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Modeling and analysis of the impact of Critical Infrastructures on the Fast Moving Consumer Goods supply chain

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“The future belongs to those who believe
in the beauty of their dreams”
(Eleanor Roosevelt)

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Abstract

The modeling and analysis of interdependencies in Critical Infrastructures and Key Resources Supply Chains are fundamental to discover hidden societal vulnerabilities.

In this work the concept of Critical Infrastructure Protection is introduced and described, followed by an overview of the most important models and modeling techniques.

The identification of the most appropriate modeling technique is important in the assessment of critical infrastructure and supply chain interdependencies and the consequences when one or more of them are disrupted.

Many of the techniques presented in the scientific literature fall short when evaluating such consequences. For instance they are limited to single infrastructures or, at best, one sector; they may require impracticable large amounts of detailed data; or fail to capture consequence propagation in sufficient detail, hence the need arises for a new methodology and modeling technique.

To this end this work presents a novel method, based on Fuzzy Cognitive Map (FCM) theory and Group Technology (GT) clustering algorithms, to model interdependencies between critical service infrastructures and Key Resource Supply Chains. The model sets out to discriminate major impacts on key industries or supply chains due to service disruptions of one or more infrastructures.

Thanks to its qualitative nature and reliance on experts' judgments, the proposed method allows a complete static and dynamic (forward) analysis of diverse and multiple interactions at operational-organizational levels and across different temporal frames. Something that alternative approaches e.g. the IIM model and its extensions, do not afford.

The features of the proposed method suggest a candidate method hence since it distinguishes major economic and social impacts of service disruptions or infrastructure damages at regional or national scales. It is also beneficial for the decision-makers when contemplating contingency plan modifications and the improvement of complete system resiliency.

The proposed method has been applied to a case study for the preliminary vulnerability analysis of the Fast Moving Consumer Goods (FMCG) supply chain in which critical service infrastructure disruptions have taken place at time increments of one day, four days and three weeks. This study shows the importance of workforce and the relative vulnerability of this supply chain. While further development is required, the method is now regarded as an important candidate approach for ex-ante loss estimation.

Keywords

Fuzzy Cognitive Maps, Group Technology, Critical Infrastructures, Fast Moving Consumer Goods, Supply Chain, Interdependency Analysis.

Parole Chiave

Mappe Cognitive Fuzzy, Group Technology, Infrastrutture Critiche, Grande Distribuzione Organizzata, Supply Chain, Analisi interdipendenze.

Sommario

Introduzione

Un importante obiettivo dell'Europa è la protezione e la sicurezza dei suoi cittadini contro i rischi naturali e tecnologici, così come contro le minacce che coinvolgono il terrorismo. Per realizzare questo obiettivo è fondamentale garantire la continuità dei servizi offerti dalle infrastrutture. Esse infatti offrono una serie di servizi fondamentali, da cui dipendono la società e i cittadini. Questi includono la fornitura del cibo, dei trasporti e la la possibilità di comunicare, e sono garantiti dalla presenza di reti e risorse, come le reti elettriche, le strade e le infrastrutture di telecomunicazione. L'interruzione o la distruzione (perdita) di alcune di queste infrastrutture può essere gravemente invalidante per le esigenze della società e dei singoli cittadini; il ripristino inoltre potrebbe richiedere molto tempo, in particolare quando si verifica un danno fisico. Per tali motivi queste infrastrutture sono chiamate "Infrastrutture Critiche" (IC).

La protezione della società e dei cittadini richiede, come conseguenza di quanto detto in precedenza, una protezione delle Infrastrutture Critiche; un modo per ottenere un'efficace protezione è quello di identificare IC-beni basati sulle potenziali conseguenze che possono essere causate dalla loro perdita. In particolare, la Direttiva Europea 2008/114/CE introduce i criteri per l'individuazione e la designazione di un'infrastruttura come Infrastruttura Critica Europea, sulla base del numero di vittime, dei danni economici e delle conseguenze per i cittadini, derivanti dall'interruzione o la distruzione di un'infrastruttura. Molti Stati Membri designano le loro infrastrutture nazionali utilizzando approcci simili a quello indicato nella Direttiva. Diversi fattori però complicano la determinazione delle potenziali conseguenze di tali interruzioni di servizio.

Obiettivi

Il lavoro di tesi è focalizzato nel risolvere un problema specifico, cercando di valutare, qualitativamente, l'impatto che l'interruzione o la perdita di un'infrastruttura critica genera sull'intero sistema in analisi, composto da IC e supply chain. I danni si propagano in maniera complessa partendo dalla perdita iniziale di una risorsa e, attraverso la rete di infrastrutture, giungendo alle altre reti dipendenti da quest'ultima e verso Key Resource Supply Chains (KRSC). Le conseguenze della perdita di una KRSC possono essere significative per la società tanto quanto le conseguenze dirette causate dalla sola perdita di infrastrutture. Esse devono pertanto essere tenute in considerazione nell'analisi. Per fare questo, una maggiore comprensione del meccanismo interno di propagazione della 'failure' è necessaria.

Studi preliminari

Alcuni studi preliminari sulle Infrastrutture Critiche e sugli approcci per la loro protezione sono stati eseguiti per migliorare la conoscenza del sistema in analisi e per capire quali erano le principali contromisure per far fronte alla perdita di tali servizi. In particolare si introduce il concetto di Protezione delle Infrastrutture Critiche (PIC) suddividendolo in quattro macro aree:

- Eventi passati e disastri
- Protezione Civile
- Interdipendenze tra IC e approcci PIC
- Analisi di rischio, vulnerabilità e criticità

Per quanto riguarda le supply chain, si è deciso di utilizzare come caso studio la Grande Distribuzione Organizzata (GDO) per la sua importanza a livello nazionale, considerando solo i beni deperibili da essa commercializzati. Per analizzare l'impatto subito da tale supply chain nel caso di perdita di IC è necessario conoscere i nodi che la compongono, e per questo lavoro i nodi presi in esame sono: fornitori, produttori, grossisti e distributori finali.

In seguito, una ricerca sulle varie tecniche per la modellizzazione e analisi di interdipendenze tra IC è stata eseguita per capire se in letteratura è presente o meno uno strumento in grado di supportare il raggiungimento degli obiettivi del lavoro.

Da tale stato dell'arte si è riscontrato come recentemente molti sforzi sono stati concentrati nella modellizzazione delle (inter-)dipendenze tra IC: Agent-Based (Barton and Stamber, 2000; Eusgeld, 2008), High Level Architecture (Seliger et al., 1999), Petri Nets (Pye and Warren, 2006), e molti altri. Recensioni critiche di queste e altre tecniche di modellizzazione, e modelli correlati, possono essere trovate in Pederson et al. (2006), Eusgeld et al. (2008) e Griot (2009). Tecniche precedenti, come Input-output modelling (Leontief, 1951; Haimes and Jiang, 2001) e System Dynamics (Forrester, 1961; Sterman, 2000), sono tuttora importanti per lo studio di tali fenomeni.

Molte di queste tecniche tuttavia non soddisfano completamente gli obiettivi di questo lavoro. Per esempio, alcune sono limitate alle sole infrastrutture critiche o addirittura a un solo dominio, come l'energia elettrica; altre richiedono una grande quantità di dati e un elevato livello di dettaglio che, in pratica, non può essere soddisfatto. Molte di queste tecniche inoltre non modellano la propagazione delle conseguenze in modo sufficientemente dettagliato (modelli economici di Leontief). Questo porta quindi alla necessità di una nuova metodologia/modello per valutare l'impatto generato da perdite o interruzioni di IC sulle supply chains.

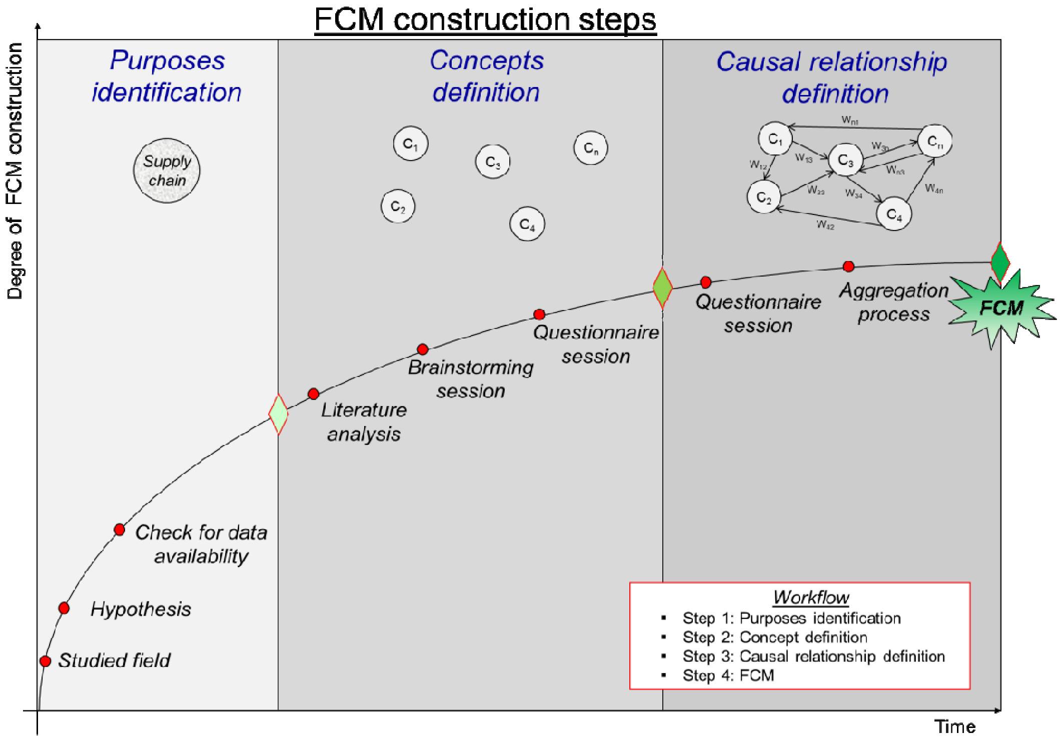
Metodologia sviluppata

Per lo sviluppo di questa metodologia è importante prendere in considerazione le complesse interdipendenze esistenti tra le supply chain e le infrastrutture critiche. Come già detto, non esiste alcun modello o metodologia in letteratura che descriva il comportamento di supply chain, in particolare quella della GDO, durante una perdita o un'interruzione di una o più di queste IC. Anche una mancanza di dati, relativi a precedenti eventi su questo tema, va tenuta in considerazione. Di conseguenza, l'approccio modellistico corretto è quello che utilizza una tecnica di modellazione in grado di rappresentare una complessa supply chain e le sue interdipendenze con le infrastrutture critiche, in un contesto di incertezza, dando però un risultato realistico nonostante si sia in possesso di informazioni incomplete. Per questo motivo la Logica Fuzzy e gli strumenti ad essa correlati sono stati scelti per questo scopo.

L'idea di base della metodologia proposta è di raggiungere una descrizione qualitativa del comportamento dinamico del sistema analizzato, fornendo valide discussioni sui risultati ottenuti. La metodologia può essere divisa in due fasi basate su due diversi strumenti che svolgono diversi tipi di analisi:

- Mappe Cognitive Fuzzy (MCF): questo strumento della Fuzzy Logic è in grado di descrivere tutte le interdipendenze tra i diversi nodi e dare loro un peso attraverso degli archi. Essa rappresenta le conseguenze qualitative della perdita dei nodi del sistema su tutti gli altri nodi, in modo relativo. Questa tecnica ottiene la conoscenza del comportamento di infrastrutture critiche e supply chain per mezzo di interviste strutturate ad esperti dei settori studiati. Queste interviste non cercano informazioni dettagliate sul funzionamento di ciascun sistema, ma su quali sono le interdipendenze tra di loro in termini di conseguenze in caso di 'failure'. A causa della mancanza di dati quantitativi specifici questo primo passo riveste un ruolo fondamentale per raggiungere una comprensione completa della supply chain e di come essa reagisce ad un evento imprevisto. Gli step di costruzione delle MCF sono rappresentati nella successiva figura.

- Algoritmo di clustering della Group Technology: questo strumento è utilizzato per dividere i concetti utilizzati nelle mappe cognitive fuzzy in "famiglie di resilienza"; attraverso l'analisi di queste famiglie è possibile capire quali sono le misure di emergenza necessarie per migliorare la continuità aziendale dell'intero sistema. L'algoritmo di Rank Order Clustering (ROC) è utilizzato per raggiungere questo scopo (otto step presentati nel paragrafo 4.2.1).

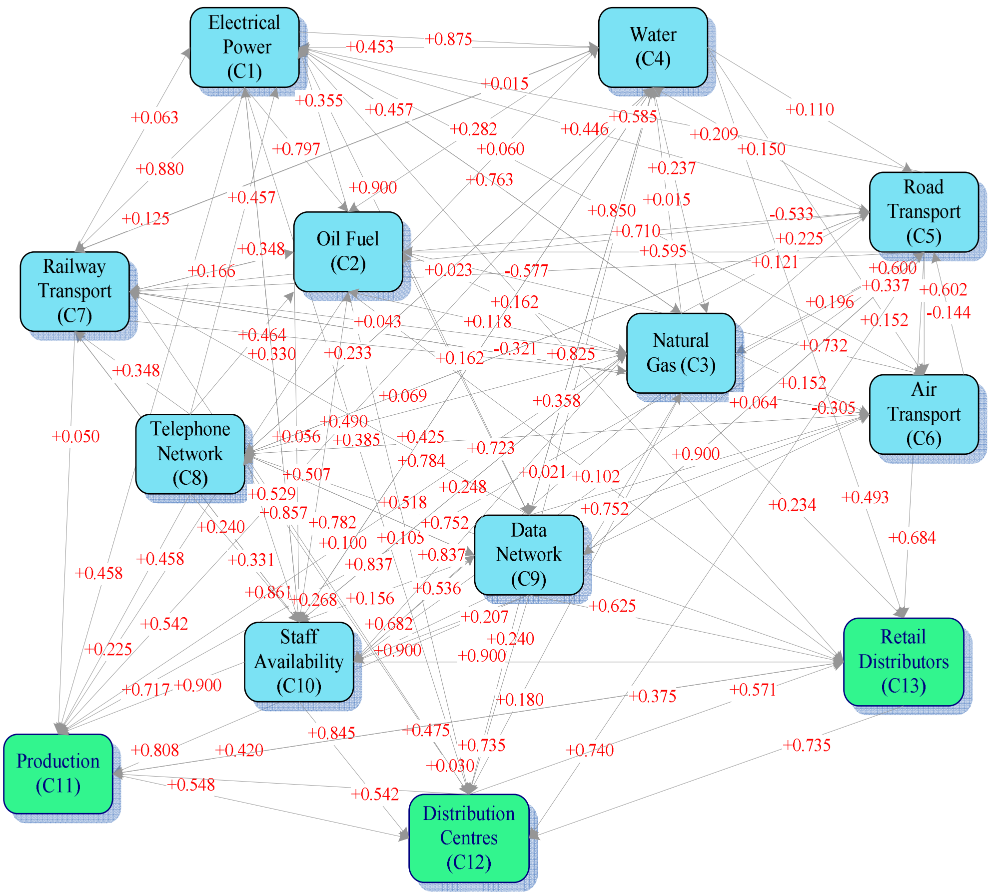


La metodologia sviluppata in questa tesi può essere riassunta dallo schema riportato in seguito, basato su sette diversi step.

METODOLOGIA		
Prima parte-> Mappe Cognitive Fuzzy	***1° step***	*Identificazione del sistema da analizzare e scopo dello studio*
	2° step	*Definizione dei nodi del sistema*
	3° step	*Definizione degli intervalli di tempo*
	4° step	*Definizione delle interdipendenze tra i nodi*
	5° step	*Analisi statica*
	6° step	*Analisi dinamica*
Seconda parte -> GT	***7° step***	*Analisi di resilienza*

Caso studio: risultati

L'intero sistema, infrastrutture critiche e supply chain, è descritto utilizzando 13 concetti (9 per le infrastrutture critiche, 3 nodi per rappresentare la supply chain della GDO e uno per la forza lavoro), e le interviste agli esperti sono utilizzate per individuare le relazioni dirette tra tali concetti e la loro intensità. Attraverso l'uso di queste informazioni può essere costruita una MCF come quella mostrata nella figura sottostante; in particolare in questo lavoro ne saranno costruite tre, una per ogni step temporale (1 giorno, 4 giorni e 3 settimane), in modo tale da analizzare il comportamento del sistema per 'failure' di diversa durata.



Tali mappe possono poi essere studiate attraverso analisi statiche e dinamiche. L'analisi statica, per ogni mappa cognitiva fuzzy, consiste nell'applicazione delle tecniche relative dei grafi (approccio statistico) per studiare le caratteristiche della mappa e delle relazioni pesate che caratterizzano il sistema. L'analisi dinamica è invece utilizzata per studiare gli effetti a catena generati dall'indisponibilità di un concetto, su tutti gli altri.

Il modello sviluppato è in grado di studiare due tipi di scenario per quanto riguarda l'analisi dinamica: uno elementare, in cui solo un servizio non è disponibile (in tabella i risultati che si riferiscono ai 3 step), e l'altro complesso, in cui due servizi subiscono delle interruzioni nello stesso momento.

1 DAY

sigmoid function (λ=0.6)		Effect on the concept C_i												
		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
Failure of the concept C_i	C1	-	medium	medium	medium	weak	medium	medium	medium	medium	medium	medium	medium	medium
	C2	weak	-	weak	weak	weak	weak	weak	weak	weak	weak	weak	weak	weak
	C3	weak	weak	-	weak	weak	weak	weak	weak	weak	weak	weak	weak	weak
	C4	weak	weak	weak	-	weak	weak	weak	weak	weak	weak	weak	weak	weak
	C5	weak	medium	weak	weak	-	medium	weak	weak	weak	medium	medium	medium	medium
	C6	weak	weak	weak	weak	weak	-	weak	weak	weak	weak	weak	weak	weak
	C7	weak	weak	weak	weak	weak	weak	-	weak	weak	weak	weak	weak	weak
	C8	medium	medium	medium	weak	weak	medium	medium	-	medium	weak	medium	medium	medium
	C9	medium	medium	medium	medium	weak	medium	medium	medium	-	medium	medium	medium	medium
	C10	medium	medium	medium	medium	medium	medium	medium	medium	medium	-	medium	medium	medium
	C11	null	null	null	null	null	null	null	null	null	null	-	weak	weak
	C12	null	null	null	null	null	null	null	null	null	null	weak	-	weak
	C13	null	null	null	null	null	null	null	null	null	null	weak	weak	-

4 DAYS

sigmoid function (λ=0.6)		Effect on the concept C_i												
		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
Failure of the concept C_i	C1	-	medium	medium	medium	medium	strong	medium	medium	medium	medium	strong	strong	strong
	C2	medium	-	medium	weak	medium	medium	weak	weak	weak	weak	medium	medium	medium
	C3	medium	medium	-	weak	weak	medium	weak	weak	weak	weak	medium	medium	medium
	C4	medium	medium	medium	-	weak	medium	weak	weak	weak	medium	medium	medium	medium
	C5	medium	medium	medium	medium	-	medium	weak	medium	weak	medium	strong	strong	strong
	C6	weak	weak	weak	weak	weak	-	weak	weak	weak	weak	weak	weak	weak
	C7	weak	weak	weak	weak	weak	weak	-	weak	weak	weak	weak	weak	weak
	C8	medium	medium	medium	medium	medium	medium	medium	-	medium	medium	strong	strong	strong
	C9	strong	strong	medium	medium	medium	strong	medium	medium	-	medium	strong	strong	strong
	C10	strong	strong	medium	medium	medium	strong	medium	medium	medium	-	strong	strong	strong
	C11	null	null	null	null	null	null	null	null	null	null	-	weak	weak
	C12	null	null	null	null	null	null	null	null	null	null	weak	-	weak
	C13	null	null	null	null	null	null	null	null	null	null	weak	medium	-

3 WEEKS

sigmoid function (λ=0.6)		Effect on the concept C_i												
		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
Failure of the concept C_i	C1	-	strong	strong	medium	medium	strong	medium	medium	medium	medium	strong	strong	strong
	C2	medium	-	medium	medium	medium	strong	medium	medium	medium	medium	strong	strong	strong
	C3	medium	medium	-	medium	medium	strong	medium	medium	medium	medium	strong	strong	strong
	C4	medium	medium	medium	-	medium	strong	medium	medium	medium	medium	strong	strong	strong
	C5	medium	strong	medium	medium	-	strong	weak	medium	medium	medium	strong	strong	strong
	C6	weak	weak	weak	weak	weak	-	weak	weak	weak	weak	medium	medium	medium
	C7	medium	medium	medium	medium	weak	medium	-	weak	weak	medium	strong	medium	medium
	C8	strong	strong	medium	medium	medium	strong	medium	-	medium	medium	strong	strong	strong
	C9	strong	strong	strong	medium	medium	strong	medium	medium	-	medium	strong	strong	strong
	C10	strong	strong	strong	medium	medium	strong	medium	medium	medium	-	strong	strong	strong
	C11	weak	weak	weak	weak	weak	weak	weak	weak	weak	weak	-	medium	medium
	C12	weak	weak	weak	weak	weak	weak	weak	weak	weak	weak	medium	-	medium
	C13	weak	weak	weak	weak	weak	weak	weak	weak	weak	weak	medium	medium	-

Partendo dai risultati dell'analisi dinamica della MCF, si applica la seconda parte del modello, che utilizza un algoritmo della Group Tecnology per permettere un'analisi di resilienza. Nella tabella sottostante sono riportate le famiglie di resilienza per lo step temporale "4 giorni".

4 DAYS														
sigmoid function (lambda=0.6)		*Effect on the concept C_i*												
		C13	*C11*	*C12*	*C6*	*C2*	*C1*	*C3*	*C10*	*C8*	*C9*	*C4*	*C5*	*C7*
Failure of the concept C_i	*C10*	strong	strong	strong	strong	strong	strong	medium	-	medium	medium	medium	medium	medium
	C9	strong	strong	strong	strong	strong	strong	medium	medium	medium	-	medium	medium	medium
	C1	strong	strong	strong	strong	medium	-	medium	medium	medium	medium	medium	medium	medium
	C8	strong	strong	strong	medium	medium	medium	medium	medium	-	medium	medium	medium	medium
	C5	strong	strong	strong	medium	medium	medium	medium	medium	medium	weak	medium	-	weak
	C4	medium	medium	medium	medium	medium	medium	medium	medium	weak	weak	-	weak	weak
	C2	medium	medium	medium	medium	-	medium	medium	weak	weak	weak	weak	medium	weak
	C3	medium	medium	medium	medium	medium	medium	-	weak	weak	weak	weak	weak	weak
	C13	-	weak	medium	null	null	null	null	null	null	null	null	null	null
	C11	weak	-	weak	null	null	null	null	null	null	null	null	null	null
	C12	weak	weak	-	null	null	null	null	null	null	null	null	null	null
	C6	weak	weak	weak	-	weak	weak	weak	weak	weak	weak	weak	weak	weak
	C7	weak	weak	weak	null	weak	weak	weak	weak	weak	weak	weak	weak	-

Conclusioni

Il sistema ('1 day') è particolarmente vulnerabile agli eventi che coinvolgono l'interruzione dell'alimentazione elettrica (C1), della rete dati (C9) e della disponibilità di personale (C10), come risulta anche dall'analisi statica. Guardando gli altri step temporali, l'impatto di una perdita risulta maggiore: ad esempio, nel caso di un evento di 'failure' della durata di 3 settimane, il trasporto aereo (C6), le strutture di produzione (C11), i centri di distribuzione (C12) e i distributori al dettaglio (C13), diventano i nodi più colpiti.

Un'osservazione interessante guardando la tabella dei risultati dell'analisi dinamica è che le infrastrutture sono generalmente meno interdipendenti rispetto alla supply chain della GDO. I nodi della supply chain, infatti, sono in grado di supportare le interruzioni di 1 giorno, grazie a buffer di sistema, ma in caso di periodi più lunghi di interruzione del servizio perdono efficienza e operatività. Questo conferma l'ipotesi iniziale che le supply chains devono essere incluse nella stima delle conseguenze di tali scenari, per non trascurare degli aspetti fondamentali per la comprensione dei fenomeni da essi generati.

Con uno sforzo relativamente limitato, i risultati dell'intero modello risultano essere interessanti. Per esempio, essi mostrano rapidamente l'importanza della forza lavoro e la complessiva vulnerabilità delle supply chains rispetto alle IC. Mostrano anche le famiglie di resilienza in cui ogni infrastruttura critica, o nodo di supply chain, è allocata, permettendo così un miglior sviluppo di 'contingency plans'. I risultati sembrano intuitivamente corretti, e il fatto che si basino sulla conoscenza di esperti dà ulteriori garanzie.

Introduction

Nowadays one of the most important priorities of the society is the protection and security of the citizens, according also with the main disasters due to terrorism and natural events. Trying to achieve a safer society, one of the emerging issues faced by the most advanced regions is the service continuity of some fundamental services. These services are guaranteed by the so called critical infrastructures, like electricity grids, transportation or communication systems and so on. It does not exist in this moment a unified classification of these critical infrastructures, and sometimes they depend on the priorities set by each country. As it is possible to see in the literature, someone is still discussing on what is the real meaning of the term "critical", but in the last few years the European Commission tries to make some clarifications.

Studying the risk associated to critical infrastructures some interdependencies can be noticed and they cannot be analyzed just individually if a complete understanding of the related phenomena wants to be reached. It will be used the term "system of systems" to describe this complex and interconnected world. In the chapter of the state of the art a brief description of which are the models used to analyze these interdependencies is provided, giving also an introduction to risk and vulnerability models, that are important for the complete analysis of critical infrastructures. One of the major problems in the risk analysis of critical infrastructures is the full identification and correct modeling of these dependencies; for this reason recent scientific literature is rich of different models, based on different mathematical approaches. Nevertheless a complete model able to describe all the types of interdependencies does not exist yet, since it is a quite new topic and the scientific research is still working to get better results.

In the modern society also some industries are considered critical, in particular their supply chain are even more dependent on other critical infrastructures; for this reason they have to be protected in order to prevent business disruptions, that would have repercussions on the citizens and also on the economy. The most relevant supply chain in the Italian economic context, considering its contribution to the growth of the Gross Domestic Product (GDP), is the Fast Moving Consumer Goods (FMCG) sector. A description of this sector, with a scheme of the supply chain is given in the second chapter. As said before the FMCG supply chain is interconnected with all the main critical infrastructures, and the occurrence of service disruptions on one or more of them result in an important economic loss and a large impact on the entire society.

This work wants to relate the impact that adverse events on critical infrastructures would have on the Fast Moving Consumer Goods supply chain, in order to evaluate the expected consequences and improve the resilience of the system. The objective is to develop a model that is able to study how FMCG supply chain reacts to service disruption or destruction events impacting on a critical infrastructure, considering its interdependencies with all the other infrastructures. The model should also be able to predict the loss of service of the supply chain.

In order to understand the characteristics of this complex supply chain a preliminary study regarding the Italian FMCG supply chain has been done.

Several contributing factors complicate determining the potential consequences of potential critical infrastructures losses.

The project has been developed in collaboration with the European Commission's Joint Research Centre (JRC). The JRC is a department (Directorate-General, DG) of the European Commission providing independent scientific and technological support for EU policy-making.

In particular this work is part of a bigger research project of the Institute for the Protection and Security of the Citizen (IPSC), which is one of the seven institutes of the European Commission's Joint Research Centre (JRC). The mission of the IPSC, placed in Ispra (VA), is to provide research results and to support EU policy-makers in their effort towards global security and towards protection of European citizens from accidents, deliberate attacks, fraud and illegal actions against EU policies (source: European Commission – Joint Research Center –). The European Directive 2008/114/EC is a central point of this project, due to the fact that it is a European project. Another priority coming from the collaboration with the JRC is the need of flexibility and dynamicity of the model.

The thesis is organized as follows. Firstly introductions on Critical Infrastructures Protection and on FMCG are given. Then a state of the art on modeling and simulation for critical infrastructures interdependency analysis is provided. Subsequently a novel method for discriminating Critical Infrastructures for Key Resources Supply Chains is explained and a case study on Fast Moving Consumer Goods supply chain is discussed. At the end findings are presented and discussed in the conclusions and possible future works are provided.

1. Critical Infrastructure Protection

Critical Infrastructure Protection (CIP) is a very complex issue and it contains many different topics. First of all the studies on disasters are important to understand which are the possible threats to be managed and they help in the comprehension of these phenomena.

The Civil Protection deals with population and society problems due to disasters and hazardous events. Its work is based on different steps: prevention and mitigation, preparation, response, recovery. In particular the prevention and mitigation phase is really fundamental because it concern with reduction of vulnerability, protection of Critical Infrastructures (CIs) and also attenuation of the effects of a disaster. The CIP and also the European Programme of Critical Infrastructure Protection (EPCIP) is an important part of the Civil Protection and it focuses on the prevention and mitigation, using different approaches and different risk management frameworks.

The European Directive 2008/114/EC, presented in this chapter, introduces criteria for identifying and designating an infrastructure as European Critical Infrastructure (ECI), based on the number of casualties, economic damage and public effect that may result from the disruption or destruction of an infrastructure. These ECI are the infrastructures taken into consideration for the construction of the model.

In this chapter there is also a description of the meaning of risk, vulnerability and criticality analysis, the differences are underlined and the best approach for this work will be discussed.

1.1 Reporting and investigation of past events and disasters

Critical infrastructures are subjected to many different threats: natural hazards, accidents, political events and intentional acts (i.e. terrorist attacks).

Many big disasters in the history called for the need of improving the protection of the most important infrastructures in all the areas of the world.

The destruction that accompanied the Hurricane Katrina, as well as the Haiti and Chile earthquakes demonstrate how our physical and social infrastructures are still vulnerable. It is by the examination of these disasters that it is possible start a study that could bring us to avoid these events, or at least reduce their effects (Rivers, 2006).

The impact of a disaster, or a deviation, in a CI is one of the key concepts talking about critical infrastructure protection. After a disaster who is impacted is not just people, but there is a negative effect on the economy of a nation, like after 11th September 2001 with the Stock Exchange crash, and also the government can be destabilized. The Gulf of Mexico's offshore disaster on 2010 is an example of how the impact of a disaster can be spread in different fields of a nation, from the problems for the population and the environment, to the economic problems of the area that survive with two main jobs, the oil extraction and the fishing, till the impact on Obama's government, that has many difficulties in tackling the problem and it loose consensus after this disaster (source: The Washington Post).

In the literature it can be found a wide variety of papers that analyze disasters, their consequences and providing also some practical suggestions on how reduce the impact of similar disasters in the future.

Many authors discuss about the real meaning of the term disaster, when it can be used for a particular event and which are the differences between the term crisis and disaster. Parker (1992) reviewed the concept of disaster, proposing a new definition: ''An unusual natural or man-made event, including an event caused by failure of technological systems, which temporarily overwhelms the response capacity of human communities, groups of individuals or natural environments and which causes massive damage, economic loss, disruption, injury, and/or loss of life. This definition encompasses medical accidents and disasters.''

Crisis is defined as an abnormal situation which presents some extraordinary, high risk for business and which will develop into a loss of it unless carefully managed. The disasters are similar to the crisis in terms of developing phases but they are still two different events (Shaluf et al., 2003).

Recent disasters underscore also the need to understand the human behavior in order to coordinate in a more effectively way the response to these events (Drabek and McEntire, 2003).

Trying to study disasters it is possible to encounter some contradictions, like the presence of dubious statistical data and the widespread of conceptual disagreements. That is why there will never be a perfect answer, there will be always a degree of uncertainty about any statistics and different points of view about how to conceptualize disasters (Quarantelli, 2001). "Most disaster analysis is based on shaky foundations. Institutional bias, political interests and technical insufficiencies make disaster statistics unsatisfactory and unreliable (…). This contributes to preserve myths about the effects of disasters on the economy and society" (Albala-Bertrand, 1993).

In Figure 1.1, using some statistical data, it is proposed a comparative view of the major disasters of the recent history, in which the number of death and the economic loss due to the event are used as variables for the construction of the graph. The different colors of the balls in the figure show the environmental impact of each disaster, while their dimensions depend from the size of the event. In the highest part of the figure are reported the security funds of some countries.

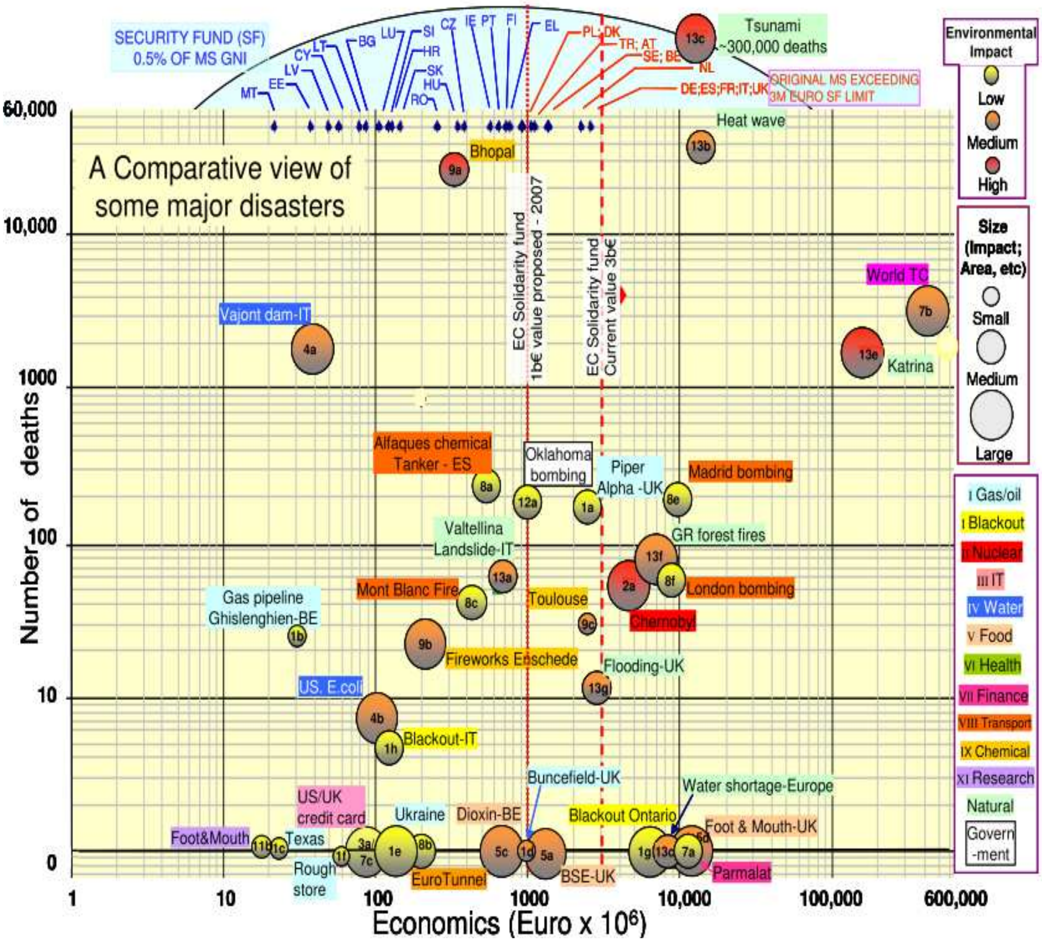


Figure 1.1 A comparative view of some of the major disasters (Bouchon et al., 2009)

Considering only the natural disasters, in order to have an idea of the dimensions and the importance of these events, it is possible to analyze some statistics made by the UN International Strategy for Disaster Reduction (UN / ISDR).

Table 1.1 shows the number of natural disasters collected by type (hydro meteorological, geological and biological disasters), classified with a continental distribution between 1991 and 2005, while Figure 1.2 represent the world distribution of disasters by type, in which the two most important natural hazards are: floods (32%) and wind storms (25%).

	Hydrometeorological disasters							Geological disasters			Biological disasters			
	Drought	Extreme Temperature	Flood	Slide	Wild Fire	Wind Storm	**Total**	Earthquake & Tsunami	Volcano	**Total**	Epidemic	Insect Infestation	**Total**	**Total**
Africa														
Eastern Africa	87		132	7	2	46	**274**	11	3	**14**	146	3	**149**	**437**
Middle Africa	8		37	2	2	1	**50**	1	1	**2**	50	2	**52**	**104**
Northern Africa	9	6	56	2	2	9	**84**	12		**12**	19	2	**21**	**117**
Southern Africa	23	1	24	1	7	17	**73**	2		**2**	12		**12**	**87**
Western Africa	18	2	87	2	2	15	**126**		1	**1**	151	8	**159**	**286**
Sub-total	**145**	**9**	**336**	**14**	**15**	**88**	**607**	**26**	**5**	**31**	**378**	**15**	**393**	**1 031**
Americas														
Carribean	6		44	2	2	95	**149**	5	4	**9**	6		**6**	**164**
Central America	20	13	82	12	7	76	**210**	31	19	**50**	30		**30**	**290**
North America	8	11	90	1	56	236	**402**	10	1	**11**	9		**9**	**422**
South America	23	21	165	46	20	36	**311**	34	10	**44**	28	3	**31**	**386**
Sub-total	**57**	**45**	**381**	**61**	**85**	**443**	**1 072**	**80**	**34**	**114**	**73**	**3**	**76**	**1 262**
Asia														
Eastern Asia	31	8	132	34	8	219	**432**	81	5	**86**	17	1	**18**	**536**
South Central Asia	22	47	285	63	7	137	**561**	95		**95**	103	4	**107**	**763**
South East Asia	25		198	47	13	140	**423**	56	23	**79**	61	1	**62**	**564**
Western Asia	13	11	57	7	5	23	**116**	38		**38**	12		**12**	**166**
Sub-total	**91**	**66**	**672**	**151**	**33**	**519**	**1 532**	**270**	**28**	**298**	**193**	**6**	**199**	**2 029**
Europe														
Eastern Europe	7	46	108	10	23	47	**241**	12		**12**	19	1	**20**	**273**
Northern Europe	2	12	22	2		27	**65**	2	1	**3**	6		**6**	**74**
Southern Europe	9	19	70	5	25	20	**148**	22	2	**24**	10		**10**	**182**
Western Europe	1	19	60	6	3	38	**127**	5		**5**	6		**6**	**138**
Sub-total	**19**	**96**	**260**	**23**	**51**	**132**	**581**	**41**	**3**	**44**	**41**	**1**	**42**	**667**
Oceania														
Australia	6	5	36	2	11	49	**109**	1	1	**2**	2	2	**4**	**115**
Melanasia	5		9	5	1	24	**44**	11	9	**20**	5		**5**	**69**
Micronesia	2					10	**12**	1		**1**	2		**2**	**15**
Polynesia	1			2		16	**19**	1		**1**	2		**2**	**22**
Sub-total	**14**	**5**	**45**	**9**	**12**	**99**	**184**	**14**	**10**	**24**	**11**	**2**	**13**	**221**
Total	**326**	**221**	**1 694**	**258**	**196**	**1 281**	**3 976**	**431**	**80**	**511**	**696**	**27**	**723**	**5 210**

Table 1.1 Number of natural disasters by type: regional distribution 1991-2005 (source: UN / ISDR)

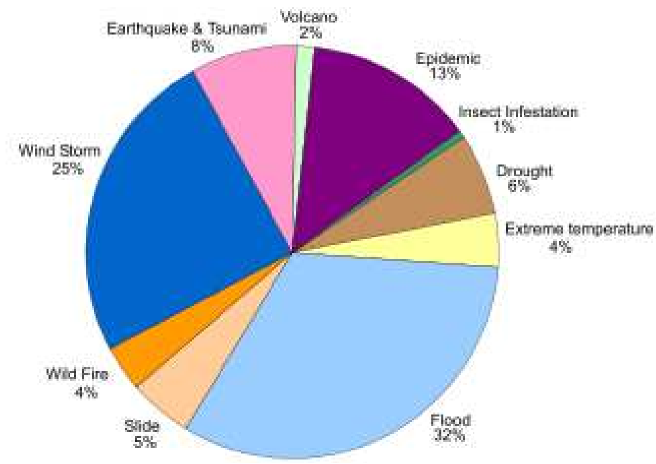


Figure 1.2 World distribution of disasters by type from 1991 to 2005 (source: UN / ISDR)

All these disasters can be translated also in an economic loss for the country, and it is essential to estimate this amount of money in order to understand which could be the importance of having a good protection of critical infrastructures, not only for citizens but also for the economy of a region.

Figure 1.3 reports an estimate of the economic loss due to major disasters in some of the most important nations.

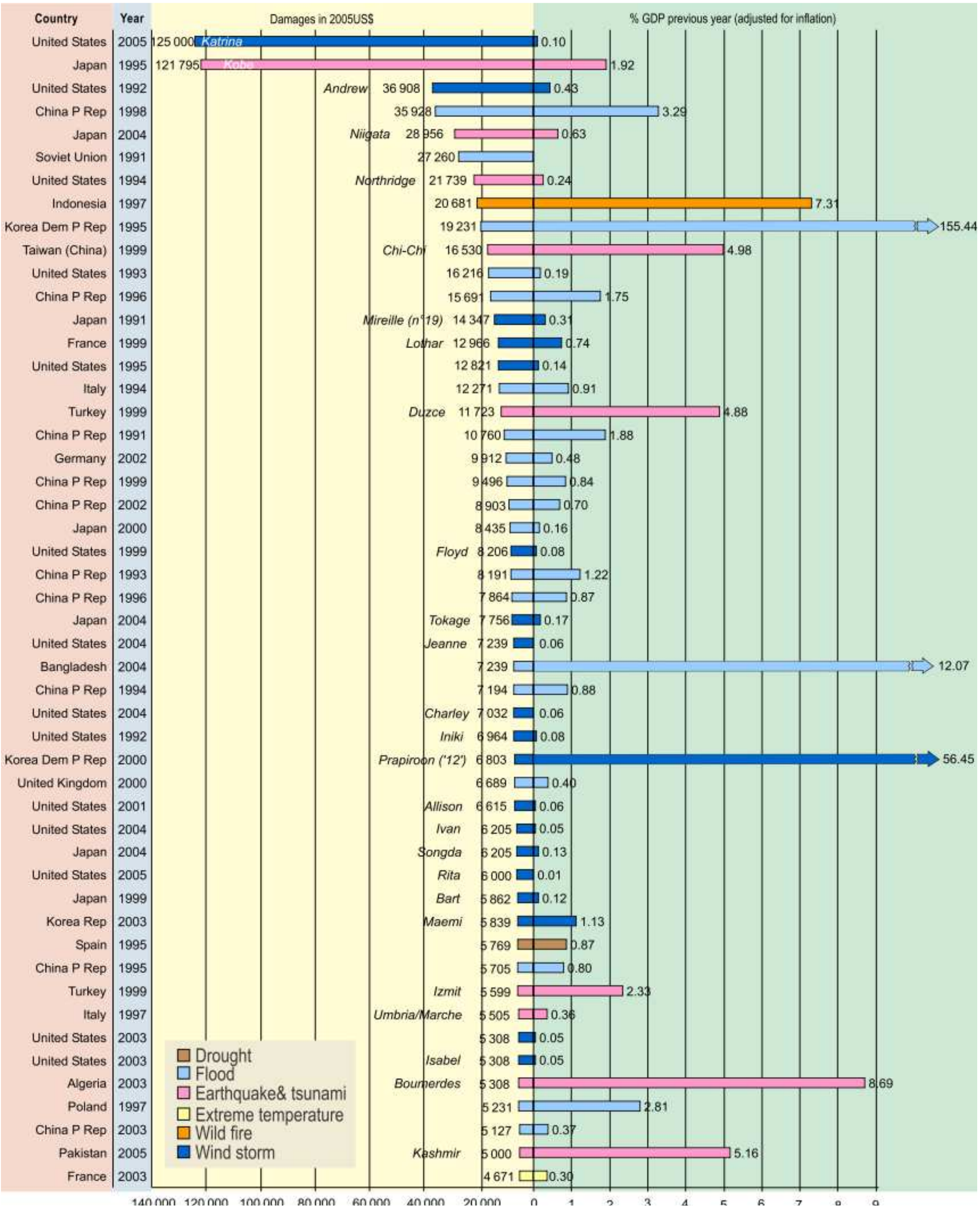


Figure 1.3 Economic damages, reported by natural disaster and country, in absolute (US $) and relative (% GDP) terms. Period: 1991 – 2005 (source: UN / ISDR)

1.2 Civil Protection

Civil protection aims to better protect people, their environment, property and cultural heritage in the event of major natural or manmade disasters (European Civil Protection, 2010).

The fundamental approach to an effective civil protection operation relies on three key modes of action: prevention, preparedness, response. Another important mode of action is also the recovery, as reported in Figure 1.4.

