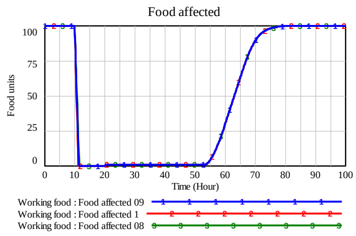
Transport resources needed per transport unit (2,3,4)3



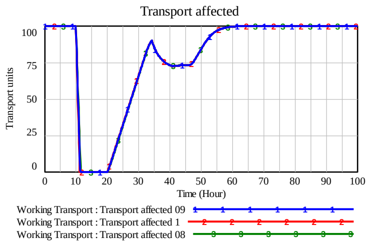
Triggering event affecting energy (0.8,0.9,1)



Triggering event affecting food (0.8,0.9,1)



Triggering event affecting Transport (0.8,0.9,1)



C.5 Simulation model equations

Accumulated damaged energy= INTEG (Damaged energy accumulation rate,0)

Units: Energy units*Hour

Accumulated damaged food= INTEG (Damaged food accumulation rate,0)

Units: Food units*Hour

Accumulated damaged Transport= INTEG (Damaged Transport accumulation rate,0)

Units: Transport units*Hour

Damaged energy accumulation rate=(Damaged energy due to dependency+Damaged Energy due to triggering event+Reparable Energy)

Units: Energy units

Damaged energy due to dependency= INTEG (Energy dependency failure rate-Energy Reparable rate due to dependency,0)

Units: Energy units

Damaged Energy due to triggering event= INTEG (Energy triggering event failure rate-Energy reparable rate due to triggering event,0)

Units: Energy units

Damaged food accumulation rate=(Damaged food due to dependency+Damaged food due to triggering event+Reparable Food)

Units: Food units

Damaged food due to dependency= INTEG (Food dependency failure rate-Food Reparable rate due to dependency,0)

Units: Food units

Damaged food due to triggering event= INTEG (Food triggering event failure rate-Food reparable rate due to triggering event,0)

Units: Food units

Damaged Transport accumulation rate=(Damaged Transport due to dependency+Damaged Transport due to triggering event+Reparable Transport)

Units: Transport units

Damaged Transport due to dependency= INTEG (Transport dependency failure rate-Transport Reparable rate due to dependency,0)

Units: Transport units

Damaged Transport due to triggering event= INTEG (Transport triggering event failure rate-Transport reparable rate due to triggering event,0)

Units: Transport units

Dependency of Energy on Food to fail=IF THEN ELSE(Food failure duration>168 , 0 ,min(1,(IF THEN ELSE(Input data from tool 3 DIM2 Energy redundancy on food>0,Input data from tool 3 DIM2 Energy redundancy on food,Input data from tool 3 DIM1 Energy dependency on food)+Input data from tool 3 DIM3 Energy Social effect on food)))

Units: Energy units/Food units

Dependency of Energy on transport to fail=IF THEN ELSE(Transport failure duration>168 , 0 ,min(1,(IF THEN ELSE(Input data from tool 3 DIM2 Energy redundancy on transport>0,Input data from tool 3 DIM2 Energy redundancy on transport,Input data from tool 3 DIM1 Energy dependency on transport)+Input data from tool 3 DIM3 Energy Social effect on transport)))

Units: Energy units/Transport units

Dependency of food on energy to fail=IF THEN ELSE(Energy failure duration>168 , 0 ,min(1,(IF THEN ELSE(Input data from tool 3 DIM2 Food Redundancy on energy>0,Input data from tool 3 DIM2 Food Redundancy on energy,Input data from tool 3 DIM1 Food dependency on energy)+Input data from tool 3 DIM3 Food Social effect on energy)))

Units: Food units/Energy units

Dependency of food on transport to fail=IF THEN ELSE(Transport failure duration>168 , 0 ,min(1,(IF THEN ELSE(Input data from tool 3 DIM2 Food Redundancy on transport>0,Input data from tool 3 DIM2 Food Redundancy on transport,Input data from tool 3 DIM1 Food dependency on transport)+Input data from tool 3 DIM3 Food Social effect on transport)))

Units: Food units/Transport units

Dependency of transport on energy to fail=IF THEN ELSE(Energy failure duration>168 , 0 ,min(1,(IF THEN ELSE(Input data from tool 3 DIM2 transport redundancy on energy>0,Input data from tool 3 DIM2 transport redundancy on energy,Input data from tool 3 DIM1 transport dependency on energy)+Input data from tool 3 DIM3 transport Social effect on energy)))

