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Master of Science in
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System Dynamics modelling and analysis of the impact of Critical Infrastructures disruptions on the Fast Moving Consumer Goods supply chain

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Abstract

What this work mainly concerns is about the modeling and analysis of interdependencies between Critical Infrastructures and Key Resource Supply Chain. The purpose is to protect critical infrastructures and human safety to reach economic loss reduction eventually.

In this work, what is vital to Critical Infrastructure Protection is introduced and described. Besides, a detailed demonstration and comparison of modeling techniques is discussed.

Many of the modeling techniques fall short in this case because they are usually limited to 1 infrastructure disruption or at best 1 sector, which is not enough for detailed modeling and analysis. They even fail to capture the propagated consequence after critical infrastructure disruption. Therefore, in this work, we need to adopt a new methodology and modeling technique to overcome the drawbacks.

System Dynamics is a qualitative and quantitative modeling technique which is capable to analyze the interdependencies between Critical Infrastructures and Key Resource Supply Chain. Hence the SD technique is adopted by this work.

The critical infrastructures considered are in the scope of the entire Italy. Besides the interdependencies between CIs themselves, in this work, the interdependencies between CIs and Fast Moving Consumer Goods supply chain are also analyzed and described through modeling creating and simulation. The simulation is done by a software called Anylogic.

All the data required are demonstrated in economic terms because in this way it is convenient and straightforward to simulate in System Dynamic methodology.

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.

Keywords

System Dynamic, Critical Infrastructure, Fast Moving Consumer Goods, Supply Chain, Interdependency Analysis.

Introduction

Because of the main disasters due to terrorism and natural events, the protection of the citizens' lives and properties become one of the most important priorities of the society. To form a safe and normal-functioning society, a lot of fundamental services which include electricity, transportation, communication and energy system and so on are required. If one or more of the basic services is at risk or vulnerable, it is impossible or very difficult to maintain the economic development. These kinds of public services are so called critical infrastructures. Recently years, critical infrastructures protection has been attracting more and more attention from many countries in the world, especially advanced countries such as European countries and the United State. The European Commission, the United State Department of Homeland Security has been concerned about the security of their country infrastructure as a result of new international threats. In 2005 the EC adopted the green paper "European program for critical infrastructure protection". In 2009, the US published and launched the US National Infrastructure Protection Plan (NIPP, 2009).

When studying the risk and vulnerability associated to critical infrastructures, interdependencies must be paid attention to and they should be analyzed based on the point of view "system of systems" to describe this complex and interconnected world. One of the major problems in the risk analysis of critical infrastructures is the full identification and correct modeling of these dependencies.

Nowadays, 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. The most relevant supply chain in Italian economic context is the Fast Moving Consumer Goods sector, considering its contribution to the growth of the Gross Domestic Product (GDP). Consequently, finding the interdependency between CIs and FMCG supply chain becomes the most important step during the work.

In this paper, a System Dynamics model will be demonstrated to analyze the interdependencies between Critical Infrastructures and Fast Moving Consumer Goods supply chain. In order to understand the characteristics of this complex supply chain a preliminary study regarding the FMCG supply chain has been done.

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

General introduction of CIP

First of all, the term “Critical Infrastructure” is defined as any element, system or part thereof, situated in a state that is considered essential for the maintenance of vital societal functions, health, physical integrity and security, social and economic welfare (J.M. Yusta et al., 2011). The concept of critical infrastructure includes all assets that are so vital for any country that their destruction or degradation would have a debilitating effect on the essential functions of government, national security, national economy or public health (Hull et al., 2006). Literature generally agrees to define a country’s energy system as interconnected and complex. Disruptions in one part of the infrastructure may spread out through the system. This definition is called “interdependency” (Consolini, 2009). Fig.1 outlines how the critical infrastructures, for example, water services, electronics, telecommunications and transportation are interlinked (Ness, 2006). As we can see from the figure, Disruption of a single sector of critical infrastructure sector, due to terrorist attacks or natural disasters, is very likely to cause cascading effects on other sectors. Therefore, Critical Infrastructure Protection is extremely important because infrastructure systems are getting more vulnerable and critical due to the interdependency. CIP is a concept that relates to the preparedness and response to serious incidents that involve the critical infrastructure of a region or nation.