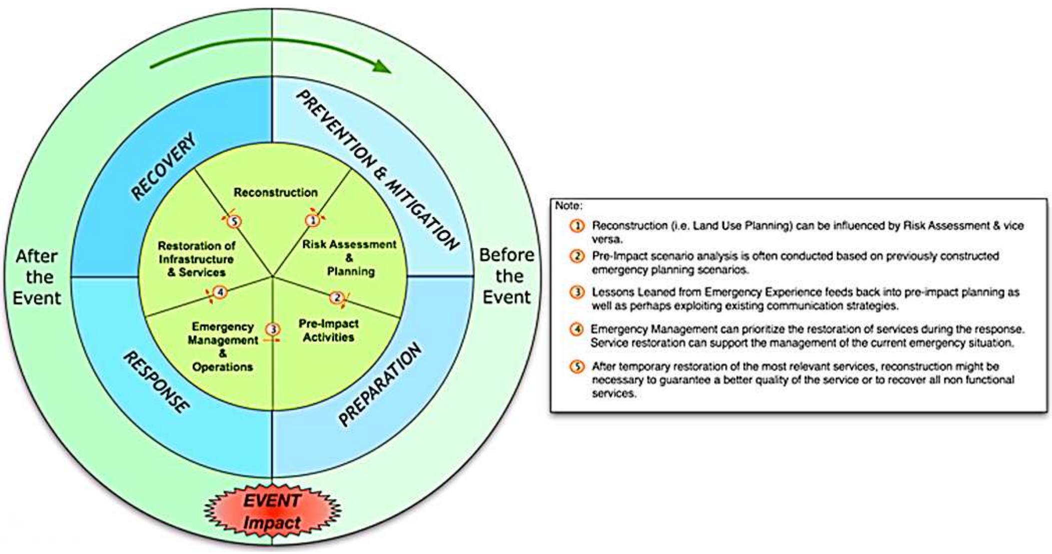


Figure 1.4 Framework of civil protection: the steps before and after a disaster event (Bouchon, 2006)

The CIP is an important part of emergency management and civil protection, in particular for the prevention and mitigation step. It is useful to have a good prevention and protection of infrastructures, but also a quick response to a disasters and the recovery of CIs are fundamental to adequately protect citizens and the society. Indeed modern societies are increasingly dependent on CIs, that is why is so important to have a plan in case of emergencies. The civil protection develops its own emergency management plan, dealing also with crisis and disaster management. On the other side business continuity and contingency plans are in charge to CIs operators.

Luijif and Klaver (2005) defined the emergency response cycle as a set of activities that comprise the anticipation, assessment, prevention, preparation, response and recovery. It is possible to see in Figure 1.5 that in an all-hazard approach all this tasks are mentioned. In the following parts of this chapter it will be described how a crisis or a disaster are managed, how recovery is pursued and a state of the art on business continuity and contingency plan frameworks is going to be presented.

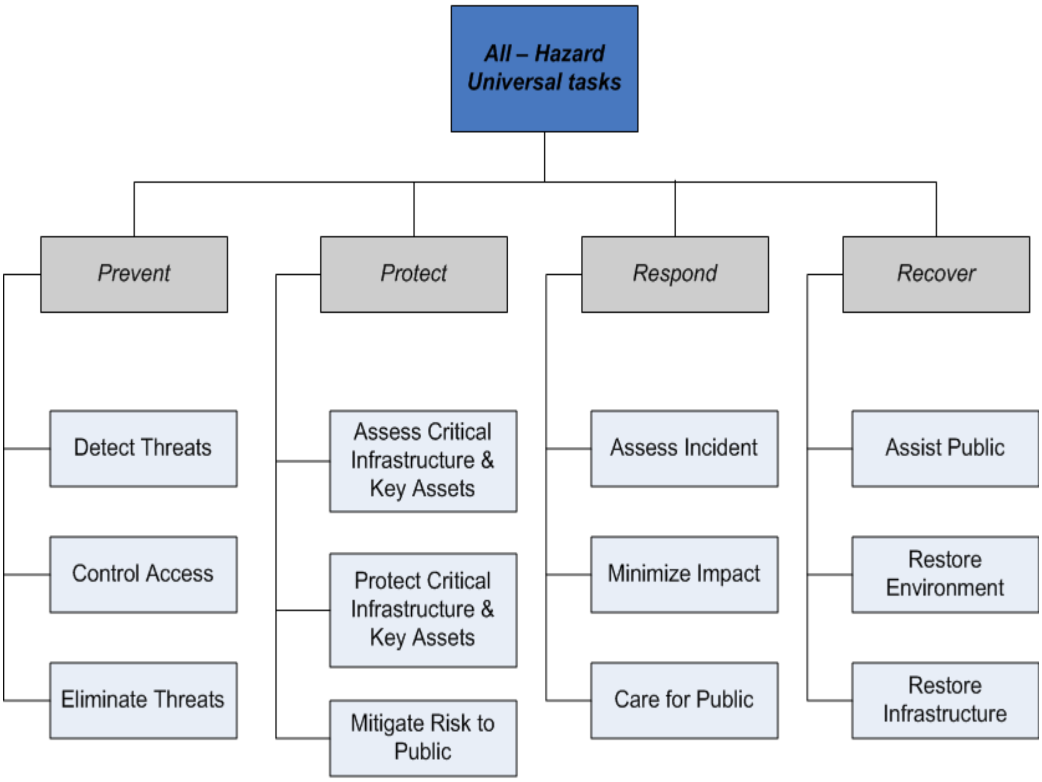


Figure 1.5 All-Hazards universal tasks (adapted from Von Lubitz et al., 2008)

1.2.1 Crisis and Disasters management

The objectives of crisis and disasters management are the identification, inventory and assessment of all the response activities and measures in a given area, to reduce social and economic damages and losses (Weichselgartner, 2001).

It is possible to say that one of the main goals of disaster management is the reduction of damage to human life and properties, but disaster management covers a wider and more complex body of knowledge, incorporating also, among others, the concept of community policing (Trim, 2004). Trying to obtain these objectives is important to have practical frameworks to balance operational effectiveness and cost efficiency (Kelly, 1995).

In Figure 1.6 a conceptual scheme of disaster management is reported; different components are highlighted: mitigation, disaster response, vulnerability assessment and risk management.

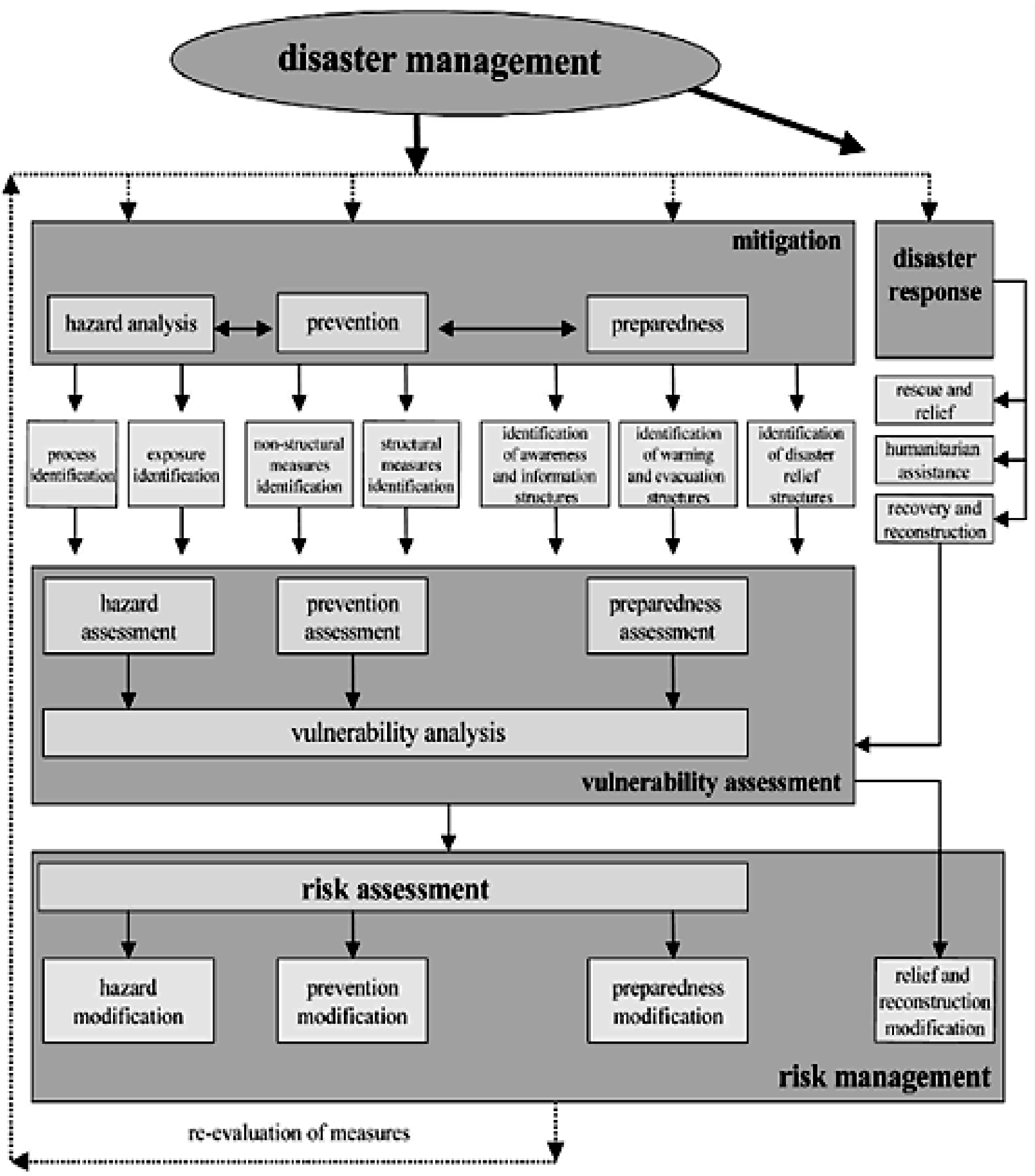


Figure 1.6 Disaster management process (Weichselgartner, 2001)

It is also possible to define a disaster timeline, divided in different steps (Figure 1.7); in particular the crisis and disaster management processes and systems deal with the mitigation of the right part of the curve, the "consequence management", in order to anticipate the end point.

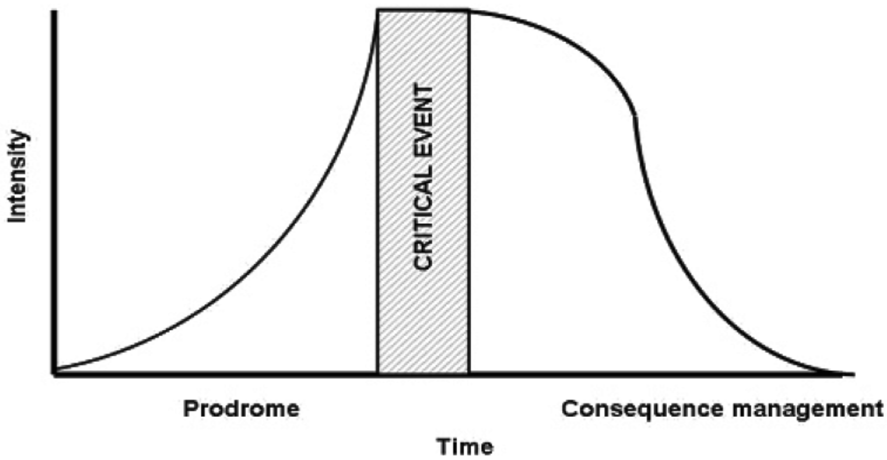


Figure 1.7 Disaster stages (Von Lubitz et al., 2008)

The intensity of the prodrome stage increases exponentially due to the cumulative effect of pre-disaster events, while the intensity at the consequence management stage has a reverse but sigmoid course, where the initial slow phase of immediate response is followed by a rapid recovery stage, and the final, typically much slower, “mop-up”.

One of the greatest barriers in planning the response to disasters is the difficulty of understanding natural hazards. Also the rarity of disasters and thus the opportunities to gain an in depth experience necessary for effective all-hazard response capability represents a significant constraint. Another significant problem in planning this kind of emergency’s interventions is the inability to combine technological understanding and sociological awareness to political competence (Beroggi, 2001).

Developing training strategies is fundamental for disaster readiness planning, in order to compensate the lack of disaster experience. The assessment center provides not only a framework for the development and critical evaluation of performance in simulations, it can also promote the development of the cognitive competencies essential for communication and decision making in emergencies, and for facilitating operational integration (Paton and Jackson, 2002).

A key factor in the emergency response is the co-operation and co-ordination which contribute to the reduction of losses and to a better efficiency of rescue and recovery, that is why in the literature is illustrated how to organize the emergency response in terms of collaboration between different organizations or simply between people interested to hazardous events (Granot, 1999).

Quarantelli (1982) focuses his attention on three particular difficulties in coordinating emergency organizations:

- Co-ordination of the interests of public and private sector agencies in disaster is difficult because of their diverse perspectives.
- Co-ordination in disaster is qualitatively different from day-to-day co-ordination since disaster is not simply a large emergency.
- Co-ordination can have a different connotation to different organizations and even various departments of the same organization, leading to considerable conflict over emergency roles and domains.

Considering the approach to crisis management it is observable that it is still fundamentally a local affair and the perspective is bottom up: local authorities begin to deal with a disaster, regional and national authorities offer assistance (Boin et al., 2003).

Nevertheless Dealing with crisis and disaster management the concept of resilience of citizens is a key point in the effective response to an event, as well as first line responders and operational commanders (Boin and McConnell, 2007).

Each country and city as well is trying to improve the management of disasters (Oakville city, 2006; Department of Public Safety Vermont Emergency Management, 1996), but still a huge development must be done in order to reach a good level of protection for all the citizens.

1.2.2 Business continuity and Contingency plan

Business continuity management (BCM) can be defined as the ongoing process of ensuring the continual operation of critical business processes through the evaluation of risk and resilience, and the implementation of mitigation measures (Booty, 2009). This term is more used in business situation and inside the companies.

The term contingency plan (CP), more used in governmental and organizational institutions, defines the set of activities undertaken to ensure that proper and immediate follow up steps will be taken in an emergency. Its major objectives are: ensure containment of damage or injury and provide the continuity of key operations.

Figure 1.8 shows a possible business continuity lifecycle, but many other frameworks could be followed (Gibb and Buchanan, 2006).

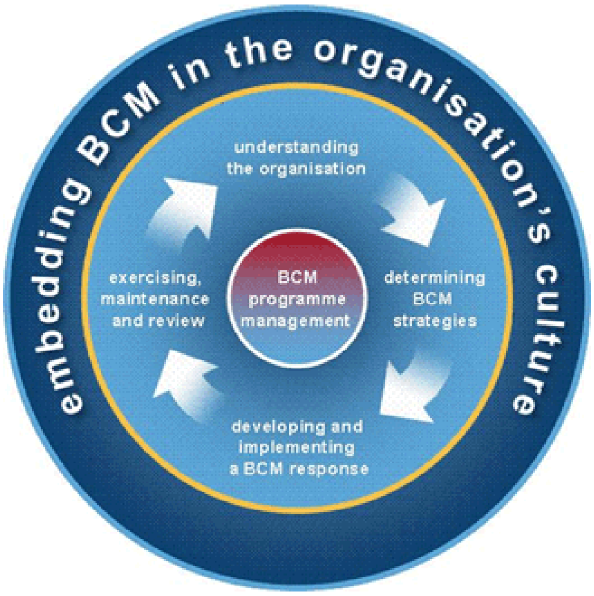


Figure 1.8 Business continuity management lifecycle (source: SafetyNet 247)

Many countries have a business continuity plan for hazardous events, in which the disruption of critical infrastructures occur (Woodman, 2007). In a BCM plan, in order to restore the normal activity of what was affected by the disaster, the recovery of CIs is really fundamental.

1.2.3 Recovery

The main difference between business continuity (BC) and disaster recovery (DR) is that the first one is proactive and its focus is to avoid or mitigate the impact of a hazard or a threat, while DR is reactive and its focus is to pick up the pieces and restore the organization to business as usual after a risk occurs. Disaster recovery is an integral part of a business continuity plan.

Disaster recovery is the process used by the organizations to recover access to critical infrastructures that are needed to resume the standard performance levels of critical business functions, after the event of either a natural or a man-made disaster. While Disaster Recovery Plan (DRP) is a system for internal control and security that focuses on quick restoration of service for critical organizational processes, when there are operational failures due to natural or man-made disasters. A DRP aims to minimize potential losses by identifying, prioritizing and safeguarding those organizational assets that are most valuable and that need the most protection (Bryson et al., 2002). A DRP should have the properties of feasibility, completeness, consistency, and reliability.

The first priority in disaster situations must be human survival and rescue, and the key element for a successful planning is awareness. Awareness of what can happen (Levitt, 1997). Being the human survival the main objective of disaster response, the timing of the response is the most critical thing in a plan. Martí et al. (2008) proposed a time-domain infrastructures interdependencies simulator that aims at providing a system solution framework to the combined working of multiple infrastructures.

Many countries have themselves introduced a Disaster Recovery Plan to cope with the problem of reducing the time of inoperability of critical infrastructures and try to protect the population during crisis (Office of Homeland Security, 2002; Le Livre Blanc, 2008).

It is possible to say that the process of creating a DRP is simply the result of determining the organization’s goals and objectives for the business continuation of CIs.

1.3 Critical Infrastructure Protection policy framework

Dealing with the development of a policy framework for Critical Infrastructure Protection it is important to take into consideration two aspects: the approaches to the problem assumed by the governments and the authorities, in particular when the criteria for the definition and identification of CIs is concerned, and the identification of the instruments and the approaches that they use to plan the protection of these infrastructures.

1.3.1 European regulatory context

Almost each single country has its own vision on what a “critical” infrastructure is, that is why many definitions of this term exist. The European Union (EU) through the Council Directive 114/08 provides a uniform definition for all the Member States and tries also to explain which are the CIs to be firstly considered in an internal protection plan.

“Critical infrastructures, for the last European Directive, are those assets, systems or parts thereof located in the EU Member States which are 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 in a Member State as a result of the failure to maintain those functions.” (Council Directive, 2008)

In Table 1.2 all the CI sectors for the European countries as written in the Council Directive of 2008 are listed, while in Table 1.3 it is possible to see which are the critical infrastructures and key resources (CIKR) for the U.S.. These two tables let us make a comparison between the different approaches between Europe and U.S.A. in terms of what they really consider critical or not (Carbonelli, 2008).

Sector	Subsector	
I Energy	1. Electricity	Infrastructures and facilities for generation and transmission of electricity in respect of supply electricity
	2. Oil	Oil production, refining, treatment, storage and transmission by pipelines
	3. Gas	Gas production, refining, treatment, storage and transmission by pipelines LNG terminals
II Transport	4. Road transport	
	5. Rail transport	
	6. Air transport	
	7. Inland waterways transport	
	8. Ocean and short-sea shipping and ports	

Table 1.2 List of critical infrastructure sectors from the European Council Directive of the 8th December 2008 (Council Directive, 2008)

Critical infrastructure and key resource sector
Agriculture and Food
Defense Industrial Base
Energy[d]
Healthcare and Public Health
National Monuments and Icons
Banking and Finance
Water[e]
Commercial Facilities Critical Manufacturing Emergency Services Nuclear Reactors, Materials, and Waste Dams and Chemical Sectors
Information Technology Communications Sectors
Postal and Shipping
Transportation Systems[g]
Government Facilities[i]

Table 1.3 List of critical infrastructures and key resources from the U.S. Office of Homeland Security (U.S. Office of Homeland Security, 2002)

Indeed, it is evident that a different approach between Europe and U.S.A. has been followed in order to classify critical sectors. For the EU there are just two critical sectors: energy and transportation, each one divided in other subsectors, while for the U.S. there are 18 sectors. The main difference is that the U.S. ones consider also the key resource sectors, while for the E.U. these key assets depend directly from the energy and transportation infrastructures.

The key assets (or key resources) can be defined as: “Individual targets whose destruction would not endanger vital systems, but could create local disaster or profoundly damage our Nation’s morale or confidence. Key assets include symbols or historical attractions, such as prominent national, state, or local monuments and icons. In some cases, these include quasi-public symbols that are identified strongly with the United States as a Nation (...). Key assets also include individual or localized facilities that deserve special protection because of their destructive potential or their value to the local community” (Office of Homeland Security, 2002). The three main categories of what can be considered a key resource are:

- national monuments, symbols and icons;
- facilities and structures that represent the national economic power and technological advancement;
- commercial centers, office buildings, and sports stadiums, where large numbers of people regularly congregate to conduct business or personal transactions, shop, or enjoy a recreational pastime.

After having understood and classified which are the CIs, each country has the duty of trying to protect them, in order to guarantee a reasonable societal safety (Olsen et al., 2007).

The Green Paper, introduced in 2005 by the Commission, suggests an ambitious goal for the European Programme for Critical Infrastructure Protection (EPCIP): to ensure adequate levels of protection and rapid recovery arrangements within the Union (Fritzon et al., 2007). The Green Paper adopts the principle of subsidiarity, whereby Member States remain responsible for national CIP under a common framework.

As reported by the Federal Office for Information Security (2004) there are two universal statements that can be made regarding the protection of critical infrastructures: it is not possible to achieve 100% security of CIs in any country and there is not a single way to counter the problem.

A good protection strategy, always proposed by the Federal Office for Information Security (2005a), can be summarized as follow:

- taking preventive measures at all levels
- improving capacities for early detection and rapid reaction
- limiting the effects of disruptions
- ensuring that the affected systems continue to function at a minimum level or can be restored within the shortest possible time

Although every country adopted heterogeneous approaches, it is possible to identify three main categories of Critical Infrastructure Protection (CIP) (Federal Office for Information Security, 2004). First of these is the Critical Information Infrastructure Protection (CIIP) approach, which refers to the security and protection of Information Technology (IT) connections and solutions within and between the individual infrastructure sectors (Presidenza del Consiglio dei Ministri, 2010). The second approach, called All Hazard approach, entails both the protection of critical IT infrastructures and the physical protection of CIs (Commonwealth of Virginia, 2008). The third one is a special case, only used in China, in which there is no cooperation between public and private sectors, this approach is more useful to preserve the system of government than to protect national CIs.

An essential term in dealing with CIP is the “criticality” concept, which describes the importance of an infrastructure/service with respect to the potential consequences that a disruption or a destruction of this infrastructure/service could have on: the population, the economy, the society and the environment.

There are three main factors that drive the identification of a critical infrastructure and its degree of criticality (Commission of the European Communities, 2004):

- Scope. The loss of a critical infrastructure element is rated by the extent of the geographic area which could be affected by its loss or unavailability (international, national, provincial/territorial or local);
- Magnitude. The degree of the impact or loss can be assessed as None, Minimal, Moderate or Major. Among the criteria which could be used to assess potential magnitude are:
  - Public impact (amount of population affected, loss of life, medical illness, serious injury, evacuation)
  - Economic impact (GDP effect, significance of economic loss and/or degradation of products or services)
  - Environmental impact (on the public and surrounding location)
  - Interdependency (between other critical infrastructure elements)
  - Political impact (confidence in the ability of government)
- Effects of time. This criteria ascertains at what point the loss of an element could have a serious impact (i.e. immediate, 24-48 hours, one week, other).

Reinermann and Weber (2003) consider that through the combination of effects and failure probability it is possible to derive the criticality of a process, or of a single infrastructure failure. To make this classification it is used the Risk Assessment Matrix (Figure 1.9 – T=tolerable, L=low, M=medium, l=low, T=tolerable), with Military Standard (MIL-STD) 882. However it should be noticed that in the most common risk theory the criticality index usually accounts only for the magnitude of consequences and the vulnerability of the target.

Likelihood \ Consequences	Insignificant	Minor	Moderate	Major	Catastrophic
Almost Certain	M	H	H	E	E
Likely	L	M	H	H	E
Possible	L	L	M	H	H
Unlikely	T	L	L	M	H
Rare	T	T	L	L	M

Figure 1.9 Matrix to assess criticality in infrastructures and process (Alvarez et al., 2010)

Assuming these criteria it comes that something that is critical for a nation might be noncritical for another one and vice versa; even in the same country from region to region or from city to city it is possible to have different level of criticality for the same infrastructure. In particular, cities are more prone to face disasters events, not only due to the higher concentration of people in areas exposed to several hazards, but also due to the increasing vulnerability of modern society (Lewis and Mioch, 2005).

1.3.2 Critical infrastructure interdependencies

In order to guarantee a good CIP one of the major issues is how to manage the interdependencies between the infrastructures. The modern socio-technological panorama is characterized by a progressive organizational and functional integration of all the different infrastructures. This evolution involves many economical and organizational advantages, but also an increased level of criticality of each infrastructure. Actually these systems, that are more and more interconnected and interdependent, could present malfunctioning or inefficiency due to uncontrollable or unexpected cascading phenomena.

Rinaldi et al. (2001) suggest six dimensions, reported in Figure 1.10, for identifying, understanding and modeling interdependencies between infrastructures.

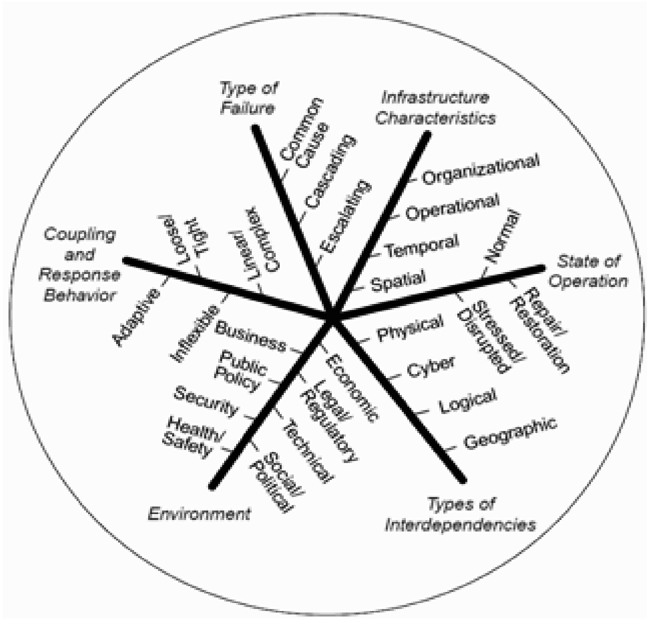


Figure 1.10 Dimensions for describing infrastructure interdependencies (Rinaldi et al., 2001)

These dimensions are classified as follow:

- *Types of interdependencies*. It's possible to divide the interdependencies in four principal classes that are not mutually exclusive.
  - Physical interdependency: two infrastructures are interdependent because of the exchange of material or energy;
  - geographical interdependency: two infrastructures are interdependent because of geographical proximity that bring to a greater vulnerability to disruption by the same, or successive, regional event (Parfomak, 2008);
  - cyber-interdependency: two infrastructures are interdependent because they exchange information;
  - logical interdependency: two infrastructures are logical interdependent if the state of each infrastructure is not a physical, cyber, or geographical connection and human decisions may play a predominant role on them.

- *Infrastructure environment*. The infrastructure environment is the framework in which the owners and operators establish goals and objectives, construct value systems for defining and viewing their business, model and analyze their operations and make decisions that affect infrastructure architectures and operations.
    - Economic
    - Business
    - Public policy
    - Legal and regulatory
    - Technical
    - Security
    - Social/political
    - Health/safety

- *Coupling and response behavior*. This “dimension” examines the characteristics of the couplings among infrastructures and their effects on infrastructure responses to perturbations.
    - Degree of coupling: it can be, taking this classification from Perrow (1984), tight or loose. Tight coupling refers to agents or infrastructures that are highly dependent on one another;
    - type of interaction: we can classify it in linear or complex (Perrow, 1984). Linear interactions are those intended by design, with few unintended or unfamiliar feedback loops, while complex interactions exist when agents can interact with other agents outside the normal production or operational sequence;
    - response behavior: an infrastructure when stressed or perturbed can be adaptive or inflexible. A collection of flexible agents is more likely to respond well to the disturbances and continue to provide essential goods and services than is an inflexible, rigid system that is incapable of learning from past experiences.

- *Infrastructure characteristics*. Infrastructures have many key characteristics that figure in interdependency analysis but Rinaldi frames just several important aspect that warrant consideration in models, simulations and analysis.
    - Organizational;
    - operational: how the infrastructure reacts when stressed or perturbed;

  - temporal: infrastructure time constants, time scales of interest;
  - spatial: components (part, unit, subsystem, system, infrastructure, interdependent infrastructures), geographic scale (cities, regions, national, international).

- *Types of failures*. Interdependencies increase the risk of failure or disruption in multiple infrastructures and we can classify these disruptions or outages as:
  - cascading failure: a disruption in one infrastructure causes a disruption in a second infrastructure;
  - escalating failure: a disruption in one infrastructure exacerbates an independent disruption of a second infrastructure;
  - common cause failure: a disruption of two or more infrastructures at the same time because of a common cause.

- *State of operation*. In order to understand and analyze infrastructure interdependencies, it's necessary to determine, for each infrastructure, which other infrastructures it depends on continuously or nearly continuously for normal operations, which ones it depends on during times of high stress or disruption, and which it depends on to restore service following the failure of a component or components that disrupt the infrastructure.
  - Normal
  - Stressed / disrupted
  - Repair / restoration

To have an idea of how much complicated could be a thorough analysis of all these interdependencies, a possible framework, utilized by Rinaldi et al. (2001) in their article is reported in Figure 1.11. In the round shapes the authors put different critical infrastructures (oil, transportation, water, electric power, natural gas, and telecommunications) and then they link with some arrows these concepts, underlying and describing which are the most important dependencies between these CIs.

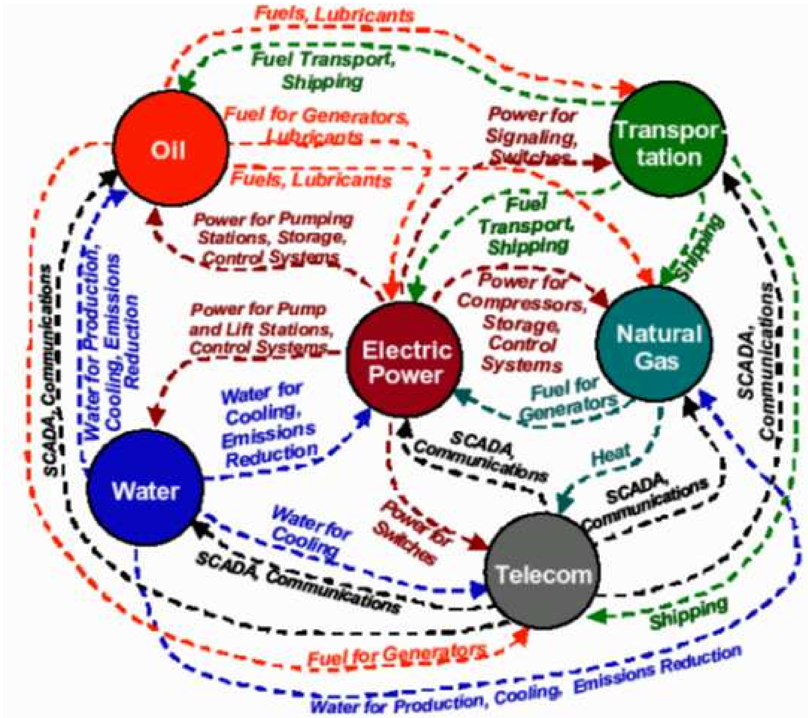


Figure 1.11 Example of infrastructure interdependencies (Rinaldi et al., 2001)

1.3.3 Approaches to CIP

In order to provide an efficient critical infrastructure protection, a methodology is required and each country developed it individually. The CIP and CIIP analysis methodologies used by eight different countries are analyzed by Wenger et al. (2002) in their handbook.

The Netherlands is probably the European countries most involved in the development of a methodology for national infrastructure protection, (Luiijf et al., 2003a; Luiijf et al., 2003b). A methodology for the planning of CIP is the first step that will bring to a complete risk analysis of the entire sector. The study starts with the aim to obtain answers to a series of questions (Luiijf, 2003a):

- what are the sectors, products and services comprising the nations' critical infrastructure of government and industry?
- what are the underlying processes?
- what are the (inter)dependencies?

Quick-scan questionnaires were developed and a systematic review of the direct and indirect vitality of critical products and services was generated, using a top-down approach through some dedicated workshops (Luiijf, 2003b). The aim of this job is to identify the chains of essential processes supporting the delivery of the vital products and services of the nation. The next steps are a threat and vulnerability analysis and a gap analysis of the protection measure, in this way a complete approach to the CIP would be completed.

As far as the U.S.A. strategy to CIP is concerned, the Department of Homeland Security wrote a National Infrastructure Protection Plan (NIPP) (2009) in which the American approach to the problem of the definition of a methodology for the CIP is explained; the document also proposes a NIPP risk management framework that cover every step of the process, from the planning to the risk assessment.

The approach followed by the European Union is different; it gives guided lines to each country, which has the objective of create its own CIP plan. In the EU Council Directive 114/08 is stated that common methodologies may be developed for the identification and classification of risks, threats and vulnerabilities to infrastructure assets. And the cross-cutting criteria that shall be followed are:

- casualties criterion
- economic effect criterion
- public effect criterion

Some studies (Lieb-Dòczy et al., 2003) underline also the problem of the identification of a theoretical optimum of security level for a critical infrastructure; this analysis should be done before selecting the methodological approach. There is a sort of range of consumer willingness to pay for security (Figure 1.12), the "zone of adequacy" is the zone within which security will be adequate and where costs will not rise excessively.

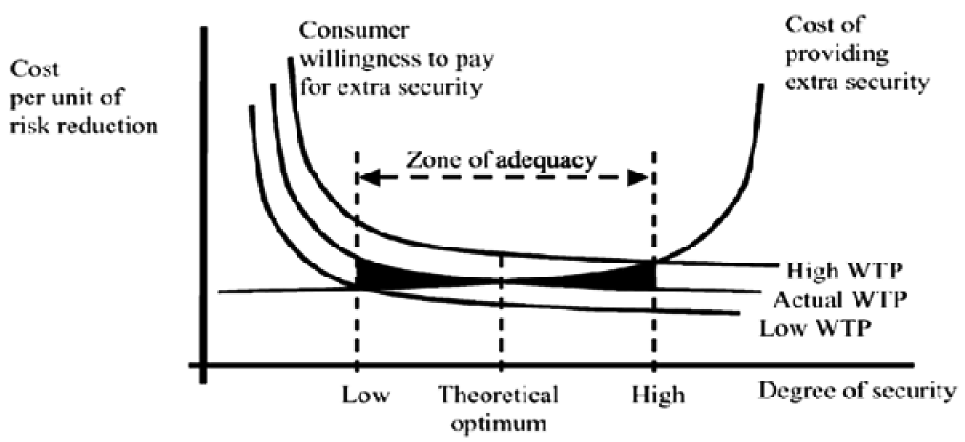


Figure 1.12 Theoretical optimum on the basis of the costs and benefits of security (Lieb-Dòczy et al., 2003)

1.4 Risk, Vulnerability and Criticality Analysis

A fundamental part of critical infrastructures and key resources protection is risk management. Many different risk management frameworks have been proposed in past years, but one of the most complete and accurate is the National Infrastructure Protection Plan (NIPP) Risk Management Framework, adopted by the Department of Homeland Security (2009) and reported in Figure 1.13.

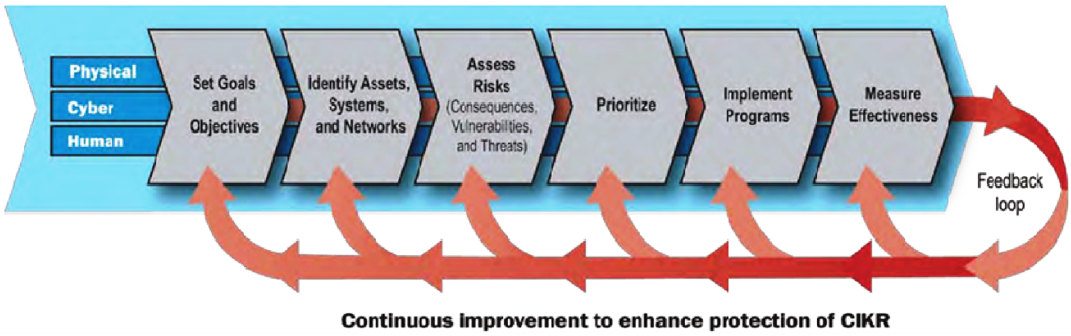


Figure 1.13 NIPP Risk Management Framework

Each step of the framework is important for the achievement of the goals of the plan, but the most relevant ones are definitely the assessment and prioritization of risks. That is why an overview of models and methodologies for risk, vulnerability and criticality analyses are discussed in the following.

Risks (or criticality) analysis focuses on the severity of consequences within the context of a scenario with an expected likelihood of occurrence, whereas vulnerability analysis highlights the notion of susceptibility to a scenario. That is why vulnerability assessments are not the same as risk assessments (Ezell, 2007). Regarding prioritization, these approaches identify which CIKR should be given priority for risk reduction, analyzing the criticality of the infrastructures. These processes are strictly correlated and an analysis of the literature about these topics gives a complete view of which is the core of risk management.

1.4.1 Overview of Models and Methodologies

Risk assessment process is related with a triplet of questions posed by Kaplan and Garrick (1981):

1. *What can go wrong?*
2. *What is the likelihood that it would be wrong?*
3. *What are the consequences?*

There are many different methods to conduct a risk analysis, traditionally the assessment of risks have been deterministic and "conservative" (Lester et al., 2007). In Lester et al. (2007) a series of studies related to Probabilistic Risk Assessment (PRA) are illustrated. PRA is a tool for the quantitative estimation of risks and associated uncertainties.

A standard risk assessment methodology is Hazard United States (HAZUS) developed by the Federal Emergency Management Agency (FEMA) (1997); it is a simple instrument used to assess risks and potential losses due to hazards and multiple hazards. There is also a European multi-hazard risk assessment project that is called TEMRAP (Serafini, 2000) and has the aim of develop an integrated methodology on multi-hazard and global risk assessment, on the basis of different experiences carried out in several European countries on natural disasters. Alp et al. (2004) developed a risk assessment procedure for municipalities and industries in order to provide guidance in land-use planning and siting decisions.

Starting from these "standard" risk assessment methodologies new approaches have been developed, like the three-dimensional risk assessment approach for both individual and group risk (Suddle et al., 2005), that help in quantifying the risks of buildings over critical infrastructures.

The *vulnerability assessment* can be considered a stand-alone process or part of a full risk assessment. The term vulnerability can be divided into two different dimensions: social vulnerability and systems vulnerability.

Social vulnerability refers to the inability of people, societies and the economy to withstand adverse impacts from disasters or deviations to which they are exposed. It is a pre-existing condition that affects a society's ability to recover and to be prepared to a disruptive event.

System vulnerability differently defines the susceptibility of a critical infrastructure to a natural or human threat.

The Community Vulnerability Assessment Tool (CVAT) is a risk and vulnerability assessment methodology designed to provide a comprehensive and systematic framework to identify and prioritize hazards and to assess vulnerabilities of critical facilities, economy, societal elements and environment (Flax et al., 2002). Vulnerability is a condition of the system and it can be quantified using also the Infrastructure Vulnerability Assessment Model (I-VAM) developed by Ezell (2007). Nordvik et al. (2010) in their work for the European Union, for which the objective is to create a methodology to assess the consequences of infrastructure failure, developed also a vulnerability model.

Both risk and vulnerability analyses have to take into consideration the interdependencies that CIs present. Ouyang et al. (2009) made a methodological approach to analyze vulnerability of interdependent infrastructures, in which they studied two types of vulnerabilities: structural and functional vulnerability.

The *criticality analysis* deals with the prioritization of vulnerabilities in critical infrastructures and key resources. The key question for this analysis is:

"What happens if one component in the process breaks down and what is the probability of this occurring?"

Criticality analysis is a tool that examines potential product/service features against a list of critical factors, evaluates feature priorities, and helps determine what organization or internal function is responsible for the critical factors. It is mainly a quality planning tool (Concordia University, 1997).

One of the most relevant works on this topic is the article of Apostolakis and Lemon (2005) in which they apply a screening methodology for the identification and ranking of infrastructure vulnerabilities due to terrorism to the campus of Massachusetts Institute of Technology (MIT).

The criticality of a process is derived from the combination of effects and failure probability using the MIL-STD-882, like showed in Figure 2.4 (Federal Office for Information Security, 2005b), or with the introduction of other standards.

The study of risk, vulnerability and criticality analysis need a complete understanding of which are the interdependencies between the CIKR, because without a precise knowledge of these interdependencies all the risk management process would be inaccurate. So the risk, vulnerability and criticality analyses have to take into consideration the results obtained by models and simulations for CI interdependencies.

1.5 Conclusions and work objectives

The issue of critical infrastructure protection is widely approached by the literature, in particular after 11th September 2001. The disruption or destruction of a critical infrastructure may have a direct impact on society (macro/micro), but it might also have an indirect impact on certain supply chains, which in turn has an impact on the society.

According to the European Directive EC/114/2008, in this work we will study the vulnerability of the Fast Moving Consumer Goods (FMCG) supply chain, which can have a huge impact on the society in case of severe disruptions. Through a criticality analysis of the nodes of this supply chain the impact due to a deviation on a critical infrastructure is going to be analyzed.

As mentioned before the prevention and mitigation is a very important part of the civil protection system in all nations, and this work deal with this matter, trying to better understand which are the relationships between CIs and the complex supply chain of FMCG, dealing with the Italian case study. This topic has never been discussed before in the literature and for this reason it is not easy to find out data and descriptions about CIs and FMCG supply chain interdependencies.

The objectives of this work are: the understanding of the functioning of the FMCG supply chain, according to the interdependencies with CIs and their possible failure, and the construction of a mathematical model to study cascading effects on the FMCG supply chain due to CI disruptions.

In particular the mathematical model is important in order to be able to describe and represent a real system, according to the variables that will be possible to define and quantify. In Figure 1.14: vector *x* represents the decision variables, *u* the input variables, α the exogenous variables, *r* the random variables, *s* the state variables and *y* the output ones.

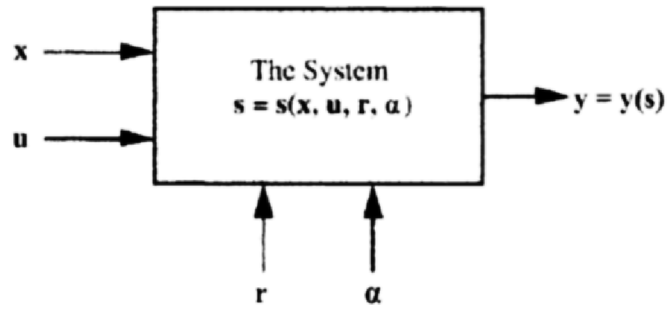


Figure 1.14 Example of a mathematical model built using a transfer function (Haimes, 2009)

In this work a suitable modeling technique is going to be selected and it will be used to develop a novel methodology for specific applications, like the one analyzed in the case study presented.

As said before one of the major barriers to a quantitative criticality analysis of the FMCG-CIs coupling is related to the limited availability of data from the operators in different domains. The methodology that will be developed in this work has to face these difficulties and has to find a modeling technique that is able to represent the impacts of a deviation or disruption in a CI on the FMCG supply chain.

The project has been carried out in collaboration with the Institute for the Protection and Security of the Citizen (IPSC), Joint Research Centre (JRC) of Ispra. One of the objectives of the JRC is to obtain a flexible model that can be used in future studies not only in the Italian case study, but also elsewhere in Europe.

2. Fast Moving Consumer Goods (FMCG) sector

The sector of FMCG, or grocery, comprehends a broad range of commercial products and a possible classification can be:

- Fresh food;
- No-Fresh food;
- Other (health & care products, flowers, …).

This classification it is important because each class of products has different properties and these properties are the basic points from which start the development of the model. The fresh food is perishable and it cannot remain at stock too much time, while the no-fresh food can be stored for longer periods. This means that if a problem in the supply chain occurs, for example due to a disruption event in a transportation infrastructure, different approaches have to be followed for the different categories of goods. Another key factor that has to be taken into consideration is that for each different type of class, the means of transport can change and this is relevant for the analysis that will be done in this work. Also the way in which they are kept on stock is different and if a blackout happens the results of this event can change according to the kind of goods considered. In particular the case study analyzed deal only with perishable goods.

The proposed classification is surely a simplification of the highly fragmented grocery world, but it has been chosen in order to simplify the analysis while making it as much realistic as possible, according to the few data available.

The FMCG industry is extremely competitive and it represents in Italy one of the most important sectors regarding its economic impact on the national gross domestic product (GDP), 1,4% of the Italian GDP in 2009 (source: Federdistribuzione). This sector is also called “mass retail” and it is a market where there is an organized methodology for the sale of goods. A group of firms, in order to gain profits, sell products that they bought from the producer or the wholesaler into the retail market.

Considering the sales, the most important companies in the fast moving consumer goods sector in Italy are represented in the graph in Figure 2.1.