Units: Transport units/Energy units

Dependency of transport on Food to fail=IF THEN ELSE(Food failure duration>168 , 0 ,min(1,(IF THEN ELSE(Input data from tool 3 DIM2 transport redundancy on food>0,Input data from tool 3 DIM2 transport redundancy on food,Input data from tool 3 DIM1 transport dependency on food)+Input data from tool 3 DIM3 transport Social effect on food)))

Units: Transport units/Food units

Desired Energy repair time=3

Units: Hour

Desired Food repair time=3

Units: Hour

Desired resources for energy=(Reparable Energy)*Energy resources needed per energy unit/Desired Energy repair time

Units: Resources/Hour

Desired resources for food=(Reparable Food)*Food resources needed per food unit/Desired Food repair time

Units: Resources/Hour

Desired resources for transport=(Reparable Transport)*Transport resources needed per transport unit/Desired Transport repair time

Units: Resources/Hour

Desired Transport repair time=3

Units: Hour

Duration of triggering event=10

Units: Hour

Energy dependency failure rate=min(Working energy/TIME STEP , Failed energy due to dependency on food+Failed energy due to dependency on transport)

Units: Energy units/Hour

Energy failure duration= INTEG (Energy failure duration rate,0)

Units: Hour

Energy failure duration rate=IF THEN ELSE(Working energy<99, 1, 0)

Units: 1

Energy failure occurrence=IF THEN ELSE(Working energy<99 , 1 , 0)

Units: Dmnl

Energy repair rate=min(Reparable Energy/TIME STEP,max(0,Resources deployed for energy/(Energy resources needed per energy unit*(1+Input data from tool 3 DIM5 Energy delay due to resources sharing with food+Input data from tool 3 DIM5 Energy delay due to resources sharing with transport))))

Units: Energy units/Hour

Energy Reparable rate due to dependency= DELAY FIXED (Energy dependency failure rate,Reparable Delay of Energy due to dependency,0)

Units: Energy units/Hour

Energy reparable rate due to triggering event= DELAY FIXED (Energy triggering event failure rate,Duration of triggering event,0)

Units: Energy units/Hour

Energy resources fraction=IF THEN ELSE((Desired resources for transport+Desired resources for food+Desired resources for energy)>0,(Desired resources for energy/(Desired resources for transport+Desired resources for food+Desired resources for energy)), 0)

Units: Dmnl

Energy resources needed per energy unit=3

Units: Resources/Energy units

Energy triggering event failure rate=max(0,min(Working energy,Triggering event effect on Energy))/TIME STEP

Units: Energy units/Hour

Failed energy due to dependency on food=IF THEN ELSE(Food failure occurrence>0,IF THEN ELSE(Food failure duration>Input data from tool 3 Energy survival time for food failure, (100-Working food)*Dependency of Energy on Food to fail/Time unit,0),0)

Units: Energy units/Hour

Failed energy due to dependency on transport=IF THEN ELSE(Transport failure occurrence>0,IF THEN ELSE(Transport failure duration>Input data from tool 3 Energy survival time for transport failure, (100-Working Transport) *Dependency of Energy on transport to fail/Time unit,0),0)

Units: Energy units/Hour

Failed food due to dependency on energy=IF THEN ELSE(Energy failure occurrence>0,IF THEN ELSE(Energy failure duration>Input data from tool 3 Food survival time for energy failure, (100-Working energy)*Dependency of food on energy to fail/Time unit,0),0)

Units: Food units/Hour

Failed food due to dependency on transport=IF THEN ELSE(Transport failure occurrence>0,IF THEN ELSE(Transport failure duration>Input data from tool 3 Food survival time for transport failure, (100-Working Transport)*Dependency of food on transport to fail/Time unit,0),0)

Units: Food units/Hour

Failed Transport due to dependency on food=IF THEN ELSE(Food failure occurrence>0,IF THEN ELSE(Food failure duration>Input data from tool 3 Transport survival time for food failure, (100-Working food)*Dependency of transport on Food to fail/Time unit,0),0)

Units: Transport units/Hour

Failed transport due to energy dependency=IF THEN ELSE(Energy failure occurrence>0,IF THEN ELSE(Energy failure duration>Input data from tool 3 Transport survival time to energy failure, (100-Working energy) *Dependency of transport on energy to fail/Time unit,0),0)