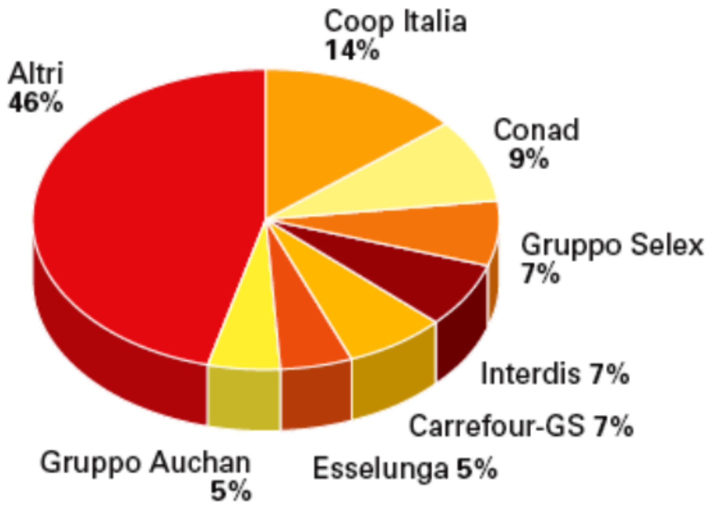


Figure 2.1 Most important companies in the FMCG sector in Italy considering the sales of 2005 (Dallari and Melacini, 2007)

In this chapter the supply chain of this complex sector it is introduced and a classification by families of goods it is also made, since they are particularly useful for the subsequent development of the model. The distinction between group purchasing organizations and distribution centers it is also discussed.

The influence of CIs on this sector is very important in order to guarantee the right functioning of the entire supply chain, but before trying to understand where are the interdependencies between CIs and FMCG supply chain it is important to focus the attention on the entire sector.

2.1 FMCG supply chain

Differences between FMCG classes are not so pronounced to require different models for analyzing specific vulnerability of the supply chain. However, these distinctions will be useful during the construction of the model to better understand the relationships between the different actors in the different class of goods.

In the fresh food supply chain the majority of the goods pass directly from the supplier to the wholesaler, without the intervention of a producer, with the objective of make the goods flow straightforward and faster. The intervention of the producer is necessary only for some kind of fresh goods, like meat. In Figure 2.2 is reported the scheme of the fresh food supply chain, in which the broken line means that the flows of goods in those directions is not so common.

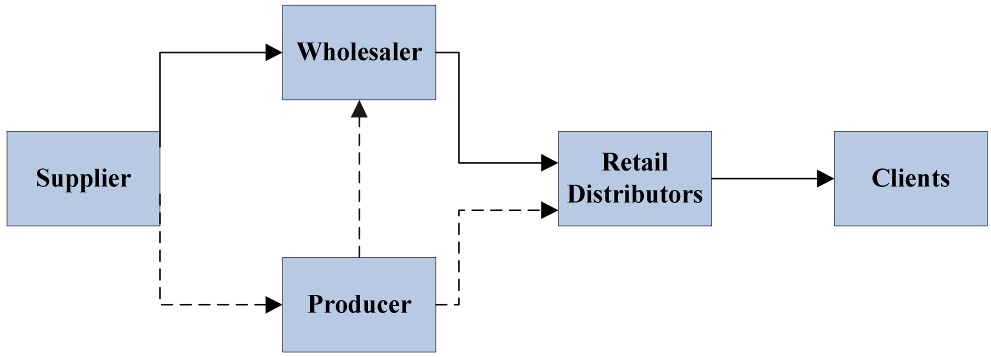


Figure 2.2 Fresh food supply chain

The primary actor of the supply chain of no-fresh food is the producer (big or small producer depending to the sales), while the wholesaler sometimes does not enter in the flow of material, because the producer send the goods directly to the retailers (Figure 2.3).

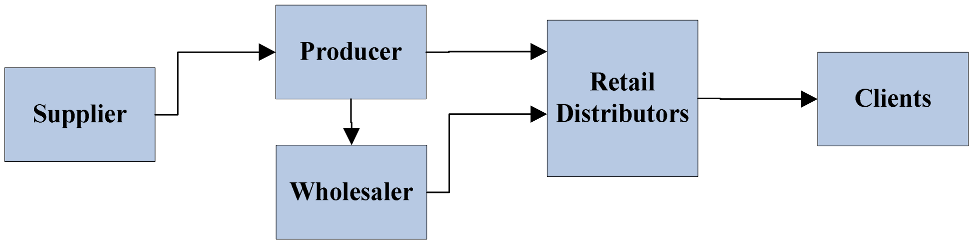


Figure 2.3 No-fresh food supply chain

For the other products the supply chain and the process followed by the goods are similar to the no-fresh food, and also the scheme is similar (Figure 2.4), but in this case the wholesaler is not present anymore in the supply chain.

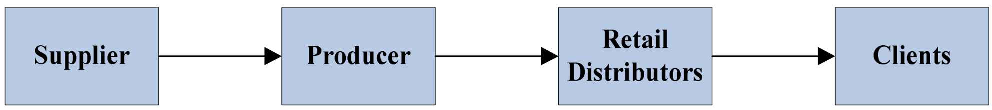


Figure 2.4 Other grocery products supply chain

Without considering the classification of goods is possible to make a FMCG supply chain scheme like the one in Figure 2.5 that can be considered the global supply chain regarding the grocery sector.

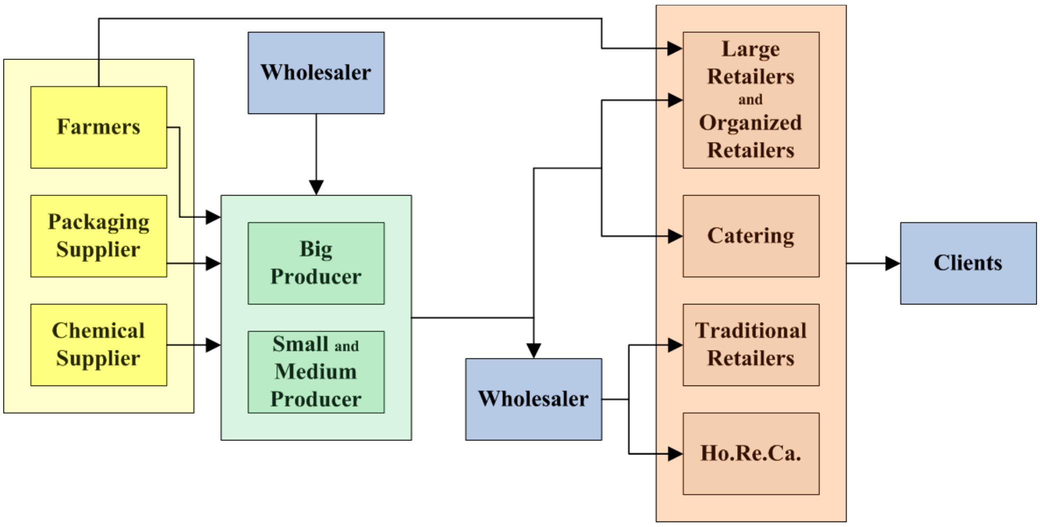


Figure 2.5 General Fast Moving Consumer Goods supply chain (Rangone et al., 2005)

In order to have a better comprehension of the FMCG supply chain is good to have a brief introduction of all its actors. In particular, in the next paragraphs the roles, objectives and activities of suppliers, producers, wholesaler and retail distributors are presented.

2.1.1 Suppliers

Suppliers are the first stage of the FMCG supply chain and they can be divided in two macro-categories (Rangone et al., 2005):

- Raw material suppliers, that for their complexity can be divided again in other two sectors: the farmers, that provide exclusively food and the chemical industry suppliers, that serve the food categories and also health and care and other class of products;
- Packaging suppliers that during the years earn more and more importance in the grocery sector, due to the fact that packaging is fundamental in order to guarantee the integrity and freshness of the food.

In this work the suppliers are not considered for the study of the interdependencies between critical infrastructures and the FMCG supply chain.

2.1.2 Producers

The producers in the FMCG sector can be classified considering both the firm dimensions and the typology of products (Rangone et al., 2005).

Talking about firm dimensions is possible to distinguish producers in:

- Big producers; belong to this category all the companies, in particular multinational, with a turnover higher than 500 million of Euro, generating the 30% of the invoice of whole producers;
- Small and medium producers; at this category belong the majority of the companies, in particular for the food, and they generate the 70% of the invoice of food producers.

While if a typology product division is made:

- Food producers. In Italy this category is really important and it represent one of the principal manufacturing division;
- Health & Care producers.

2.1.3 Wholesalers

The wholesaler trades have the function of create a connection between producers and retailers, in particular the small ones. A wholesaler has two possible functions, the first one is to stock material and in a second moment sell these products to the retail distributors.

The second function can be the food-processing, in particular for the fresh food (fruits, vegetables and fish for example); in this case the world of producers is not involved.

In the last years, in particular in the large and organized retail sector, the wholesalers become secondary actors in the supply chain, because the retailers want to reduce the costs and also the risk in the supply chain.

2.1.4 Retail distributors

The principal operators in the FMCG sector in Italy are:

- “Mass Organized Retailers” (MOR) or “Large organized Retailers” (LOR). In this class it is possible to find large retailers, that have a central structure and they have a direct control on the distribution centers and the sales network. Some example can be: GS, Esselunga, Metro, Auchan. In this class there are also the organized retailers formed by consortium, voluntary union and group purchasing organizations.

- Traditional retailers. These independent operators are sometimes called “small commerce”; these retailers are different from large organized retailers not only for the firm dimensions, but in particular because all the supplying is made with the mediation of the wholesalers;

- Hotel, Restaurant and Catering (Ho.Re.Ca).

2.2 Group Purchasing Organizations and Distribution Centers

A Group Purchasing Organization (GPO) is an entity that is created to leverage the purchasing power of a group of businesses, in this case in the sector of FMCG, to obtain discounts from supplier and producer based on the collective buying power of the GPO members.

The large organized retailers utilize these GPO in order to buy the products. In this work they are not considered because they never exchange goods or data, and so they never figure out in the supply chain flow in spite of their importance for the FMCG sector’s economy.

In Italy the most important group purchasing organizations and their LOR are resumed in Table 2.1, while in Figure 2.6 the market share of each GPO is summarized, this make simpler to understand which are the preferred channels for the grocery sector.

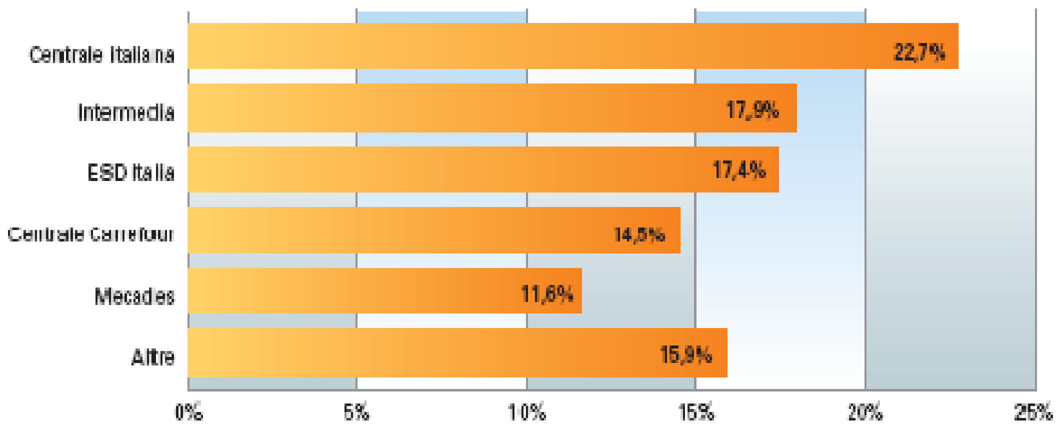


Figure 2.6 Market share of the group purchasing organizations in Italy (Federdistribuzione, 2006)

Centrale/Aziende	Iper	Supermercati	Superette	Discount	Tradizionali
Centrale Italiana:					
Coop Italia	Ipercoop	Coop	Coop, Minicoop, Incoop	Dico, Dicoop	–
Sigma	-	Sigma	OK Sigma	D.AI.	Negozio Italia
Gruppo Il Gigante	Il Gigante	Il Gigante/	–	–	-
Despar	Interspar	Despar, Eurospar	Despar	–	Despar
Gruppo Rewe-Italia					
Billa	IperStanda	Billa, Standa	–	Penny Market	–
Conad:	E. Leclerc Conad	Conad, Cross, Superstore Conad, Conad City	Margherita	Todis	–
Consorzio C3	-	Lando Supermercati, Supermercato Tosano, Vivo	–	–	–
Coralis	–	Bontò, Ecco, Verdeblu	–	–	–
Esd Italia:					
Agorà Network	Iperal, Sermark	Iperal, Basko, Poli, Tigros, etc.	DoroCentry, Gran Di, Tigros, etc.	Ekom –	
Gruppo Sogegross	Iperfresco Basko	Iperfresco Basko, Super Basko	DoroCentry, Basko –	Ekom	
Gruppo Selex	Iper Famila Galassia Famila/ Aliper/Iper Dolomiti/Iper Zerbimark/Iper Pan/Mega	Super A&O, Uni, Alì, Supermercati/Dok Supermercati/Marpiù Supermercati/Super Pan/Alì A&O	–	HarDis, Su discount, Dimeno, MD discount, Dipiù	–
Esselunga	–	Esselunga Supermarket, Superstore	Sottocasa	—	–
Eurospin Italia	–	–	-	Eurospin	–
Centrale Carrefour					
Carrefour-GS	Carrefour/Continente	Supermercati GS	Diperdì	–	Diperdì
Finiper	Iper	Unes	Tuttok/U!, Savoini	U2	–
Intermedia:					
Auchan	Auchan, Cityper	Sma	Punto Sma	Simply	–
Gruppo Pam	Panorama	Pam, Superal	Metà, Pam Club, Ildi	In's	–
Gruppo Lombardini	Pellicano, Continente	Comprabene	Comprabene	LD Market	–
Gruppo Bennet	Bennet	–	–	-	–
Consorzio Sun	n.d.	n.d.	n.d.	n.d.	n.d.
Gabrielli	Oasi	Maxi Tigre, Tigre	Tigre	Dis	–
Lidl	–	–	–	Lidl	–
Mecades					
Interdis	Ipersidis, Iperdì, IperAlvi, IperDugan, altre varie	Supermercati Brianzoli, Super M, Sidis, Maxi Sidis, Di meglio	Sidis, Tuttodì, Scudo, Puntomarket, Alvi, altre varie	Sosty	
Sisa	Sisa Superstore	Sisa	Issimo	–	–
Crai	IperCrai, Ipermirabella	Crai, Paper Supermercato, Supercrai	Super Crai, Simpatia Crai	Europa Europa	–

Table 2.1 Group purchasing organizations and their large organized retailers (Dallari and Melacini, 2007)

Distribution Centers (DC) are network storages of the retailers, built not too far from the sale points in order to maintain a stock of products for a certain period of time. The function of the DC is to receive daily orders from the retailers and deliver them to the group purchasing organization that will buy the products required directly from the suppliers or the producer.

The characteristics of the distribution centers are really important for this work, because their position and their stock capability can change the type of interaction between the global FMCG supply chain and the different critical infrastructures. In Table 2.2 are reported the most important DC in the Milan Logistic Region (MLR) (Curi and Dallari, 2009), an area in Lombardia region, as example of the geographical distribution of these DC.

Firm	***Site***	***Prov.***	***mq***
Auchan (Italtrans)	Calcinate	BG	81000
Bennet	Origgio	VA	25000
Billa Standa	Lacchiarella	MI	36100
Billa Standa	Tribiano	MI	5000
Billa Standa	Casorate	PV	2000
Billa Standa	Suno	NO	10000
Carrefour (Kuehne Nagel)	Cameri	NO	90000
Conad (CCN)	Calcinate	BG	2150
Coop Lombardia	Pieve Emanuele	MI	39000
Coop Lombardia	Pieve Emanuele	MI	6260
Coop Lombardia	Casorate Primo	PV	22100
Coop Lombardia	Siziano	PV	3000
Coop Lombardia	Siziano	PV	10300
Coop Lombardia	Treviolo	BG	1946
Coop Lombardia	Galliate	NO	10100
Despar (Sadas SpA, Cecis Srl)	Seveso	MI	9926
Esselunga	Pioltello	MI	52000
Finiper	Soresina	CR	30000
Ikea	Piacenza	PC	216000
Il Gigante	Trezzo sull'Adda	MI	20000
Lombardini	Trezzo sull'Adda	MI	23000
Lombardini	Vignate	MI	30000
Lombardini	Capriate San Gervasio	BG	10000
Metro	Siziano	PV	15000
Metro	Settala	MI	20000
Metro (ND Logistics)	Trezzo sull'Adda	MI	65000
Penny Market Italia	Desenzano	BS	14000
Penny Market Italia	Arborio	VC	14000
SISA	Siziano	PV	17000
SMA	Segrate	MI	26000
Unes	Segrate	MI	24000

Table 2.2 Distribution Centers of the large organized retailers in the MLR

3. Modeling and simulation techniques for CI Interdependency Analysis - State of the art -

This chapter analyzes the literature about modeling and simulation, regarding two main subjects: risk, vulnerability and criticality analysis and the interdependencies between the different critical infrastructures.

This overview of models is important to understand which is the correct way to analyze the subject of this work, trying to find an existent approach useful to model the interdependencies between critical infrastructures, as transportation, electricity and gas, and the supply chain of fast moving consumer goods. The first part of this state of the art analyzes the modeling techniques used to create models and methodologies for the study of critical infrastructure interdependencies (CII) and in the second part a description of some of the most used models is given.

The understanding of the interdependencies in critical infrastructures is relevant for their protection because they dramatically increase the overall complexity of the related system of systems (Rinaldi et al., 2001). There is a difference between the terms dependency and interdependency, the first one means a linkage or connection between two infrastructures, through which the state of one infrastructure influences or is correlated to the state of the other, while interdependency is a bidirectional relationship between two infrastructures (Rinaldi et al., 2001).

Presenting the outcomes of the analysis of a scientific approach dedicated to CII modeling and simulation (M&S), Griot (2010) proposed eleven criteria, partially used in the next paragraphs, to describe and analyze the approaches in a consistent and standardized manner:

1. Modeling focus and main objectives
    - Modeling focus
    - List and description of the objectives of the approach
2. Domain and scale of application
    - Sectors being considered
    - Type of threats
    - Granularity
3. Methodological design strategy
    - Bottom-up or top-down

4. Conceptual paradigms
    - CI handlings
    - CI characterization
    - Interdependency handling and characterization
    - Cascading effect handling
5. Mathematical features
    - Mathematical techniques
    - M&S approach properties
6. Requirements and resources
    - Data required by the model
    - Validation and verification
    - Expertise
7. Types of outputs
8. Advantages and limits
9. Tools
10. Interoperability
    - Type of framework
    - Models of interest
11. References
    - Bibliography
    - Expertise resources
    - Websites
    - Maturity

3.1 Modeling formalisms and techniques

A comparative evaluation of the most important modeling techniques to study interdependencies in critical infrastructures is presented in this part. Six of them are analyzed in more detail, while all the others are resumed in a table, that also presents an evaluation of these mathematical approaches using the criteria adopted by Eusgeld et al. (2008) in their article.

3.1.1 Agent-based model

Agent-based model (ABM) is a promising modeling and simulation technique used to study interdependencies in critical infrastructures and it consists of dynamically interacting rule-based agents.

Complex infrastructures systems are modeled as a population of interacting agents (Rinaldi, 2004). The “agent” is an autonomous software object implemented on a computer network; it is autonomous because its actions or behavior depend at least partially on its own experience (Barton and Stamber, 2000). An agent describes an entity characterized by three main things: a location identifying its physical space, which may also be abstract; its capabilities, to say what the agent is able to do; its history, consisting in past experiences of the entity such as overuse or aging (Eusgeld et al., 2008).

In order to implement this approach it is important to identify every portion of the critical infrastructure (nodes) with an agent, it has to communicate with all the other agents of the infrastructures, because the output of an agent is the input of another.

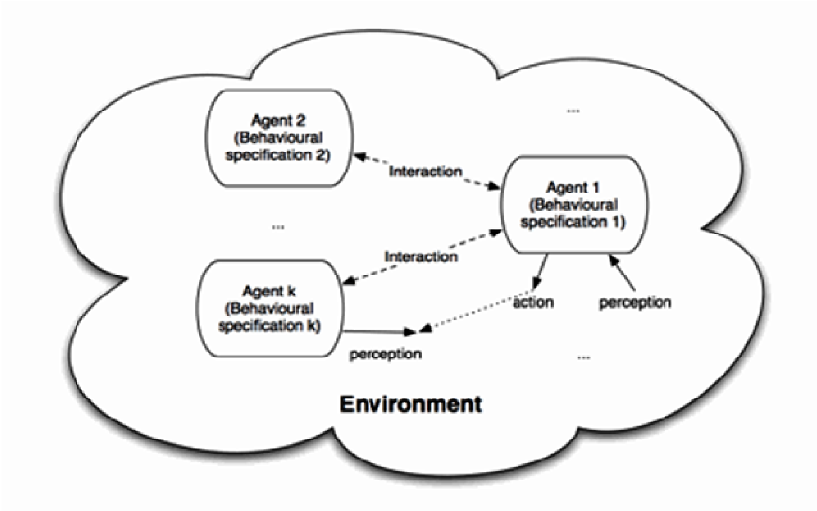


Figure 3.1 Agent-based modeling technique: a scheme of how it works

ABM uses a bottom-up approach to model the entire system, starting from its individual parts, this approach allow us to simulate complex systems composed by many subsystems (Casalicchio et al., 2007). The interactions among different infrastructures elements, in the study of their interdependencies, are modeled individually by intelligent software agents representative of real world decision-maker.

The ABM simulation is very time consuming and it requires a large number of data, not always readily available in practice, this is the biggest defect of this technique. While the major advantage of this approach for modeling and simulation of critical infrastructures interdependencies is the possibility to emulate an emergent behavior (Eusgeld, 2008).

In the literature is possible to find many applications of the ABM approach, like models of supply chains (Julka et al., 2002), communications network (Matsuyama and Terano, 2008), electric power (Chappin and Dijkema, 2007), banking (Robertson, 2002) and many others.

3.1.2 Fuzzy Logic and Fuzzy Cognitive Maps

Lotfi Zadeh (1965) is the first that published a description and analysis of Fuzzy Logic (FL). This is a true superset of Boolean Logic and provides a simple way to arrive at a definite conclusion based upon vague, ambiguous, imprecise, noisy, or missing input information.

Fuzzy logic starts with the concept of a fuzzy set. To understand what a fuzzy set is, first of all it is necessary to consider the definition of a classical set: a container that wholly includes or wholly excludes any given element.

A fuzzy set is a class of objects with a continuum of grades of membership. Let X be a space of points (objects), with a generic element of X denoted by x. Thus, X={x}. The fuzzy set A in X is characterized by a membership (characteristic) function $f_A(x)$ which associates with each point in X a real number in the interval [0 1], with the value of $f_A(x)$ representing the "grade of membership" of x in A. Thus, the nearer the value of $f_A(x)$ to unity, the higher the grade of membership of x in A (Zadeh, 1965). In the Figure 3.2 an example of membership function is represented, but it is possible to have different shapes according to what is going to be modeled.

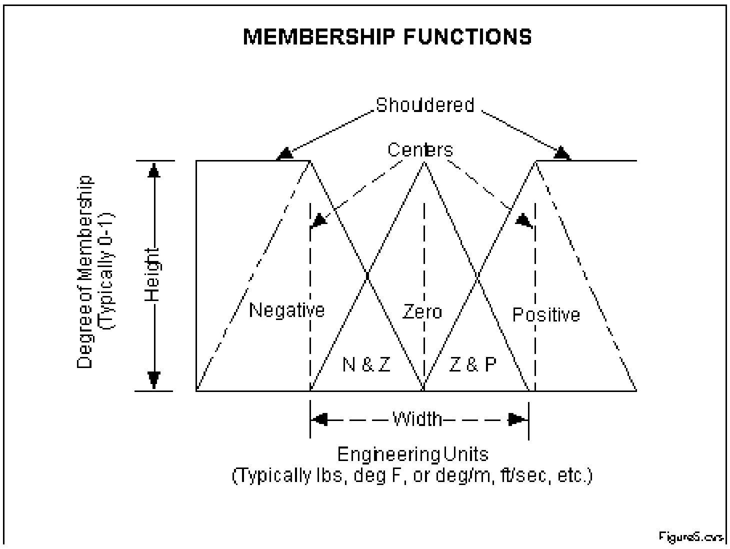


Figure 3.2 Example of a triangular membership function (Kaehler, 2000)

The rule-based structure of FL breaks the control problem down into a series of "*IF x AND y THEN z*" rules that define the desired system output response for given system input conditions.

In order to get the most representative value of all the ones inside the space (X), a process of defuzzification is done and one of the methods used to do this process is the center of gravity (COG) method or centroid method. Figure 3.3 shows the result of this method.

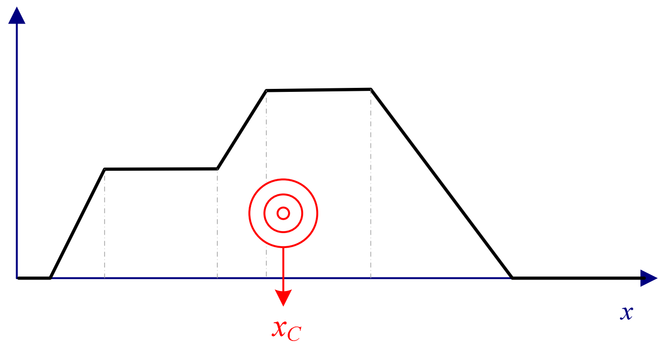


Figure 3.3 Application of the centroid method for the defuzzification

Using the mathematical language is possible to write this equation:

$$x_C = \frac{\int \mu(x)xdx}{\int \mu(x)dx} = \frac{\int \mu(x)xdx}{Area} \tag{3.1}$$

Kosko (1997) also developed a theorem called "Fuzzy Approximation Theorem" that explain how a fuzzy system can be used to approximate a function. He describes a class of additive fuzzy systems. An additive fuzzy system approximates a function by covering its graph with fuzzy patches; the approximation improves as the fuzzy patches grow in number, as it is possible to see in Figure 3.4. Each single fuzzy rule takes a portion of the curve, approximating its trend. Increasing the number of rules the level of approximation will increase, but also the computing time will increase, so a correct equilibrium has to be found.

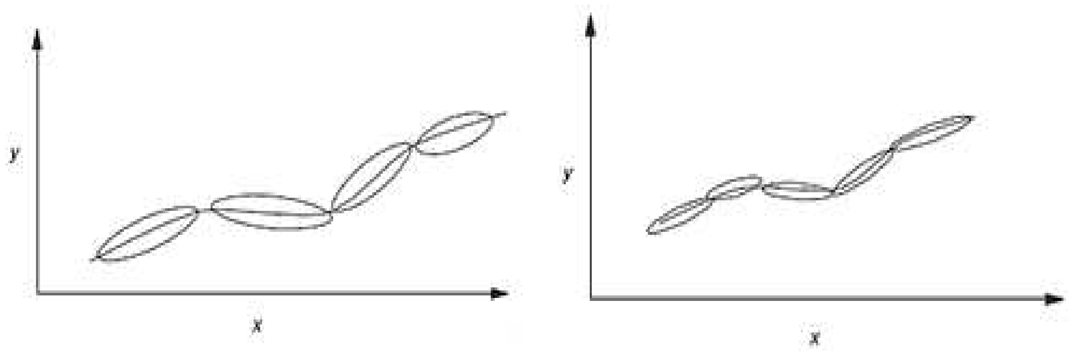


Figure 3.4 Fuzzy approximation theorem

Combining together fuzzy logic and neural networks, Kosko (1986) developed an hybrid tool: Fuzzy Cognitive Maps (FCMs). Kosko introduced this term to describe a cognitive map model with two significant characteristics:

- Causal relationships between nodes are fuzzified. Instead of only using signs to indicate positive or negative causality, a number is associated with the causal link to express the degree of relationship between two concepts.
- The system is dynamic, that is, it evolves with time. It involves feedback, where the effect of change in a concept node may affect other concept nodes, which in turn can affect the node initiating the change.

The interconnection strength between two nodes (concepts) C_i and C_j is W_{ij}, with W_{ij} that can take any value in the range that goes from -1 to +1 (Figure 3.5). Values –1 and +1 represent, respectively, full negative and full positive causality, zero denotes no causal effects, and all the other values correspond to different fuzzy levels of causal effects (Khan et al., 2000).

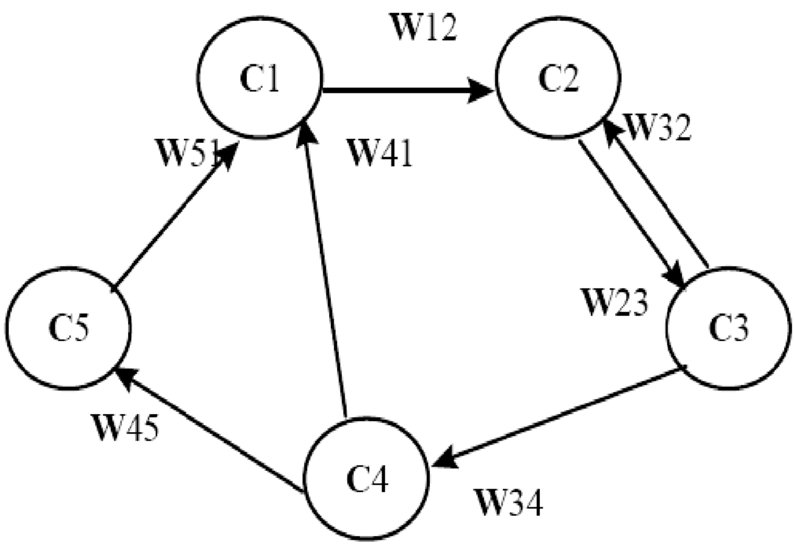


Figure 3.5 A simple Fuzzy Cognitive Map (Stylios et al., 1998)

The value of each concept is influenced by the values of the connected concepts with the appropriate weights and by its previous value.

So the value A_i for each concept C_i is calculated by the following rule:

$$A_i = f\left(\sum_{\substack{j=1 \\ j\neq i}}^{n} A_j W_{ij}\right) + A_i^{old} \tag{3.2}$$

where A_i is the activation level of concept C_i at time $t+1$, A_j is the activation level of concept C_j at time t, A_i^{old} is the activation level of concept C_i at time t, and W_{ij} is the weight of the interconnection between C_j and C_i , and f is a threshold function.

The function to calculate the threshold value could be a sigmoid function like the one represented by this function (Banerjee, 2009):

$$Y_j = \frac{1}{1 + e^{-\left(\sum_{i=1}^{n} \lambda C_i W_{ij}\right)}} \tag{3.3}$$

where Y_j is the threshold value of the j^{th} concept and λ is a constant that determine how fast the output goes from 0 to 1.

With FCMs is possible to model different parts of critical infrastructures and the external events through the concepts, while the arcs between the concepts represent the internal dependencies and interdependencies between them.

3.1.3 High Level Architecture

High Level Architecture (HLA) is a general architecture for modeling and simulating complex distributed systems.

This modeling technique divides the whole system into individually operating sub-systems and the communication between the "system-of-systems" is managed by a runtime infrastructure (RTI). A single simulation is referred to as a federate and the total of single simulations connected via RTI is called federation (Eusgeld, 2008).

A HLA consists of the following components (Seliger et al., 1999):

- Rules which govern the behavior of the overall distributed simulation (federation) and its members (federates);
- Interface specification, which define the interface between each federate and the RTI;
- Object Model Template (OMT), which defines how federations and federates have to be documented.

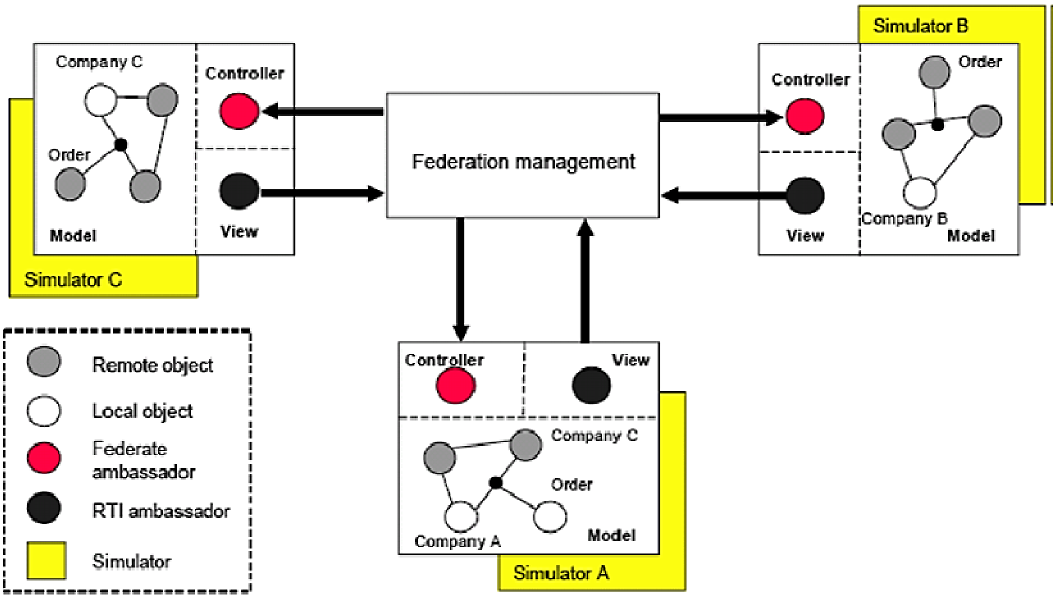


Figure 3.6 Example of a meta-model in HLA (Seliger et al., 1999)

There are many software tools supporting this methodological approach. It has many advantages, in particular for modeling system of systems, but it has also the problem of the huge time of simulation and resource consuming.

3.1.4 Input-output Inoperability Model

The Input-output Inoperability Model (IIM) developed by Haimes and Jiang (2001) is a simple, but powerful, mechanism for analyzing the cascading effects induced by critical infrastructure dependencies and interdependencies.

This model is based on the theory of the market equilibrium developed by Wassily Leontief (1951) and it focuses on the spread of operability degradation in a networked system.

IIM introduces the concept of “inoperability”, which is the inability of a system to perform its intended functions, and analyzes how a given amount of inoperability in one component affects the operability of other components.

The Leontief input-output model, using a high level of approximation, assumes that each infrastructure can be modeled as an atomic entity whose level of operability depends on the availability of resources supplied by the other infrastructures (Haimes and Jiang, 2001).

Inoperability (x_i) is often assumed to be a continuous variable, evaluated between 0 and 1, with 0 corresponding to a flawless operable system, while 1 is used when systems become completely inoperable; it may be manifested in several dimensions: geographical, functional, temporal and political.

An assessment of the impact of a negative event on critical infrastructure system can be obtained, with some simplifications and hypothesis, from this linear system:

$$x(k+1) = Ax(k) + c \tag{3.4}$$

where x and c are respectively the vector of the inoperability and the vector of the exogenous disturbances. A is the matrix of the Leontief coefficients, in which the element a_{ij} describes the degree of dependence of the i^{th} infrastructure on the j^{th} infrastructure. For example, if a_{ij} = 1, then this means a complete failure of the j^{th} infrastructure will lead to a complete failure of the i^{th} infrastructure.

Setola (2007) introduces two indices to better quantify the role played by each infrastructure. One is the "dependency index" δ_i, which is defined as the sum of the Leontief coefficients along a row and expresses the exposure of the i^{th} infrastructure to failures in other infrastructure:

$$\delta_i = \frac{1}{n-1}\sum_{j\neq i}^{n} a_{ij} \tag{3.5}$$

The other is the "influence gain" ρ_j, which is defined as the column sum of the Leontief coefficients and expresses the overall influence exercised by the j^{th} infrastructure:

$$\rho_j = \frac{1}{n-1}\sum_{i\neq j}^{n} a_{ij} \tag{3.6}$$

A high value of the dependency index means that the infrastructure is vulnerable to the "failure" of his supplier, while a high value of the influence gain indicates that degradation of the operational capacity of the j^{th} infrastructure is able to highly influence the effectiveness of the other sectors.

The most difficult passage in IIM is the definition of the matrix A, that is why some general guidance principles exist (Setola et al., 2009):

- define the level of resolution and the boundary conditions of each infrastructure;
- identify physical connections among the infrastructure;
- if there are any deterministic correlations among any infrastructures, then these relationships should be singled at first;
- if the correlation between two infrastructures is of a stochastic nature, then all conceivable scenarios must be analyzed and a statistical average must be taken to obtain a_{ij} and a_{ji}.

There are more and more solutions of IIM that take into consideration more factors, i.e. the inventory (Barker and Santos, 2010), trying to achieve the best result in terms of critical infrastructure interdependencies analysis. Also combinations of different modeling techniques are possible, as the merge of agent-based and IIM approaches (Oliva et al., 2010) that is designed to overcome the holistic and agent-based paradigms.

3.1.5 Petri Nets

Petri Nets are abstract, formal models of information flow, showing static and dynamic properties of highly interconnected, cooperating networked systems (Eusgeld, 2008).

A Petri net consists of (Pye and Warren, 2006):

- places, that represent particular infrastructures;
- transitions, that are the exchange of services between cooperating infrastructures;
- arcs, which are connections between infrastructures.

Places may contain any number of tokens and a distribution of tokens avers the places of a net are called a marking. A transition of a Petri net may fire whenever there is a token at the end of all input arcs and when it fires it consumes these tokens, and places tokens at the end of all output arcs.

Execution of Petri nets is nondeterministic: when multiple transitions are enabled at the same time, any one of them may fire; if a transition is enabled, it may fire, but it doesn't have to.

Many variants on the basic Petri Net approach exist, like:

- Generalized Stochastic Petri Nets (GSPNs), that have two types of transitions, the immediate one and the timed one (Krings and Oman, 2002);
- Colored Petri Nets, in which also the tokens have a value;
- Prioritized Petri Nets, that add priorities to transitions;

The biggest problem of Petri Nets technique is the difficulty in determining the behavior of a series of infrastructures just with places, transitions and arcs; another problem could be the high number of data that is needed for example for a cascading simulation.

3.1.6 System Dynamics

System Dynamics (SD) is a powerful methodology and computer simulation modeling technique for framing, understanding and discussing the behavior and the underlying structure of a complex system over time. It was developed initially by Forrester (1961) and extended by Sterman (2000) and basically it represents an interdisciplinary top-down approach (Eusgeld et al., 2008).

The central concepts in this methodology are: stocks (the accumulation of resources in a system), flows (the rates of change that alter those resources), and feedback.

SD uses two diagrams to build up the structure of systems: casual loop diagrams (Figure 3.7a) and stock-and-flow diagrams (Figure 3.7b).

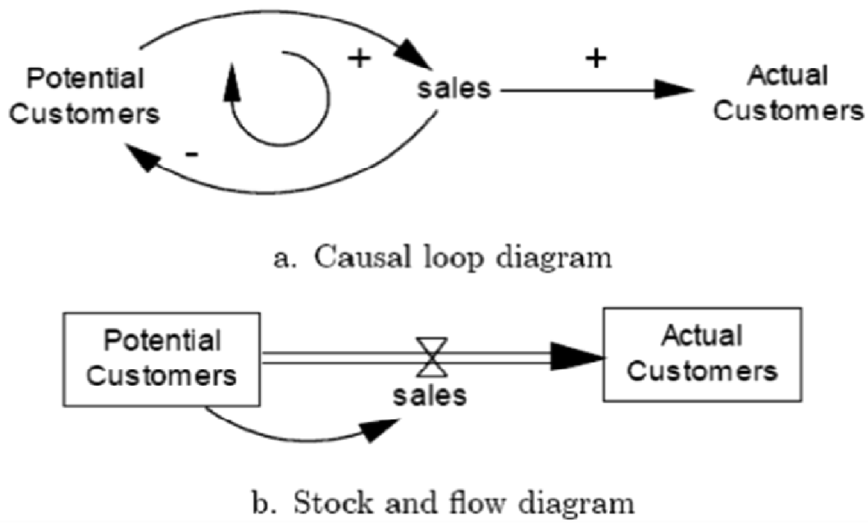


Figure 3.7 Example of casual loop (a) and stock-and-flow (b) diagram (Kirkwood, 1998)

A casual loop diagram consists of variables connected by arrows, each loop has an associated identifier, which shows whether the loop is positive (reinforcing) or negative (balancing) feedback.

A '+' sign denotes that the causal link is positive or a change in potential customers produces a change in sales in the same direction. A '-' sign denotes a negative causal link or a change in sales produces a change in potential customers in the opposite direction.

The casual loop diagrams provide a high-level view of relationships, interactions and feedback processes, while to see the physical buildup and flow of information and products through the system is used the stock-and-flow diagram.

Stock-and-flow diagrams, used to generate the differential equations that govern the evolution of the system, consist of stocks, that are any entity that accumulate or depletes over time (integral or state variables), flow (derivatives of rates), valves (controlling the flow) and clouds that are sources and sinks for the flow (Min et al., 2005).

With this approach is also possible to study the interdependencies between critical infrastructures, they can be seen as flows of services or infrastructure commodities among multiple infrastructures (Rinaldi, 2004).

3.1.7 Review of modeling techniques

In Table 3.1 a brief description of the most important mathematical approaches presented in the literature is reported along with the number of occurrences of each technique in a collection of articles (Griot, 2009).

Mathematical approaches (Occurrences)	**Definition**
Agent-based Model (7)	Agent-based models (ABM) consist of dynamically interacting, rule-based agents. An agent-based model can exhibit complex behavior patterns and provide valuable information about the dynamics of the real-world system simulated. An agent is a software object implemented on a computer network. Agents are able to interact with each other according to some behavioral rules. ABM are often used to handle aggregate activity for a population of agents.
Fuzzy Logic (1)	Fuzzy system modeling (FSM) is one of the most prominent tools that can be used to identify the behaviour of highly non-linear systems with uncertainty. FSM techniques have been used to capture the uncertainty in a system using linguistic logical connectives.
Graph Theory (2)	In Mathematics and Computer Science, Graph theory is the study of graphs. A "graph" refers to a collection of vertices/nodes and a collection of edges that connect pairs of vertices. A graph may be undirected or directed. The introduction of probabilistic methods in graph theory gave rise to "random graph theory".
Hierarchical Holographic Model (1)	The term hierarchical refers to an understanding of risks due to different levels in a hierarchy (systems-of-systems level, individual system level...). The term holographic modeling refers to a multi-view image of a system with regard to identifying vulnerabilities. Central to the mathematical and systems basis of HHM is the overlapping among various holographic models (...). Through HHM, multiple models can be developed and coordinated to capture the many dimensions and perspectives of infrastructure systems.
High Level Architecture (2)	HLA is a general architecture for modeling dynamic behavior of system-of-systems. It is a high-level simulation architecture that facilitates the interoperability of multiple models and simulations. Within HLA, simulation objects exist as federates in a simulation federation. HLA is an IEEE open standard. See also "Distributed Interactive Simulation" framework.
Hybrid System Model (1)	The term is related to mathematical methodologies for the M&S of complex computational systems which display discrete and continuous system behavior. The primary goal of such models is to facilitate the simulation of interdependent systems, which includes continuous behavior and discrete events. Continuous behavior is specified as a set of algebraic differential equations and discrete events are represented with a state of a state machine.
Input-output Model (6)	Based on Leontief's work and developed by Haimes and Jiang, 2001, this model considers multiple intra- and interconnected systems. The output is assumed to be the inoperability that can be triggered by one or multiple failures due to their inherent complexity or to external perturbations. Within each specific time frame, the model can describe a conceptual situation of equilibrium, before which the system will have evolved to a distinct and new frame of interactions.
Markov Chain Model (2)	A discrete, stochastic model in which the probability that the model is in a given state at a certain time depends only on the value of the immediately preceding state

Table 3.1 Overview of the main features of mathematical approaches used in Critical infrastructures interdependencies modeling and simulation (1/2) (Griot, 2009)

Mathematical approaches (Occurrences)	Definition
Monte Carlo Simulation **(1)**	A deterministic simulation in which random statistical sampling techniques are employed such that the result determines estimates for unknown values
Network Theory **(5)**	These models typically consider flows of discrete packets that are injected and removed from all nodes and follow least distance paths. The importance of links or nodes is measured by "betweenness" which is proportional to the number of least distance paths through the link or node. The models can also consider an abstract graph, neglecting power flows. Then CI networks can be considered as "small-worlds" Network theory is part of graph theory.
Ordinary Differential Equations **(1)**	An ordinary differential equation (ODE) is a differential equation in which the unknown function (=dependent variable) is a function of a single independent variable. In the simplest form, the unknown function is a real or complex valued function, but more generally, it may be vector-valued or matrix-valued. ODE are further classified according to the order of the highest derivative with respect to the dependent variable appearing in the equation.
Petri Nets **(3)**	An abstract, formal model of information flow, showing static and dynamic properties of a system. The Petri net is defined by its places, transitions, input function and output function.
Physics-based Model **(3)**	Physical aspects of infrastructures can be analyzed with standard engineering techniques. These models can provide highly detailed information, down to the individual component level, on the operational state of the infrastructures.
Probabilistic/ Stochastic Model **(2)**	A model in which the results are determined by using one or more random variables to represent uncertainty about a process or in which a given input will produce an output according to some statistical distribution. (Contrast with "Deterministic model").
Supply Chain Analysis **(2)**	A supply chain is a network of facilities that procure raw materials, transform them into intermediate goods and then final products, and deliver the products to customers through a distribution system. Modeling is an important tool for understanding and managing the supply chain. The dynamic behavior of a real life system is usually so complex that analytic models are not powerful enough to analysis the system, simulation must therefore be used.
System Dynamics **(7)**	System Dynamics is a method for studying and understanding the behavior and the underlying structure of a complex system over time. It represents a fundamentally interdisciplinary top-down approach. All dynamics in a system are assumed to arise from the interaction of two types of feedback loops, positive and negative ones, which are represented in "loop diagrams", including "stocks" and "flows".

Table 3.1. Overview of the main features of mathematical approaches used in Critical infrastructures interdependencies modeling and simulation (2/2) (Griot, 2009)

The criteria, called "evaluation keys", used by Eusgeld et al. (2008) in order to make a comparative evaluation of the modeling techniques are:

1. Modeling technique
2. Methodical design strategies
3. Types of interdependencies
4. Types of events
5. Course of triggered events
6. Data needs
7. Monitoring area
8. Modeling and simulation paradigms
9. Maturity

In Table 3.2 the evaluation keys criteria are applied to eight modeling techniques, showing the differences between them.

	Modeling Focus	Design strategies	Type of Interdependencies	Events	Course of triggered events	Data needs	Monitoring area	Paradigm	Maturity
ABM	- System Analysis	- Bottom-up	- Physical - Cyber - Geographic - Logical	- Accidents - Attacks - Failures	- Cascading - Escalating - Common cause - Confined	- High - Low	- Failure analysis - Information generation	- Discrete	- High
SD	- System Analysis - Interdep. Analysis	- Top-down	- Physical - Cyber	- Failures	- Cascading - Confined	- Low	- Information generation	- Discrete - Continuous	- High
HSM	- System Analysis	- Top-down	- Physical - Cyber - Geographic - Logical	- Accidents - Attacks - Failures	- Cascading - Confined	- Low	- Vulnerability assessment - Failure analysis - Information generation	- Discrete - Continuous	- Poor
I/OM	- Interdep. Analysis	- Top-down	- Physical	- Failures	- Cascading - Confined	- Low	- Failure analysis	- Continuous	- Middle
HHM	- Interdep. Analysis	- Top-down	- Physical - Geographic - Logical	- Accidents - Attacks	- Common cause - Confined	- High	- Vulnerability assessment	- Continuous	- Middle
CPM	- System Analysis - Interdep. Analysis	- Top-down	- Physical - Cyber - Geographic - Logical	- Failures	- Cascading - Confined	- High	- Failure analysis - Information generation	- Discrete	- Poor
HLA	- System Analysis - Interdep. Analysis	- Bottom-up - Top-down	- Physical - Cyber - Geographic - Logical	- Accidents - Attacks - Failures	- Cascading - Escalating - Common cause - Confined	- Low	- Failure analysis - Mitigation/Prevention	- Discrete	- Poor
PN	- System Analysis - Interdep. Analysis	- Top-down	- Physical	- Failures	- Cascading - Common cause - Confined	- High - Low	- Failure analysis - Information generation	- Discrete	- Middle

ABM: agent-based Modeling
SD: System Dynamics
HSM: Hybrid System Modeling
I/OM: Input/Output Analysis
HHM: Hierarchical Holographic Modeling
CPM: Critical Path method
HLA: High Level Architecture
PN: Petri nets

Table 3.2 Comparative evaluation of methods for CII Analysis (Eusgeld et al., 2008)

3.2 Methodologies and methods for CI interdependency analysis

The main objective of this paragraph is to describe which are the principal methodologies and methods proposed in literature to study the interdependencies between critical infrastructures.

Referring to the reviews completed by Pederson et al. (2006), Eusgeld et al. (2008) and Griot (2009 and 2010), twenty-one different methods, with different characteristics and levels of maturity, will be presented and discussed. All these methods are synthetically reported in Table 3.3 with a description of the scope and features, of the method, the owner or developer organization, the maturity level, the reference modeling technique or formalism, the number and types of critical infrastructures, and types of interdependencies addressed by the method.

It is important to underline that the models studied in this paragraph are not the only ones presented in the wide world of the international literature, also approaches to identifying geographic interdependencies among critical infrastructures (Robert and Morabito, 2010) exist or methods for studying the ramifications of cross-infrastructure dependencies (Tolone et al., 2004). But it can be said that the ones discussed here are the most advanced and the more interesting for the objectives of this work.

The Joint Research Centre introduces also a model to assess operability of European Critical Infrastructures (ECIs) over time due to cascading effects. This model is based on the ABM technique and it considers the interdependencies between all the ECIs. It is a dynamic model, in which the general time increment is one hour; for its implementation a new generation modeling tool called "RePast" (developed by Argonne National Laboratory in 2008) is used.

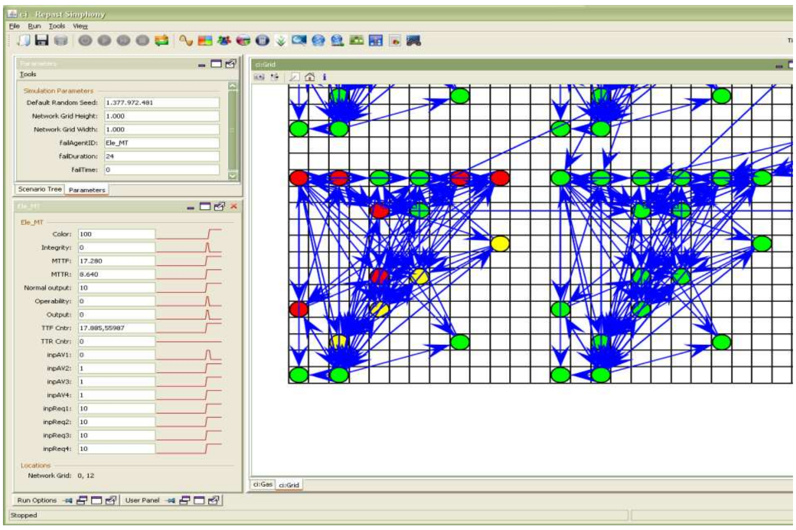


Figure 3.8 Example of infrastructure disruption – cascading effects with RePast

Model name	Owner/Organization	CI addressed	Approach & Tools	Maturity level	Description
1. Athena	On-Target Technologies, Inc.	All: from physical to conceptual	System of systems	Mature internal	An analysis & modelling tool that is designed to analyze a network of nodes (actors, concepts and physical), allowing inter-and intra- dependency analysis. Provides representations of the interdependencies.
2. CARVER	National Institute Center for Infrastructure Expertise	User defined	Relational database	Mature commercial	Free software tool that provides a non-technical method of comparing and ranking CI and key-resources. Provides a mathematical score for each potential target. No simulation capacity.
3. Critical Infrastructures Interdependencies Integrator (CI^3)	Argonne National Laboratory	EP, NG, Scada, TC	Transition diagram coupled to Monte Carlo simulator	Mature internal	Software tool that provides a framework for recognizing interdependencies and incorporating uncertainty into the analysis of CI. Output: Graphs & tables of completion time and cost distributions for repairs to quantify the impacts of infrastructure disruptions.
4. Critical Infrastructure Modeling System (CIMS)	Idaho National Laboratory (INL)	EP, HA, HW, POL, Scada	Network Theory Agent-Based Model	Development	Combines geospatial information and a 4 dimensional environment to support 'what-if' analysis. Provides a rapid modelling and analysis capability that does not require extensive data collection. Output: Graphic representations of interdependencies & maps.
5. Critical Infrastructure Protection Decision Support System (CIP/DSS)	Los Alamos National Laboratory	All	Consequence models Oracle relational database	Mature internal	Vensim Software that simulates the dynamics of individual infrastructures and couples separate infrastructures to each other according to their interdependencies. Provides graph representations of interdependencies.
6. Critical Infrastructure Protection (CIP) Modeling & Analysis (CIPMA)	Australian Attorney General's Department	EP, FN, NG, OL, TC	System Dynamic Models GIS	Mature internal	Tool designed to examine the relationships and dependencies within and between CI systems and to demonstrate how a failure in one sector can affect the operations of CI in other sectors. Includes a series of impact models to analyze the effects of a disruption to CI services. Output: Maps, time-based impacts of disruptive events on infrastructure networks.
7. Critical Infrastructure Simulation by Interdependent Agents (CISIA)	University Roma Tre	Many heterogeneous CI	Complex Adaptive Systems Agent-Based Model	Development	Simulator designed as a hybrid of two approaches: Interdependency analysis & System analysis. Based on Repast open-source software. Output: Graphic models showing the operative level incidence matrix and physical fault incidence matrices between elements in the model.

CN: Computer Networks, DW: Drinking water, EP: Electric power, FN: Financial Network, HA: Human Activity, HW: Highway System, NG: Natural Gas, OL: Oil Pipeline, POL: Policy/Regulatory constraints, RL: Rail System, Scada, TC: Telecom, WW: Waterway System

Table 3.3 Overview of some models for the analysis of CI interdependencies (1/3)

Model name	***Owner/Organization***	***CI addressed***	***Approach & Tools***	***Maturity level***	***Description***
8. Distributed Engineering Workstation (DEW)	Electrical Distribution Design, Inc.	Many heterogeneous CI	Graph theory Physical network modeling Generic programming	Mature commercial	Tool designed to identify and analyze interdependencies in large scale electrical; power systems and fluid systems of aircraft carriers. Provides support for cross-collaborations among different groups. Outputs: Graph representations of interdependencies . Can be coupled with GIS.
9. Electricity Market Complex Adaptive System (EMCAS)	Argonne National Laboratory	EP, FN	Complex Adaptive Systems Network theory Agent-Based Model Power flow model	Mature internal	Software for simulating the operation of complex power systems. Probes the possible operational and economic impacts on the power system of various external events. Output: Graph representations of interdependencies, many graphic representations on the same screen, maps.
10. Fast Analysis Infrastructure Tool (FAIT)	Sandia National Laboratory (SNL)	EP, NG, POL, TC, Emergency Services	Object oriented expert system model Input/Output method	Development	Expert-system for interdependency analysis taking into account: proximity, service boundaries, ownership, characteristics of assets. Output: Graphic representations of interdependencies using 'Connectivity models', direct & indirect economic consequences of a CI disruption.
11. Inoperability Input-Output Model (Haimes)	University of Virginia Center of Risk Management of Engineering Systems	FN, HN	Leontief's input-output model	Research	Computer-based analytical model for analyzing the impacts of an attack on a CI. Cascading effects on interconnected & interdependent infrastructures can be simulated in terms of economic and inoperability terms. Output: prioritization of infrastructure sectors, workforce recovery, recovery rates of CI sectors.
12. Interdependent Energy Infrastructure Simulation System (IEISS)	Los Alamos National Laboratory	EP, NG	System dynamics	Mature internal	M&S software for analyzing interdependent energy infrastructures. Simulations performed by a continuous time based model. Output: Map-based view of scenarios.
13. Multi-Layer Infrastructure Networks (MIN)	Purdue School of Civil Engineering G. Mason University	HA, HW	Network theory Dynamic flow model Agent-based Model	Research	Network flow equilibrium model of dynamic multi-layer infrastructure networks in the form of differential game. Output: charts, graphs, behavioral trends.
14. Multi-Network Interdependent critical infrastructure program for analysis of lifelines (MUNICIPAL)	Rensselaer Polytechnic Institute	EP, RL, TC	Network flow based model GIS	Prototype system	Decision support system designed to identify CI interdependencies. Provides capabilities to understand the impacts of a disruption on CI. Output: GIS Databases & maps.

CN: Computer Networks, DW: Drinking water, EP: Electric power, FN: Financial Network, HA: Human Activity, HW: Highway System, NG: Natural Gas, OL: Oil Pipeline, POL: Policy/Regulatory constraints, RL: Rail System, Scada, TC: Telecom, WW: Waterway System

Table 3.3 Overview of some models for the analysis of CI interdependencies (2/3)

Model name	Owner/Organization	CI addressed	Approach & Tools	Maturity level	Description
15. Net-Centric effects-based operations Model (NEMO)	SPARTA	TC, EP, NG, DW	On/off interaction behavior Service Oriented Architecture GIS	Development	Application designed for modeling cascading effects of events across multiple infrastructure networks. Second and higher order effects can be analyzed. Output: "what-if" analysis, maps, simulation web-service.
16. Network-Centric GIS	York University, CA	RL, HW, WW	GIS Hydraulic simulations	Research	Framework for GIS interoperability for supporting emergency management decision makers. Identifies CI sectors in the study area, analyzes dependencies, assesses damages following an event. Visualization (interoperable 3D internet based).
17. Network Security Risk Assessment Model for Critical Infrastructure Protection (NSRAM)	James Madison University	CN, EP	Complex network systems	Research	Simulation tool that emphasizes the analysis of large interconnected multi-infrastructure models. Provides a framework to simulate large networks and analyze their behavior under conditions where the network suffers failures or structural breakdowns.
18. Next-generation agent-based economic laboratory (N-ABLE)	Sandia National Laboratory (SNL)	FN, POL	Agent-based discrete-event model Micro-simulation of economy GIS	Mature internal	Software system for analyzing the economic factors, feedbacks and downstream effects of infrastructures interdependencies. Identification of CI sectors, impact assessment in terms of economic performance… Output: Geographical charts and statistical data.
19. NEXUS Fusion Framework	InterPoint, LLC	EP, TC, HW, HA, RL	Complex system network Agent-based system Behavior model GIS	Mature commercial	Tool that visualizes intended and unintended effects and consequences of an event across multiple infrastructures. Provides cross system analysis of cascading events within and between complex networks. Contents social and population behavior models. Output: Critical relationships, system of system causality analysis, temporal view, thematic maps.
20. MIT Screening Methodology (G.E. Apostolakis)	Massachussetts Institute of Technology, Dept of Nuclear Science and Engineering	EP, NG, DW	Graph theory MAUT Mathematical Network Analysis	Research & Development	Methodology for the identification and prioritization of vulnerabilities in CI. Scenarios generation and screening. Output: list of prioritized vulnerabilities, rated impact of losing infrastructure services.
21. The Urban Infrastructure Suite (UIS)	Los Alamos National Laboratory	HW, HA, TC, AST, SW, DW	Social network model Epidemic model Differential equation based Agent-based model GIS	Mature internal	Set of interoperable modules that evaluates infrastructure's performance under unusual conditions by assessing the effects of interdependencies and simulating the dynamics of their interconnections. Output: Graphical overlays, textual based output.

CN: Computer Networks, DW: Drinking water, EP: Electric power, FN: Financial Network, HA: Human Activity, HW: Highway System, NG: Natural Gas, OL: Oil Pipeline, POL: Policy/Regulatory constraints, RL: Rail System, Scada, TC: Telecom, WW: Waterway System

Table 3.3 Overview of some models for the analysis of CI interdependencies (3/3)

3.3 Conclusions and discussions

In order to discriminate and study the most relevant interdependencies between CIs and supply chains, all the different models reported in the previous state of the art review had been evaluated, verifying their suitability for this purpose. Indeed, the approach that is useful for this work has to be able to model in the correct way the impact that an event on a critical infrastructure has on the key asset supply chain analyzed. It has also to represent the interdependencies between CIs and supply chain nodes, considering the lack of precise data obtainable through the literature.

Many of the techniques presented in the scientific literature however fall short to the needs of evaluating consequences. For instance they are limited to infrastructures only or even to one domain such as electrical power; they may have high and detailed data needs that in practice cannot be satisfied (as is true of many of the recent methods and system dynamics), or they do not model consequence propagation in sufficient detail (economic Leontief models). For this reason a new methodology has to be developed and a modeling technique has to be chosen.

Reviewing all the different modeling techniques the one that seems good to the work's purposes is Fuzzy Logic, because it is able to arrive to quite precise results dealing with the uncertainty of the available information.

In this case also the Fuzzy Cognitive Maps can be used in order to understand the dependencies and interdependencies between all the parts of the supply chain and then to have a qualitative static idea of which are the consequences of a failure of a node of the FMCG sector on all the other nodes. FCM are also able to represent the cascading effect due to a failure, and this important property is not present in all the other techniques. The knowledge of the experts, for FCM's technique, is really important in order to obtain qualitative information on how their systems would be affected in case of the loss of resources provided by infrastructure services. This information is then used to build the FCMs.

The developed methodology has also to give results that can be used in the reality to understand the behavior of the supply chain considered, improve the entire system and develop new contingency plans. In order to accomplish this goal another technique can be used: Group Technology clustering algorithms. Using the results coming from the FCMs, it is possible to rielaborate them and create families of resilience that lead to a complete vision of the way a CI or a supply chain node reacts to a disruption in the system.

In the next chapter the developed methodology for discriminating CIs for key resources supply chains is presented and explained.

4. Method for discriminating Critical Infrastructures for key resources supply chains (KRSC)

This chapter shows a new methodology, and the related model, which is being developed in order to evaluate the impact that disruption events in critical infrastructures would have on key resources supply chains (KRSC). The final purpose of this model is to understand which are the consequences of these events and improve the resilience of the system.

For the development of this model is important to take into consideration the complex interdependencies existing between the supply chains and critical infrastructures. As previously said there is not a model or methodology in literature able to describe the behavior of a supply chain during a deviation or a disruption of one or more of these CIs, taking into consideration their interdependencies. There is also a lack of data concerning past events on this matter. Consequently, the proper modeling approach has to use a modeling technique able to represent a complex supply chain and its interdependencies with CIs in a context of uncertainty and it has to give a realistic result also under incomplete information. For this reason the fuzzy logic technique and its correlated tools have been chosen.

The basic idea of the proposed methodology is to reach a qualitative description of the dynamic behavior of the system analyzed and then provide valid discussions on the results obtained. For the implementation of this methodology the tools that can be used are limited, because of the lack of data. The methodology can be divided in two steps, based on two different tools:

- *Fuzzy Cognitive Map*

  This Fuzzy Logic tool is able to describe all the interdependencies between the different nodes and to give them a weight through the arcs. At the end it represents the qualitative consequences of the failure of nodes of the system on all the other nodes, in a relative way. Due to the lack of data this first step is a fundamental part to reach a complete understanding of the supply chain and how it reacts to an unexpected event.

- *Group Technology Clustering Algorithm*

  Group Technology, and its clustering algorithm, is used in order to divide the concepts used in the FCMs in “resiliency’s families”; through the analysis of these families it is possible to understand which are the necessary contingency measures to improve the business continuity of the entire system. The Rank Order Clustering algorithm is used to reach this scope.

4.1 Fuzzy Cognitive Map

Fuzzy Cognitive Maps (FCMs), first introduced by Kosko in the 1986, are fuzzy-graph structures for the representation of causal reasoning. FCMs allow the forecasting of how complex events develop and interact with each other (Kosko, 1993).

Reliable and accurate FCM modeling of the FMCG supply chain requires introducing also the concept of time dependency. Although in the literature several authors have proposed different solutions for integrating time dependency in FCM modeling (Park and Kim, 1995; Miao et al., 2001), the model presented in this paper is based on a different approach. Different timeframes are defined described through specific Fuzzy Cognitive Maps with the same concepts but with different fuzzy values of the edges (arcs).

With these completed maps both static and dynamic analyses can then be performed so as to obtain a more detailed understanding of the system and a wider view of what happens inside the supply chain when a service disruption occurs in one or more CIs.

4.1.1 How to build the FCM

Fuzzy Cognitive Maps are composed of: concepts that reflect attributes, characteristics, qualities and senses of the system being modeled and edges (arcs) that are the interconnections between concepts (Papageorgiou and Groumpos, 2005). The edges represent the cause-effect relationships that a concept has on the other concepts and can take any value in the range of [-1 +1].

The construction of a FCM follows a process consisting of sequence of logical steps, which can vary in relationship to numerous factors, for instance the level of detail or the resources used. A brief summary of each step is provided herein.

In Figure 4.1 is schematically reported the procedure used in this work for the construction of the FCM.

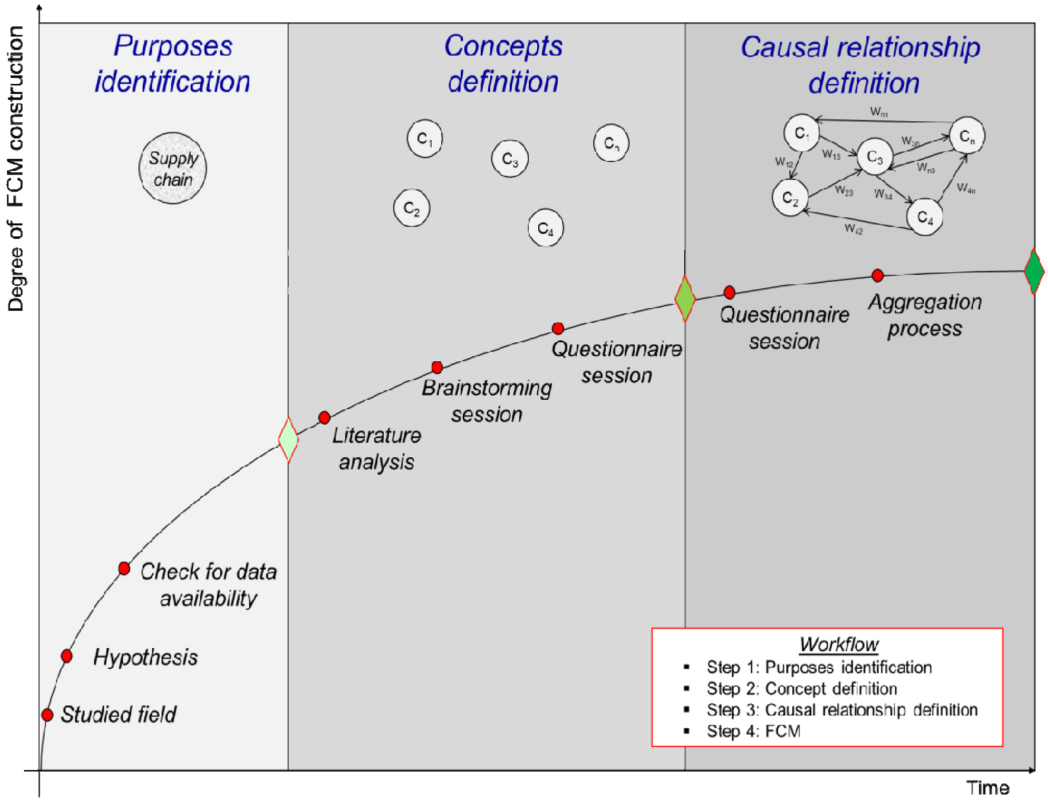


Figure 4.1 Steps for the construction of the Fuzzy Cognitive Map

Step 1 – Purposes identification

The first step for the construction of a FCM is the definition of its purpose and what it will actually mimic. Therefore it is important to understand what the FCM is to represent, how this will be achieved and what is the expected outcome.

In order to reduce the complexity related to the number of relationships between the concepts and the quantity of concepts, certain assumptions are needed.

Since a FCM can be used to model only part of a system, the need to define the relevant factors becomes paramount. In addition the availability of data and the types of available data are equally key issues, since they too forge the purpose of the overall model.

Nevertheless by studying past events, case studies and/or organizing interviews and constructing questionnaire based surveys it is possible to collect data. The level of detail of such data depends on the scope of the analysis so a compromise between time and effort on one side and precision of the results on the other has to be found.

Step 2 – Concepts definition

A concept can be a property of the system being analyzed, a state, a variable, an input or an output of the system itself (Stylos and Groumpos, 1998).

Graphically, concepts are represented by the nodes of the fuzzy cognitive map and are characterized by an activation level that can assume a positive or negative value.

Once the purpose has been identified it is possible to describe the concepts of the FCM and there are several different ways of doing so. One possible solution is to compile the list of concepts using empiric evaluations, self-experience and past case studies. Another option is to conduct brainstorming sessions with the experts of each sector that, together, will end up with a description of all the concepts of the map. Yet another way is to prepare a questionnaire based on a pool of concepts from which each expert selects a preferred or suggested list, subsequently these suggestions define the final list for the map.

In the model discussed here a combination of the above 3 solutions have been exploited, namely:

- a list of concepts was defined based on the personal experience in the field of critical infrastructures (leveraging also the European Directive 2008) and of the FMCG supply chain, studying the literature and trying to identify the most relevant components of this system and their roles;
- then a brainstorming session with some experts was organized to pinpoint missing or redundant concepts in the first draft list of concepts;
- a final list of concepts was assembled and assumed to define the directions and the weights of the edges (arcs). However, the final list was left ‘open’ to further possible additions of concepts should these arise during the discussion of the questionnaire with the experts and the assignment of causal relationship values.

Step 3 – Causal relationships definition

The influence of one concept on the others can be expressed by three different types of causal relationship values. The weights of the arcs between concept C_i and concept C_j could be positive ($W_{ij} > 0$), which means that an increase in the value of concept C_i leads to the increase of the value of concept C_j, and a decrease in the value of concept C_i leads to the decrease of the value of concept C_j. On the other hand there could be a negative causality ($W_{ij} < 0$), which means that an increase in the value of concept C_i leads to the decrease of the value of concept C_j and vice versa. In the event of a null causality ($W_{ij} = 0$) this implies there is no correlation between the concepts (Stylos and Groumpos, 1998; Papageorgiou and Groumpos, 2005). All of these relationships are expressed not only by a sign, but also by a value within the range of -1 to +1, as shown in the example provided in Figure 4.2. A matrix, called the adjacency matrix (W), can be used to include all these values.

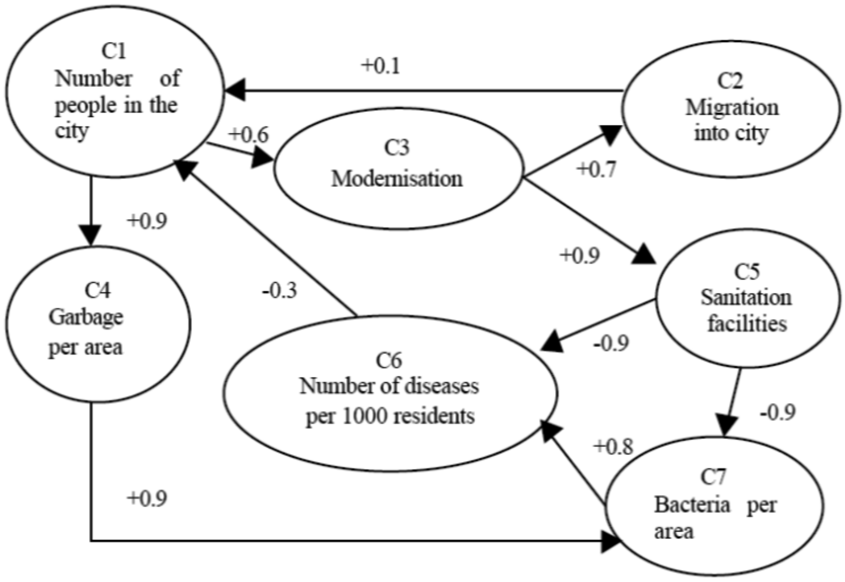


Figure 4.2 Example of a Fuzzy Cognitive Map, with the concepts and their causal relationships (Khan et al., 2000)

The issue of gathering data and defining both concepts and casual relationships can be managed through different solutions; the approach used herein was based on a questionnaire distributed to experts. This affords multiplicity in sources that directly reduces the subjectivity in the definition of these relationships. Moreover experts' judgments provide a more accurate and complete picture than the limited data that can be mined from literature sources or operators' data warehouses. Nevertheless, in some cases still experts found it difficult to assign a value to a causal relationship between two concepts. Thus, Fuzzy logic and the relative fuzzy sets (Klir and Yuan, 1995; Chen and Pham, 2001) can be useful in helping experts to determine the weights of these links. In this way the expert can choose a fuzzy set that is previously defined and inserted in the questionnaire instead of assigning a single value. Indeed it is easier for an expert to define a relationship between two concepts as "medium" or "high" instead of assigning a value such as 0.4, 0.7 etc.

Each fuzzy set can assume a different value between 0 and 1, and membership functions are associated to each fuzzy set. Usually these membership functions are triangular or trapezoidal in shape, but they can also have irregular shapes.

Figure 4.3 reports an example of a fuzzy set with triangular membership functions.

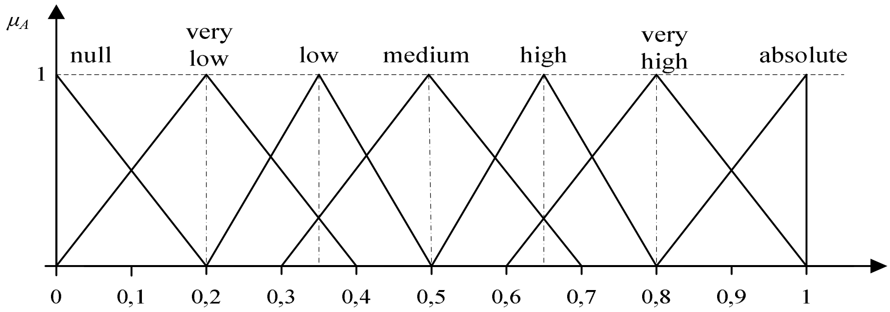


Figure 4.3 Example of a fuzzy set

Once the experts provide their individual evaluations of the weights of all the causal relationships, the linguistic variables have to be aggregated and normalized in the range of values of [0 1] using a defuzzification process (Van Leekwijck and Kerre, 1999).

The first step for this aggregation is the conversion of all the linguistic variables into fuzzy numbers. Each expert is assigned an ‘experience number’, λ_i, which is then normalized, so as to obtain a weight for every expert:

$$ew_i = \frac{\lambda_i}{\lambda_1 + \ldots + \lambda_n} \qquad i = 1, \ldots, n \qquad \sum_{i=1}^{n} ew_i = 1 \tag{4.1}$$

where n is the identification number of the expert and ew_i is the relative expert weight. At the end of the aggregation process a weighted mean is obtained.

By considering all the triangular membership functions, in which the function is characterized by three main points $A_i = (a_1, a_M, a_2)$, and the n weights ew_i, it is possible to write:

$$\bar{A}_w = \left(\sum_{i=1}^{n} ew_i a_1^{(i)}, \sum_{i=1}^{n} ew_i a_M^{(i)}, \sum_{i=1}^{n} ew_i a_M^{(i)} \right) \tag{4.2}$$

The result of this operation is now expressed in a three component number that represents the triangular shape of the membership function which is then defuzzified in order to get a real number.

That is, defuzzification is applied to $\bar{A}_w$ set, using the centroid method (Opricovic and Tzeng, 2003; Runkler, 1996).

The values $\bar{A}_w$ are inserted in the adjacency matrix *W*, which contains all the weights of the relationships between all the concepts used to build the FCM. It provides an *n* x *n* matrix where *n* is the number of concepts and is crucial for the subsequent analysis done on the map. In this way the FCM is completed with all the causal relationships quantified.

4.1.2 Time dependency

A key omission in fuzzy cognitive maps developed so far is the modeling of time delays before a change in node C_i has an effect on node C_j (Park and Kim, 1995). FCMs assume all the effects are taking place in the same single unit of time or timeframe but clearly if a more realistic model needs to be developed then the dynamic of the system is fundamental and time delays need to be considered in the analysis. A further justification of this need is that time is a crucial underpinning of the European Directive (2008/114/EC) concerning critical infrastructure protection.

The introduction of time as a variable in FCMs can be achieved in different ways but for the model developed and discussed herein time is considered as a timeframe with a known or pre-established increment e.g. 1 day, 3 weeks etc.

The introduction of a time increment affords the analysis of changes in the system i.e. the effects of the activation of concepts considering different durations of the disruption for a given input. In this way it is possible to see which are the changes in the system during the time, and which are the effects of the activation of a concepts considering different duration of the disruption of an input. The first two FCM construction steps described before remain unaffected, while another third step has to be done in order to define the new causal relationships for the assigned time duration. Using a detailed description, as it is done in this work, is possible to consider all the timeframes in the same questionnaire.

As an example consider the following three concepts or events: Iceland volcano eruption, Iceland airport closure and European airport closure (http://scienceblogs.com/eruptions/). In the first instance the Iceland volcano eruption leads immediately (timeframe 1) to the closure of Iceland's Reykjavik International Airport, with a negligible impact on the European counterparts. During the subsequent timeframes, which implies a continuation of the eruption, (timeframe 2 and 3) many European airports will close due to the possible effects of the ash cloud and the closer relationships between the main European airports: this will continue until the complete closure of all airports involved? In general terms, this phenomenon can be modeled by increasing the weight of the causal link between concepts C_i and C_j moving from frame 1 to 2, while the weight remains the same or stabilizes moving from frame 2 to 3 (see Figure 4.4).

Finally, a specific fuzzy cognitive map is prepared for each one of the timeframes relevant for the analysis of the CIs-KRSCs system under study.

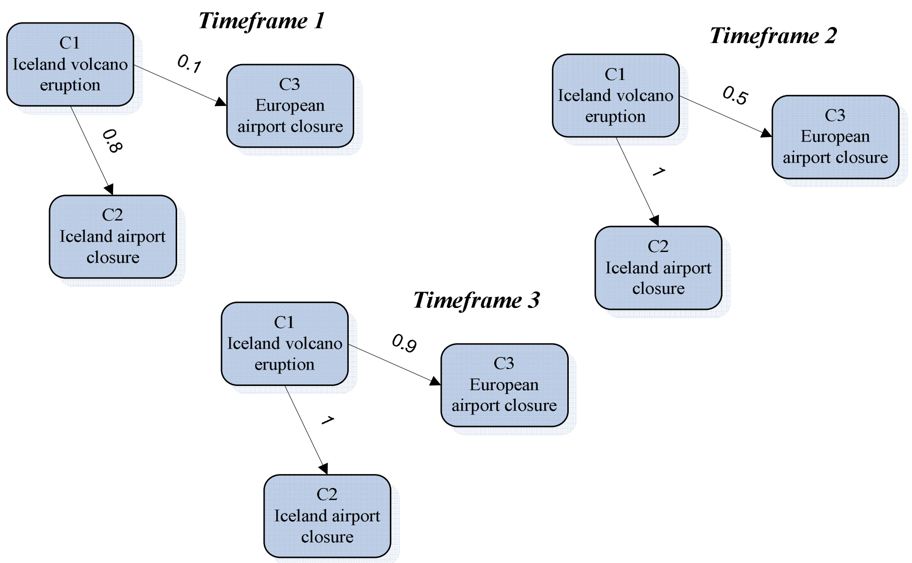


Figure 4.4 Example of the timeframes in a simplified fuzzy cognitive map

4.1.3 Static Analysis

Each fuzzy cognitive map is prepared for the relative timeframe exploiting the relative graph theory techniques (Harary et al., 1965) so as to study the characteristics of the weighted directed graph that represents the system. In this way a static analysis is afforded.

However, this kind of analysis has several limitations but if confined to being a preliminary study it can lead to a better understanding of the system analysed, the validity of rationale of the concepts chosen and the values attributed to each arc in each map.

The analysis of complex timeframe FCMs is difficult based on a graphical study alone, but the use of a matrix of the weighted links between concepts (adjacency matrix *W*) can be very constructive for this purpose.

To proceed with a static analysis first of all the number of the concepts (*n*) in each FCM and also the number of causal relationships (*R*) indicated by the experts need to be known.

The number of concepts is fixed, while the calculation of the number of causal relationships is done through the analysis of the weight link matrix, counting every non-zero number.

In this part of the chapter are explained and discussed some of the indices that can be used for a static analysis of each timeframe fuzzy cognitive map (Kosko, 1986; Harary, 1965; Özesmi and Özesmi, 2004; Bougon et al., 1977). The scope is also to compare the changes during the different temporal frames and studying the different values of these indices.

Density or clustering coefficient

The density, or clustering coefficient, of a fuzzy cognitive map is an index of connectivity, which shows how connected or sparse the maps are, hence it gives an indication of the complexity of the model. Density (D) can be expressed as follows:

$$D^{(t)} = \frac{R}{n(n-1)} \qquad t = 1, \dots, m \tag{4.3a}$$

where R is the number of causal relationships in the FCM, n is the number of concepts and t is the timeframe, which corresponds to a number that ranges from *1* to m.

If the concepts of the FCM can have causal effects on themselves then the maximum number of connection is no longer $(n\text{-}1)$, as seen in Equation 4.3a, but would be n^2. Hence it can be written:

$$D^{(t)} = \frac{R}{n^2} \qquad t = 1, \dots, m \tag{4.3b}$$

Out-degree and In-degree

The out-degree and the in-degree are two indexes defined for each concept C_i and for each timeframe t.

Out-degree is the row sum of the absolute values of the adjacency matrix W. It shows the cumulative strength, for each timeframe t, of the connections (W_{ij}) exiting or leaving the concept.

$$od^{(t)}(C_i) = \sum_{j=1}^{n} \left|W_{ij}\right| \qquad t = 1, \dots, m \tag{4.4}$$

In-degree is the column sum of absolute values of a variable. It shows the cumulative strength, for each timeframe t, of the weighted links entering the concept taken into consideration.

$$id^{(t)}(C_i) = \sum_{i=1}^{n} \left|W_{ij}\right| \qquad t = 1, \dots, m \tag{4.5}$$

By looking at its in-degree and out-degree indexes, it can also be seen whether the variable is mainly influencing other variables, or if other variables influence it, or both.

It is possible to divide the concepts of the map in different types (Bougon et al., 1977):

- Transmitter. Variables with a positive outdegree and zero indegree;
- Receiver. Variables that have a positive indegree and zero outdegree;
- Ordinary. Variables with both a non-zero indegree and outdegree.

The type of concepts in a fuzzy cognitive map is important because it shows how the variables act in relation to the other variables and also because it facilitates the understanding of the structure of the analyzed system.

Centrality or Total degree

The centrality index (or total degree, *td*) describes a measure for determining the importance of nodes in all the timeframe FCMs. In a FCM a concept can be more central, although it has fewer connections, if the connections carry larger weights. The importance of a concept C_i is evaluated as:

$$td^{(t)}(C_i) = id^{(t)}(C_i) + od^{(t)}(C_i) \qquad t = 1, \dots, m \tag{4.6}$$

where $id(C_i)$ is the number of incoming arcs of node C_i, $od(C_i)$ is the number of outcoming arcs of the same node, while t is the timeframe considered.

If this total degree value is null, this means that the concept analyzed is has been considered negligible inside the system, while concepts with high centrality values deserve special attention in any analysis used for decision support.

4.1.4 Dynamic Analysis – Forward Simulation

The dynamic analysis is an inference process (Liu and Miao, 1999). Using the adjacency matrix it is possible to run the model in order to see where the system will go, if the things continue as they were at the beginning or if they are changing; in this way it is possible to determine the steady state of the system. The term ‘dynamic’ does not mean a time variation, but it can be seen as a *domino* effect on the system in a fixed temporal frame. Later through the usage of the different timeframe maps it is possible to perform a study taking also into consideration time.

Forward simulation is a method within which planners estimate the impact on the effect variables caused by a change of a cause variable. It studies how the FCM changes when activating one or more concepts. The impact is expressed in terms of an increase or decrease of the effect variables (Kardaras and Karakostas, 1999).

With the "activation" of a concept is simulated a deviation or disruption on that precise node of the system occurs signifying that a change of an input variable causes a variation on the entire system.

The first step for the implementation of a forward simulation is the construction of the adjacency matrix (*W*). After the process of defuzzification of the linguistic variables obtained from the questionnaire, an *n* x *n* matrix is created (where *n* is the number of concepts for each timeframe map). The row components of the matrix represent the cause concepts, while the column components represent the effect concepts: the element in the i^{th} row and j^{th} column of *W* matrix shows the weight of the causal link that goes out from node C_i and goes inside node C_j.

After the creation of the adjacency matrix the next step is the activation of one or more nodes of the fuzzy cognitive map. To make this activation a state vector is done, which has *n* columns, and all the values of this vector are initially equal to zero (a zero value means that the concept i^{th} is inactive), except the ones corresponding to the activated concepts.

The state vector, indicating the input activated concepts, has to be multiplied with the adjacency matrix: thus a new vector is obtained, with new values for each concept that are determined by the actual value of the node and the intensity of the causal relationships. These new values represent the level of activation of the other nodes due to the activation of the concept $C_i=1$ in the state vector.

In Equation 4.7 an example of the process for the calculation of the new vector representing the state of the concepts is presented.

$$\underbrace{\begin{bmatrix} 0 & 1 & 0 & 0 \end{bmatrix}}_{\text{State Vector}} \cdot \underbrace{\begin{bmatrix} 0 & 0.4 & 0.5 & 0 \\ 0.1 & 0 & 0.7 & 0.3 \\ 0.9 & 0 & 0 & 0.3 \\ 0.7 & 0.2 & 0.4 & 0 \end{bmatrix}}_{\text{Adjacency Matrix}} = \underbrace{\begin{bmatrix} 0.1 & 0 & 0.7 & 0.3 \end{bmatrix}}_{\substack{\text{New State Vector} \\ \text{at iteration } k+1}} \qquad (4.7)$$

The new level of activation of the concept C_j, considering the iteration step $k+1$, is obtained using a sum operation between the product of each concept C_i and the weight of the causal link W_{ij}. The calculation is showed in Figure 4.5.

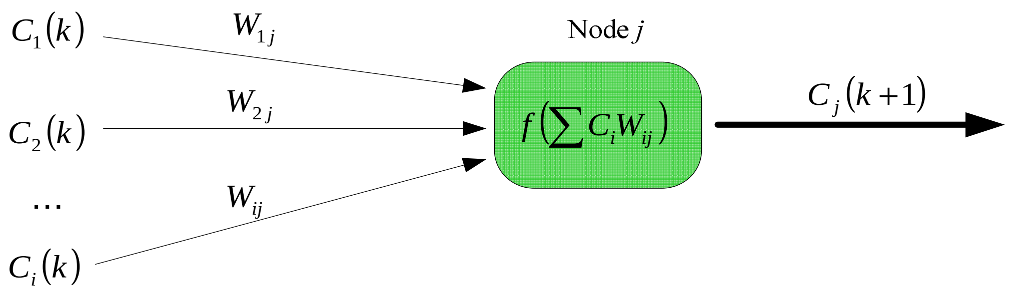


Figure 4.5 Process for the calculation of the new level of activation of the concept C_j for the step k+1

The new concept vector $C_{new}^{(k+1)}$ coming through this process can be written as follow:

$$C_{new}^{(k+1)} = f\left[\sum_{i=1}^{n} C_i^{(k)}\, W_{i1} \quad \sum_{i=1}^{n} C_i^{(k)}\, W_{i2} \quad \cdots \quad \cdots \quad \sum_{i=1}^{n} C_i^{(k)}\, W_{in}\right] \qquad (4.8)$$

where *k* is the iteration step, *n* is the number of concepts of the FCM, $C_i^{(k)}$ is the i^{th} element of the "old" state vector and *f* is the threshold function.

The threshold function is a cut-off function which decides if the belief about a kind of relationship between any two concepts should be put active or inactive in the new concept vector (Banerjee, 2009). The output can have different values according to the function chosen, it can be positive and negative, or just positive, and it can also be discrete or continuous.

In the model developed it is important to have both positive and negative values, in order to see the sign of the value of activation of the concepts and understand what happens if an input changes its starting value, hence simulating in this way the unavailability of one or more nodes of the system. For the purpose of this model both continuous and discrete functions can be used. It is interesting to see also the differences in the results changing the threshold function, in comparison to the output.