Units: Transport units/Hour

FINAL TIME = 250

Units: Hour

Food dependency failure rate=min(Working food/TIME STEP , Failed food due to dependency on energy+Failed food due to dependency on transport)

Units: Food units/Hour

Food failure duration= INTEG (Food failure duration rate,0)

Units: Hour

Food failure duration rate=IF THEN ELSE(Working food<99, 1, 0)

Units: 1

Food failure occurrence=IF THEN ELSE(Working food<99 , 1 , 0)

Units: Dmnl

Food repair rate=min(Reparable Food/TIME STEP,max(0,Resources deployed for food/(Food resources needed per food unit*(1+Input data from tool 3 DIM5 Food delay due to resources sharing with energy+Input data from tool 3 DIM5 Food delay due to resources sharing with transport))))

Units: Food units/Hour

Food Reparable rate due to dependency= DELAY FIXED (Food dependency failure rate,Reparable Delay of Food due to Energy,0)

Units: Food units/Hour

Food reparable rate due to triggering event= DELAY FIXED (Food triggering event failure rate , Duration of triggering event ,0)

Units: Food units/Hour

Food resources fraction=IF THEN ELSE((Desired resources for transport+Desired resources for food+Desired resources for energy)>0,(Desired resources for food/(Desired resources for transport+Desired resources for food+Desired resources for energy)), 0)

Units: Dmnl

Food resources needed per food unit=3

Units: Resources/Food units

Food triggering event failure rate=max(0,min(Working food,Triggering event effect on Food))/TIME STEP

Units: Food units/Hour

INITIAL TIME = 0

Units: Hour

Input data from tool 3 DIM1 Energy dependency on food=1

Units: Energy units/Food units

Input data from tool 3 DIM1 Energy dependency on transport=1

Units: Energy units/Transport units

Input data from tool 3 DIM1 Food dependency on energy=1

Units: Food units/Energy units

Input data from tool 3 DIM1 Food dependency on transport=1

Units: Food units/Transport units

Input data from tool 3 DIM1 transport dependency on energy=1

Units: Transport units/Energy units

Input data from tool 3 DIM1 transport dependency on food=1

Units: Transport units/Food units

Input data from tool 3 DIM2 Energy redundancy on food=0

Units: Energy units/Food units

Input data from tool 3 DIM2 Energy redundancy on transport=0

Units: Energy units/Transport units

Input data from tool 3 DIM2 Food Redundancy on energy=0

Units: Food units/Energy units

Input data from tool 3 DIM2 Food Redundancy on transport=0

Units: Food units/Transport units

Input data from tool 3 DIM2 transport redundancy on energy=0

Units: Transport units/Energy units

Input data from tool 3 DIM2 transport redundancy on food=0

Units: Transport units/Food units

Input data from tool 3 DIM3 Energy Social effect on food=0

Units: Energy units/Food units

Input data from tool 3 DIM3 Energy Social effect on transport=0

Units: Energy units/Transport units

Input data from tool 3 DIM3 Food Social effect on energy=0

Units: Food units/Energy units

Input data from tool 3 DIM3 Food Social effect on transport=0

Units: Food units/Transport units

Input data from tool 3 DIM3 transport Social effect on energy=0

Units: Transport units/Energy units

Input data from tool 3 DIM3 transport Social effect on food=0

Units: Transport units/Food units

Input data from tool 3 DIM4 Energy reparable delay due to food=1

Units: Hour

Input data from tool 3 DIM4 Energy reparable delay due to transport=1

Units: Hour

Input data from tool 3 DIM4 Food reparable delay due to energy=1

Units: Hour

Input data from tool 3 DIM4 Food reparable delay due to transport=1

Units: Hour

Input data from tool 3 DIM4 Transport reparable delay due to energy=1

Units: Hour

Input data from tool 3 DIM4 Transport reparable delay due to food=1

Units: Hour

Input data from tool 3 DIM5 Energy delay due to resources sharing with food=0

Units: Dmnl

Input data from tool 3 DIM5 Energy delay due to resources sharing with transport=0

Units: Dmnl

Input data from tool 3 DIM5 Food delay due to resources sharing with energy=0

Units: Dmnl

Input data from tool 3 DIM5 Food delay due to resources sharing with transport=0

Units: Dmnl

Input data from tool 3 DIM5 Transport delay due to resources sharing with energy=0