The threshold functions utilized for the model developed in this work are:

- <u>Error function</u>

$$erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt \qquad (4.9)$$

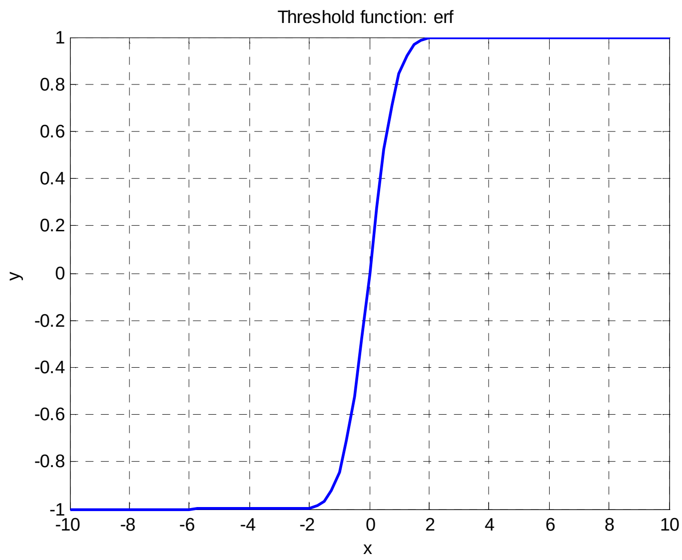


Figure 4.6 Error function representation

– <u>Hyperbolic tangent function</u>

$$tanh(x) = \frac{sinh(x)}{cosh(x)} = \frac{e^x - e^{-x}}{e^x + e^{-x}} \tag{4.10}$$

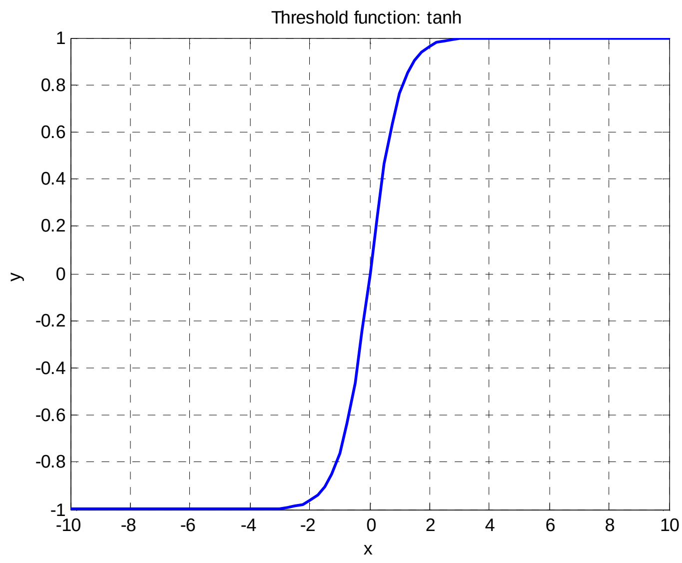


Figure 4.7 Hyperbolic tangent function representation

– <u>Sigmoidal function</u>

$$Y_j = \frac{1 - e^{-\left(\sum_{i=1}^{n} \lambda C_i W_{ij}\right)}}{1 + e^{-\left(\sum_{i=1}^{n} \lambda C_i W_{ij}\right)}} \qquad (4.11)$$

where λ is a constant that determine how fast the output goes from 0 to 1.

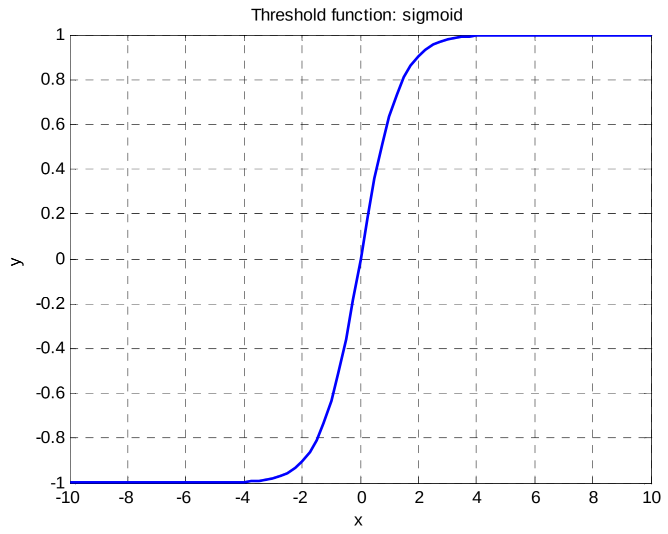


Figure 4.8 Sigmoidal function representation with λ=1.5

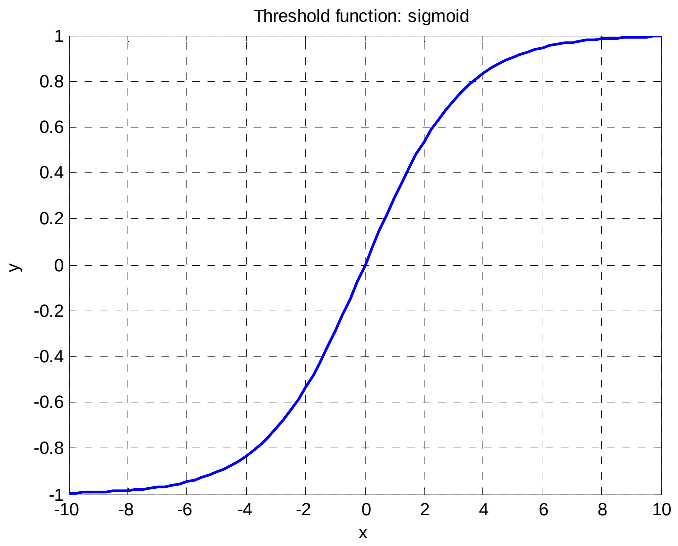


Figure 4.9 Sigmoidal function representation with λ=0.6

– Discrete function

$$f(x) = \begin{cases} +1 & x \leq -a \\ 0 & -a < x < +a \\ -1 & x \geq +a \end{cases} \tag{4.12}$$

where *a* is the value in which the discrete function changes its value and it depends from the system analyzed.

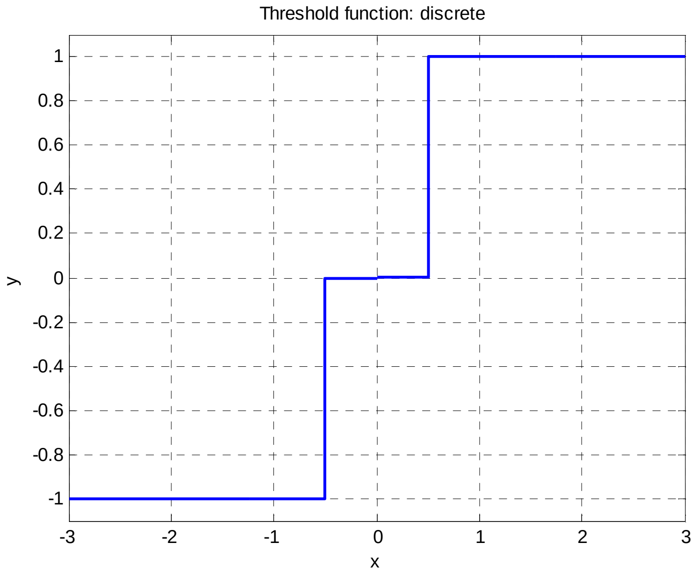


Figure 4.10 Discrete function representation with a=0.5

After choosing a threshold function it is possible to obtain the different vectors representing the new activation values of each concept, which is done through an iterative process. This process will continue until the model (Papageorgiou and Groumpos, 2005) possesses the following:

- reaches equilibrium at a fixed point;
- exhibits limit cycle behavior, with the output values falling in a loop of numerical values under a specific time period;
- exhibit a chaotic behavior, with each output value reaching a variety of numerical values in a nondeterministic way.

The last vector obtained is the final impact that the node, or the nodes, activated during the first step has on the system analyzed by the fuzzy cognitive map.

Moreover, forward simulation is carried out for all the timeframe FCMs and this operation can show not only an instantaneous *domino* effect, but also the reactions of the system considering different time durations of services unavailability.

4.1.5 Methodology Discussion

With this first part of the model a better comprehension of the system can be reached, both considering a static analysis of the nodes and also studying the behavior of the system in case of an input interruption and the cascading effects originated. The usage of the timeframes for the development of more than one FCM permits a larger view on the changes of the phenomenon during time. With this different approach to the FCM, using timeframes, this work tried to overcome the main weakness of this modeling technique, which is the lack of the variable of time. In this way it is also easier to model without any specific data a key resource supply chain, moving closer to the reality.

One of the things that this first part of the model is not able to do is to quantify the loss of service of the studied supply chain due to the disruption or deviation of an input. It can only give a relative value respect all the concepts represented in the map. Having a more clear idea of the system analyzed by this work, in a future study a more quantitative analysis based on the results of this model could be carried out. Another thing that Fuzzy Cognitive Maps are not able to do is to understand where the resources are allocated in the system. This technique cannot analyze the rigidity of nodes and components of the system. In order to improve the quality of the FCMs results another technique is introduced in the methodology: Group Technology clustering algorithm. This second part of the methodology is able to classify the nodes of the system in different resiliency families, adding more information to the results of the first part.

4.2 System Resiliency Analysis through Group Technology Clustering Algorithm

Traditionally Group Technology (GT) has been a manufacturing philosophy in which parts are identified and grouped together in part families, to take advantage of their similarities (Girdhar, 2001). These part families are then grouped together to form production cells with a group of dissimilar machines and processes.

In this work GT is inserted in the model with a different purpose: group together different infrastructures or nodes of the supply chain that have the same “intensity” of impact or response in case of disruption or destruction of parts of the system.

The algorithm chosen to apply the Group Technology in this model is the Rank Order Clustering one. It fits better with the purposes of this part of the methodology, avoiding the concept of ‘similarity coefficient’, used for example in the Single Linkage Clustering algorithm, which cannot be introduced for the case study analyzed, due to the kind of variable considered.

4.2.1 Rank Order Clustering algorithm

The Rank Order Clustering (ROC) algorithm was developed by J.R. King (1980) for the machine-component cells in Group Technology.

This algorithm can be used to obtain groups of objects based on attributes. In this work it will be used to group CIs and supply chain nodes based on their resiliency.

The incidence matrix considered by J.R. King contains just 0-1 entities. If the object i has the attribute j, then the respective matrix element R_{ij} is assumed as 1, otherwise it is assumed as 0.

The steps of ROC algorithm can be listed as follow (Panneerselvam, 2006):

Step 1 - Input: total number of objects, attributes.

Step 2 - Input: object-attributes incidence matrix.

Step 3 - Compute binary equivalent of each row (be_i).

$$be_i = \sum_{j=1}^{m} R_{ij} 2^{m-j} \qquad (4.13)$$

with i is indicated the row considered, j is the column, m the total number of columns and R_{ij} is the value of the incidence matrix for row i and column j.

Step 4 - Rearrange the rows of the matrix in rank-wise (high to low from top to bottom).

Step 5 - Compute binary equivalent of each column (be_j).

$$be_j = \sum_{i=1}^{n} R_{ij} 2^{n-i} \qquad (4.14)$$

with i is indicated the row considered, j is the column, n the total number of rows and R_{ij} is the value of the incidence matrix for row i and column j.

Check whether the columns of the matrix are in rank-wise (high to low from left to right). If not, go to step 6; otherwise go to step 8.

Step 6 - Rearrange the columns of the matrix in rank-wise and compute the binary equivalent of each row.

Step 7 - Whether the rows of the matrix are in rank-wise. If not go to step 4; otherwise, go to step 8.

Step 8 - Output: final object-attribute incidence matrix.

In this work the incidence matrix is the one that comes from the dynamic analysis of the FCMs. The rows of this matrix are the failed concepts, while the columns are the effects on each concept. This means that the numbers contained in the matrix depend on the threshold function chosen and in many cases they are comprised between 0 and 1. For this reason, due to the fact that it is impossible to compute a binary number, a modification of the process has to be considered.

The binary numeral system represents numeric values using two symbols, 0 and 1. More specifically, the usual base-2 system is a positional notation with a radix of 2. The most important bit in a binary representation is the first one on the left side. For example to obtain the binary equivalent of a number (from binary to decimal):

$$(1\ 1\ 0\ 1) = 1 \cdot 2^3 + 1 \cdot 2^2 + 0 \cdot 2^1 + 1 \cdot 2^0 = 13 \qquad (4.15)$$

In order to keep the same concept also in this study, each value in the result's matrix has to be associated to a weight that decrease linearly going from the left to the right, and from the top to the bottom, of the matrix. The value of the weight is the total number of columns plus one, minus the column number considered. In this way, as for obtaining the binary equivalent, the left vector numbers takes more importance than the right ones. For example, having the incidence vector $(0.5\ \ 0.25\ \ 0\ \ 0.78\ \ 0.92)$ and the weight vector $(5\ \ 4\ \ 3\ \ 2\ \ 1)$, the weighted equivalent is:

$$we = 0.5 \cdot 5 + 0.25 \cdot 4 + 0 \cdot 3 + 0.78 \cdot 2 + 0.92 \cdot 1 = 24.48 \qquad (4.16)$$

Given these changes in the algorithm the only two modified steps are 3 and 5, that becomes:

Step 3 new- Compute weighted equivalent of each row (we_i).

$$we_i = \sum_{j=1}^{m} R_{ij}(m + 1 - j) \qquad (4.17)$$

with i is indicated the row considered, j is the column, m the total number of columns and R_{ij} is the value of the incidence matrix for row i and column j.

Step 5 new- Compute weighted equivalent of each column (we_j).

$$we_j = \sum_{i=1}^{n} R_{ij}(n + 1 - i) \qquad (4.18)$$

with i is indicated the row considered, j is the column, n the total number of rows and R_{ij} is the value of the incidence matrix for row i and column j.
Check whether the columns of the matrix are in rank-wise (high to low from left to right). If not, go to step 6; otherwise go to step 8.

4.2.2 Methodology Discussion

Group Technology and in particular the Rank Order Clustering algorithm is used in this work to complete the analysis on the FCMs simulations. This second part of the model, starting from the result's matrix obtained with the dynamic analysis of the maps, facilitate the discussion on the various concepts, supporting the definition of contingency measures. It is able to analyze the rigidity of the different nodes of the system. The final result of this ROC algorithm is a rearrangement of the result's matrix, with a division in families of resiliency.

In the next part of the chapter a complete overview of the methodology is provided, and all the steps of it are listed.

4.3 Overview of the Methodology

The methodology introduced for discriminating critical infrastructures for key resources supply chains can be summarized as in Figure 4.11.

METHODOLOGY		
First part -> Fuzzy Cognitive Map	1 st step	Identification of the system that has to be analyzed and of the purposes of the study
	2 nd step	Definition of the nodes of the system
	3 rd step	Definition of the timeframes
	4 th step	Definition of interdependencies between nodes
	5 th step	Static analysis
	6 th step	Dynamic analysis
Second part -> GT	7 th step	Resiliency analysis

Figure 4.11 Review of the methodology for discriminating CIs for KRSC

The proposed methodology is divided in two different parts: the first one based on Fuzzy Cognitive Maps, and the second one based on Group Technology's algorithms. These two parts are correlated because the second part uses the results of the FCMs analysis to provide a clearer and wider view of the behavior of the system affected by CIs losses. With the GT results resiliency's families will be created and they could be used to plan buffers or new contingency measures based for example on service switching.

In the next chapter a case study is presented. The supply chain studied is the Fast Moving Consumer Goods one, which has been previously introduced in this work. The entire methodology and relative steps are applied in order to understand first of all in a qualitative way which are the most important CIs for the loose of service of this key resource supply chain (Fuzzy Cognitive Maps part) and then to define the system resiliency (Group Technology Algorithm – ROC).

5. Case study: interdependencies analysis of CIs and Fast Moving Consumer Goods supply chain

The supply chain chosen as case study is the Fast Moving Consumer Goods one, with particular attention on perishable goods.

The concept of durability is closely linked to the perishability of a good while the Fast Moving Consumer good is typically related to the concept of a low cost and 'sold quickly' product, examples being foodstuffs, beverages and so forth. Furthermore perishable goods tend to have short shelf life depending on consumer demand and how fast the good deteriorates implying that time becomes a critical operational factor. Hence a certain foodstuff may deteriorate quickly (think of meat) or have a high consumer demand such as toiletries, beverages, pre-packed food and so forth. The time frame of durability and turnover for perishable goods is typically in the order of days to weeks and the combination of these two concepts is crucial in the case study discussed. To this end the analysis discussed herein offers several interesting disruption scenarios affecting CIs and affords the appraisal of the expected consequences on the FMCG supply chain.

FMCGs are identifiable by their features depending if they are seen from the supply side (retailers) or the demand side (consumer), examples being:

- Extensiveness and efficiency of the distribution networks;
- Horizontally differentiated products, e.g. low price, high volumes, low consumer involvement in product selection (excluding brand awareness effects);
- Durability of the products (e.g. shelf life);
- High revenues and high stock turnover;
- Limited storage time.

Further, supply chains are clearly human intensive processes hence decisions are also based on experience and behavioral response to rolling circumstances, often with business intelligence support. This peculiar cognitive behavioral aspect affords the need to handle fuzzy yet definitive knowledge.

In this chapter the model presented is applied to the FMCG supply chain, the first part of the chapter shows how FCMs are constructed and analyzed, while the second part present the Group Technology clustering algorithm application. At least a final discussion on the overall results is done.

5.1 FCM's construction and analysis

The first step of the model described in the previous chapter is applied to the FMCG supply chain, in particular, as said, for perishable goods. All the steps for the construction and analysis of the FCMs are presented and discussed herein.

In the annexes it is possible to find also all the other results and information, not included in the chapter, used to implement the model.

5.1.1 Purpose of the analysis

The FMCG supply chain is an ideal case for the application of FCMs, especially when considering perishable goods. In particular the Italian FMCG supply chain is going to be analyzed. To this end the case study sets out to tackle or investigate two key points in the event of a service disruption (temporary or permanent) affecting one or more CIs:

- the impact of the disruption on the services provided by the CI;
- the resilience of the overall system and relative services.

Using FCM, in particular, it is possible to investigate the *domino* effects that characterize the different nodes and CIs of the studied system.

5.1.2 Definition of the nodes of the system

The conceptual mapping chosen for the construction of the FCMs represents both the CIs or key resources, and the FMCG supply chain nodes.

Figure 5.1 illustrates the concepts selected for the construction of the FCM representing the overall CIs-FMCG supply chain system. They were chosen after brainstorming sessions, in which a list of possible concepts was analyzed and discussed starting from personal experience.

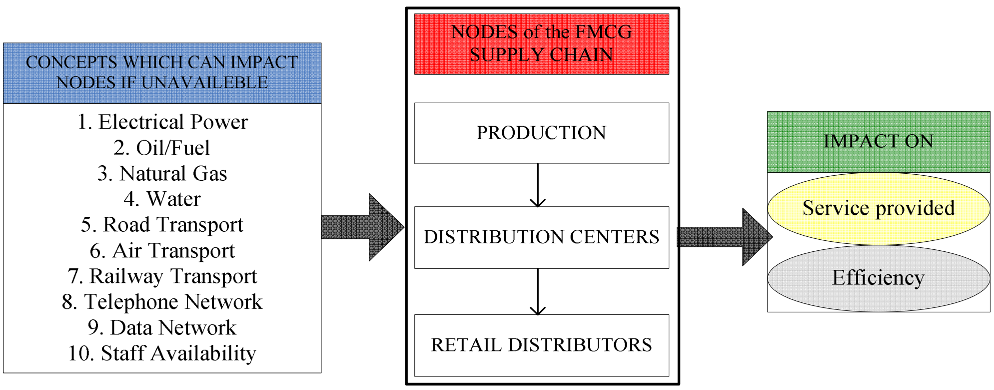


Figure 5.1 Modeling the overall CIs-FMCG supply chain system with FCMs

In particular the case study involves:

- concepts that represent the CIs or key resources which may impact the nodes of the FMCG supply chain, if unavailable, and namely:

    - *C1 – Electrical Power*
      This utility powers electrical equipment, and has to be available within specifications. It is provided by infrastructures and facilities for generation, transmission and distribution of electricity.

    - *C2 – Oil/Fuel*
      This powers vehicles and machinery and may be required for heating. It is provided by infrastructures and facilities for oil production, refining, treatment, storage, transmission and distribution.

    - *C3 – Natural Gas*
      This utility is required for heating, some machinery and vehicles and may also be used by power generation. It is provided by infrastructures and facilities for production, refining, treatment, storage, transmission and distribution of natural gas.

    - *C4 – Water*
      This utility provides both fresh water (for drinking, cooling, etc.) and also includes wastewater and drainage. It is provided by facilities for water production and distribution, sours, drainage systems (storm sewers, ditches, etc...), major irrigation systems (reservoirs, irrigation canals) and major flood control systems.

    - *C5 – Road Transport*
      This service provides the transport of goods and people by roads, it is provided by the road network infrastructure and vehicles. Vehicles include automobiles, buses, motorcycles, and all types of trucks.

    - *C6 – Air Transport*
      This service provides the transport of goods and people by air. It is provided by aircraft, air traffic control infrastructure, and airport infrastructure.

- *C7 – Railway Transport*
  This service provides the transport of goods and people by rail. It is provided by railway infrastructure, freight cars, and locomotives.
- *C8 – Telephone Network*
  This service provides voice and fax communication. It is provided by telephone networks including switching systems and involves both fixed and mobile telephony.
- *C9 – Data Network*
  This service provides data communication. It may be provided by the same infrastructure as telephony, but may also involve other systems such as cable, or wireless. It includes communication between computer systems, such as internet connections, e-mail, and proprietary protocols.
- *C10 – Staff Availability*
  This is the human workforce.

– nodes of the FMCG supply chain, which are impacted by the unavailability of the previously mentioned concepts, thus showing a reduction in product delivery performance (disturbances or disruptions in business continuity), estimated in terms of service level and efficiency reductions. More specifically the model contemplates:

- *C11 – Production*
  All the activities and operations that transform or process “raw” materials (in this case perishable goods coming from suppliers) into the final product purchased by the customer.
- *C12 – Distribution Centers*
  Stock facility which stores and redistributes products intended for sale. There are two different levels of Distribution Centers: central and peripheral.
- *C13 – Retail Distributors*
  It includes large retailers, that have a central structure and they have a direct control on the distribution centers and the sales network, and also the organized retailers formed by consortium or voluntary union.

5.1.3 *Timeframes*

In order to develop time dependent scenarios, i.e. timeframe FCMs, three temporal frames have been defined:

- *1 day*: for 1 day the concept C_i (cause concept) is unavailable;
- *4 days*: for 4 days the concept C_i (cause concept) is unavailable;
- *3 weeks*: for 3 weeks the concept C_i (cause concept) is unavailable.

The temporal frames have been set given the specific features of the supply chain in question and reflected typically in business continuity plans.

In general, for the FMCG supply chain 1 day disruption is considered as being valuable to understand the immediate impact on the sector.

A temporal frame of 4 days is considered as being the standard time period for which the most common contingency plans are adopted or ideated by the operators. The longest temporal frame i.e. 3 weeks, reflects the average stock turnover of perishable goods for producers and distribution centers. Indeed research conducted by BCG-ECR (1996) reports the differences in stock (expressed in days) by the producer and distributor (see Figure 5.2).

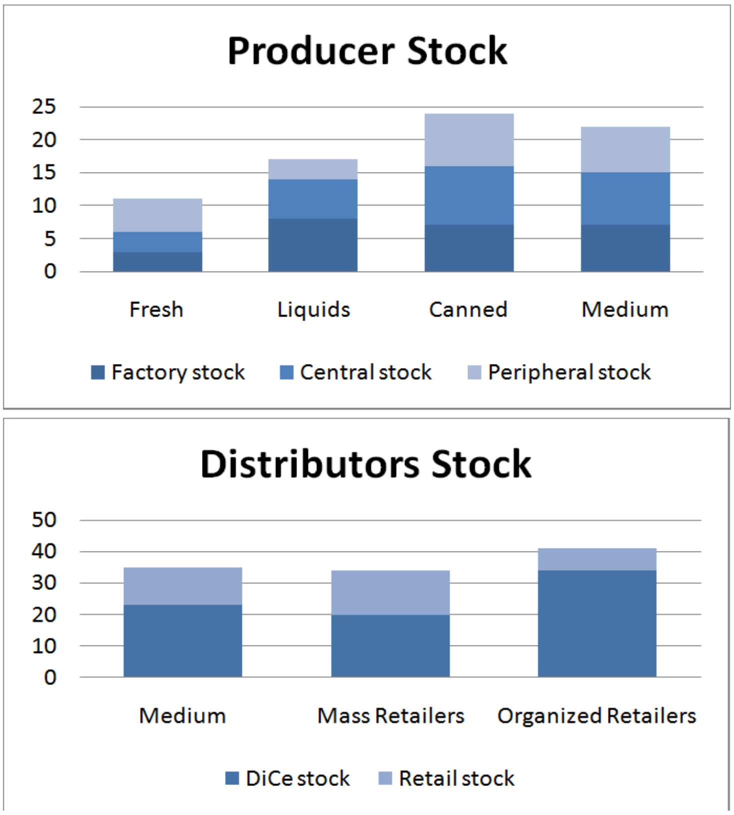


Figure 5.2 Producer and Distributor Stocks expressed in days (BCG-ECR Italia, 1996)

5.1.4 Definition of interdependencies between nodes

The use of fuzzy logic requires a fuzzy set, its membership functions and linguistic variables, to convert the experts' linguistic judgments into real numbers and comprised within the set [-1, 1]. Each fuzzy set can assume a different value between 0 and 1, and membership functions are associated to each fuzzy set.

Usually these membership functions are triangular or trapezoidal in shape, but they can also have irregular shapes. This study uses fuzzy set with triangular membership functions because this shape fits and describe better in and around a value. Moreover the dimensions of membership functions are different from each other and they depend from the direct meaning that they assume in the case study.

The linguistic variables chosen for this work are:

- T = total;
- S = strong;
- W = weak;
- N = negligible;
- *NULL*. This value in particular is a discrete value (no causal relationship between concepts); due to its discreteness it has not been associated any membership function.

As it can be seen, excluding the discrete value *NULL*, an even number of variables were chosen, in order to avoid that the experts express a safer opinion choosing the average value, without considering the real effect.

The definition of the fuzzy set used for this case study, with all the linguistic variables and their membership functions, is shown in Figure 5.3.

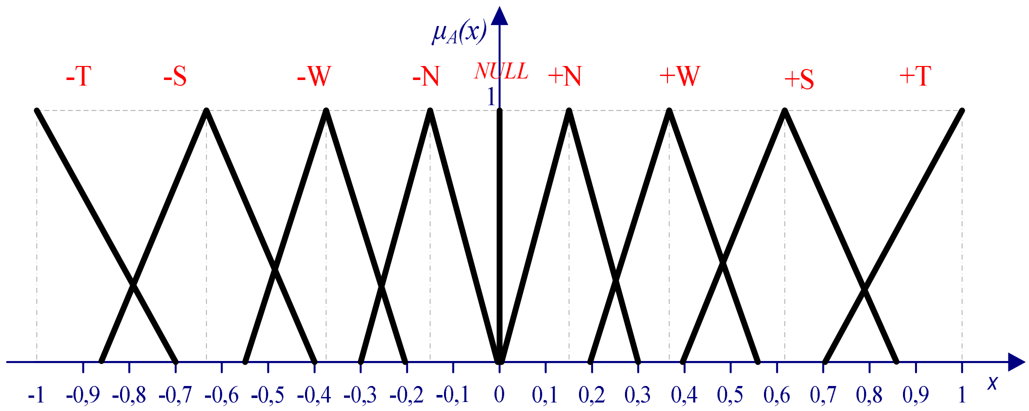


Figure 5.3 Assignment of linguistic variable values used in the modeling

In order to define the causal relationships between the 13 concepts chosen for the case study, FMCG supply chain, experts' judgment is needed and it is obtained through questionnaires.

The questionnaire used during the interviews, and fully reported in Appendix A, essentially directly represents the adjacency matrix for the 13 concepts and the three time frames. An expert has to insert into this matrix a single 'X' for each timeframe (*1 day – 4 days – 3 weeks*). The correlation between concepts could be expressed according to the predefined linguistic values: negligible (N) (i.e. something happen but it is not relevant), weak (W), strong (S), total (T), or *NULL*. The sign of the correlation had to be added in the '*Trend*' row. Though this lead to 13x12x4 questions, not all experts were asked about all correlations; their knowledge would only address part of the system anyway (Figure 5.4).

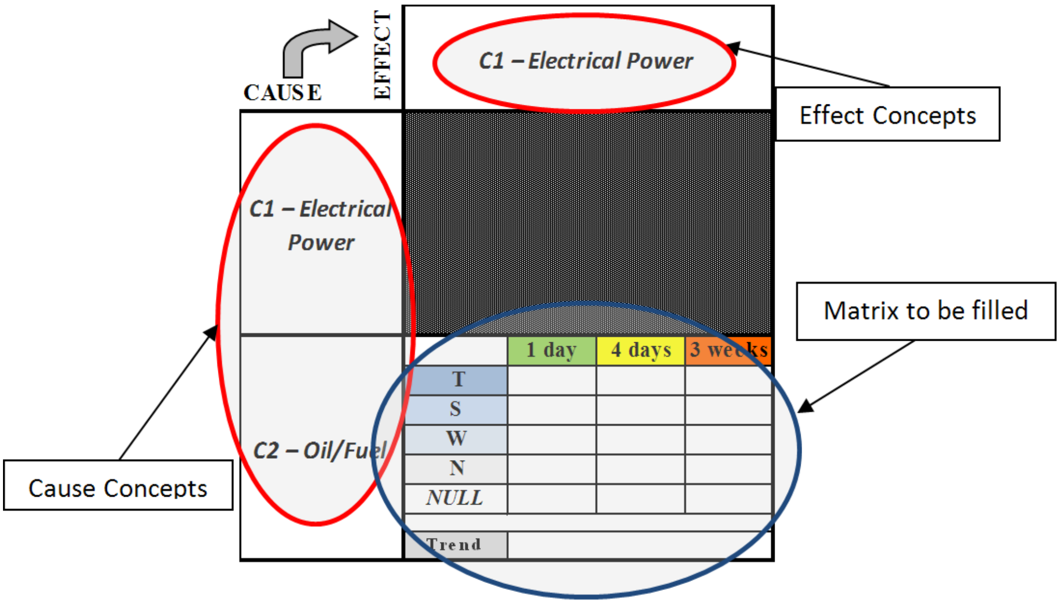


Figure 5.4 Excerpt from 13x13 matrix showing boxes to be ticked by expert. One box in each timeframe column, one + or – for the sign

The fourteen experts (Appendix B) interviewed for this study were therefore subdivided in two competence groups; one group on CIs, and one group on FMCG. There were 9 experts in the CI group, 3 university professors, and 6 experts from the European Commission. In the FMCG there were 2 university professors, and 3 directors from major FMCG companies. Each expert has experience numbers related to all the concepts analyzed by the questionnaire. They can be: 1 (low experience), 2 (medium experience) or 3 (high experience).

- *Yellow part*: 9 CI experts;
- *Blue part*: 5 FMCG experts;
- *Green part*: 14 experts (this concerns workforce);
- *Grey part*: 0 experts, *NULL* by assumption;
- Some experts could not answer questions on ranges of cells.

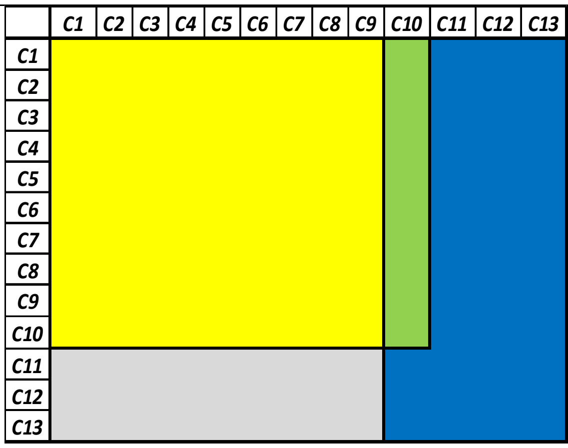


Figure 5.5 Subdivision in competences groups

The questionnaires were presented during interviews. The interview would offer explanation, ensure consistency, check for expertise, and make notes about remarks made by the experts additional to the matrix.

The data obtained through the questionnaires was processed with MATLAB using the theoretical framework presented in the previous chapter. Appendix C contains the executable m-file (Link_Matrix_Construction.m), which takes as input all the answers of the experts and their experience number and gives as output the entire matrix of causal relationships (*W*). For each causal relationship a table like the one showed in Table 5.1 can be done, and its information is used in running the MATLAB code.

Causal relationship $C_i \rightarrow C_j$				
Expert	***Trend***	***Linguistic variable***	***Fuzzy number***	***Experience number (λ)***
e_1	+	total	(0.7 1 1)	2
e_2	+	weak	(0.2 0.375 0.55)	1
…	…	…	…	…
e_n	+	strong	(0.4 0.625 0.85)	3

Table 5.1 Review of the results coming from the questionnaires for each causal relationship

Considering the causal relationship between concept 8 (telephone network) and concept 13 (retail distributors), 5 experts gave their judgments on the existing direct dependency. The example of the mathematical process that is done by the m-file is reported herein.

Causal relationship $C_8 \rightarrow C_{13}$ (1 day)					
Expert	***Trend***	***Linguistic variable***	***Fuzzy number (a)***	***Experience number (λ)***	***Expert weight (ew)***
e_1	+	negligible	(0 0.15 0.3)	3	0.2
e_2	+	weak	(0.2 0.375 0.55)	3	0.2
e_3	+	strong	(0.4 0.625 0.85)	3	0.2
e_4	+	weak	(0.2 0.375 0.55)	2	0.1
e_5	+	weak	(0.2 0.375 0.55)	3	0.2

Table 5.2 Example of evaluation of the expert elicitation through questionnaires

The next step is the calculation of the weighted mean of the fuzzy number:

$$\bar{A}_w = \left(\sum_{i=1}^{n} ew_i a_1^{(i)}, \sum_{i=1}^{n} ew_i a_M^{(i)}, \sum_{i=1}^{n} ew_i a_M^{(i)} \right) = (0.2 \quad 0.38 \quad 0.56) \qquad (5.1)$$

At the end the defuzzification process, using the centroid method, gives the final value of the causal relationship $C_8 \rightarrow C_{13}$.

$$x_C = \frac{\int \mu(x) x dx}{\int \mu(x) dx} = \frac{\int \mu(x) x dx}{Area} = \frac{0.026}{0.068} = 0.380 \qquad (5.2)$$

5.1.1 FMCG supply chain FCMs

The MATLAB software developed uses the approach described in the previous example and is able to aggregate all the expert elicitations for all the three timeframes, giving as final result three adjacency matrixes ($W_{1\text{day}}$, $W_{4\text{days}}$, $W_{3\text{weeks}}$). In Table 5.3 is reported the adjacency matrix for the timeframe '1 day', in rows are represented the cause concepts, while in the columns the effects concepts. The other adjacency matrixes are in Appendix D.

1 DAY

	C1 Electrical Power	C2 Oil/Fuel	C3 Natural Gas	C4 Water	C5 Road Transport	C6 Air Transport	C7 Railway Transport	C8 Telephone Network	C9 Data Network	C10 Staff Availability	C11 Production	C12 Distribution Centers	C13 Retail Distributors
C1 Electrical Power	0	0,758	0,688	0,685	0,394	0,630	0,900	0,612	0,630	0,209	0,175	0,105	0,504
C2 Oil/Fuel	0,257	0	0,127	0,030	0,190	0,361	0,134	0	0	0,024	0	0,060	0,102
C3 Natural Gas	0,284	0,118	0	0,015	0,115	0,116	0,043	0	0	0,135	0,175	0,060	0,086
C4 Water	0,304	0,246	0,162	0	0,115	0,123	0,107	0,023	0,021	0,135	0,125	0,060	0,166
C5 Road Transport	0,122	0,295	0,127	0,090	0	0,580	-0,282	0,035	0,032	0,702	0,375	0,475	0,464
C6 Air Transport	0	0	0	0	-0,058	0	-0,155	0	0	0,106	0	0	0
C7 Railway Transport	0,016	0,283	0,069	0,015	-0,446	-0,157	0	0	0	0,336	0,125	0,030	0
C8 Telephone Network	0,414	0,364	0,332	0,235	0,225	0,402	0,398	0	0,436	0,222	0,383	0,335	0,380
C9 Data Network	0,784	0,630	0,673	0,283	0,263	0,900	0,743	0,752	0	0,195	0,725	0,590	0,529
C10 Staff Availability	0,900	0,802	0,858	0,588	0,562	0,900	0,900	0,296	0,348	0	0,900	0,690	0,900
C11 Production	0	0	0	0	0	0	0	0	0	0	0	0,271	0,041
C12 Distribution Centers	0	0	0	0	0	0	0	0	0	0	0,300	0	0,230
C13 Retail Distributors	0	0	0	0	0	0	0	0	0	0	0,175	0,462	0

Table 5.3 Adjacency matrix W of the FCM for the timeframe '1 day'

As it is possible to see in Figure 5.6 the diagonal of the adjacency matrix is equal to 0, because a concept is not able to influence itself (as introduced in the hypothesis). The matrix is built as the questionnaire and it can be read in the same way, for example: the unavailability of C1 for 1 day has a direct influence on C4, and the intensity of this relationship is +0.685.

Figure 5.6 provides a visual representation of the FCM for a one day timeframe, where each arrow is associated to its corresponding value in the adjacency matrix (W_{ij}). The FCMs for the other two timeframes are inserted in Appendix D.

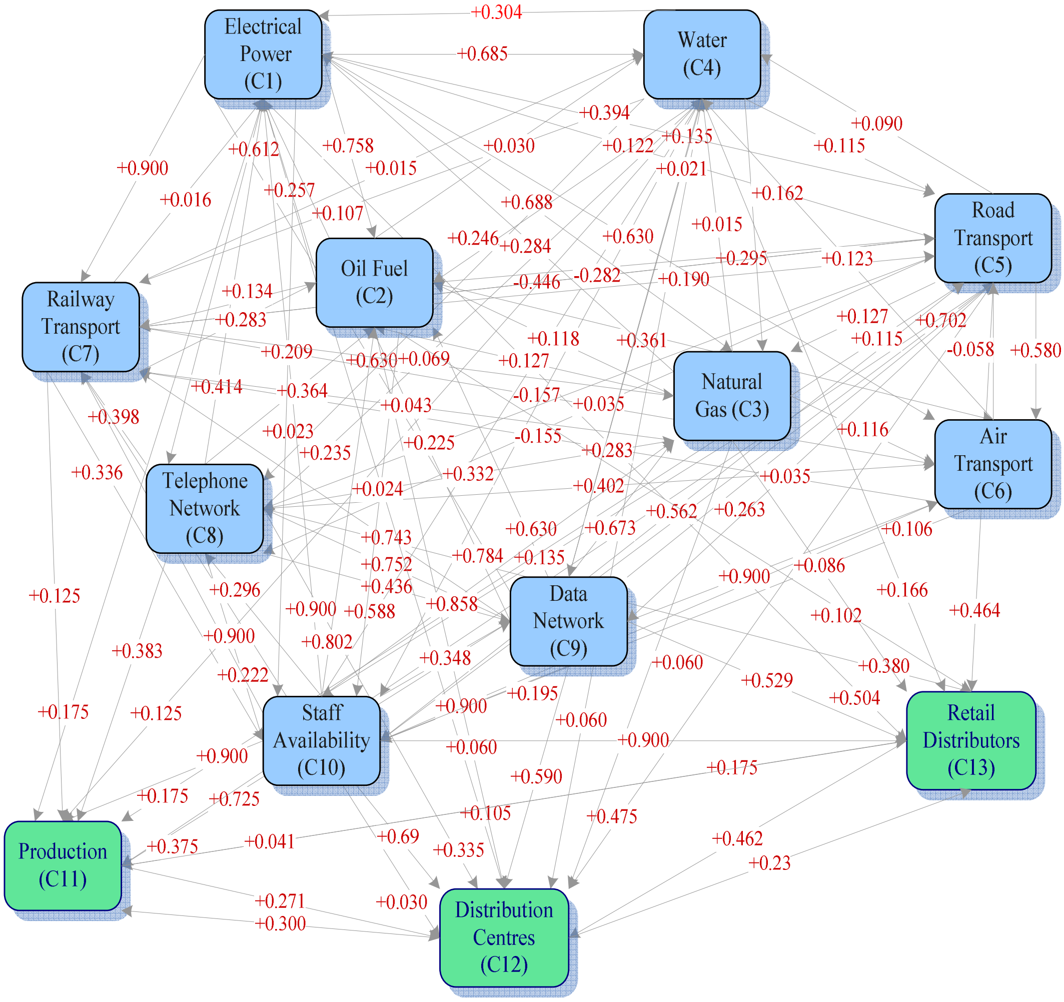


Figure 5.6 Fuzzy Cognitive Map for timeframe 1 (t = 1 day)

5.1.2 Static analysis

Table 5.4 shows the results of the static analysis for each timeframe, including in-degree (*id*), out-degree (*od*), total degree (*td*) and the difference in percentage of the *td* for subsequent timeframes. All of the concepts used for the FMCG supply chain case study are included.

Concept	Describtion	1 day			4 days			td(Ci) % difference 1day-4days	3 weeks			td(Ci) % difference 4days-3weeks
		$id(C_i)$	$od(C_i)$	$td(C_i)$	$id(C_i)$	$od(C_i)$	$td(C_i)$		$id(C_i)$	$od(C_i)$	$td(C_i)$	
C1	Electrical Power	3.1	6.3	9.4	3.8	8.4	12.1	22.8	4.1	8.9	13.0	6.8
C2	Oil/Fuel	3.5	1.3	4.8	4.1	2.7	6.8	29.5	4.4	3.9	8.3	18.7
C3	Natural Gas	3.0	1.1	4.2	3.6	1.7	5.3	20.6	3.6	2.8	6.4	18.1
C4	Water	1.9	1.6	3.5	2.3	2.9	5.2	32.6	2.8	4.4	7.2	26.9
C5	Road Transport	2.4	3.6	5.9	3.2	5.3	8.5	30.1	3.6	6.3	9.9	14.4
C6	Air Transport	4.2	0.3	4.5	5.0	0.6	5.6	20.4	5.5	1.2	6.8	16.5
C7	Railway Transport	3.7	1.5	5.1	4.1	1.7	5.9	12.2	4.3	2.0	6.3	6.6
C8	Telephone Network	1.7	4.1	5.8	2.3	4.9	7.2	18.6	2.6	5.1	7.7	6.8
C9	Data Network	1.5	7.1	8.5	2.0	7.9	9.9	13.9	2.5	7.9	10.4	4.4
C10	Staff Availability	2.1	8.6	10.7	2.5	9.1	11.6	8.1	3.1	9.6	12.7	8.4
C11	Production	3.5	0.3	3.8	5.2	1.0	6.1	38.6	7.7	1.6	9.4	34.5
C12	Distribution Centers	3.1	0.5	3.7	5.0	1.1	6.1	40.2	6.3	1.7	8.0	23.6
C13	Retail Distributors	3.4	0.6	4.0	5.4	1.1	6.5	37.7	6.7	1.7	8.4	23.2
TOTAL		37.0	37.0	74.0	48.5	48.5	96.9	23.6	57.3	57.3	114.5	15.4

FCM Density (1 DAY)	69.9 %	→	R = 109
FCM Density (4 DAYS)	70.5 %	→	R = 110
FCM Density (3 WEEKS)	75.6 %	→	R = 118

Table 5.4 Summary results of the static analysis

The *id* and *od* values respectively show the most vulnerable "concepts" in the system and which influence the most. Total degree values considers both factors and may be used to rate the importance of each node in the system.

Based on total degree, the two most important concepts in all timeframes are staff availability (C10) and electrical power (C1), in particular for a 1 day disruption C10 is strongest, while for 4 days and 3 weeks C1 is predominant in the map.

If one focuses only on a 1 day disruption then the most vulnerable services are air transport (C6) and railway transport (C7); with their lowest values of *id* (4.2 and 3.7), while the most influential sector with the highest *od* value, is staff availability (8.6) followed by data network (C9) with a value of 7.1. Looking at the three concepts that represent the nodes of the FMCG supply chain it can be see that the most vulnerable nodes is the production one while the more flexible is the distribution center. These three nodes do not really affect the overall system of critical infrastructures; they only have a little impact on it (C11 → 0.3, C12 → 0.5 and C13 → 0.6).

For the other two timeframes the same reasoning can be applied, but these show different concepts as most vulnerable or influential. In particular for 4 days the most vulnerable concept is the retail distributor node (C13) with *id*=5.4; while the most influential one is still staff availability (C10) followed this time by electrical power (C1). For 3 weeks the main difference compared with the previous temporal frame is in the most vulnerable concept, which is in this case the production node (C11).

The percentage difference between *td* of different timeframes facilitates the understanding of the increase or decrease of the importance of a concept while a disruption continues. For example, between 4 days and 3 weeks the critical infrastructure that gains more importance is the water network ($\%td_{4d\text{-}3w}$ = 26.9%), while if one considers the nodes of the supply chain the production node gains more ($\%td_{4d\text{-}3w}$ = 34.5%).

Another index that provides useful insights is the FCM density. It can be observed that increasing the time duration of the event the density of the FCM increases, rising from 69.9% to 75.6% (the number of relationships (R) start from a value of 109 and reach 118). This means that the level of interdependency between critical infrastructures and the nodes of the FMCG supply chain increases, with an escalation of cascading effects for longer crisis events.

According to the previously explained classification of types' concepts from Bougon et al. (1977), all the concepts introduced in this work are ordinary variables, with both a non-zero indegree and outdegree. However, an accurate analysis of the numbers shows that C6, C11, C12 and C13 have *od* values really close to zero, in particular for the first timeframe. They rarely influence the other concepts and so they can be considered somehow receiver variables.

Other consideration on the FCMs and the intensity of their causal relationships can be done. Using MATLAB (Appendix C – PieCharts.m –) it is possible to realize pie charts (Figure 5.7) that represent the distribution, in the different FCMs, of the intensity of the causal relationships (considering absolute values). Five classes of intensity are considered:

- $W_{ij} < 0.2$
- $0.2 \leq W_{ij} < 0.4$
- $0.4 \leq W_{ij} < 0.6$
- $0.6 \leq W_{ij} < 0.8$
- $0.8 \leq W_{ij} \leq 1$

These charts and their percentages show how the intensities of the causal relationship are subdivided for the three timeframes and how they change going from a timeframe to another. Analyzing Figure 5.7 it is clear how the majority of the concepts have small direct causal relationships between each other: 62% for 1 day and still 47% for 3 weeks disruptions. It is also important to notice that for 3 weeks the second most important class becomes the highest one ($0.8 \leq W_{ij} \leq 1$), which means that a lot of experts, in order to quantify the intensity of relationships, answer 'Total' in the questionnaires. It is possible to say that the starting points of the scenarios change from a frame to another just looking at the direct causal relationships, without taking into consideration the *domino* effects, which will be analyzed by the forward simulation in the next part of the chapter.

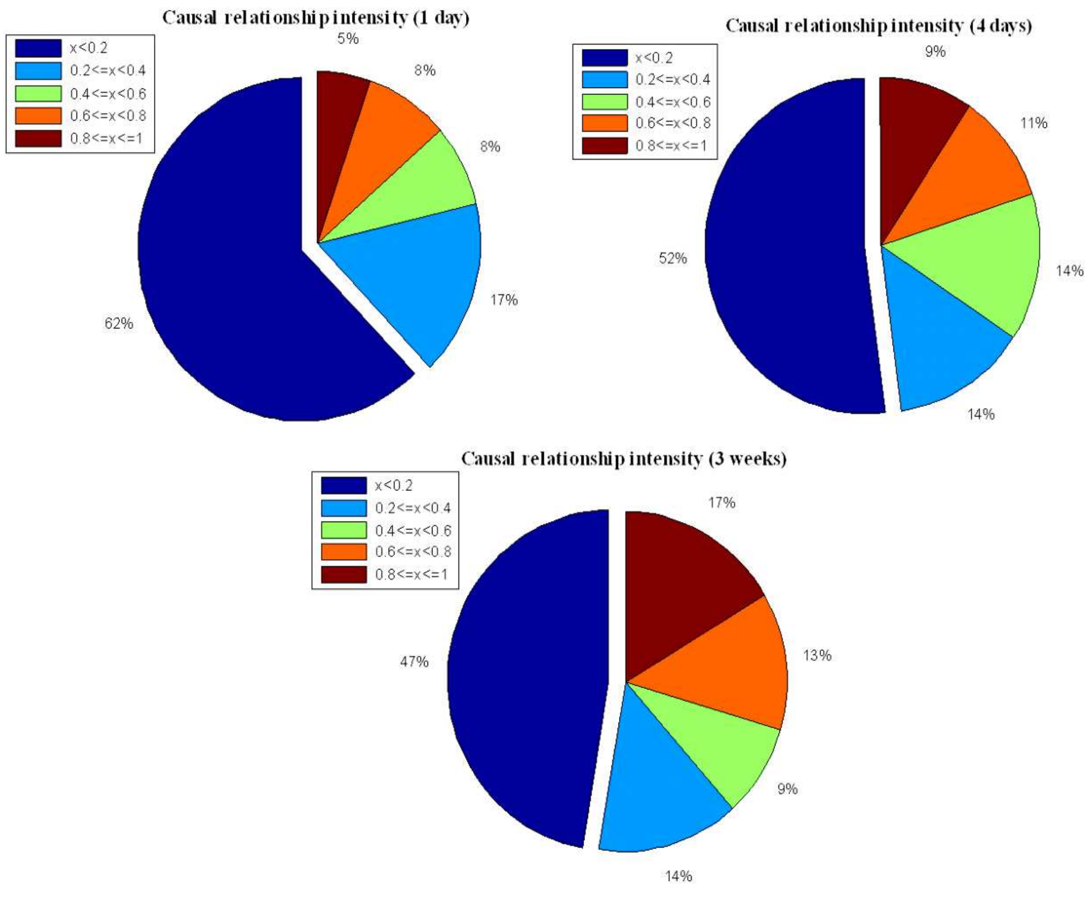


Figure 5.7 Distribution of the intensity of the causal relationships in the different FCMs

5.1.3 Dynamic analysis

The dynamic analysis (forward simulation) is based, for this case study, on two different threshold functions:

- continuous threshold function as the sigmoid function (with λ=0.6);
- discrete threshold function (with a=0.5).

This analysis is able to represent the *domino* effects that characterize a system when one of its nodes is perturbed, or as in this work destructed or disrupted. Each concept has been activated and the effects of this activation have been reported and discussed in this chapter. The results illustrated consider both the elementary failure scenario, with single concept activation, and the complex failure scenario (only using the sigmoid threshold function), with two concept activations.

The dynamic analysis is performed using the MATLAB's executable 'FCM_analyses.m' that is reported in Appendix C. Appendix D shows all the results obtained from the dynamic analysis and not included in this part.

Continuous threshold function – Elementary Failure Scenario –

The sigmoid function tends to attenuate only small correlations and to saturate very strong correlations, but which also allows continuous evaluation of the correlations. This seems to best agree with reality, where resource problems only proliferate if they are serious, and with the hypothesis of linear functions assumed by some other CI interdependency modeling techniques, e.g. Haimes et al. (2005) or Cagno et al. (2010). The error function and hyperbolic tangent exacerbate smoothing and saturation phenomena, yielding unrealistic results.

In particular the sigmoid threshold function with a λ of 0.6 exposes effect propagation of service loss through the system. The numeric results (activation levels) express the level of disruption due to *domino* effects following an initial loss.

Accordingly to the theory, the calculation process for the dynamic analysis starts with the definition of a state vector $C(k)$ in which k is the iteration step and the i^{th} concept is activated ($C_i(0) = 1$). As example it is possible to think that there is a disruption of the electrical power infrastructure (C1), so the state vector can be defined as:

$$C(0) = [1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]$$

After having defined $C(0)$ this is multiplied with the adjacency matrix W and finally the threshold function chosen is applied to the result.

$$C(0) \cdot W =$$
$$= [0 \quad 0.76 \quad 0.69 \quad 0.69 \quad 0.39 \quad 0.63 \quad 0.90 \quad 0.61 \quad 0.63 \quad 0.21 \quad 0.18 \quad 0.11 \quad 0.50]$$

$$C_{new}(1) = f\,[C(0) \cdot W] =$$
$$= [1 \quad 0.22 \quad 0.20 \quad 0.20 \quad 0.12 \quad 0.19 \quad 0.26 \quad 0.18 \quad 0.19 \quad 0.06 \quad 0.05 \quad 0.03 \quad 0.15]$$

In the new concept vector the activated concept C1, after the threshold function (*f*) application, is always considered equal to 1. The operation described before is iterated till the convergence point is reached ($C(k+1) = C(k)$). In the example it is reached after 10 iterations, and the final result is:

$$C_{new}(10) =$$
$$= [1 \quad 0.41 \quad 0.36 \quad 0.28 \quad 0.17 \quad 0.40 \quad 0.39 \quad 0.25 \quad 0.24 \quad 0.21 \quad 0.29 \quad 0.26 \quad 0.34]$$

Figure 5.8 and Figure 5.9 are reported below in order to show the behavior of concepts having a disruption or destruction, during the application of the mathematical process used in the dynamic analysis, before the application of the threshold function. Figure 5.8 represents the values of all the concepts in the different steps of the simulation (timeframe ‘1 day’), having the activation of ‘electrical power’ (C1); while Figure 5.9 represents the values for the timeframe ‘4 days’ that correspond to the activation of ‘air transport’ (C6).

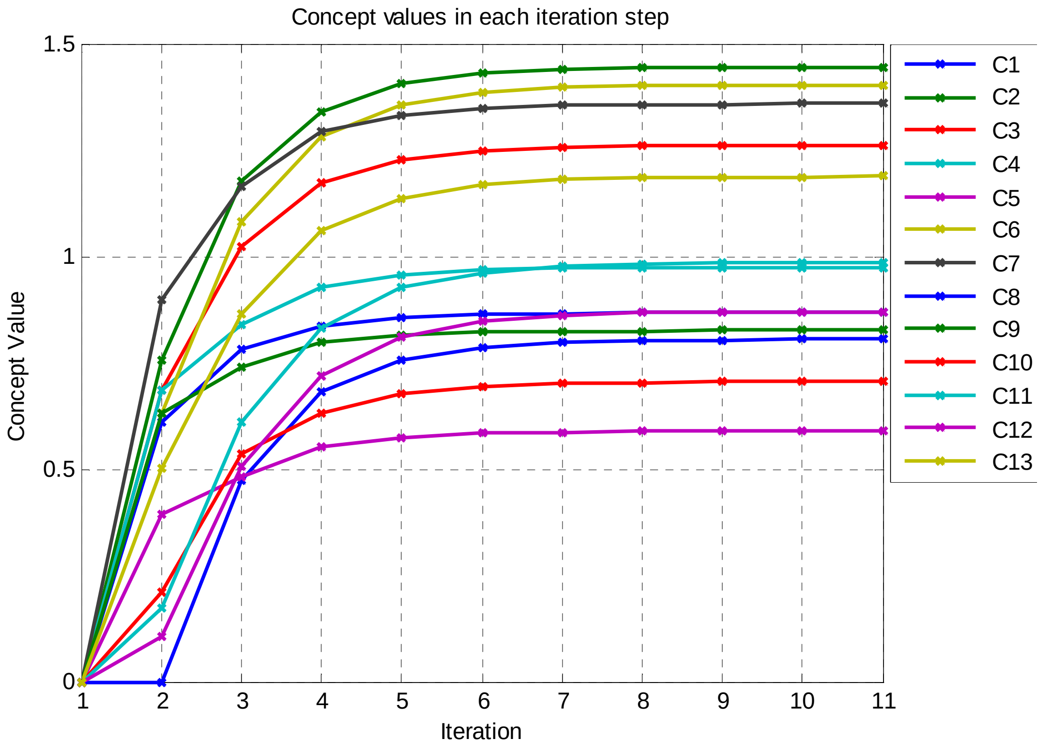


Figure 5.8 Values of the concepts for each iteration step of the mathematical process, for the activation of C1 (t = 1 day)

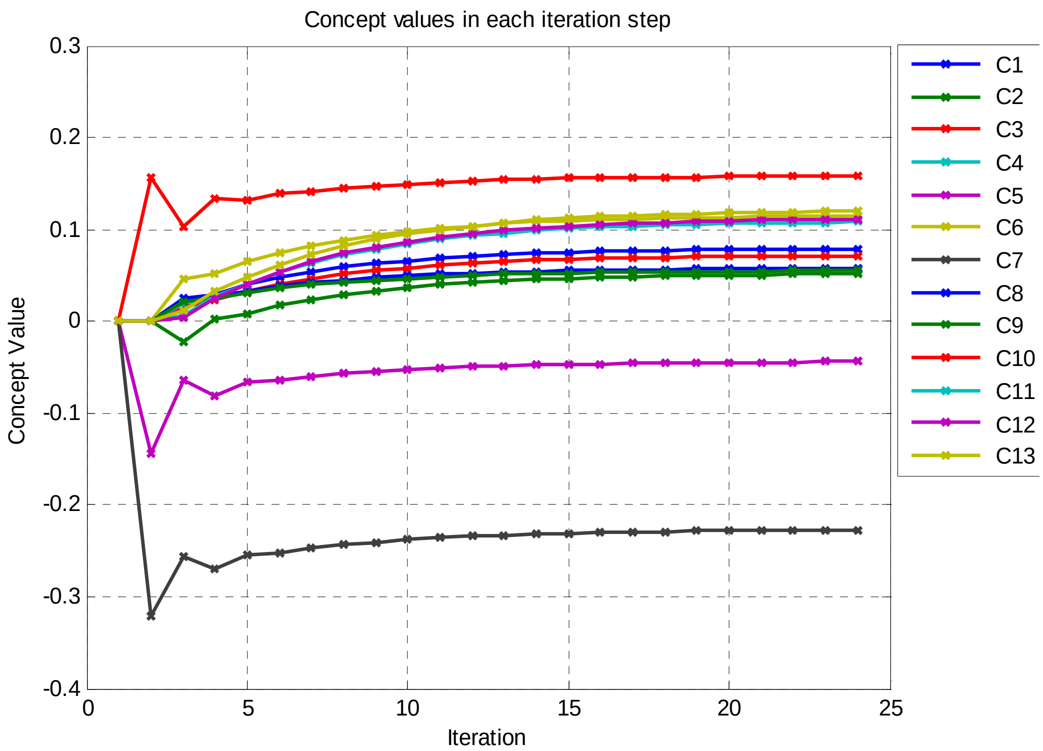


Figure 5.9 Values of the concepts for each iteration step of the mathematical process, for the activation of C6 (t = 4 days)

Analyzing the two previous figures, it can be seen that the number of iteration steps is really different: 11 for the activation of C1 (1 day) and 24 for the activation of C6 (4 days). This difference is explained by the values of out-degree obtained by the static analysis: the electrical power has od_{1day} = 6.3, while the air transport one is od_{4days} = 0.6. A high value of *od*, as explained in the theory part, means a high influence of the concept on all the others, while a low value is the opposite. Having a low impact on the other concepts, the disruption of ‘air transport’ needs more iterations to spread the effect on the system. Considering the ‘electrical power’ and its disruption, the effects are immediate, due to the high influence that this concept has on the entire FMCG supply chain and on critical infrastructures. Figure 5.8 shows this high influence, with a strong slop of the curve for the first 3 steps of the process.

It is important to underline that the behavior of the concepts described to these figures are strictly dependent to the threshold function chosen for the dynamic analysis. For every threshold function the number of iterations is different and some changes in the shape of the curve can be seen.

In Table 5.4 all the numerical results of three timeframes are provided. The simulations have been repeated with 13 different starting vectors, in which each represents a complete disruption of another single concept (activation level = 1), the other services not disrupted (activation levels = 0). The results of these 13 simulations are presented in a 13x13 matrix of which the rows are the result vectors.

1 DAY														
sigmoid function (λ=0.6)		Effect on the concept C_i												
		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
Failure of the concept C_i	C1	1	0.408	0.361	0.284	0.175	0.398	0.386	0.255	0.243	0.208	0.287	0.255	0.342
	C2	0.120	1	0.094	0.051	0.076	0.172	0.087	0.036	0.034	0.055	0.063	0.075	0.094
	C3	0.139	0.116	1	0.058	0.067	0.122	0.083	0.043	0.042	0.084	0.122	0.089	0.104
	C4	0.164	0.171	0.135	1	0.075	0.146	0.117	0.059	0.056	0.097	0.127	0.106	0.143
	C5	0.179	0.232	0.180	0.125	1	0.330	0.062	0.085	0.082	0.257	0.270	0.288	0.291
	C6	0.013	0.010	0.012	0.009	-0.004	1	-0.032	0.006	0.006	0.030	0.012	0.011	0.013
	C7	0.050	0.119	0.063	0.033	-0.099	-0.006	1	0.021	0.021	0.090	0.070	0.035	0.034
	C8	0.283	0.305	0.270	0.185	0.137	0.326	0.278	1	0.203	0.182	0.301	0.277	0.296
	C9	0.404	0.420	0.393	0.236	0.168	0.479	0.398	0.312	1	0.220	0.423	0.380	0.383
	C10	0.428	0.459	0.430	0.302	0.233	0.486	0.422	0.217	0.215	1	0.463	0.414	0.462
	C11	0	0	0	0	0	0	0	0	0	0	1	0.084	0.018
	C12	0	0	0	0	0	0	0	0	0	0	0.093	1	0.070
	C13	0	0	0	0	0	0	0	0	0	0	0.065	0.143	1

4 DAYS														
sigmoid function (λ=0.6)		Effect on the concept C_i												
		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
Failure of the concept C_i	C1	1	0.539	0.499	0.395	0.306	0.589	0.397	0.390	0.374	0.343	0.629	0.628	0.681
	C2	0.270	1	0.232	0.155	0.270	0.415	0.132	0.134	0.127	0.177	0.376	0.366	0.375
	C3	0.295	0.252	1	0.152	0.155	0.296	0.150	0.143	0.136	0.196	0.342	0.367	0.390
	C4	0.340	0.330	0.296	1	0.181	0.347	0.197	0.172	0.164	0.232	0.493	0.456	0.508
	C5	0.336	0.417	0.321	0.232	1	0.498	0.054	0.205	0.194	0.334	0.583	0.600	0.599
	C6	0.024	0.015	0.021	0.017	-0.013	1	-0.068	0.017	0.016	0.047	0.032	0.033	0.036
	C7	0.093	0.155	0.114	0.051	-0.085	0	1	0.047	0.045	0.086	0.097	0.090	0.092
	C8	0.443	0.468	0.441	0.291	0.263	0.513	0.312	1	0.318	0.316	0.593	0.604	0.623
	C9	0.552	0.561	0.529	0.353	0.310	0.627	0.419	0.409	1	0.343	0.686	0.685	0.693
	C10	0.556	0.578	0.546	0.395	0.360	0.637	0.427	0.377	0.361	1	0.710	0.711	0.732
	C11	0	0	0	0	0	0	0	0	0	0	1	0.197	0.159
	C12	0	0	0	0	0	0	0	0	0	0	0.182	1	0.192
	C13	0	0	0	0	0	0	0	0	0	0	0.150	0.240	1

3 WEEKS														
sigmoid function (λ=0.6)		Effect on the concept C_i												
		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
Failure of the concept C_i	C1	1	0.617	0.555	0.487	0.357	0.692	0.417	0.469	0.460	0.478	0.894	0.823	0.845
	C2	0.483	1	0.398	0.330	0.369	0.616	0.234	0.301	0.293	0.364	0.820	0.739	0.741
	C3	0.508	0.452	1	0.322	0.269	0.556	0.257	0.306	0.298	0.397	0.819	0.725	0.754
	C4	0.524	0.516	0.449	1	0.311	0.595	0.303	0.334	0.325	0.439	0.868	0.784	0.805
	C5	0.520	0.593	0.464	0.389	1	0.670	0.155	0.369	0.358	0.485	0.885	0.834	0.842
	C6	0.102	0.087	0.088	0.076	-0.007	1	-0.030	0.080	0.078	0.123	0.300	0.255	0.239
	C7	0.297	0.341	0.283	0.207	0.048	0.262	1	0.186	0.181	0.259	0.604	0.514	0.519
	C8	0.574	0.584	0.532	0.438	0.334	0.659	0.365	1	0.445	0.467	0.870	0.815	0.835
	C9	0.644	0.637	0.586	0.478	0.360	0.723	0.439	0.492	1	0.481	0.902	0.848	0.859
	C10	0.649	0.658	0.597	0.510	0.417	0.735	0.443	0.496	0.483	1	0.914	0.859	0.873
	C11	0.126	0.128	0.112	0.091	0.072	0.158	0.072	0.087	0.085	0.125	1	0.465	0.447
	C12	0.075	0.076	0.066	0.054	0.042	0.094	0.043	0.052	0.050	0.074	0.448	1	0.412
	C13	0.123	0.124	0.108	0.089	0.069	0.153	0.070	0.085	0.082	0.122	0.503	0.474	1

Table 5.5 Dynamic Analysis with sigmoid function: numerical results

These results cannot be interpreted in a direct physical sense, but provide a better understanding of the relative variation of the activation levels of the concepts which represent the level of disruption of CIs and supply chain nodes when a single disruption occurs (activation of one concept).

With these results a comparative analysis of the numbers can be done and some comments on the different impacts of a disruption or destruction on concepts are possible. Looking at the numbers of the different timeframes it is possible to observe that the impact increases with longer duration of the disruption. This means that some contingency measures exist, but they are not enough to support longer events. Another conclusion is that the resilience of the system is not very high due to the interdependency of its elements.

However, for a better understanding and discussion of these numerical results a conversion to linguistic values can be done.

Table 5.6 contains the results of the dynamic analysis interpreted using linguistic values classified according to the threshold function chosen, its value of λ and also the experience:

- *White* ⟶ null activation = 0
- *Green* ⟶ 0 < weak activation ≤ 0.2
- *Yellow* ⟶ 0.2 < medium activation < 0.55
- *Red* ⟶ strong activation ≥ 0.55

Disruption events of 1 day only show weak or medium consequences on CIs. This is thanks to buffers and contingency measures that mitigate the effects of the lost services. One should however notice the FCM approach cannot retain such causal information; this information is known from additional notes taken during the interviews.

The system is particularly vulnerable to disruption events (‘1 day’) involving the Electrical Power (C1), Data network (C9) and Staff Availability (C10), as is also apparent from the static analysis. Looking at the other timeframes the impact of a loss is greater: for example, in case of a disruption event longer than 3 weeks, Air Transport (C6), Production Facilities (C11), Distribution Centers (C12) and Retail Distributors (C13) become the most affected nodes.

An interesting observation looking at Table 5.6 is that infrastructures are generally less interdependent than the FMCG supply chain is. Supply chain’s nodes are able to support 1 day disruptions due to buffering system existing in the supply chain, but in case of longer durations of the failure they lose efficiency and operability. This behavior is strictly correlated to the specific type of goods considered in the analysis: perishable goods. These results confirm the initial hypothesis that supply chains need to be included in estimating the resulting damage.

1 DAY														
sigmoid function (λ=0.6)		Effect on the concept C_j												
		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
Failure of the concept C_i	C1	-	medium	medium	medium	weak	medium	medium	medium	medium	medium	medium	medium	medium
	C2	weak	-	weak	weak	weak	weak	weak	weak	weak	weak	weak	weak	weak
	C3	weak	weak	-	weak	weak	weak	weak	weak	weak	weak	weak	weak	weak
	C4	weak	weak	weak	-	weak	weak	weak	weak	weak	weak	weak	weak	weak
	C5	weak	medium	weak	weak	-	medium	weak	weak	weak	medium	medium	medium	medium
	C6	weak	weak	weak	weak	weak	-	weak	weak	weak	weak	weak	weak	weak
	C7	weak	weak	weak	weak	weak	weak	-	weak	weak	weak	weak	weak	weak
	C8	medium	medium	medium	weak	weak	medium	medium	-	medium	weak	medium	medium	medium
	C9	medium	medium	medium	medium	weak	medium	medium	medium	-	medium	medium	medium	medium
	C10	medium	medium	medium	medium	medium	medium	medium	medium	medium	-	medium	medium	medium
	C11	null	null	null	null	null	null	null	null	null	null	-	weak	weak
	C12	null	null	null	null	null	null	null	null	null	null	weak	-	weak
	C13	null	null	null	null	null	null	null	null	null	null	weak	weak	-

4 DAYS														
sigmoid function (λ=0.6)		Effect on the concept C_j												
		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
Failure of the concept C_i	C1	-	medium	medium	medium	medium	strong	medium	medium	medium	medium	strong	strong	strong
	C2	medium	-	medium	weak	medium	medium	weak	weak	weak	weak	medium	medium	medium
	C3	medium	medium	-	weak	weak	medium	weak	weak	weak	weak	medium	medium	medium
	C4	medium	medium	medium	-	weak	medium	weak	weak	weak	medium	medium	medium	medium
	C5	medium	medium	medium	medium	-	medium	weak	medium	weak	medium	strong	strong	strong
	C6	weak	weak	weak	weak	weak	-	weak	weak	weak	weak	weak	weak	weak
	C7	weak	weak	weak	weak	weak	weak	-	weak	weak	weak	weak	weak	weak
	C8	medium	medium	medium	medium	medium	medium	medium	-	medium	medium	strong	strong	strong
	C9	strong	strong	medium	medium	medium	strong	medium	medium	-	medium	strong	strong	strong
	C10	strong	strong	medium	medium	medium	strong	medium	medium	medium	-	strong	strong	strong
	C11	null	null	null	null	null	null	null	null	null	null	-	weak	weak
	C12	null	null	null	null	null	null	null	null	null	null	weak	-	weak
	C13	null	null	null	null	null	null	null	null	null	null	weak	medium	-

3 WEEKS														
sigmoid function (λ=0.6)		Effect on the concept C_j												
		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
Failure of the concept C_i	C1	-	strong	strong	medium	medium	strong	medium	medium	medium	medium	strong	strong	strong
	C2	medium	-	medium	medium	medium	strong	medium	medium	medium	medium	strong	strong	strong
	C3	medium	medium	-	medium	medium	strong	medium	medium	medium	medium	strong	strong	strong
	C4	medium	medium	medium	-	medium	strong	medium	medium	medium	medium	strong	strong	strong
	C5	medium	strong	medium	medium	-	strong	weak	medium	medium	medium	strong	strong	strong
	C6	weak	weak	weak	weak	weak	-	weak	weak	weak	weak	medium	medium	medium
	C7	medium	medium	medium	medium	weak	medium	-	weak	weak	medium	strong	medium	medium
	C8	strong	strong	medium	medium	medium	strong	medium	-	medium	medium	strong	strong	strong
	C9	strong	strong	strong	medium	medium	strong	medium	medium	-	medium	strong	strong	strong
	C10	strong	strong	strong	medium	medium	strong	medium	medium	medium	-	strong	strong	strong
	C11	weak	weak	weak	weak	weak	weak	weak	weak	weak	weak	-	medium	medium
	C12	weak	weak	weak	weak	weak	weak	weak	weak	weak	weak	medium	-	medium
	C13	weak	weak	weak	weak	weak	weak	weak	weak	weak	weak	medium	medium	-

Table 5.6 Dynamic Analysis with sigmoid function: linguistic results

Discrete threshold function – Elementary Failure Scenario –

The discrete threshold function is less precise than the sigmoid one, it only gives back which are the concepts activated and which not, without considering a real numerical impact. The mathematical process for the calculation of the state vectors is always the same explained previously, the only thing that change is the function *f*. If a concept is activated more than the *a* value, that in this work is 0.5, it means that it is activated completely.

The value of $a = 0.5$ have been chosen according to the experience on CIs and also to the phenomena that this work wants to study.

As for the continuous threshold function it is possible to represent with Figure 5.10 and Figure 5.11 the behavior of concepts having a disruption, during the application of the mathematical process used in the dynamic analysis, before the application of the discrete threshold function. Figure 5.10 represents the values of all the concepts in the different steps of the simulation (timeframe '1 day'), having the activation of 'data network' (C9); while Figure 5.11 represents the values for the timeframe '3 weeks' that correspond to the activation of 'staff availability' (C10).

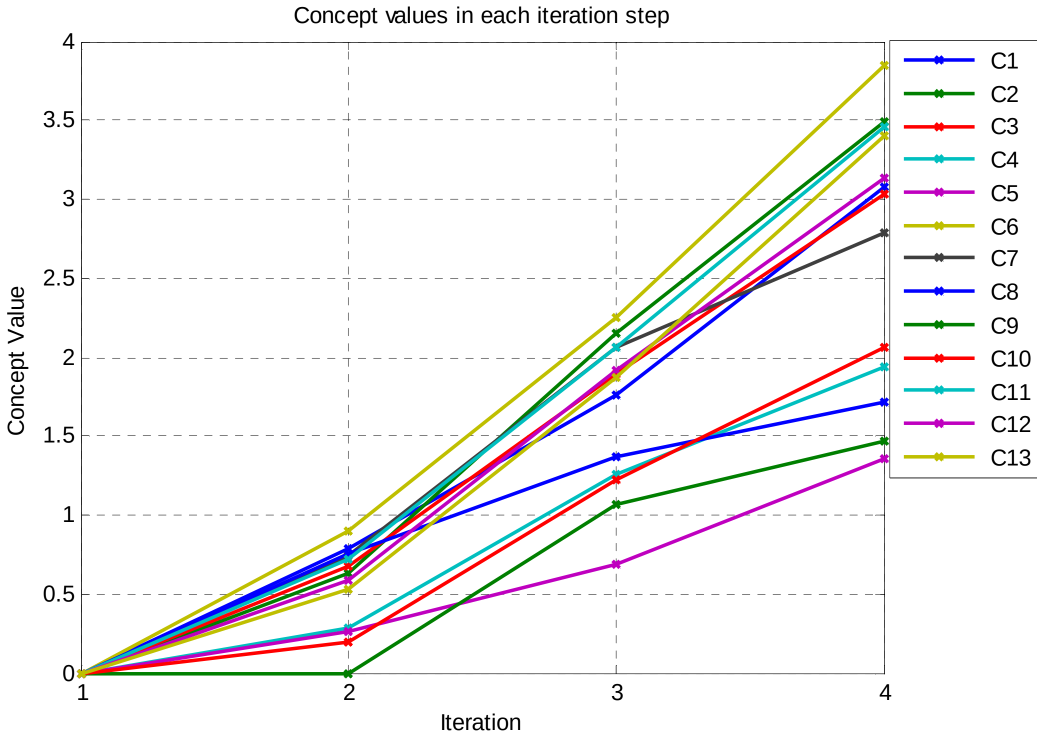


Figure 5.10 Values of the concepts for each iteration step of the mathematical process, for the activation of C9 (t = 1 day)

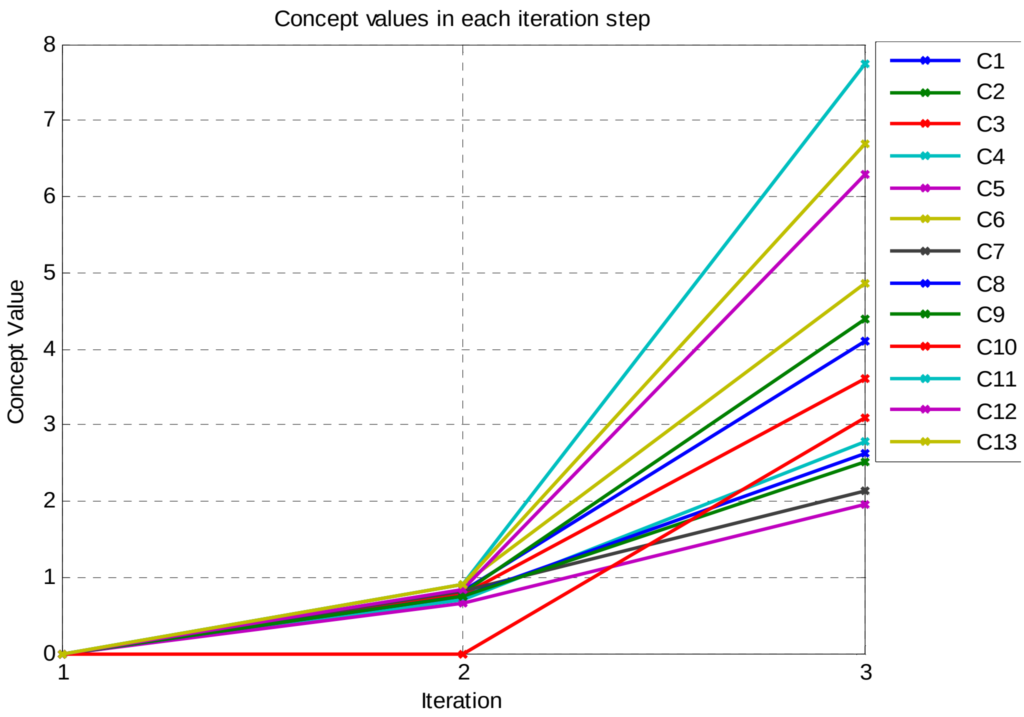


Figure 5.11 Values of the concepts for each iteration step of the mathematical process, for the activation of C10 (t = 3 weeks)

Table 5.7 represents the results of the dynamic analysis, using a discrete threshold function, for the three timeframes. If the value of a concept is 1 it means that it reached the 0.5 and it has been activated. If it is 0 it means that the impact of the failure on the concept considered is not enough to make it fail too.

Analyzing the table is possible to see that if the failed concept activates at least another concept, all the others are activated in the same way. The strong relationship and interdependency between CIs and the FMCG supply chain brings to this result. In particular considering the three timeframes, differences can be seen in the impact of every concept on the system. After 1 day the three concepts that, if they should fail, will bring about the disruption of all the remaining concepts, are: electrical power (C1), data network (C9) and staff availability (C10). Increasing the duration of the disruption more concepts are affected, for 4 days disruptions also oil and fuel, road transport and telephone network unavailability brings to the complete unavailability of all the studied system. For 3 weeks the concepts that do not affect more than 0.5 the other concepts are the air and railway transport and the three nodes of the FMCG supply chain.

These results are conceptually different from the ones obtained using the sigmoid threshold function, but at the end, if compared, are practically the same.

They bring to the same conclusions. In addition it does not have any sense to translate the numerical results of the discrete threshold function into linguistic results. They are already self-explanatory.

1 DAY														
Discrete function (a=0.5)		***Effect on the concept C_i***												
		C1	***C2***	***C3***	***C4***	***C5***	***C6***	***C7***	***C8***	***C9***	***C10***	***C11***	***C12***	***C13***
Failure of the concept C_j	***C1***	1	1	1	1	1	1	1	1	1	1	1	1	1
	C2	0	1	0	0	0	0	0	0	0	0	0	0	0
	C3	0	0	1	0	0	0	0	0	0	0	0	0	0
	C4	0	0	0	1	0	0	0	0	0	0	0	0	0
	C5	1	1	1	1	1	1	1	1	1	1	1	1	1
	C6	0	0	0	0	0	1	0	0	0	0	0	0	0
	C7	0	0	0	0	0	0	1	0	0	0	0	0	0
	C8	0	0	0	0	0	0	0	1	0	0	0	0	0
	C9	1	1	1	1	1	1	1	1	1	1	1	1	1
	C10	1	1	1	1	1	1	1	1	1	1	1	1	1
	C11	0	0	0	0	0	0	0	0	0	0	1	0	0
	C12	0	0	0	0	0	0	0	0	0	0	0	1	0
	C13	0	0	0	0	0	0	0	0	0	0	0	0	1

4 DAYS														
Discrete function (a=0.5)		***Effect on the concept C_i***												
		C1	***C2***	***C3***	***C4***	***C5***	***C6***	***C7***	***C8***	***C9***	***C10***	***C11***	***C12***	***C13***
Failure of the concept C_j	***C1***	1	1	1	1	1	1	1	1	1	1	1	1	1
	C2	1	1	1	1	1	1	1	1	1	1	1	1	1
	C3	0	0	1	0	0	0	0	0	0	0	0	0	0
	C4	0	0	0	1	0	0	0	0	0	0	1	1	1
	C5	1	1	1	1	1	1	1	1	1	1	1	1	1
	C6	0	0	0	0	0	1	0	0	0	0	0	0	0
	C7	0	0	0	0	-1	0	1	0	0	0	0	0	0
	C8	1	1	1	1	1	1	1	1	1	1	1	1	1
	C9	1	1	1	1	1	1	1	1	1	1	1	1	1
	C10	1	1	1	1	1	1	1	1	1	1	1	1	1
	C11	0	0	0	0	0	0	0	0	0	0	1	1	1
	C12	0	0	0	0	0	0	0	0	0	0	1	1	1
	C13	0	0	0	0	0	0	0	0	0	0	1	1	1

3 WEEKS														
Discrete function (a=0.5)		***Effect on the concept C_i***												
		C1	***C2***	***C3***	***C4***	***C5***	***C6***	***C7***	***C8***	***C9***	***C10***	***C11***	***C12***	***C13***
Failure of the concept C_j	***C1***	1	1	1	1	1	1	1	1	1	1	1	1	1
	C2	1	1	1	1	1	1	1	1	1	1	1	1	1
	C3	1	1	1	1	1	1	1	1	1	1	1	1	1
	C4	1	1	1	1	1	1	1	1	1	1	1	1	1
	C5	1	1	1	1	1	1	1	1	1	1	1	1	1
	C6	0	0	0	0	0	1	0	0	0	0	0	0	0
	C7	0	0	0	0	-1	0	1	0	0	0	0	0	0
	C8	1	1	1	1	1	1	1	1	1	1	1	1	1
	C9	1	1	1	1	1	1	1	1	1	1	1	1	1
	C10	1	1	1	1	1	1	1	1	1	1	1	1	1
	C11	0	0	0	0	0	0	0	0	0	0	1	1	1
	C12	0	0	0	0	0	0	0	0	0	0	1	1	1
	C13	0	0	0	0	0	0	0	0	0	0	1	1	1

Table 5.7 Dynamic Analysis with discrete function: numerical results

Continuous threshold function – Complex Failure Scenario –

The dynamic analysis on a complex failure scenario is done only using the sigmoid threshold function, but it can be done also with the discrete one.

For this work it has been analyzed the scenario in which ’electrical power’ (C1) is always unavailable and then all the other concepts are activated one at the time. But the model developed is able to simulate all the possible scenarios, with all the possible combinations. The mathematical concept that regulates the dynamic analysis in case of complex failure scenarios is the effect overlapping.

In Table 5.8 is showed the results of the dynamic analysis on the mentioned scenario, for the timeframe ‘1 day’. For the other timeframes is possible to look at Appendix D.

1 DAY (Complex Failure Scenario)														
sigmoid function (lambda=0.6)		Effect on the concept C_i												
		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
Failure of the concept C_i	C1													
	C2	1	1	0.387	0.293	0.208	0.459	0.407	0.257	0.245	0.224	0.301	0.279	0.369
	C3	1	0.438	1	0.294	0.202	0.431	0.400	0.259	0.247	0.242	0.334	0.285	0.372
	C4	1	0.467	0.406	1	0.207	0.442	0.416	0.265	0.253	0.250	0.337	0.294	0.394
	C5	1	0.509	0.437	0.337	1	0.563	0.373	0.283	0.271	0.379	0.441	0.430	0.498
	C6	1	0.410	0.365	0.287	0.171	1	0.367	0.256	0.244	0.224	0.291	0.259	0.346
	C7	1	0.457	0.383	0.294	0.107	0.381	1	0.259	0.247	0.255	0.317	0.266	0.349
	C8	1	0.521	0.468	0.356	0.241	0.527	0.492	1	0.341	0.294	0.434	0.394	0.470
	C9	1	0.572	0.529	0.372	0.251	0.607	0.549	0.415	1	0.307	0.507	0.456	0.510
	C10	1	0.601	0.559	0.424	0.307	0.614	0.568	0.339	0.331	1	0.543	0.487	0.571
	C11	1	0.408	0.361	0.284	0.175	0.398	0.386	0.255	0.243	0.208	1	0.310	0.353
	C12	1	0.408	0.361	0.284	0.175	0.398	0.386	0.255	0.243	0.208	0.350	1	0.387
	C13	1	0.408	0.361	0.284	0.175	0.398	0.386	0.255	0.243	0.208	0.326	0.341	1

Table 5.8 Dynamic Analysis with sigmoid function for complex failure scenario (C1 is always unavailable): numerical results

As it is possible to see from the results, the impact of the failure of more than one critical infrastructure is more severe than the unavailability of only one of them. All the values contained in the matrix are higher than in Table 5.5. The same discussions made for the elementary failure scenario could be done for the complex one, using also the linguistic variables for a better understanding of the results.

This kind of study is useful to appreciate the escalation factor introduced by simultaneous events in different nodes of the system. Using this model it is also possible to understand the impact of this unavailability for different time durations of the events.

5.2 Resiliency Analysis through Group Technology Clustering Algorithm

When the FCM construction and analysis is completed it is possible to proceed with the second part of the methodology, based on an original application of Group Technology and Rank Order Clustering to the resiliency analysis problem. This part of the model is applied only on the elementary failure scenario with the sigmoid threshold function

In the following it will be explained how the ROC algorithm has been applied to the case study and a critical review of the results is given. The results obtained and not included in this chapter are fully reported in Appendix D. The software used to implement this part of the model is Microsoft Excel and its tools.

5.2.1 ROC algorithm application

For the FMCG case study it has been chosen to apply the ROC algorithm on the numerical results given by the dynamic analysis, when a sigmoid threshold function is assumed. In order to apply the ROC algorithm, the steps illustrated in chapter 4 have been followed.

Table 5.9, Table 5.10 and Table 5.11 show the iteration steps of the algorithm for the 3 weeks' timeframe. Table 5.9 represent the first 3 steps of the algorithm, in particular the row weight equivalents (we_i) are computed. After a rapid analysis of the rank order of the we_i, the rows had been rearranged in rank-wise (step 4) as illustrated in Table 5.10. This second table also includes step 5; column weight equivalents (we_j) are calculated after the rows' rearrangement.

Table 5.11 concludes the first iteration step of the algorithm and includes step 6 and 7: the rows are not in rank-wise due to the position of row C6, this means that the process has to be repeated at least for another iteration to obtain the final distribution of the matrix.

3 WEEKS															
sigmoid function (λ=0.6)		Effect on the concept C_i													
		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	we_i
Failure of the concept C_i	C1	1	0.617	0.555	0.487	0.357	0.692	0.417	0.469	0.460	0.478	0.894	0.823	0.845	55.253
	C2	0.483	1	0.398	0.330	0.369	0.616	0.234	0.301	0.293	0.364	0.820	0.739	0.741	45.246
	C3	0.508	0.452	1	0.322	0.269	0.556	0.257	0.306	0.298	0.397	0.819	0.725	0.754	44.498
	C4	0.524	0.516	0.449	1	0.311	0.595	0.303	0.334	0.325	0.439	0.868	0.784	0.805	47.987
	C5	0.520	0.593	0.464	0.389	1	0.670	0.155	0.369	0.358	0.485	0.885	0.834	0.842	49.415
	C6	0.102	0.087	0.088	0.076	-0.007	1	-0.030	0.080	0.078	0.123	0.300	0.255	0.239	14.825
	C7	0.297	0.341	0.283	0.207	0.048	0.262	1	0.186	0.181	0.259	0.604	0.514	0.519	29.064
	C8	0.574	0.584	0.532	0.438	0.334	0.659	0.365	1	0.445	0.467	0.870	0.815	0.835	50.695
	C9	0.644	0.637	0.586	0.478	0.360	0.723	0.439	0.492	1	0.481	0.902	0.848	0.859	54.474
	C10	0.649	0.658	0.597	0.510	0.417	0.735	0.443	0.496	0.483	1	0.914	0.859	0.873	55.457
	C11	0.126	0.128	0.112	0.091	0.072	0.158	0.072	0.087	0.085	0.125	1	0.465	0.447	13.558
	C12	0.075	0.076	0.066	0.054	0.042	0.094	0.043	0.052	0.050	0.074	0.448	1	0.412	9.217
	C13	0.123	0.124	0.108	0.089	0.069	0.153	0.070	0.085	0.082	0.122	0.503	0.474	1	12.373

Table 5.9 ROC application: step 1 – 2 – 3

3 WEEKS													
sigmoid function (λ=0.6)	Effect on the concept C_j												
Failure of the concept C_i	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
C10	0.649	0.658	0.597	0.510	0.417	0.735	0.443	0.496	0.483	1	0.914	0.859	0.873
C1	1	0.617	0.555	0.487	0.357	0.692	0.417	0.469	0.460	0.478	0.894	0.823	0.845
C9	0.644	0.637	0.586	0.478	0.360	0.723	0.439	0.492	1	0.481	0.902	0.848	0.859
C8	0.574	0.584	0.532	0.438	0.334	0.659	0.365	1	0.445	0.467	0.870	0.815	0.835
C5	0.520	0.593	0.464	0.389	1	0.670	0.155	0.369	0.358	0.485	0.885	0.834	0.842
C4	0.524	0.516	0.449	1	0.311	0.595	0.303	0.334	0.325	0.439	0.868	0.784	0.805
C2	0.483	1	0.398	0.330	0.369	0.616	0.234	0.301	0.293	0.364	0.820	0.739	0.741
C3	0.508	0.452	1	0.322	0.269	0.556	0.257	0.306	0.298	0.397	0.819	0.725	0.754
C7	0.297	0.341	0.283	0.207	0.048	0.262	1	0.186	0.181	0.259	0.604	0.514	0.519
C6	0.102	0.087	0.088	0.076	-0.007	1	-0.030	0.080	0.078	0.123	0.300	0.255	0.239
C11	0.126	0.128	0.112	0.091	0.072	0.158	0.072	0.087	0.085	0.125	1	0.465	0.447
C13	0.123	0.124	0.108	0.089	0.069	0.153	0.070	0.085	0.082	0.122	0.503	0.474	1
C12	0.075	0.076	0.066	0.054	0.042	0.094	0.043	0.052	0.050	0.074	0.448	1	0.412
we_j	*51.158*	*50.734*	*45.117*	*39.697*	*33.298*	*57.025*	*31.519*	*39.158*	*38.595*	*43.982*	*75.473*	*68.752*	*70.328*

Table 5.10 ROC application: step 4 – 5

3 WEEKS														
sigmoid function (lambda=0.6)	Effect on the concept C_j													
Failure of the concept C_i	C11	C13	C12	C6	C1	C2	C3	C10	C4	C8	C9	C5	C7	we_i
C10	0.914	0.873	0.859	0.735	0.649	0.658	0.597	1	0.510	0.496	0.483	0.417	0.443	*67.709*
C1	0.894	0.845	0.823	0.692	1	0.617	0.555	0.478	0.487	0.469	0.460	0.357	0.417	*65.254*
C9	0.902	0.859	0.848	0.723	0.644	0.637	0.586	0.481	0.478	0.492	1	0.360	0.439	*64.994*
C8	0.870	0.835	0.815	0.659	0.574	0.584	0.532	0.467	0.438	1	0.445	0.334	0.365	*61.796*
C5	0.885	0.842	0.834	0.670	0.520	0.593	0.464	0.485	0.389	0.369	0.358	1	0.155	*59.710*
C4	0.868	0.805	0.784	0.595	0.524	0.516	0.449	0.439	1	0.334	0.325	0.311	0.303	*58.368*
C2	0.820	0.741	0.739	0.616	0.483	1	0.398	0.364	0.330	0.301	0.293	0.369	0.234	*55.860*
C3	0.819	0.754	0.725	0.556	0.508	0.452	1	0.397	0.322	0.306	0.298	0.269	0.257	*55.324*
C7	0.604	0.519	0.514	0.262	0.297	0.341	0.283	0.259	0.207	0.186	0.181	0.048	1	*34.698*
C6	0.300	0.239	0.255	1	0.102	0.087	0.088	0.123	0.076	0.080	0.078	-0.007	-0.030	*23.428*
C11	1	0.447	0.465	0.158	0.126	0.128	0.112	0.125	0.091	0.087	0.085	0.072	0.072	*30.034*
C13	0.503	1	0.474	0.153	0.123	0.124	0.108	0.122	0.089	0.085	0.082	0.069	0.070	*30.112*
C12	0.448	0.412	1	0.094	0.075	0.076	0.066	0.074	0.054	0.052	0.050	0.042	0.043	*25.661*

Table 5.11 ROC application: step 6 – 7

After the application of the ROC algorithm and once a convergence point has been reached, for each timeframe, a rearranged matrix is available. These matrixes contain the same numbers obtained in the dynamic analysis using a sigmoid threshold function, but in a different order (Appendix D). This is important because gives a logical order to all the concepts, that they did not have before. The numbers of the concepts are somehow casual and in any case not strictly related to a criticality ranking order. Conversely, after the application of this part of the model it is possible to better analyze the results according also to the disposition of the most impacted concepts.