Units: Dmnl

Input data from tool 3 DIM5 Transport delay due to resources sharing with food=0

Units: Dmnl

Input data from tool 3 Energy survival time for food failure=168

Units: Hour

Input data from tool 3 Energy survival time for transport failure=168

Units: Hour

Input data from tool 3 Food survival time for energy failure=2

Units: Hour

Input data from tool 3 Food survival time for transport failure=48

Units: Hour

Input data from tool 3 Transport survival time for food failure=168

Units: Hour

Input data from tool 3 Transport survival time to energy failure=24

Units: Hour

Reparable Delay of Energy due to dependency=Duration of triggering event+Input data from tool 3 DIM4 Energy reparable delay due to food+Input data from tool 3 DIM4 Energy reparable delay due to transport

Units: Hour

Reparable Delay of Food due to Energy=Duration of triggering event+Input data from tool 3 DIM4 Food reparable delay due to energy+Input data from tool 3 DIM4 Food reparable delay due to transport

Units: Hour

Reparable Delay of Transport due to dependency=Duration of triggering event+Input data from tool 3 DIM4 Transport reparable delay due to food+Input data from tool 3 DIM4 Transport reparable delay due to energy

Units: Hour

Reparable Energy= INTEG (Energy reparable rate due to triggering event+Energy Reparable rate due to dependency-Energy repair rate,0)

Units: Energy units

Reparable Food= INTEG (Food Reparable rate due to dependency+Food reparable rate due to triggering event-Food repair rate,0)

Units: Food units

Reparable Transport= INTEG (Transport reparable rate due to triggering event+Transport Reparable rate due to dependency-Transport repair rate,0)

Units: Transport units

Resources deployed for energy=min(Desired resources for energy,(Total resources*Energy resources fraction))

Units: Resources/Hour

Resources deployed for food=min(Desired resources for food,(Total resources*Food resources fraction))

Units: Resources/Hour

Resources deployed for transport=min(Desired resources for transport,(Total resources*Transport resources fraction))

Units: Resources/Hour

SAVEPER = TIME STEP

Units: Hour

Time of triggering event=10

Units: Hour

TIME STEP = 0.125

Units: Hour

Time unit=1

Units: Hour

Total deployed resources=Resources deployed for energy+Resources deployed for food+Resources deployed for transport

Units: Resources/Hour

Total resources=60

Units: Resources/Hour

Transport dependency failure rate=min(Working Transport/TIME STEP,Failed Transport due to dependency on food+Failed transport due to energy dependency)

Units: Transport units/Hour

Transport failure duration= INTEG (Transport failure duration rate,0)

Units: Hour

Transport failure duration rate=IF THEN ELSE(Working Transport<99, 1, 0)

Units: 1

Transport failure occurrence=IF THEN ELSE(Working Transport<99 , 1 , 0)

Units: Dmnl

Transport repair rate=min(Reparable Transport/TIME STEP,max(0,Resources deployed for transport/(Transport resources needed per transport unit*(1+Input data from tool 3 DIM5 Transport delay due to resources sharing with food+Input data from tool 3 DIM5 Transport delay due to resources sharing with energy))))

Units: Transport units/Hour

Transport Reparable rate due to dependency= DELAY FIXED (Transport dependency failure rate,Reparable Delay of Transport due to dependency,0)

Units: Transport units/Hour

Transport reparable rate due to triggering event= DELAY FIXED (Transport triggering event failure rate,Duration of triggering event,0)

Units: Transport units/Hour

Transport resources fraction=IF THEN ELSE((Desired resources for transport+Desired resources for food+Desired resources for energy)>0,(Desired resources for transport/(Desired resources for transport+Desired resources for food+Desired resources for energy)), 0)

Units: Dmnl

Transport resources needed per transport unit=3

Units: Resources/Transport units

Transport triggering event failure rate=max(0,min(Working Transport,Triggering event effect on Transport))/TIME STEP

Units: Transport units/Hour

Triggering event=10*PULSE(Time of triggering event , Duration of triggering event)

Units: Event

Triggering event affecting energy=1

Units: Energy units/Event

Triggering event affecting food=1

Units: Food units/Event

Triggering event affecting Transport=1

Units: Transport units/Event

Triggering event effect on Energy=Triggering event affecting energy*Triggering event