For a better understanding of the results it is possible to translate the numerical results into linguistic results, using the same formalism applied for the dynamic analysis (in the case of sigmoid threshold function) and already explained in the previous paragraph (strong, medium, weak and null).

Table 5.12 represents the results of the second part of the model, with its families of resilience and a new order of the concepts.

1 DAY

sigmoid function (λ=0.6)	Effect on the concept C_i												
Failure of the concept C_i	C2	C1	C6	C3	C11	C7	C13	C10	C12	C8	C9	C4	C5
C10	medium	medium	medium	medium	medium	medium	medium	-	medium	medium	medium	medium	medium
C1	medium	-	medium	medium	medium	medium	medium	medium	medium	medium	medium	medium	weak
C9	medium	medium	medium	medium	medium	medium	medium	medium	medium	medium	-	medium	weak
C8	medium	medium	medium	medium	medium	medium	medium	weak	medium	-	medium	weak	weak
C3	weak	weak	weak	-	weak	weak	weak	weak	weak	weak	weak	weak	weak
C5	medium	weak	medium	weak	medium	weak	medium	medium	medium	weak	weak	weak	-
C2	-	weak	weak	weak	weak	weak	weak	weak	weak	weak	weak	weak	weak
C4	weak	weak	weak	weak	weak	weak	weak	weak	weak	weak	weak	-	weak
C7	weak	weak	weak	weak	weak	-	weak	weak	weak	weak	weak	weak	weak
C6	weak	weak	-	weak	weak	weak	weak	weak	weak	weak	weak	weak	weak
C11	null	null	null	null	-	null	weak	null	weak	null	null	null	null
C13	null	null	null	null	weak	null	-	null	weak	null	null	null	null
C12	null	null	null	null	weak	null	weak	null	-	null	null	null	null

4 DAYS

sigmoid function (λ=0.6)	Effect on the concept C_i												
Failure of the concept C_i	C13	C11	C12	C6	C2	C1	C3	C10	C8	C9	C4	C5	C7
C10	strong	strong	strong	strong	strong	strong	medium	-	medium	medium	medium	medium	medium
C9	strong	strong	strong	strong	strong	strong	medium	medium	medium	-	medium	medium	medium
C1	strong	strong	strong	strong	medium	-	medium	medium	medium	medium	medium	medium	medium
C8	strong	strong	strong	medium	medium	medium	medium	medium	-	medium	medium	medium	medium
C5	strong	strong	strong	medium	medium	medium	medium	medium	medium	weak	medium	-	weak
C4	medium	medium	medium	medium	medium	medium	medium	medium	weak	weak	-	weak	weak
C2	medium	medium	medium	medium	-	medium	medium	weak	weak	weak	weak	medium	weak
C3	medium	medium	medium	medium	medium	medium	-	weak	weak	weak	weak	weak	weak
C13	-	weak	medium	null	null	null	null	null	null	null	null	null	null
C11	weak	-	weak	null	null	null	null	null	null	null	null	null	null
C12	weak	weak	-	null	null	null	null	null	null	null	null	null	null
C6	weak	weak	weak	-	weak	weak	weak	weak	weak	weak	weak	weak	weak
C7	weak	weak	weak	null	weak	weak	weak	weak	weak	weak	weak	weak	-

3 WEEKS

sigmoid function (λ=0.6)	Effect on the concept C_i												
Failure of the concept C_i	C11	C13	C12	C6	C1	C2	C3	C10	C4	C8	C9	C5	C7
C10	strong	strong	strong	strong	strong	strong	strong	-	medium	medium	medium	medium	medium
C1	strong	strong	strong	strong	-	strong	strong	medium	medium	medium	medium	medium	medium
C9	strong	strong	strong	strong	strong	strong	strong	medium	medium	medium	-	medium	medium
C8	strong	strong	strong	strong	strong	strong	medium	medium	medium	-	medium	medium	medium
C5	strong	strong	strong	strong	medium	strong	medium	medium	medium	medium	medium	-	weak
C4	strong	strong	strong	strong	medium	medium	medium	medium	-	medium	medium	medium	medium
C2	strong	strong	strong	strong	medium	-	medium	medium	medium	medium	medium	medium	medium
C3	strong	strong	strong	strong	medium	medium	-	medium	medium	medium	medium	medium	medium
C7	strong	medium	medium	medium	medium	medium	medium	medium	medium	weak	weak	weak	-
C13	medium	-	medium	weak	weak	weak	weak	weak	weak	weak	weak	weak	weak
C11	-	medium	medium	weak	weak	weak	weak	weak	weak	weak	weak	weak	weak
C12	medium	medium	-	weak	weak	weak	weak	weak	weak	weak	weak	weak	weak
C6	medium	medium	medium	-	weak	weak	weak	weak	weak	weak	weak	weak	weak

Table 5.12 ROC application results: families of resiliency

Three families (clusters of concepts, i.e. portions of the entire FMCG-CI network) of resiliency can be identified: low resiliency (strong cells), medium resiliency (medium cells) and high resiliency (weak and null cells). Looking at the different timeframes it is immediately clear how the dimensions of the families change modifying the duration of the disruption. For 1 day the low resiliency family is not present and the biggest family here is the high resiliency one. Moving from 1 day to 3 weeks the proportion changes a lot: the red zone increases, while the green and white one decreases.

The reasons of these modifications are concordant with the behavior of the system in analysis. The FMCG supply chain and CIs are able to support 1 day disruption, thanks to the contingency measure and to buffering systems; but increasing the duration of the unavailability of one or more nodes these countermeasures are not enough and the system is not able to find new solutions for maintaining standard service levels (note that the extent of the impact in term of service disruption or interruption cannot be quantitatively estimated via FCMs).

Analyzing these results is possible to better understand which are the changes needed to improve the resilience of the entire system. New buffers can be designed and new contingency measures, able to face long disruptions, can be introduced. Another solution, less expensive and easier to apply, can be the identification of alternative service delivery paths within the network or the identification of a way to decouple the system, reducing the dependencies on CIs. For the new contingency measures one of the most important aspects is the possibility to switch from a concept to another. If a concept is unavailable while another concept is more resilient and can be used, it is good to have plans in order to let the switch possible. For example, looking at Table 5.12, timeframe ‘4 days’, road transport (C5) if unavailable completely paralyze the nodes of the FMCG supply chain, but the railway transport (C7) is still available. By changing the means of transportation to bring goods to the FMCG nodes from the road to the railway vehicles, it is possible to reduce the impact of road transport unavailability on the supply chain. The same reasoning can be done for other concepts, like data network (C9) and telephone network (C8), which can easily be switched in case of long lasting disruptions.

5.3 Comments on the results of the case study

An interesting observation coming from the analysis of the results of the overall model application in the case study is that infrastructures are generally less interdependent than the FMCG supply chain is. This confirms the initial hypothesis that supply chains need to be included in estimating the resulting damage. Also it confirms the importance of staff. We expect that staff will be actually more affected by CI failures than is actually apparent from the current analysis; in fact only employers were asked about staff dependence on CI availability. Other observations regarding the results include that the chosen timeframes are appropriate. These clearly distinguish between different effects both in the static and dynamic analysis. And they also give appropriate results when the ROC algorithm is applied.

Lastly, when interpreting the results one should bear in mind the limited number of interviewed experts. However, the quality of the results is not fully correlated to the number of experts used; given the agreement between the expert judgments it seems the results would remain stable with a higher number of experts.

Using this model, based on FCMs and ROC algorithm, is possible to analyze in a qualitative way the behavior of CIs and KRSC for elementary or complex failure scenarios, as shown in the case study. From this analysis new contingency plans can be studied, having a better comprehension of the impact of the disruption of each part of the system considered. And also counter measures in order to have business continuity can be detected, looking at the resilience families obtained from the second part of the model.

The current study has the important objective of developing and evaluating a new model for assessing the impact of CI unavailability on KRSCs. From this point of view the first comment is that the model and the associated methodology affords insights in CI and KRSC systems with a relatively limited amount of effort. This certainly is an important step towards with respect to the state of the art; moreover, the way it obtains data works well. Indeed rather than building detailed understanding about the underlying processes in the system, the method simply uses the knowledge of the experts. The method is also scalable, there is no limit to the number of experts, and supplementary concepts can be added in a relatively straightforward manner.

6. Conclusions and Future Developments

An important objective in Europe is the protection and security of its citizens against natural and technological hazards as well as to threats involving terrorism. A part of the work to fulfill this objective is to ensure the continuity of services provided by infrastructures. Indeed, infrastructures provide a number of fundamental services, on which society and citizens depend. These include the provision of food, transportation, communication and health, and are brought about by networks and assets including electricity grids, roads and communication networks. The disruption or destruction (loss) of some of these infrastructures can be debilitating to the needs of society and individual citizens; restoration may take significant time, in particular when physical damage occurs. Such infrastructures are therefore addressed as ‘critical infrastructures’ (CIs). These damages propagate in a complex manner via the initial loss of an asset, through the infrastructure network to other dependent networks and to Key Resource Supply Chains (KRSC). The consequences of loss of KRSC’s may be at least as significant to society as direct consequences caused by lost infrastructure assets. Therefore consequences of KRSC loss need to be quantified for evaluating the criteria; this however requires understanding about the whole propagation mechanism.

In this work, after a brief description of the meanings of ‘Critical Infrastructure’ and of their protection plans, an in-depth examination of the modeling techniques has been done. Afterwards an analysis of the models reported in the scientific literature has been performed in order to see if one of them could fit with the work’s purposes. At the end many of these techniques and models fall short to the needs of the work of evaluating consequences. For instance they are limited to infrastructures only or even to one domain such as electrical power; they may have high and detailed data needs that in practice cannot be satisfied (as is true of many of the recent methods and system dynamics applications), or they do not model consequence propagation in a sufficiently detailed way (economic Leontief models).

This work, given some above mentioned preliminary remarks, presents a novel model to study the interdependency of infrastructures and supply chains. The proposed approach is part of a candidate solution that seems capable of qualifying the knowledge of key players in infrastructure and supply chain sectors. Currently, the approach focuses at consequence propagation, but does not yet address damage estimation. It applies Fuzzy Cognitive Maps (FCMs) to model propagation of service losses in and between infrastructure and supply chain systems. It obtains the knowledge of infrastructure and supply chain domain experts by means of structured interviews. These interviews do not seek detailed information on how their systems function. Instead they focus at obtaining qualitative information on how their systems would be affected in case of the loss of resources provided by infrastructure services. This information is then used to build the FCMs. In effect it is a way to combine the knowledge of experts, who only have direct experience of a part of a network, into a complete picture of how the network functions.

In the second part of the model Group Technology theory and in particular the Rank Order Clustering algorithm, has been used to group together concepts with the same activation degree, thus identifying tightly or weakly coupled portions of the network. This process brings the analysis to a step forward, with the possibility to improve or design contingency plans starting from resiliency related information.

The bottom line of this method is that it is highly promising, its resource requirements and scalability allow using it in practice, its problems are well understood and solutions are on the horizon. The method therefore presents a viable approach to establishing consequence propagation, and authors are committed to further developing it to meet their needs.

Furthermore, the proposed model has been applied in a case study: the Italian Fast Moving Consumer Goods supply chain.

The entire model has been exploited to study the impact of a disruption or destruction of a service on the entire system taken into consideration. The basic idea of the methodology is to return a qualitative representation of the behavior of the FMCG supply chain and its supporting CIs. The entire system, CIs and supply chain nodes, was described using 13 concepts (9 critical infrastructures, 3 nodes of the FMCG supply chain and the human workforce), and through experts' interviews direct relationships were detected. Using this information a Fuzzy Cognitive Map of the entire system can be drawn, as the one showed in Figure 6.1, and then studied through static and dynamic analyses. With the static analysis each fuzzy cognitive map was studied using the relative graph theory techniques so as to study the characteristics of the weighted directed graph that represents the system. The dynamic analysis was then used to study the cascading effects, due to the unavailability of a concept, on all the other ones. For the case study the most appropriate threshold functions resulted to be the sigmoid and the discrete ones.

In addition the model is able to study both elementary (only one service is unavailable) and complex failure scenarios (with two or more service disruptions in the same moment).

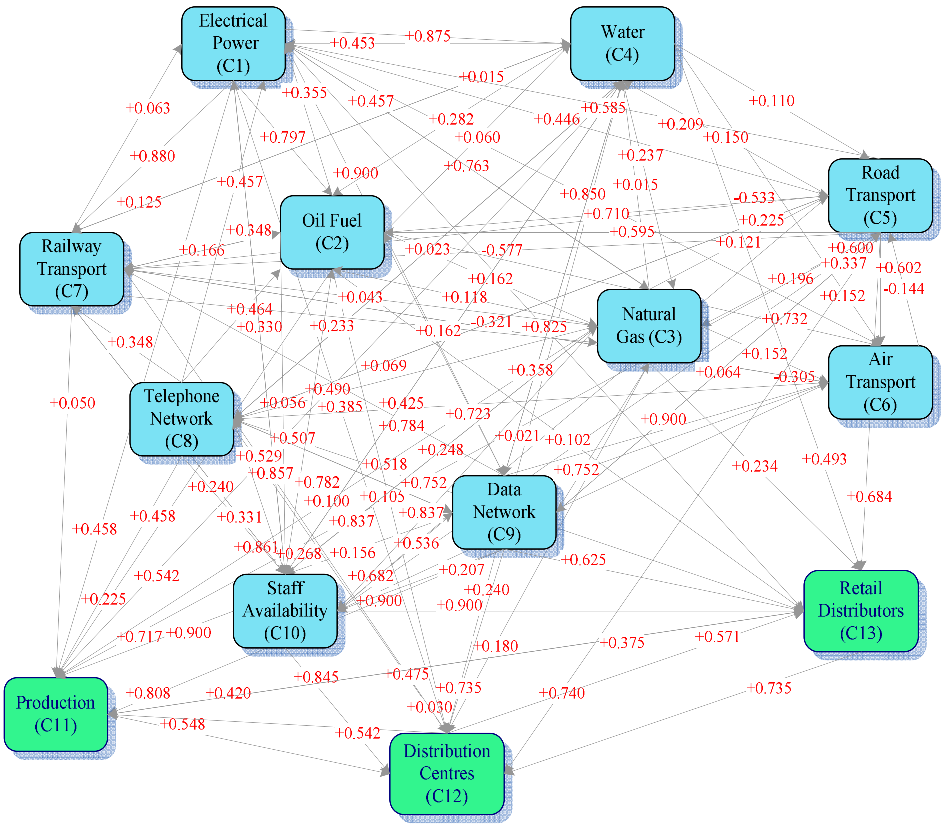


Figure 6.1 Fuzzy Cognitive Map for timeframe 2 (t = 4 days)

Starting from the results of the FCMs' dynamic analysis the second part of the model was applied returning families of resiliency, like the one for the timeframe '4 days' showed in Table 6.1.

4 DAYS														
sigmoid function (lambda=0.6)		*Effect on the concept C_j*												
		C13	**C11**	**C12**	**C6**	**C2**	**C1**	**C3**	**C10**	**C8**	**C9**	**C4**	**C5**	**C7**
Failure of the concept C_i	**C10**	strong	strong	strong	strong	strong	strong	medium	-	medium	medium	medium	medium	medium
	C9	strong	strong	strong	strong	strong	strong	medium	medium	medium	-	medium	medium	medium
	C1	strong	strong	strong	strong	medium	-	medium	medium	medium	medium	medium	medium	medium
	C8	strong	strong	strong	medium	medium	medium	medium	medium	-	medium	medium	medium	medium
	C5	strong	strong	strong	medium	medium	medium	medium	medium	medium	weak	medium	-	weak
	C4	medium	medium	medium	medium	medium	medium	medium	medium	weak	weak	-	weak	weak
	C2	medium	medium	medium	medium	-	medium	medium	weak	weak	weak	weak	medium	weak
	C3	medium	medium	medium	medium	medium	medium	-	weak	weak	weak	weak	weak	weak
	C13	-	weak	medium	null	null	null	null	null	null	null	null	null	null
	C11	weak	-	weak	null	null	null	null	null	null	null	null	null	null
	C12	weak	weak	-	null	null	null	null	null	null	null	null	null	null
	C6	weak	weak	weak	-	weak	weak	weak	weak	weak	weak	weak	weak	weak
	C7	weak	weak	weak	null	weak	weak	weak	weak	weak	weak	weak	weak	-

Table 6.1 ROC application results: families of resiliency for the timeframe '4 days'

With a relatively limited effort interesting and unique results were obtained. For instance, they quickly show the importance of workforce, and the relative vulnerability of KRSC when compared to the CI sectors. They also show the family of resiliency in which each CI or supply chain node is allocated. The results seem intuitively correct, and that they are based on the knowledge of experts gives additional assurance.

Talking about the validation process, it must be underlined that it is currently difficult to fully validate the results. The validation of the model cannot be performed through canonical error assessment methods, i.e. by the comparison of model's results against real data, due to the structural lack of the latter. The scenarios studied do not have an elevate repeatability in order to guarantee sufficient data for a statistical analysis. Thus only a qualitative validation is possible; no counterintuitive or illogical results should be observed, which is the case. Also the experts must be able to provide clear and consistent explanations of all the dependencies and cause-effect relationships shown by the final model. They have to understand if all the scenarios have found plausible explanations and if they are logical and in line with their experience. The notes taken during the interview support this to a certain extent. However to be fully reliable, a feedback of the results to the experts or another means of validation is required.

Regarding future works, some important points to take into consideration are:

- The results may appear quantitative, in fact they are essentially qualitative. This may make it difficult to estimate societal consequences. Solutions may include adding consequences as concepts, or converting the results into probabilities (thus shifting from FCM to BBN).

- The results are not necessarily clear or univocal in operational terms. The model assesses the strength and sign (+/-) of the dependent activation, but the physical meaning of this change is not univocal: Is a service unavailable for part of the time or to part of the customers? Is there just an elevated probability that it can become unavailable, or does it imply a decrease of the quality of service?

- Another issue is that time plays a crucial role in the propagation of failure in the systems studied. The current approach of independent timeframes models only discrete time steps, without considering a continuous system evolution.

Future work on this method needs to be focused on improving some weak features or responding to the above issues. The theoretical framework that underlies the FCM requires improved understanding and improvement to meet these needs. Also the framework of the concepts itself may need reviewing and time will need to become an important aspect of this development. The scalability of the method with respect to the level of detail in modeling the system must be further explored. Further, the reliability and the possibility to estimate damage needs to be enhanced. Currently thinking suggests the feasibility of leveraging statistical techniques, however, this still needs to be put in place.

Figure 6.2 shows the focus of this work and which could be the future works able to improve the model and get more information from it.

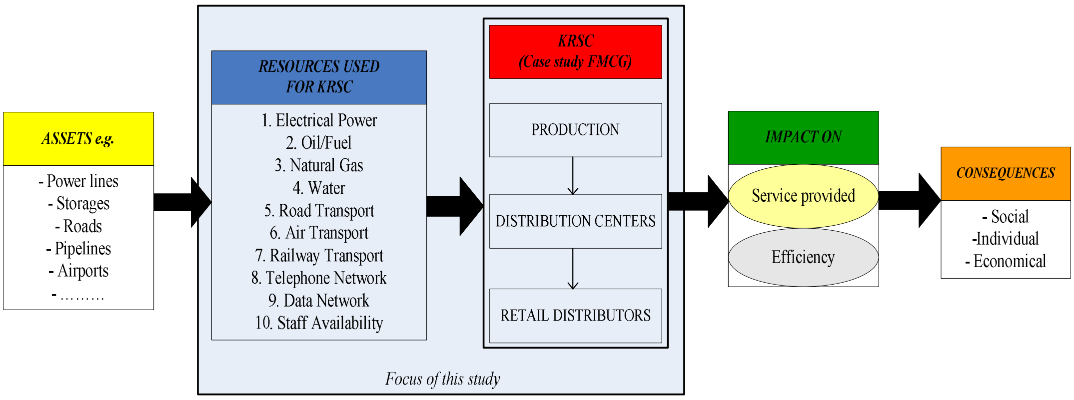


Figure 6.2 Propagation of consequences from asset failure to society and the citizens; this study focuses only at supply chains and their resources

Appendix A

JOINT RESEARCH CENTRE

Institute for the Protection and
Security of the Citizen (IPSC)

JRC
EUROPEAN COMMISSION

and

POLITECNICO DI MILANO

Industrial Engineering Faculty
Master of Science in
Mechanical Engineering

QUESTIONNAIRE

MODELING AND ANALYSIS OF THE IMPACT OF CRITICAL INFRASTRUCTURES ON THE FAST MOVING CONSUMER GOODS SUPPLY CHAIN

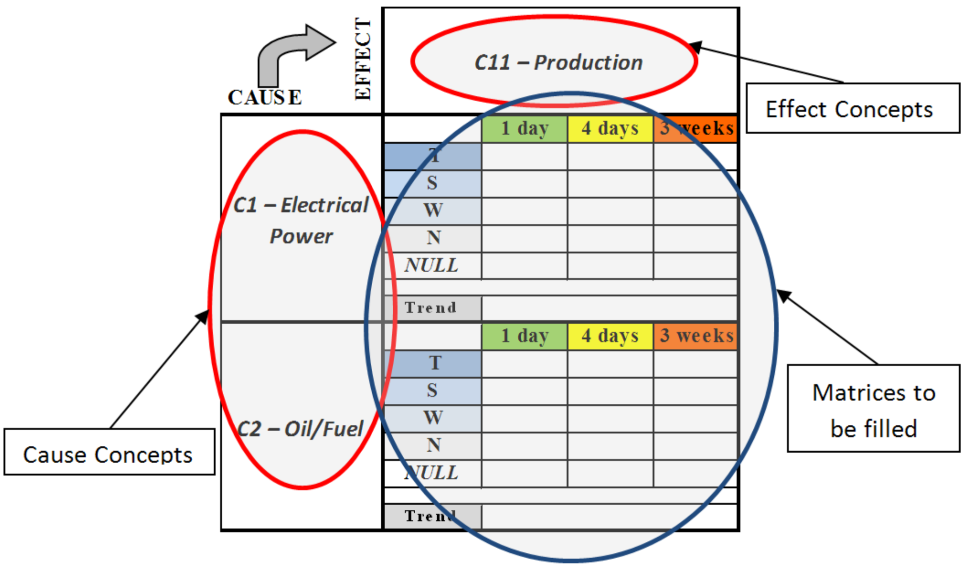
Introduction

The purpose of the questionnaire is to collect information so as to improve the understanding of interdependencies that exist in the Fast Moving Consumer Goods (FMCG) supply chain, especially that of *perishable goods*. The data obtained will be employed to model the relative supply chain. This model will be used to analyze the impact of critical infrastructures on the FMCG supply chain.

This activity is carried out in partnership with the Joint Research Centre in Ispra and is an integral part of a thesis for the degree of Master of Science in Mechanical Engineering at the Politecnico di Milano.

What do you need to do?

- You need to fill out matrix questions which establish what is the impact of the failure of a service on another service.
- For each matrix you need to put three crosses and one ‘ + ’ or ‘ – ’.
- A single ‘X’ for each time duration (*1 day – 4 days – 3 weeks*) has to be inserted into the matrix and a sign ‘ + ’ or ‘ – ’ has to be added in the ‘*Trend*’ row.
- The dependence may be negligible (N) (i.e. something happen but it is not relevant), weak (W), strong (S), total (T) (i.e. electricity service would fail completely), or NULL.
- For each cause-effect relationship a trend has to be established, it can be ‘+’ (follow trend) or ‘ – ’ (opposite trend).
- All the questions follow the format showed in the example below



- *Example:* Production may depend on the availability of electrical power. You fill out in the matrix (blue circle) what happens when there is no electrical power for one day, when there is no electrical power for four days and when there would be no electrical power for three weeks.

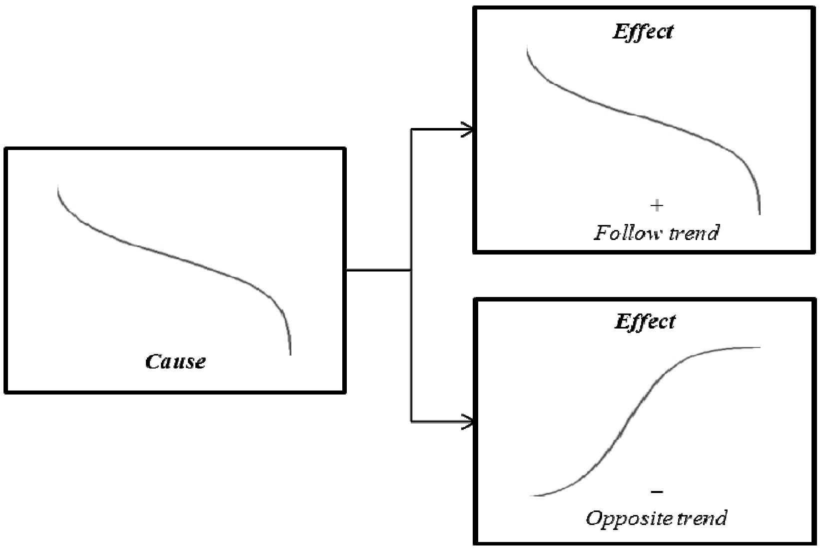
What do you need to think of?

- Contingency measures, such as those found in general business continuity plans e.g. in the event of an electricity blackout a UPS intervenes to guarantee continuity of service for a given period of time.
- Trend, does the effect concept follow the trend of the cause concept or is it opposite?
- Remember that the analysis done in this questionnaire is related to perishable goods.

Legend of the questionnaire

A summarizing description of the key information is indicated in the preconfigured tables provided below:

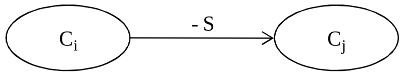
- ***<u>Trend</u>***
  - ‘ + ’ *follow trend*: if the cause decrease also the effect will decrease;
  - ‘ – ’ *opposite trend*: if the cause decrease the effect will increase, if the cause increase the effect will decrease.



- ***Timeframe***
    - *1 day*: for 1 day the concept C_i (cause concept) is unavailable;
    - *4 days*: for 4 days the concept C_i (cause concept) is unavailable;
    - *3 weeks*: for 3 weeks the concept C_i (cause concept) is unavailable.

- ***Intensity of the causal link***
    - T= *total*. Total relationship between the cause concept C_i and the effect concept C_j;
    - S= *strong*. Strong relationship between the cause concept C_i and the effect concept C_j;
    - W= *weak*. Weak relationship between the cause concept C_i and the effect concept C_j;
    - N = *negligible*. Negligible relationship between the cause concept C_i and the effect concept C_j;
    - NULL. No relationship exists between the cause concept C_i and the effect concept C_j.

	SYMBOL		***LEGEND***
Trend of the causal link	**Trend** → +		follow trend: if the cause increase/decrease also the effect will increase/decrease
	Trend → −		opposite trend: if the cause increase/decrease the effect will decrease/increase
Intensity of the causal link	T	=	Total
	S	=	Strong
	W	=	Weak
	N	=	Negligible
	NULL	=	Null
Time step	**1 day**	=	For 1 day the concept C_i (cause concept) is unavailable
	4 days	=	For 4 days the concept C_i (cause concept) is unavailable
	3 weeks	=	For 3 weeks the concept C_i (cause concept) is unavailable
Example			The concept C_i is the cause and C_j the effect. If C_i increase C_j will suffer a strong decrease (-S), so the effect concept has an opposite trend respect the cause one



Excel File

CIs experts questionnaire

Part 1

CAUSE / EFFECT	C1 – Electrical Power				C2 – Oil/Fuel				C3 – Natural Gas				C4 – Water				C5 – Road Transport				C6 – Air Transport				C7 – Railway Transport				C8 – Telephone Network				C9 – Data Network				C10 – Staff Availability			
C1 – Electrical Power					T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks
					S				S				S				S				S				S				S				S				S			
					W				W				W				W				W				W				W				W				W			
					N				N				N				N				N				N				N				N				N			
					NULL				NULL				NULL				NULL				NULL				NULL				NULL				NULL				NULL			
					Trend				Trend				Trend				Trend				Trend				Trend				Trend				Trend				Trend			
C2 – Oil/Fuel	T	1 day	4 days	3 weeks					T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks
	S								S				S				S				S				S				S				S				S			
	W								W				W				W				W				W				W				W				W			
	N								N				N				N				N				N				N				N				N			
	NULL								NULL				NULL				NULL				NULL				NULL				NULL				NULL				NULL			
	Trend								Trend				Trend				Trend				Trend				Trend				Trend				Trend				Trend			
C3 – Natural Gas	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks					T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks
	S				S								S				S				S				S				S				S				S			
	W				W								W				W				W				W				W				W				W			
	N				N								N				N				N				N				N				N				N			
	NULL				NULL								NULL				NULL				NULL				NULL				NULL				NULL				NULL			
	Trend				Trend								Trend				Trend				Trend				Trend				Trend				Trend				Trend			
C4 – Water	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks					T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks
	S				S				S								S				S				S				S				S				S			
	W				W				W								W				W				W				W				W				W			
	N				N				N								N				N				N				N				N				N			
	NULL				NULL				NULL								NULL				NULL				NULL				NULL				NULL				NULL			
	Trend				Trend				Trend								Trend				Trend				Trend				Trend				Trend				Trend			
C5 – Road Transport	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks					T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks
	S				S				S				S								S				S				S				S				S			
	W				W				W				W								W				W				W				W				W			
	N				N				N				N								N				N				N				N				N			
	NULL				NULL				NULL				NULL								NULL				NULL				NULL				NULL				NULL			
	Trend				Trend				Trend				Trend								Trend				Trend				Trend				Trend				Trend			
C6 – Air Transport	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks					T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks
	S				S				S				S				S								S				S				S				S			
	W				W				W				W				W								W				W				W				W			
	N				N				N				N				N								N				N				N				N			
	NULL				NULL				NULL				NULL				NULL								NULL				NULL				NULL				NULL			
	Trend				Trend				Trend				Trend				Trend								Trend				Trend				Trend				Trend			
C7 – Railway Transport	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks					T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks
	S				S				S				S				S				S								S				S				S			
	W				W				W				W				W				W								W				W				W			
	N				N				N				N				N				N								N				N				N			
	NULL				NULL				NULL				NULL				NULL				NULL								NULL				NULL				NULL			
	Trend				Trend				Trend				Trend				Trend				Trend								Trend				Trend				Trend			
C8 – Telephone Network	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks					T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks
	S				S				S				S				S				S				S								S				S			
	W				W				W				W				W				W				W								W				W			
	N				N				N				N				N				N				N								N				N			
	NULL				NULL				NULL				NULL				NULL				NULL				NULL								NULL				NULL			
	Trend				Trend				Trend				Trend				Trend				Trend				Trend								Trend				Trend			
C9 – Data Network	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks					T	1 day	4 days	3 weeks
	S				S				S				S				S				S				S				S								S			
	W				W				W				W				W				W				W				W								W			
	N				N				N				N				N				N				N				N								N			
	NULL				NULL				NULL				NULL				NULL				NULL				NULL				NULL								NULL			
	Trend				Trend				Trend				Trend				Trend				Trend				Trend				Trend								Trend			
C10 – Staff Availability	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks	T	1 day	4 days	3 weeks				
	S				S				S				S				S				S				S				S				S							
	W				W				W				W				W				W				W				W				W							
	N				N				N				N				N				N				N				N				N							
	NULL				NULL				NULL				NULL				NULL				NULL				NULL				NULL				NULL							
	Trend				Trend				Trend				Trend				Trend				Trend				Trend				Trend				Trend							

Part 2

CAUSE ↓ / EFFECT →		C1 – Electrical Power		
		1 day	4 days	3 weeks
C11 – Production	T			
	S			
	W			
	N			
	NULL			
	Trend			
C12 – Distribution Centers	T			
	S			
	W			
	N			
	NULL			
	Trend			
C13 – Retail Distributors	T			
	S			
	W			
	N			
	NULL			
	Trend			

CAUSE ↓ / EFFECT →		C2 – Oil/Fuel		
		1 day	4 days	3 weeks
C11 – Production	T			
	S			
	W			
	N			
	NULL			
	Trend			
C12 – Distribution Centers	T			
	S			
	W			
	N			
	NULL			
	Trend			
C13 – Retail Distributors	T			
	S			
	W			
	N			
	NULL			
	Trend			

CAUSE ↓ / EFFECT →		C3 – Natural Gas		
		1 day	4 days	3 weeks
C11 – Production	T			
	S			
	W			
	N			
	NULL			
	Trend			
C12 – Distribution Centers	T			
	S			
	W			
	N			
	NULL			
	Trend			
C13 – Retail Distributors	T			
	S			
	W			
	N			
	NULL			
	Trend			

CAUSE ↓ / EFFECT →		C4 – Water		
		1 day	4 days	3 weeks
C11 – Production	T			
	S			
	W			
	N			
	NULL			
	Trend			
C12 – Distribution Centers	T			
	S			
	W			
	N			
	NULL			
	Trend			
C13 – Retail Distributors	T			
	S			
	W			
	N			
	NULL			
	Trend			

CAUSE ↓ / EFFECT →		C5 – Road Transport		
		1 day	4 days	3 weeks
C11 – Production	T			
	S			
	W			
	N			
	NULL			
	Trend			
C12 – Distribution Centers	T			
	S			
	W			
	N			
	NULL			
	Trend			
C13 – Retail Distributors	T			
	S			
	W			
	N			
	NULL			
	Trend			

CAUSE ↓ / EFFECT →		C6 – Air Transport		
		1 day	4 days	3 weeks
C11 – Production	T			
	S			
	W			
	N			
	NULL			
	Trend			
C12 – Distribution Centers	T			
	S			
	W			
	N			
	NULL			
	Trend			
C13 – Retail Distributors	T			
	S			
	W			
	N			
	NULL			
	Trend			

CAUSE ↓ / EFFECT →		C7 – Railway Transport		
		1 day	4 days	3 weeks
C11 – Production	T			
	S			
	W			
	N			
	NULL			
	Trend			
C12 – Distribution Centers	T			
	S			
	W			
	N			
	NULL			
	Trend			
C13 – Retail Distributors	T			
	S			
	W			
	N			
	NULL			
	Trend			

CAUSE ↓ / EFFECT →		C8 – Telephone Network		
		1 day	4 days	3 weeks
C11 – Production	T			
	S			
	W			
	N			
	NULL			
	Trend			
C12 – Distribution Centers	T			
	S			
	W			
	N			
	NULL			
	Trend			
C13 – Retail Distributors	T			
	S			
	W			
	N			
	NULL			
	Trend			

CAUSE ↓ / EFFECT →		C9 – Data Network		
		1 day	4 days	3 weeks
C11 – Production	T			
	S			
	W			
	N			
	NULL			
	Trend			
C12 – Distribution Centers	T			
	S			
	W			
	N			
	NULL			
	Trend			
C13 – Retail Distributors	T			
	S			
	W			
	N			
	NULL			
	Trend			

CAUSE ↓ / EFFECT →		C10 – Staff Availability		
		1 day	4 days	3 weeks
C11 – Production	T			
	S			
	W			
	N			
	NULL			
	Trend			
C12 – Distribution Centers	T			
	S			
	W			
	N			
	NULL			
	Trend			
C13 – Retail Distributors	T			
	S			
	W			
	N			
	NULL			
	Trend			

FMCG supply chain experts questionnaire

Part 1

CAUSE / EFFECT	C1 – Electrical Power				C2 – Oil/Fuel				C3 – Natural Gas				C4 – Water				C5 – Road Transport			
C11 – Production		1 day	4 days	3 weeks		1 day	4 days	3 weeks		1 day	4 days	3 weeks		1 day	4 days	3 weeks		1 day	4 days	3 weeks
	T				T				T				T				T			
	S				S				S				S				S			
	W				W				W				W				W			
	N				N				N				N				N			
	NULL				NULL				NULL				NULL				NULL			
	Trend				Trend				Trend				Trend				Trend			
C12 – Distribution Centers		1 day	4 days	3 weeks		1 day	4 days	3 weeks		1 day	4 days	3 weeks		1 day	4 days	3 weeks		1 day	4 days	3 weeks
	T				T				T				T				T			
	S				S				S				S				S			
	W				W				W				W				W			
	N				N				N				N				N			
	NULL				NULL				NULL				NULL				NULL			
	Trend				Trend				Trend				Trend				Trend			
C13 – Retail Distributors		1 day	4 days	3 weeks		1 day	4 days	3 weeks		1 day	4 days	3 weeks		1 day	4 days	3 weeks		1 day	4 days	3 weeks
	T				T				T				T				T			
	S				S				S				S				S			
	W				W				W				W				W			
	N				N				N				N				N			
	NULL				NULL				NULL				NULL				NULL			
	Trend				Trend				Trend				Trend				Trend			

CAUSE / EFFECT	C6 – Air Transport				C7 – Railway Transport				C8 – Telephone Network				C9 – Data Network				C10 – Staff Availability			
C11 – Production		1 day	4 days	3 weeks		1 day	4 days	3 weeks		1 day	4 days	3 weeks		1 day	4 days	3 weeks		1 day	4 days	3 weeks
	T				T				T				T				T			
	S				S				S				S				S			
	W				W				W				W				W			
	N				N				N				N				N			
	NULL				NULL				NULL				NULL				NULL			
	Trend				Trend				Trend				Trend				Trend			
C12 – Distribution Centers		1 day	4 days	3 weeks		1 day	4 days	3 weeks		1 day	4 days	3 weeks		1 day	4 days	3 weeks		1 day	4 days	3 weeks
	T				T				T				T				T			
	S				S				S				S				S			
	W				W				W				W				W			
	N				N				N				N				N			
	NULL				NULL				NULL				NULL				NULL			
	Trend				Trend				Trend				Trend				Trend			
C13 – Retail Distributors		1 day	4 days	3 weeks		1 day	4 days	3 weeks		1 day	4 days	3 weeks		1 day	4 days	3 weeks		1 day	4 days	3 weeks
	T				T				T				T				T			
	S				S				S				S				S			
	W				W				W				W				W			
	N				N				N				N				N			
	NULL				NULL				NULL				NULL				NULL			
	Trend				Trend				Trend				Trend				Trend			

Part 2

CAUSE / EFFECT	C11 – Production				C12 – Distribution Centers				C13 – Retail Distributors			
C1 – Electrical Power		1 day	4 days	3 weeks		1 day	4 days	3 weeks		1 day	4 days	3 weeks
	T				T				T			
	S				S				S			
	W				W				W			
	N				N				N			
	NULL				NULL				NULL			
	Trend				Trend				Trend			
C2 – Oil/Fuel		1 day	4 days	3 weeks		1 day	4 days	3 weeks		1 day	4 days	3 weeks
	T				T				T			
	S				S				S			
	W				W				W			
	N				N				N			
	NULL				NULL				NULL			
	Trend				Trend				Trend			
C3 – Natural Gas		1 day	4 days	3 weeks		1 day	4 days	3 weeks		1 day	4 days	3 weeks
	T				T				T			
	S				S				S			
	W				W				W			
	N				N				N			
	NULL				NULL				NULL			
	Trend				Trend				Trend			
C4 – Water		1 day	4 days	3 weeks		1 day	4 days	3 weeks		1 day	4 days	3 weeks
	T				T				T			
	S				S				S			
	W				W				W			
	N				N				N			
	NULL				NULL				NULL			
	Trend				Trend				Trend			
C5 – Road Transport		1 day	4 days	3 weeks		1 day	4 days	3 weeks		1 day	4 days	3 weeks
	T				T				T			
	S				S				S			
	W				W				W			
	N				N				N			
	NULL				NULL				NULL			
	Trend				Trend				Trend			
C6 – Air Transport		1 day	4 days	3 weeks		1 day	4 days	3 weeks		1 day	4 days	3 weeks
	T				T				T			
	S				S				S			
	W				W				W			
	N				N				N			
	NULL				NULL				NULL			
	Trend				Trend				Trend			
C7 – Railway Transport		1 day	4 days	3 weeks		1 day	4 days	3 weeks		1 day	4 days	3 weeks
	T				T				T			
	S				S				S			
	W				W				W			
	N				N				N			
	NULL				NULL				NULL			
	Trend				Trend				Trend			
C8 – Telephone Network		1 day	4 days	3 weeks		1 day	4 days	3 weeks		1 day	4 days	3 weeks
	T				T				T			
	S				S				S			
	W				W				W			
	N				N				N			
	NULL				NULL				NULL			
	Trend				Trend				Trend			
C9 – Data Network		1 day	4 days	3 weeks		1 day	4 days	3 weeks		1 day	4 days	3 weeks
	T				T				T			
	S				S				S			
	W				W				W			
	N				N				N			
	NULL				NULL				NULL			
	Trend				Trend				Trend			
C10 – Staff Availability		1 day	4 days	3 weeks		1 day	4 days	3 weeks		1 day	4 days	3 weeks
	T				T				T			
	S				S				S			
	W				W				W			
	N				N				N			
	NULL				NULL				NULL			
	Trend				Trend				Trend			
C11 – Production						1 day	4 days	3 weeks		1 day	4 days	3 weeks
					T				T			
					S				S			
					W				W			
					N				N			
					NULL				NULL			
					Trend				Trend			
C12 – Distribution Centers		1 day	4 days	3 weeks						1 day	4 days	3 weeks
	T								T			
	S								S			
	W								W			
	N								N			
	NULL								NULL			
	Trend								Trend			
C13 – Retail Distributors		1 day	4 days	3 weeks		1 day	4 days	3 weeks				
	T				T							
	S				S							
	W				W							
	N				N							
	NULL				NULL							
	Trend				Trend							

Concepts description

These maps relate different concepts to each other, by indicating how one concept would affect another. In practice the concepts used in this questionnaire are mostly services, but can also slightly differ in meaning or scope. A brief explanation of the meaning of each concept is therefore given below.

Utilities and other services which may impact the FMCG supply chain when they become unavailable	
C1 Electrical Power	This utility powers electrical equipment, and has to be available within specifications. It is provided by infrastructures and facilities for generation, transmission and distribution of electricity.
C2 Oil/Fuel	This powers vehicles and machinery and may be required for heating. It is provided by infrastructures and facilities for oil production, refining, treatment, storage, transmission and distribution.
C3 Natural Gas	This utility is required for heating, some machinery and vehicles and may also be used by power generation. It is provided by infrastructures and facilities for production, refining, treatment, storage, transmission and distribution of natural gas.
C4 Water	This utility provides both fresh water (for drinking, cooling, etc.) and also includes wastewater and drainage. It is provided by facilities for water production and distribution, sours, drainage systems (storm sewers, ditches, etc...), major irrigation systems (reservoirs, irrigation canals) and major flood control systems.
C5 Road Transport	This service provides the transport of goods and people by roads, It is provided by the road network infrastructure and vehicles. Vehicles include automobiles, buses, motorcycles, and all types of trucks.
C6 Air Transport	This service provides the transport of goods and people by air. It is provided by aircraft, air traffic control infrastructure, and airport infrastructure.
C7 Railway Transport	This service provides the transport of goods and people by rail. It is provided by railway infrastructure, freight cars, and locomotives.

C8 Telephone Network	This service provides voice and fax communication. It is provided by telephone networks including switching systems and involves both fixed and mobile telephony.
C9 Data Network	This service provides data communication. It may be provided by the same infrastructure as telephony, but may also involve other systems such as cable, or wireless. It includes communication between computer systems, such as internet connections, e-mail, and proprietary protocols.
C10 Staff Availability	This is the human workforce.
Nodes of the FMCG, which are impacted by the unavailability of the previous services and utilities	
C11 Production	All the activities and operations that transform or process “raw” materials (in this case perishable goods coming from suppliers) into the final product purchased by the customer.
C12 Distribution Centers	Stock facility which stores and redistributes products intended for sale. There are two different levels of Distribution Centers: central and peripheral.
C13 Retail Distributors	It includes large retailers, that have a central structure and they have a direct control on the distribution centers and the sales network, and also the organized retailers formed by consortium or voluntary union.