Units: Energy units

Triggering event effect on Food=Triggering event affecting food*Triggering event

Units: Food units

Triggering event effect on Transport=Triggering event affecting Transport*Triggering event

Units: Transport units

Working energy= INTEG (Energy repair rate-Energy dependency failure rate-Energy triggering event failure rate,100)

Units: Energy units

Working food= INTEG (Food repair rate-Food dependency failure rate-Food triggering event failure rate,100)

Units: Food units

Working Transport= INTEG (Transport repair rate-Transport dependency failure rate-Transport triggering event failure rate,100)

Units: Transport units

Appendix D: Research questionnaire

This chapter shows the final questionnaire about the developed research.. The aim of the questionnaire was to evaluate the usefulness of the CriMaCID toolbox. This questionnaire was given to the fifteen participants of the final plenary session organised at Tecnun in October 2014. Thirteen answers were received.

D.1 Questionnaire about the research

After having presented the research and the developed tools we would like to know your opinion. Therefore, we ask you to evaluate from 1 to 5 the following statements, being:

1 → Totally disagree

2 → Disagree

3 → Nor agree or disagree

4 → Agree

5 → Totally agree

Impact indicators framework	1	2	3	4	5
The tool covers an existing need as problems under analysis are significant					
The tool includes the most representative variables of the problem under analysis					
The tool offers relevant information of the problem under analysis					
The difficulty level for applying the tool to my particular case is adequate					
There are similar tools that I can use					
I already use a similar tool					
Global assessment of the tool regarding value contribution					

CIs dependency-influence cluster	1	2	3	4	5
The tool covers an existing need as problems under analysis are significant					
The tool includes the most representative variables of the problem under analysis					
The tool offers relevant information of the problem under analysis					
The difficulty level for applying the tool to my particular case is adequate					
There are similar tools that I can use					
I already use a similar tool					
Global assessment of the tool regarding value contribution					

CI dependency radar	1	2	3	4	5
The tool covers an existing need as problems under analysis are significant					
The tool includes the most representative variables of the problem under analysis					
The tool offers relevant information of the problem under analysis					
The difficulty level for applying the tool to my particular case is adequate					
There are similar tools that I can use					
I already use a similar tool					
Global assessment of the tool regarding value contribution					

Simulation	1	2	3	4	5
The tool covers an existing need as problems under analysis are significant					
The tool includes the most representative variables of the problem under analysis					
The tool offers relevant information of the problem under analysis					
The difficulty level for applying the tool to my particular case is adequate					
There are similar tools that I can use					
I already use a similar tool					
Global assessment of the tool regarding value contribution					

Publications

In this chapter, the publications related to this research are included. Firstly, papers directly related to the results of this PhD thesis are included. Secondly, other papers of the author of this research are listed. The papers are structured as: journal publications, conferences and book chapters.

P.1 Papers directly related to the results of this research

Journal Publications

Authors: Ana Laugé, Josune Hernantes, Leire Labaka, Jose Mari Sarriegi
Title: Análisis y clasificación de los impactos en situaciones de crisis.
Journal: Revista Internacional de Desastres Naturales, Accidentes e Infraestructura Civil
Year: 2012 **Volume:** 12(2) **Pages:** 179-186

Authors: Ana Laugé, Josune Hernantes, Jose Mari Sarriegi
Title: The Role of Critical Infrastructures' Interdependencies on the Impacts caused by Natural Disasters
Journal: Lecture Notes in Computer Science
Year: 2013 **Volume:** 8328 **Pages:** 50-61

Authors: Ana Laugé, Josune Hernantes, Jose Mari Sarriegi
Title: Critical Infrastructures' Research
Journal: Crisis Response Journal
Year: 2013 **Volume:** 9(1) **Pages:** 42-43

Authors: Ana Laugé, Josune Hernantes, Jose Mari Sarriegi
Title: Las infraestructuras críticas, más críticas en tiempos de crisis
Journal: Revista de Ingeniería e Industria (DYNA)
Year: 2014 **Volume:** 89(5) **Pages:** 510-517

Authors: Ana Laugé, Josune Hernantes, Jose Mari Sarriegi
Title: Disasters impact analysis for crisis management improvement
Journal: International Journal of Disaster Resilience in the Built Environment
Year: 2014 **Volume:** In press **Pages:**

Authors: Ana Laugé, Josune Hernantes, Jose Mari Sarriegi
Title: Critical Infrastructures Dependencies: A Holistic, Dynamic and Quantitative Approach
Journal: International Journal of Critical Infrastructure Protection
Year: 2014 **Volume:** Under Review **Pages:**

Conference Publications

Authors: Ana Laugé, Leire Labaka, Josune Hernantes, Jose Mari Sarriegi
Title: Gestión de crisis: Resiliencia e impactos
Conference: 50th anniversary conference Engineering: Science and Technology
Place and date of the Conference: San Sebastian, Spain. June, 2012.

Authors: Ana Laugé, Josune Hernantes, Jose Mari Sarriegi
Title: Disaster Impact Assessment: A Holistic Framework
Conference: 10th International Conference on Information Systems for Crisis Response and Management (ISCRAM)
Place and date of the Conference: Baden-Baden, Germany. May, 2013.

Book Chapters

Authors: Ana Laugé, Josune Hernantes, Jose Mari Sarriegi
Chapter Title: Disasters impact analysis for crisis management improvement
Book Title: ELITE International Scientific Conference on best practices and lessons learned from natural disasters
Editors: Pawel Kepka.
Publisher: BEL Studio Sp. z o.o.
Year: 2014 **Pages:** 107-120

P.2 Other papers of the author of this research

Journal Publications

Authors: Jose Manuel Torres, Jose Maria Sarriegi, Josune Hernantes, Ana Laugé
Title: Steering security through measurement
Journal: Lecture Notes in Computer Science
Year: 2009 **Volume:** 5695 **Pages:** 95-104

Authors: Ana Laugé, Josune Hernantes, Leire Labaka, Jose Mari Sarriegi
Title: Collaborative Methodology for Crisis Management Knowledge Integration and Visualization
Journal: Communications in Computer and Information Science.
Year: 2012 **Volume:** 318 **Pages:** 105-116

Authors: Jose Mari Sarriegi, Eliot Rich, Ana Laugé, Leire Labaka, Josune Hernantes
Title: Creating and Testing Holistic Crisis Management Strategies: The Crisis Management Balanced Scorecard and Systems Modelling
Journal: Communications in Computer and Information Science.
Year: 2012 **Volume:** 318 **Pages:** 261-264

Authors: Leire Labaka, Josune Hernantes, Ana Laugé, Jose Mari Sarriegi
Chapter Title: Resilience: Approach, Definition and Building Policies
Journal: Communications in Computer and Information Science
Year: 2012 **Volume:** 318 **Pages:** 509-512

Authors: Josune Hernantes, Leire Labaka, Ana Laugé, Jose Mari Sarrieg
Title: Group Model Building: A collaborative modelling methodology applied to critical infrastructure protection
Journal: International Journal of Organisational Design and Engineering
Year: 2012 **Volume:** 2 **Pages:** 41-60

Authors: Josune Hernantes, Leire Labaka, Ana Laugé, Jose Mari Sarriegi
Title: Three complementary approaches for crisis management
Journal: International Journal of Emergency Management
Year: 2012 **Volume:** 8 (3) **Pages:** 245-263

Authors: Leire Labaka, Josune Hernantes, Ana Laugé, Jose Mari Sarriegi
Title: Políticas para Mejorar la Resiliencia ante Grandes Accidentes
Journal: Revista de Ingeniería e Industria (DYNA)
Year: 2012 **Volume:** 87 (5) **Pages:** 518-525

Authors: Leire Labaka, Josune Hernantes, Ana Laugé, Jose Mari Sarriegi
Title: Enhancing resilience: implementing resilience building policies against major industrial accidents
Journal: International Journal of Critical Infrastructures
Year: 2013 **Volume:** 9 (1/2) **Pages:** 130-147

Authors: Josune Hernantes, Eliot Rich, Ana Laugé, Leire Labaka, Jose Mari Sarriegi
Title: Learning before the storm: Modeling multiple stakeholder activities in support of crisis management, a practical case
Journal: Technological Forecasting & Social Change
Year: 2013 **Volume:** 80 (9) **Pages:** 1742–1755

Authors: Leire Labaka, Josune Hernantes, Ana Laugé, Jose Mari Sarriegi
Title: Policies to improve resilience against major industrial accidents
Journal: Lecture Notes in Computer Science
Year: 2013 **Volume:** 6983 **Pages:** 187-199

Authors: Eliot Rich, Josune Hernantes, Ana Lauge, Leire Labaka, Jose Mari Sarriegi, Jose Julio Gonzalez
Title: Improving the Crisis to Crisis Learning Process.
Journal: International Journal of Information Systems for Crisis Response and Management
Year: 2014 **Volume:** In press **Pages:**

Conference Publications

Authors: Jose Mari Sarriegi, Jose Manuel Torres, Ana Laugé
Title: Avoid remaking the same mistakes again: a framework to analyse previous errors
Conference: 16th Tiems Annual Conference
Place and date of the Conference: Istambul, Turkey. June, 2009.