Thanks for your participation to this questionnaire.

RESEARCH DEVELOPED IN COLLABORATION WITH JOINT RESEARCH CENTRE (ISPRA) AND POLITECNICO DI MILANO

Contacts

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Appendix B

EXPERTS BIOGRAPHY

Jean-Pierre Nordvik

Jean-Pierre Nordvik has an MSc in Electro-Mechanical Engineering from the Brussels Free University (ULB), Belgium. He has extensive professional experience in risk and emergency management, including methodological development, lessons-learnt mechanisms, and design and realization of large distributed ITC systems and software solutions addressing the needs of civil protection authorities, political decision makers, the scientific community and the public at large. He joined the Joint Research Centre of the European Commission in 1990 where he is currently coordinating the institutional project Critical Infrastructures in Transport and Distribution Systems (CI-TRANS), which provides support for the preparation of the forthcoming European legislation on the identification of European critical infrastructures and the assessment of the need to improve their protection.

Igor Nai Fovino

Igor Nai Fovino worked as a Research Collaborator at the University of Milan in the field of privacy-preserving data mining and computer security, and as Lecturer of the courses ‘Linux Security’ (2002) and ‘Laboratory of Computer Security’ (2003). In 2004 he was a Visiting Researcher at CERIAS Research Centre (Purdue University, West-Lafayette, Indiana, USA). In 2006, he received his PhD in Computer Science and was the recipient of the European Innovation Research Project Award. He is currently a Researcher at the Joint Research Centre of the European Commission and Contractual Professor at the University of Insubria. His main research activities are related to ICT security modeling and assessment, privacy-preserving data mining and secure protocols. In such research fields he serves as a reviewer for several international journals and services.

Christos Siaterlis

Christos Siaterlis is an Electrical & Computer Engineer and a project officer at the Joint Research Centre of the European Commission. His research interests include various aspects of the resilience, stability and security of complex systems, and specifically critical information infrastructures like the Internet.

He has a PhD in the area of Internet security management from the National Technical University of Athens and a Master of Science in Computer Science from the University of Southern California, Los Angeles. Furthermore he has working experience as a network engineer with a focus on network monitoring, measurement and security and as a researcher at the Information Sciences Institute (ISI).

Enrico Cagno

Professor of Production Systems Design and Management, and Industrial Plants at the School of Industrial Engineering, Politecnico di Milano, Italy. Professor in several international and domestic Master Courses on Risk Management and Operations Efficiency. His primary research interests are Risk Analysis & Management (within Critical Infrastructure Protection, Project Risk Management, Operational Risk Management, Enterprise Risk Management, Occupational Safety, and System Safety), Eco-Efficiency & Green Design, and, in general, Design and Management of Production System and Industrial Plant. He is author of more than two hundred publications between books and papers. He holds a MSc in Management and Production Engineering and a PhD in Production System and Industrial Plant Design.

Gino Marchet

Gino Marchet is graduated in mechanical engineering at Politecnico di Milan. Since December 2007 he is professor in some Master Couses in Politecnico di Milano. He is the director of Master in logistics of MIP and of some courses organized by MIP. It is the Director of the Centre "Material handling" that has analyzed more than eighty recent realizations of storage facilities and picking and Observatory "Intelligent Transportation Systems" of the Politecnico di Milano. Since 1990 he has been a member of the Scientific Committee of the magazine "Logistics Management", Editions Ritman and academic advisor Assologistica "Culture and Education". His research interests focus on logistics and supply chain design and management of systems, storage and picking, design and management of production systems and logistics, transport modal.

Paolo Trucco

Paolo Trucco is Associate Professor at the School of Management, Politecnico di Milano and Lecturer in Industrial Operations and Risk Management. He is also a Faculty Member of MIP (Politecnico di Milano Business School) in the area of Risk Analysis and Management.

His primary research interests are Risk Analysis and Resilience of complex socio-technical systems, Human Reliability and Organisational Risks Analysis. Most of his consulting has been concerned with Operations Management, HSE and Risk Management. He is author of more than one hundred and eighty publications between books and papers at national and international level.

He is a member of the Italian Society of Industrial Engineering (ANIMP), of the Italian Association of Experts on Critical Infrastructures and member of OSN (National Observatory for Homeland Security and Defence). He is member of ESRA (European Safety and Reliability Association).

Paolo Trucco is also a member of the Risk Management Steering Committee of the Lombardy Health General Directorate and member of the Advisory Board for Research & Innovation of the President’s Cabinet of the Lombardy Administration.

He holds a MSc in Industrial Engineering (Politecnico di Milano, 1994) and a PhD in Quality Engineering (University of Florence, 1998).

Marco Merlo

Marco Merlo took the MSc Degree in Electrical Engineering at the “Politecnico di Milano” in 1999; at the same institution in January 2003 he obtained his Phd, with a Thesis on the Hierarchical voltage control on large power systems. From 2005 to 2008 he was temporary assistant professor at the Electric Engineering Department of the “Politecnico di Milano”; in 2008 he joins the Department of Energy as an assistant professor. His research is testified by more than 40 papers and publications (including volume chapters for international editors, publications on national and international journals, on national and international conferences), dealing with the security issues of power systems.

Fabrizio Dallari

Fabrizio Dallari, Scientific Director of the C-log, is associate professor at the Università Carlo Cattaneo-LIUC, where is the holder of the courses of Logistics and Supply Chain management for the Industrial Engineering Faculty. He has an intense research and consultancy in the area of production systems, logistics and transport for important national companies and agencies. He co-authored the transport master plan and in 2004 was appointed expert for the preparation of the National Plan of Logistics. He is author of over 100 national and international scientific publications and 5 books. He is a member of the Advisory Board of ELA, Scientific Committee of Logistica journals, Logistica Management and Logistica's Systems, and columnist of Sole 24 Ore Transporti.

Daniele Maini

Daniele Maini is the Logistic Director of 'Coop Consorzio Nord Est'.

Antonio Malvestio

Antonio Malvestio is the Western Europe Physical Distribution and Managing Director at 'Procter & Gamble'.

Carmelo Di Mauro

Carmelo Di Mauro obtained an MSc degree in Environmental Engineering at the Polytechnic of Milan, Italy. He has more than 15 years of experience in the field of risk analysis. It worked at TNO (TNO Institute of Environmental Sciences, Energy Research and Process Innovation, The Netherlands) as Post-Doc Researcher and he joined the Joint Research Centre of the European Commission in 2001 where it remains until 2009. He has extensive professional experience in risk and emergency management, including methodological development, lessons-learnt mechanisms, and design and realization of large distributed ITC systems and software solutions addressing the needs of civil protection authorities, political decision makers, the scientific community and the public at large.

During the last two years at JRC, he contributed to develop the preparatory studies to support the release of the EC Directive on Critical Infrastructure Protection Identification (Directive EC 114/2008).

His research activity is mainly focused on risk assessment and risk management methodology, risk-based decision support tools and risk mapping.

Vandenbergh Michel

Michel Vandenbergh was born in Brussels, Belgium. He received his degree of electromechanical engineering from the "Université Libre de Bruxelles" in 1987, and his PhD in energy engineering in 1997 from the "Ecole des Mines de Paris", France. He has more than 15 years' experience in energy systems management, design and simulation, with a special focus on the integration of renewable energy technologies, smart grids and the production of electricity in rural areas.

In 2010, he joined the Institute of Energy of the European Commission Joint Research Center, where he is analyzing critical electricity transport infrastructures.

Vanhoorn Lenhard

Lenhard Vanhoorn is working at the Institute for Energy, one of the seven institutes of the European Commission's Joint Research Centre (JRC). The Institute for Energy is based in Petten (The Netherlands).

He is employed in the Unit "Energy Security" (F.03). Currently, he is mainly working as a gas market analyst, and this from a security of supply point of view (i.e. analysis regarding European gas infrastructure, EU gas suppliers & transit countries, gas disruptions, EU-27 country profiles, ...).

Luca Brandellero

Luca Brandellero is the Logistics Director of La Rinascente. He has an important expertise of logistics, transport and stock management for important multinational logistics providers and for other companies in retail market. He is also a member of the Board of La Rinascente.

Appendix C

EXECUTABLE 'Link_Matrix_Construction.m'

```
close all
clear all
clc

n=13;                    % Concepts number
W=zeros(n,n);
% Link value matrix (the same matrix of FCM_solver)

for i=1:n
for j=1:n
  if j==i

  W(i,j)=0;

  else

  A=zeros(1,3);         % Weighted mean vector

  disp('Concept cause:');
  i
  disp('Concept effect:');
  j

  exp_num=input('Insert the number of expert that an swered to
the cause-effect relation: ');

  v=zeros(exp_num,4);     % Experts Matrix (each row is related
with an expert)

  for k=1:exp_num

    choice=menu(['Which is the sign of the link?  Expert number
    ', num2str(k),' The cause-effect concepts considered are:
    ',num2str(i),'-',num2str(j)],'   +   ','   -   ');

    choice2=menu(['Which is the value of the link chosen by the
    expert?  Expert number ', num2str(k),' The cause-effect
    concepts considered are: ',num2str(i),'-',num2str(j)],'
    Total ',' Strong ',' Weak ',' Negligible ',' Null ');

    exp_grade=menu(['Which is the experience of the expert?
    Expert number ', num2str(k),' The cause-effect concepts
    considered are: ',num2str(i),'-',num2str(j)],' Low ','
    Medium ',' High ');
```

```
        if choice2==1

        v(k,1)=0.7;
        v(k,2)=1;
        v(k,3)=1;
        v(k,4)=exp_grade;

       else
          if choice2==2

          v(k,1)=0.40;
          v(k,2)=0.625;
          v(k,3)=0.85;
          v(k,4)=exp_grade;

          else
            if choice2==3

            v(k,1)=0.2;
            v(k,2)=0.375;
            v(k,3)=0.55;
            v(k,4)=exp_grade;

            else
              if choice2==4

              v(k,1)=0;
              v(k,2)=0.15;
              v(k,3)=0.30;
              v(k,4)=exp_grade;

              else

                v(k,1:3)=0;
                v(k,4)=exp_grade;

              end
            end
          end
        end

        if choice==2         % For negative link

                  v(k,1:3)=-v(k,1:3);

        end
    end

v(:,5)=v(:,4)/sum(v(:,4));      % weight of the expert
experience (column 5)
```

```
   for k=1:exp_num

     A(1)=A(1)+(v(k,1)*v(k,5));
     A(2)=A(2)+(v(k,2)*v(k,5));
     A(3)=A(3)+(v(k,3)*v(k,5));

   end

   W(i,j)=mean(A);

  end
 end
end

W

time_step=menu('Which timeframe do you want to study?','---- 1
day ----','---- 4 days ----','---- 3 weeks ----');

if time_step==1

    save -ascii link_matrix_step1.dat W

else
    if time_step==2

        save -ascii link_matrix_step2.dat W

    else

        save -ascii link_matrix_step3.dat W

    end
end
```

EXECUTABLE 'FCM_analyses.m'

```
close all
clear all
clc

%% Data

time_step=menu('Which timeframe do you want to study?','---- 1
day ----','---- 4 days ----','---- 3 weeks ----');
```

```
if time_step==1

    load link_matrix_step1.dat
    link_matrix=link_matrix_step1;

else
    if time_step==2

        load link_matrix_step2.dat
        link_matrix=link_matrix_step2;

    else

        load link_matrix_step3.dat
        link_matrix=link_matrix_step3;

    end
end

n=13;
state_vec=zeros(1,n);
control=0;

choice=menu('Which concept do you want activate?','----
Electrical Power ----','---- Oil/Fuel ----','---- Natural Gas --
--','---- Water ----','---- Road Transport ----','---- Air
Transport ----','---- Railway Transport ----','---- Telephone
Network ----','---- Data Network ----','---- Staff Availability
----','---- Production ----','---- Distribution Centers ----','-
--- Retail Distributors ----');

choice2=menu('Do you want to activate another concept?', ' Yes
',' No ');

if choice2==1

    choice3=menu('Which concept do you want activate?','----
Electrical Power ----','---- Oil/Fuel ----','---- Natural Gas --
--','---- Water ----','---- Road Transport ----','---- Air
Transport ----','---- Railway Transport ----','---- Telephone
Network ----','---- Data Network ----','---- Staff Availability
----','---- Production ----','---- Distribution Centers ----','-
--- Retail Distributors ----');

    state_vec(choice3)=1;
```

```
    if choice==choice3

        error('Error: you have chosen the same concept both the
time')

    end
else

    choice3=0;

end

max=100;  % maximum number of iterations

state_vec(choice)=1;
state_vec
state_concept_vec=zeros(1,n);
state_vec_old=zeros(1,n);
state_matrix=zeros(n,max);
state_concept_matrix=zeros(n,max);

for i=1:n

    state_matrix(i,1)=state_vec(i);

end

k=0;
counter=0;


%% Static analysis

id=zeros(n,1);     % Indegree
od=zeros(n,1);     % Outdegree
td=zeros(n,1);     % Total degree
R=0;               % Number of relationships between concepts

for i=1:n
    for j=1:n
        if link_matrix~=0

            R=R+1;

        end
    end
end
```

```
for i=1:n
    for j=1:n
        if link_matrix(i,j)~=0

            R=R+1;

        end
    end
end

clustering_coeff=R/(n*(n-1));

for i=1:n
    for j=1:n

                id(i)=id(i)+abs(link_matrix(j,i));
                od(i)=od(i)+abs(link_matrix(i,j));

    end
    td(i)=id(i)+od(i);
end

figure('Name','Results of the static analysis','NumberTitle',
'off')

subplot(3,1,1)
bar(id,'r')
title('Indegree')
xlabel('Concept')
ylabel('ID')

subplot(3,1,2)
bar(od,'g')
title('Outdegree')
xlabel('Concept')
ylabel('OD')

subplot(3,1,3)
bar(td,'c')
title('Total degree')
xlabel('Concept')
ylabel('TD')


%% Iterations Dynamic analysis

tol=0.0001;                  % Tolerance for convergency
graph_vec=[-10:0.25:+10];
% Vector for the representation of the threshold functions
lambda=0.6;                  % Constant for the sigmoid function
```

```
a=0.5;         % Limit value for the discrete threshold function

threshold_choice=menu('Which threshold function do you want
use?', 'erf function','tanh function','sigmoid
function','Discrete');

figure('Name','Threshold function
representation','NumberTitle','off')

if threshold_choice==1

    plot(graph_vec,erf(graph_vec));
    title('Threshold function: erf ');

else
    if threshold_choice==2

        plot(graph_vec,tanh(graph_vec));
        title('Threshold function: tanh ');

    else
        if threshold_choice==3

          plot(graph_vec,(1-exp(-lambda.*graph_vec))./(1+exp(-
lambda.*graph_vec)));
          title('Threshold function: sigmoid ');

        else

           t=0:0.001:3;
           step=.0001*(1 - .5*(sign(t-a) + 1)) + .5*(sign(t-a)
           + 1 );
           plot(t,step);
           hold on
           t=-3:0.001:0;
            step=.001*(1 - .5*(sign((-t)-a) + 1)) + .5*(sign((-
           t)-a) + 1 );
           plot(t,-step);
           axis([-3 3 -1.1 1.1]);
           title('Threshold function: discrete ');

        end
    end
end

xlabel('x');
ylabel('y');
```

```
while k==0 && counter<max

    if ((state_vec_old>=(state_vec-tol)) &
(state_vec_old<=(state_vec+tol)) | state_vec(5)==-1)

        disp('Convergence is reached')
        k=1;

    else

        state_vec_old=state_vec;

        for i=1:n
            for j=1:n

               state_concept_vec(i)=state_concept_vec(i)+state_v
               ec(j)*link_matrix(j,i);
            end
        end
        for i=1:n
            if i==choice || i==choice3

                state_vec(i)=1;

            else
                if threshold_choice==1

                    state_vec(i)=erf(state_concept_vec(i));

                else
                    if threshold_choice==2

                        state_vec(i)=tanh(state_concept_vec(i));

                    else
                        if threshold_choice==3

                            state_vec(i)=(1-exp(-lambda.*
                            state_concept_vec(i)))./(1+exp(-
                            lambda.*state_concept_vec(i)));

                        else
                            if state_concept_vec(i)>a

                                state_vec(i)=1;

                            else
                                if state_concept_vec(i)<-a
```

```
                                    state_vec(i)=-1;

                                else

                                    state_vec(i)=0;

                                end
                            end
                        end
                    end
                end
            end
        end

        for i=1:n
               state_matrix(i,counter+2)=state_vec(i);
        end

        for i=1:n

               state_concept_matrix(i,counter+2)=state_concept_v
               ec(i);
        end

  counter=counter+1;

  state_concept_vec;
  state_vec;
  state_concept_vec=zeros(1,n);

    end

end

state_concept_matrix(:,counter+2:max)=[]
state_matrix(:,counter+2:max)=[];

%% Plot

figure('Name','Concept values in each iteration
step','NumberTitle','off')
plot(state_concept_matrix.','-x');
grid on
title('Concept values in each iteration step');
xlabel('Iteration');
ylabel('Concept Value');
legend(' C1 ',' C2 ',' C3 ',' C4 ',' C5 ',' C6 ',' C7 ',' C8 ','
C9 ',' C10 ',' C11 ',' C12 ',' C13 ');
```

EXECUTABLE ‘PieCharts.m’

```
close all
clear all
clc

time_step=menu('Which timeframe do you want to study?','---- 1
day ----','---- 4 days ----','---- 3 weeks ----');

if time_step==1

    load link_matrix_step1.dat
    link_matrix=link_matrix_step1;

else
    if time_step==2

        load link_matrix_step2.dat
        link_matrix=link_matrix_step2;

    else

        load link_matrix_step3.dat
        link_matrix=link_matrix_step3;

    end
end

n=13;
cont(1,5)=0;

for i=1:n
    for j=1:n
        if abs(link_matrix(i,j))<0.2

            cont(1,1)=cont(1,1)+1;

        else
            if abs(link_matrix(i,j))<0.4 &
            abs(link_matrix(i,j))>=0.2

            cont(1,2)=cont(1,2)+1;

            else
               if abs(link_matrix(i,j))<0.6 &
               abs(link_matrix(i,j))>=0.4

                cont(1,3)=cont(1,3)+1;
```

```
                else
                   if abs(link_matrix(i,j))<0.8 &
                   abs(link_matrix(i,j))>=0.6

                   cont(1,4)=cont(1,4)+1;

                    else

                       cont(1,5)=cont(1,5)+1;

                    end
                end
            end
        end

    end
end

x=[1 2 3 4 5];
explode=[1 0 0 0 0];

figure('Name','Causal relationship intensity','NumberTitle',
'off')
pie(cont,explode);
title('Causal relationship intensity');
legend(' x<0.2 ',' 0.2<=x<0.4 ',' 0.4<=x<0.6 ',' 0.6<=x<0.8 ','
0.8<=x<=1 '
```

Appendix D

All the results related to the model are reported here.

Adjacency matrixes (W)

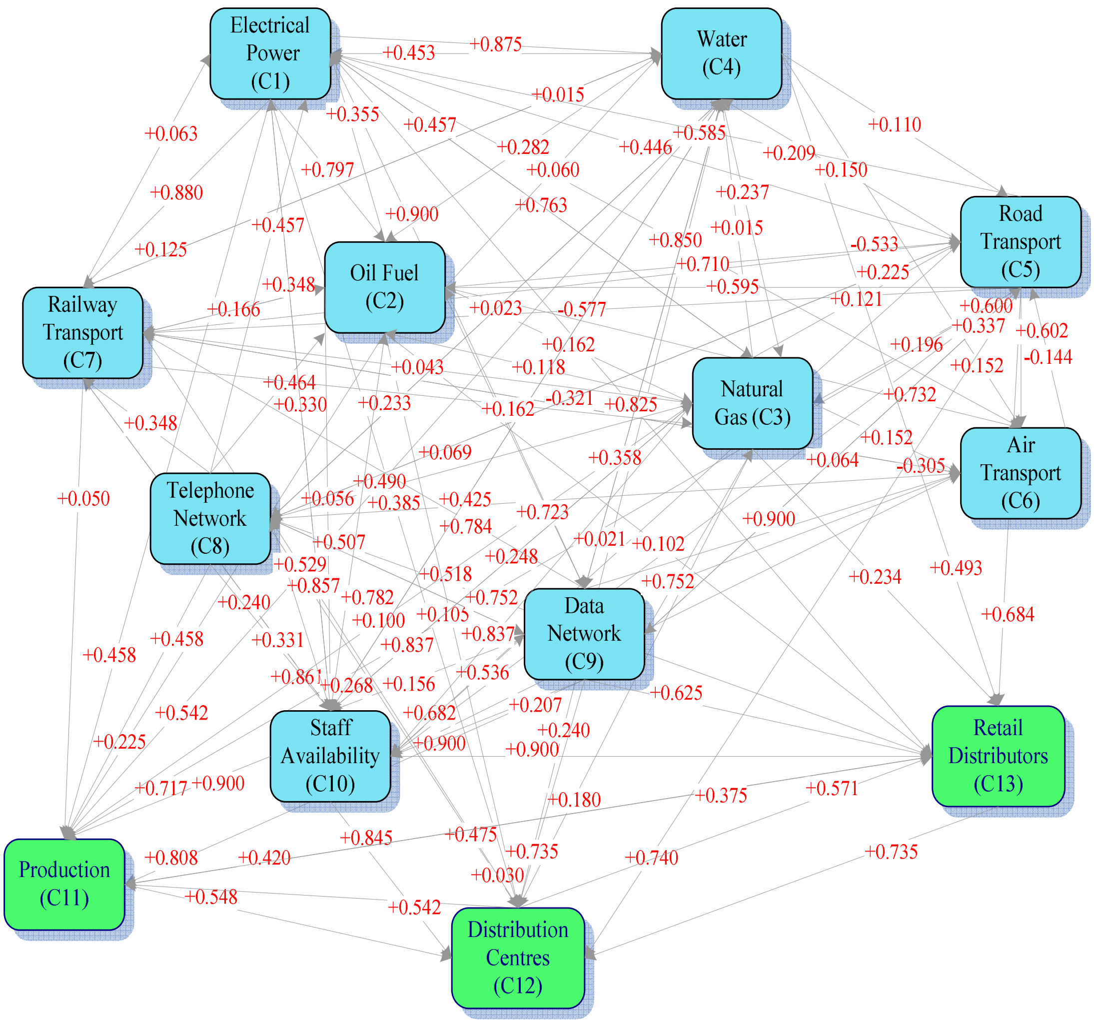
1 DAY													
	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**	**C13**
C1	0	0.758	0.688	0.685	0.394	0.630	0.900	0.612	0.630	0.209	0.175	0.105	0.504
C2	0.257	0	0.127	0.030	0.190	0.361	0.134	0	0	0.024	0	0.060	0.102
C3	0.284	0.118	0	0.015	0.115	0.116	0.043	0	0	0.135	0.175	0.060	0.086
C4	0.304	0.246	0.162	0	0.115	0.123	0.107	0.023	0.021	0.135	0.125	0.060	0.166
C5	0.122	0.295	0.127	0.090	0	0.580	-0.282	0.035	0.032	0.702	0.375	0.475	0.464
C6	0	0	0	0	-0.058	0	-0.155	0	0	0.106	0	0	0
C7	0.016	0.283	0.069	0.015	-0.446	-0.157	0	0	0	0.336	0.125	0.030	0
C8	0.414	0.364	0.332	0.235	0.225	0.402	0.398	0	0.436	0.222	0.383	0.335	0.380
C9	0.784	0.630	0.673	0.283	0.263	0.900	0.743	0.752	0	0.195	0.725	0.590	0.529
C10	0.900	0.802	0.858	0.588	0.562	0.900	0.900	0.296	0.348	0	0.900	0.690	0.900
C11	0	0	0	0	0	0	0	0	0	0	0	0.271	0.041
C12	0	0	0	0	0	0	0	0	0	0	0.300	0	0.230
C13	0	0	0	0	0	0	0	0	0	0	0.175	0.462	0

4 DAYS													
	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**	**C13**
C1	0	0.797	0.763	0.875	0.446	0.850	0.880	0.879	0.900	0.330	0.458	0.385	0.825
C2	0.355	0	0.162	0.060	0.710	0.732	0.166	0	0	0.056	0.225	0.105	0.102
C3	0.457	0.118	0	0.015	0.121	0.152	0.043	0	0	0.248	0.100	0.180	0.234
C4	0.453	0.282	0.237	0	0.110	0.152	0.125	0.023	0.021	0.268	0.542	0.240	0.493
C5	0.209	0.595	0.196	0.150	0	0.602	-0.577	0.069	0.064	0.682	0.717	0.740	0.684
C6	0	0	0	0	-0.144	0	-0.321	0	0	0.156	0	0	0
C7	0.063	0.348	0.162	0.015	-0.533	-0.305	0	0	0	0.240	0.050	0.030	0
C8	0.457	0.464	0.490	0.233	0.225	0.425	0.348	0	0.507	0.331	0.458	0.475	0.518
C9	0.900	0.723	0.752	0.358	0.337	0.900	0.784	0.752	0	0.207	0.808	0.735	0.625
C10	0.857	0.782	0.837	0.585	0.600	0.900	0.861	0.529	0.536	0	0.900	0.845	0.900
C11	0	0	0	0	0	0	0	0	0	0	0	0.548	0.420
C12	0	0	0	0	0	0	0	0	0	0	0.542	0	0.571
C13	0	0	0	0	0	0	0	0	0	0	0.375	0.735	0

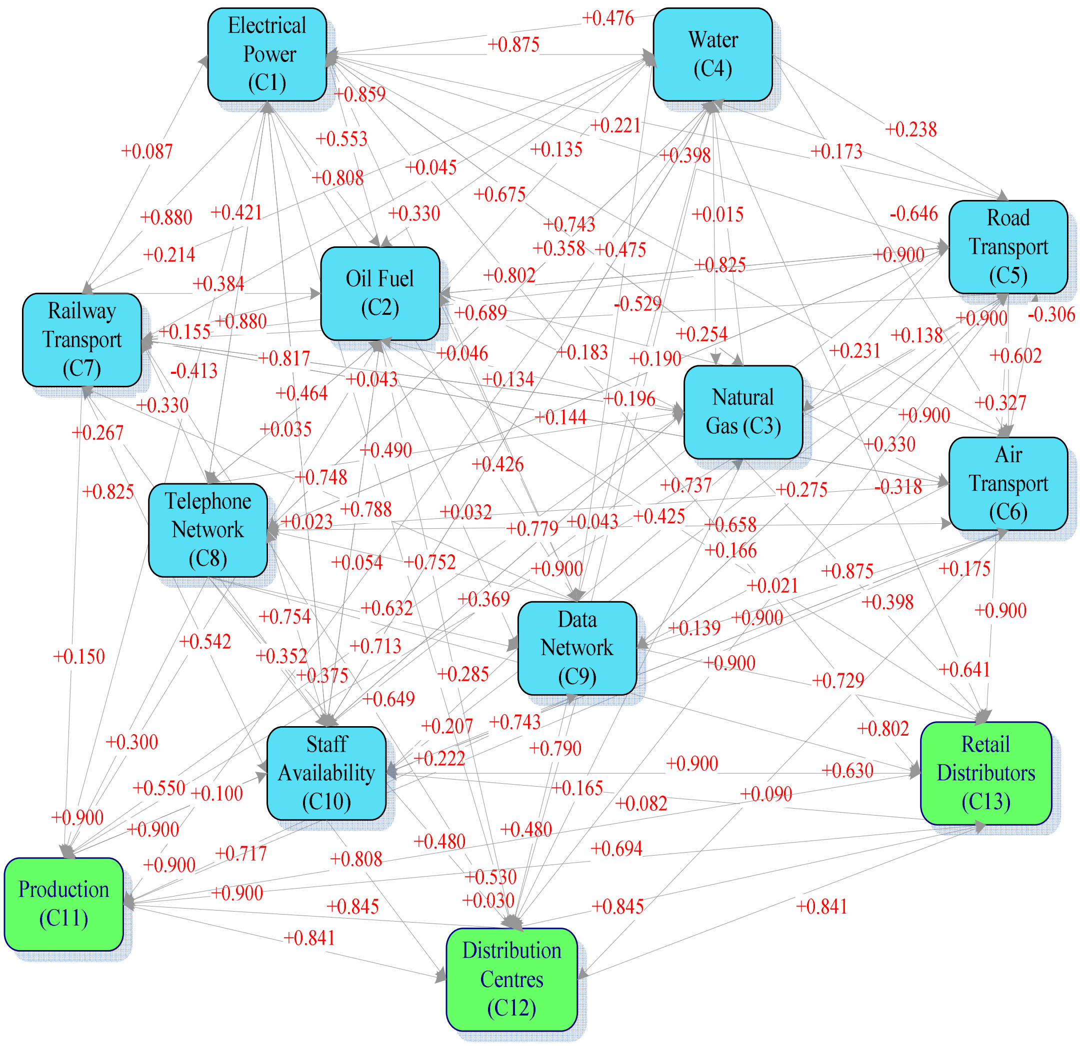
3 WEEKS													
	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**	**C13**
C1	0	0.808	0.743	0.875	0.398	0.825	0.880	0.880	0.900	0.375	0.900	0.530	0.802
C2	0.553	0	0.183	0.135	0.900	0.900	0.155	0.035	0.032	0.054	0.542	0.285	0.166
C3	0.675	0.134	0	0.015	0.138	0.330	0.043	0	0	0.369	0.550	0.165	0.398
C4	0.476	0.330	0.254	0	0.238	0.327	0.214	0.046	0.043	0.426	0.900	0.480	0.641
C5	0.221	0.802	0.231	0.173	0	0.602	-0.646	0.144	0.139	0.649	0.900	0.900	0.900
C6	0	0	0	0	-0.306	0	-0.413	0.023	0.021	0.222	0.175	0.09	0
C7	0.087	0.384	0.196	0.045	-0.529	-0.318	0	0	0	0.267	0.150	0.030	0
C8	0.421	0.464	0.490	0.358	0.190	0.425	0.330	0	0.632	0.352	0.300	0.480	0.630
C9	0.859	0.689	0.737	0.475	0.275	0.875	0.748	0.752	0	0.207	0.717	0.790	0.729
C10	0.817	0.788	0.779	0.713	0.658	0.900	0.825	0.754	0.743	0	0.900	0.845	0.900
C11	0	0	0	0	0	0	0	0	0	0.1	0	0.841	0.694
C12	0	0	0	0	0	0	0	0	0	0	0.900	0	0.841
C13	0	0	0	0	0	0	0	0	0	0.082	0.808	0.845	0

Fuzzy Cognitive Maps (4 days and 3 weeks)

4 days



3 weeks


Electrical Power (C1)
Water (C4)
Road Transport (C5)
Oil Fuel (C2)
Railway Transport (C7)
Natural Gas (C3)
Air Transport (C6)
Telephone Network (C8)
Data Network (C9)
Staff Availability (C10)
Retail Distributors (C13)
Production (C11)
Distribution Centres (C12)
+0.476
+0.875
+0.859
+0.087
+0.553
+0.221
+0.238
+0.808
+0.045
+0.135
+0.398
+0.173
+0.880
+0.421
+0.330
+0.675
+0.015
-0.646
+0.214
+0.743
+0.358
+0.475
+0.825
+0.900
+0.384
+0.802
-0.529
+0.689
+0.155
+0.880
+0.254
+0.900
-0.306
+0.817
+0.046
+0.183
+0.190
+0.231
+0.138
+0.602
-0.413
+0.043
+0.134
+0.464
+0.330
+0.196
+0.327
+0.267
+0.035
+0.144
+0.900
+0.330
+0.490
+0.426
+0.748
+0.825
+0.737
+0.275
-0.318
+0.023
+0.788
+0.032
+0.779
+0.043
+0.425
+0.658
+0.166
+0.054
+0.752
+0.900
+0.875
+0.175
+0.021
+0.369
+0.632
+0.754
+0.398
+0.900
+0.139
+0.900
+0.542
+0.713
+0.150
+0.352
+0.375
+0.285
+0.900
+0.729
+0.641
+0.649
+0.207
+0.743
+0.802
+0.300
+0.222
+0.790
+0.900
+0.630
+0.550
+0.100
+0.165
+0.082
+0.090
+0.900
+0.900
+0.480
+0.480
+0.717
+0.808
+0.694
+0.900
+0.530
+0.900
+0.030
+0.845
+0.845
+0.841
+0.841

Continuous threshold function – Complex Failure Scenario –

C1 always unavailable (4 days and 3 weeks)

4 DAY (Complex Failure Scenario)													
sigmoid function (lambda=0.6)	Effect on the concept C_i												
Failure of the concept C_j	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
C1													
C2	1	1	0.528	0.411	0.395	0.667	0.406	0.397	0.381	0.373	0.672	0.663	0.711
C3	1	0.564	1	0.405	0.333	0.619	0.408	0.397	0.381	0.384	0.657	0.663	0.715
C4	1	0.593	0.549	1	0.342	0.631	0.426	0.404	0.388	0.401	0.711	0.687	0.750
C5	1	0.646	0.565	0.446	1	0.710	0.329	0.426	0.408	0.475	0.757	0.759	0.791
C6	1	0.538	0.501	0.397	0.297	1	0.368	0.392	0.376	0.357	0.631	0.630	0.683
C7	1	0.579	0.525	0.399	0.232	0.555	1	0.393	0.377	0.369	0.632	0.628	0.679
C8	1	0.639	0.602	0.455	0.374	0.684	0.474	1	0.463	0.432	0.732	0.732	0.774
C9	1	0.673	0.637	0.475	0.391	0.730	0.527	0.515	1	0.431	0.767	0.762	0.791
C10	1	0.689	0.653	0.509	0.434	0.740	0.538	0.495	0.476	1	0.786	0.781	0.817
C11	1	0.539	0.499	0.395	0.306	0.589	0.397	0.390	0.374	0.343	1	0.667	0.708
C12	1	0.539	0.499	0.395	0.306	0.589	0.397	0.390	0.374	0.343	0.667	1	0.716
C13	1	0.539	0.499	0.395	0.306	0.589	0.397	0.390	0.374	0.343	0.655	0.671	1

3 WEEKS (Complex Failure Scenario)													
sigmoid function (lambda=0.6)	Effect on the concept C_i												
Failure of the concept C_j	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
C1													
C2	1	1	0.583	0.509	0.447	0.757	0.422	0.483	0.473	0.507	0.916	0.849	0.866
C3	1	0.643	1	0.500	0.385	0.728	0.428	0.481	0.471	0.526	0.916	0.842	0.869
C4	1	0.672	0.603	1	0.408	0.742	0.454	0.493	0.483	0.548	0.931	0.864	0.887
C5	1	0.725	0.616	0.540	1	0.787	0.345	0.519	0.508	0.587	0.940	0.893	0.907
C6	1	0.615	0.556	0.489	0.338	1	0.392	0.473	0.463	0.490	0.897	0.826	0.846
C7	1	0.654	0.583	0.497	0.292	0.668	1	0.473	0.464	0.507	0.900	0.824	0.846
C8	1	0.697	0.640	0.555	0.413	0.763	0.482	1	0.551	0.555	0.925	0.872	0.894
C9	1	0.718	0.664	0.568	0.422	0.791	0.523	0.574	1	0.551	0.936	0.885	0.900
C10	1	0.733	0.673	0.593	0.468	0.799	0.528	0.578	0.566	1	0.942	0.892	0.909
C11	1	0.618	0.556	0.488	0.358	0.692	0.418	0.470	0.461	0.481	1	0.832	0.853
C12	1	0.617	0.555	0.487	0.357	0.692	0.418	0.470	0.460	0.479	0.904	1	0.858
C13	1	0.618	0.556	0.488	0.358	0.693	0.418	0.470	0.461	0.482	0.902	0.836	1

Rank Order Clustering results

1 DAY - ROC -

sigmoid function (lambda=0.6)		*Effect on the concept C_i*												
		C2	**C1**	**C6**	**C3**	**C11**	**C7**	**C13**	**C10**	**C12**	**C8**	**C9**	**C4**	**C5**
Failure of the concept C_j	**C10**	0.459	0.428	0.486	0.430	0.463	0.422	0.462	1	0.414	0.312	0.215	0.302	0.233
	C1	0.408	1	0.398	0.361	0.287	0.386	0.342	0.208	0.255	0.217	0.243	0.284	0.175
	C9	0.420	0.404	0.479	0.393	0.423	0.398	0.383	0.220	0.380	0.255	1	0.236	0.168
	C8	0.305	0.283	0.326	0.270	0.301	0.278	0.296	0.182	0.277	1	0.203	0.185	0.137
	C3	0.116	0.139	0.122	1	0.122	0.083	0.104	0.084	0.089	0.036	0.042	0.058	0.067
	C5	0.232	0.179	0.330	0.180	0.270	0.062	0.291	0.257	0.288	0.085	0.082	0.125	1
	C2	1	0.120	0.172	0.094	0.063	0.087	0.094	0.055	0.075	0.043	0.034	0.051	0.076
	C4	0.171	0.164	0.146	0.135	0.127	0.117	0.143	0.097	0.106	0.059	0.056	1	0.075
	C7	0.119	0.050	-0.006	0.063	0.070	1	0.034	0.090	0.035	0.021	0.021	0.033	-0.099
	C6	0.010	0.013	1	0.012	0.012	-0.032	0.013	0.030	0.011	0.006	0.006	0.009	-0.004
	C11	0	0	0	0	1	0	0.018	0	0.084	0	0	0	0
	C13	0	0	0	0	0.065	0	1	0	0.143	0	0	0	0
	C12	0	0	0	0	0.093	0	0.070	0	1	0	0	0	0

4 DAYS - ROC -

sigmoid function (lambda=0.6)		*Effect on the concept C_i*												
		C13	**C11**	**C12**	**C6**	**C2**	**C1**	**C3**	**C10**	**C8**	**C9**	**C4**	**C5**	**C7**
Failure of the concept C_j	**C10**	0.732	0.710	0.711	0.637	0.578	0.556	0.546	1	0.377	0.361	0.395	0.360	0.427
	C9	0.693	0.686	0.685	0.627	0.561	0.552	0.529	0.343	0.409	1	0.353	0.310	0.419
	C1	0.681	0.629	0.628	0.589	0.539	1	0.499	0.343	0.390	0.374	0.395	0.306	0.397
	C8	0.623	0.593	0.604	0.513	0.468	0.443	0.441	0.316	1	0.318	0.291	0.263	0.312
	C5	0.599	0.583	0.600	0.498	0.417	0.336	0.321	0.334	0.205	0.194	0.232	1	0.054
	C4	0.508	0.493	0.456	0.347	0.330	0.340	0.296	0.232	0.172	0.164	1	0.181	0.197
	C2	0.375	0.376	0.366	0.415	1	0.270	0.232	0.177	0.134	0.127	0.155	0.270	0.132
	C3	0.390	0.342	0.367	0.296	0.252	0.295	1	0.196	0.143	0.136	0.152	0.155	0.150
	C13	1	0.150	0.240	0	0	0	0	0	0	0	0	0	0
	C11	0.159	1	0.197	0	0	0	0	0	0	0	0	0	0
	C12	0.192	0.182	1	0	0	0	0	0	0	0	0	0	0
	C6	0.036	0.032	0.033	1	0.015	0.024	0.021	0.047	0.017	0.016	0.017	-0.013	-0.068
	C7	0.092	0.097	0.090	0	0.155	0.093	0.114	0.086	0.047	0.045	0.051	-0.085	1

3 WEEKS - ROC -

sigmoid function (lambda=0.6)		*Effect on the concept C_i*												
		C11	**C13**	**C12**	**C6**	**C1**	**C2**	**C3**	**C10**	**C4**	**C8**	**C9**	**C5**	**C7**
Failure of the concept C_j	**C10**	0.914	0.873	0.859	0.735	0.649	0.658	0.597	1	0.510	0.496	0.483	0.417	0.443
	C1	0.894	0.845	0.823	0.692	1	0.617	0.555	0.478	0.487	0.469	0.460	0.357	0.417
	C9	0.902	0.859	0.848	0.723	0.644	0.637	0.586	0.481	0.478	0.492	1	0.360	0.439
	C8	0.870	0.835	0.815	0.659	0.574	0.584	0.532	0.467	0.438	1	0.445	0.334	0.365
	C5	0.885	0.842	0.834	0.670	0.520	0.593	0.464	0.485	0.389	0.369	0.358	1	0.155
	C4	0.868	0.805	0.784	0.595	0.524	0.516	0.449	0.439	1	0.334	0.325	0.311	0.303
	C2	0.820	0.741	0.739	0.616	0.483	1	0.398	0.364	0.330	0.301	0.293	0.369	0.234
	C3	0.819	0.754	0.725	0.556	0.508	0.452	1	0.397	0.322	0.306	0.298	0.269	0.257
	C7	0.604	0.519	0.514	0.262	0.297	0.341	0.283	0.259	0.207	0.186	0.181	0.048	1
	C13	0.503	1	0.474	0.153	0.123	0.124	0.108	0.122	0.089	0.085	0.082	0.069	0.070
	C11	1	0.447	0.465	0.158	0.126	0.128	0.112	0.125	0.091	0.087	0.085	0.072	0.072
	C12	0.448	0.412	1	0.094	0.075	0.076	0.066	0.074	0.054	0.052	0.050	0.042	0.043
	C6	0.300	0.239	0.255	1	0.102	0.087	0.088	0.123	0.076	0.080	0.078	-0.007	-0.030

Nomenclature

x_c: x value of the center of gravity

A_i: activation level of concept C_i at time $t+1$

A_j: activation level of concept C_j at time t

A_i^{old}: activation level of concept C_i at time t

W_{ij}: weight of the interconnection between C_j and C_i

f: threshold function

Y_j: threshold value of the j^{th} concept

λ: constant that determine how fast the output goes from 0 to 1

x: vector of the inoperability

c: vector of the exogenous disturbances

A: matrix of the Leontief coefficients

δ_i: dependency index

ρ_j: influence gain

ew_i: relative expert weight

λ_i: experience number

$\bar{A}_w$: three component number that represents the triangular shape of the membership function

D: density

R: number of causal relationships

W: adjacency matrix

$id(C_i)$: number of incoming arcs (in-degree) of node C_i

$od(C_i)$: number of outcoming arcs (out-degree) of node C_i

$td(C_i)$: total degree) of node C_i

$C_{new}^{(k+1)}$: new state vector at iteration k+1

$C_i^{(k)}$: i^{th} element of the old state vector

k: iteration step

R_{ij}: incidence matrix

be_i: row binary equivalent

be_j: column binary equivalent

we_i: row weighted equivalent

we_j: column weighted equivalent

Acronyms

ABM: Agent-Based Model

BC: Business Continuity

BCM: Business Continuity Management

CI: Critical Infrastructure

CII: Critical Infrastructure Interdependencies

CIIP: Critical Information Infrastructure Protection

CIKR: Critical Infrastructure and Key Resources

CIP: Critical Infrastructure Protection

COG: Center of Gravity

CP: Contingency Plan

CVAT: Community Vulnerability Assessment Tool

DC: Distribution Center

DG: Directorate General

DR: Disaster Recovery

DRP: Disaster Recovery Plan

ECI: European Critical Infrastructure

EPCIP: European Programme of Critical Infrastructure Protection

EU: European Union

FEMA: Federal Emergency Management Agency

FCM: Fuzzy Cognitive Map

FL: Fuzzy Logic

FMCG: Fast Moving Consumer Goods

GDP: Gross Domestic Product

GPO: Group Purchasing Organizations

GSPN: Generalized Stochastic Petri Net

GT: Group Technology

HAZUS: Hazard United States

HLA: High Level Architecture

Ho.Re.Ca.: Hotel, Restaurant and Catering

IIM: Input-output Inoperability Model

IPSC: Institute for the Protection and Security of the Citizen

IT: Information Technology

I-VAM: Infrastructure Vulnerability Assessment Model

JRC: Joint Research Centre

KRSC: Key Resources Supply Chain

LOR: Large Organized Retailer

MIL-STD: Military Standard

M&S: Modeling and Simulation

MLR: Milan Logistic Region

MOR: Mass Organized Retailer

NIPP: National Infrastructure Protection Plan

OMT: Object Model Template

PRA: Probabilistic Risk Assessment

ROC: Rank Order Clustering

RTI: RunTime Infrastructure

SD: System Dynamics

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Internet Resources

Federdistribuzione
http://www.federdistribuzione.it/

Eruptions
http://scienceblogs.com/eruptions/2010/04/threat_of_icelandic_ash_closes.php

European Commission – Joint Research Center –
http://ec.europa.eu/dgs/jrc/index.cfm

European Commission – Humanitarian Aid & Civil Protection –
http://ec.europa.eu/echo/

Repast (Recursive Porous Agent Simulation Toolkit)
http://repast.sourceforge.net/

SunGard Availability Services
http://www.safetynet247.co.uk/

ISDR (International Strategy for Disaster Reduction)
http://www.unisdr.org/

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