Authors: Ana Laugé, Jose Mari Sarriegi, José Manuel Torres
Title: The Dynamics of Crisis Lifecycle for Emergency Management
Conference: 27th International Conference of the System Dynamics Society
Place and date of the Conference: Alburquerque, USA. July, 2009.

Authors: Ainara Alvarez, Jose Manuel Torres, Ana Laugé, Jose Mari Sarriegi
Title: Russian-Ukrainian gas conflict case study
Conference: 27th International Conference of the System Dynamics Society
Place and date of the Conference: Alburquerque, USA. July, 2009.

Authors: Josune Hernantes, Jose Manuel Torres, Ana Laugé, Iztok Starc, Eva Zupancic, Denis Trcek, Jose Mari Sarriegi
Title: Using GMB Methodology on a Large Crisis Model
Conference: 7th International Conference on Information Systems for Crisis Response and Management (ISCRAM)
Place and date of the Conference: Seattle, USA. May, 2010

Authors: Eliot Rich, Leire Labaka, Ana Laugé, Josune Hernantes, Jose Mari Sarriegi, Finn Olav Sveen
Title: Modeling a National Power Crisis in Support of A Crisis Lifecycle Model
Conference: 28th International Conference of the System Dynamics Society
Place and date of the Conference: Seoul, Korea. July, 2010.

Authors: Josune Hernantes, Ana Laugé, Leire Labaka, Eliot Rich, Finn Olav Sveen, Ignacio Martinez-Moyano, Jose Julio González
Title: Collaborative modeling of awareness in Critical Infrastructure Protection
Conference: 44th Hawaii International Conference on System Sciences (HICSS)
Place and date of the Conference: Hawaii, USA. January, 2011.

Authors: Leire Labaka, Josune Hernantes, Ana Laugé, Jose Mari Sarriegi
Title: Three Units of Analysis for Crisis Management and Critical Infrastructure Protection
Conference: 8th International Conference on Information Systems for Crisis Response and Management (ISCRAM)
Place and date of the Conference: Lisbon, Portugal. May, 2011.

Authors: Josune Hernantes, Leire Labaka, Ana Laugé, Jose Mari Sarriegi
Title: Eliciting knowledge about crises from 3 different perspectives
Conference: The International Emergency Management Society Workshop (TIEMS)
Place and date of the Conference: Alés, France. June, 2011.

Authors: Ana Laugé, Josune Hernantes, Leire Labaka, Jose Mari Sarrieg
Title: From pre-crisis to post-crisis going through the peak
Conference: European Safety and Reliability Association Conference (ESREL)
Place and date of the Conference: Troyes, Francia. September, 2011.

Authors: Eliot Rich, Jose Mari Sarriegi, Ana Laugé, Josune Hernantes, Leire Labaka, Jose Julio González
Title: Improving the Crisis to Crisis Learning Process
Conference: 46th Hawaii International Conference on System Sciences (HICSS)
Place and date of the Conference: Hawaii, USA. January, 2013.

Authors: Raquel Gimenez, Josune Hernantes, Leire Labaka, Jose Mari Sarriegi, Ana Laugé
Title: Developing a Community of Practice to Learn, Share and Improve in Emergency Management
Conference: 15th European Conference on Knowledge Management (ECKM 2014)
Place and date of the Conference: Santarém, Portugal. September, 2014.

Book Chapters

Authors: Josune Hernantes, Ana Laugé, Leire Labaka, Jose Mari Sarriegi
Chapter Title: Vulnerabilidad y Resiliencia de la Cadena de Suministro
Book Title: Diseño y Gestión de Cadenas de Suministros Globales
Editors: Ander Errasti
Year: 2012 **Place:** San Sebastian, Spain **Pages:** 349-369