General purpose of this research

The importance of CIP is pointed out above. Obviously what we concern is how to proceed CIP, what is the techniques that were used in past years and which is the best one for specific situations. The main techniques we collect include:

Agent-based Model
Fuzzy Logic and Fuzzy Cognitive Maps
High Level Architecture
Input-output Inoperability Model
Petri Nets
System Dynamics

In this paper, System Dynamics approach is utilized to analyze and model the interdependency between CIs and Fast Moving Consumer Goods supply chain, which is the main objective of this research.

Summary of the scope of the work and how the document is organized

Disruption of a single part of critical infrastructure will cause cascading impact on other infrastructures due to interdependency, which will further cause various effects in many fields such as environment pollution, citizens’ security or economic loss. In this paper, the scope is set only in economics loss field, specifically in Fast Moving Consumer Goods supply chain case. Nine variables for critical infrastructures are defined in this paper: electrical power, fuel, gas, water, road transport, urban train, air transport, railway transport and staff availability; two variables for FMCG supply chain are as following: distribution center inventory and retail inventory. The full text of this paper includes seven chapters:

Chapter 1: The relevance of CIP and KRSC resilience in modern society

Chapter 2: State-of-the-art review on modeling techniques for vulnerabilities and interdependencies analysis for CIs and KRSC

Chapter 3: Description of Fast Moving Consumer Goods supply chain

Chapter 4: Development of the System Dynamics model for interdependency analysis between the system of CIs and the FMCG Supply Chain

Chapter 5: Data requirements, collection and fusion

Chapter 6: Simulations campaign

Chapter 7: Discussion of results and conclusions

Chapter 1: The relevance of CIP and KRSC resilience in modern society

Definition to CIP

The term *infrastructure*, is defined as "the underlying foundation or basic framework (as of a system or organization)" (Springfield, 1993). In a report to the U.S. President in October 1997, the Commission defined an infrastructure as: *a network of independent, mostly privately-owned, man-made systems and processes that function collaboratively and synergistically to produce and distribute a continuous flow of essential goods and services.* (PAI, 1997)

In its deliberations, the Commission narrowly focused on eight critical infrastructures "whose incapacity or destruction would have a debilitating impact on our defense and economic security". These eight are telecommunications, electric power systems, natural gas and oil, banking and finance, transportation, water supply systems, government services, and emergency services. The commission noted that there is no more urgent priority that assuring the security, continuity, and availability of our critical infrastructures.

Critical infrastructure protection (CIP) is a very complicated 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.

CIP has two main objectives: one is conflicting priorities (e.g. protect citizens, protect business or maintain low prices for the service), and the other one is Optimum allocation of resources

The strategies of CIP can be developed from two aspects: protection and resilience. From protection point of view, CIP is to make the infrastructure invulnerable to any kind of disruption or attack to physical systems and cyber systems. From resilience point of view, CIP is to improve redundancy, geographical isolation, backups for infrastructures and prepare emergency and mitigation plans for the society.

Definition to KRSC

Key resources are the assets required to offer and deliver value proposition to the customer. (Osterwalder, 2010) According to the nature of business models, key resources can be one or more of the following categories:

- Physical
- Intellectual
- Human
- Financial

The significance of modeling and analysis of interdependencies between CIP and KRSC

Due to the interdependency of the CIs, a deviation or a disruption of one or more of these CIs will cause cascading effect on many other CIs and therefore produce unacceptable economic loss. That is because key resource supply chain (KRSC) requires most of critical infrastructures such as communications, transportation, power, water, gas and oil and staff availability. If disruption of any CI occurs, the related KRSC will turn to a paralysis, thus economic loss appears.

As discussed above, modeling and analysis of interdependencies between CIP and KRSC is extremely significant. The final purpose of this model is to understand which are the consequences of these events and improve the resilience of the system.

Chapter 2: State-of-the-art review on modeling techniques for vulnerabilities and interdependencies analysis for CIs and KRSC

We must make it very clear that the understanding of the interdependencies in critical infrastructures is important to their protection since the interdependencies sharply increase the overall complexity of the whole system (Rinaldi et al., 2001). The terms dependency and interdependency have different meanings. The first one indicates a linkage or connection between two infrastructures, a deviation of one infrastructure causes a deviation of the related-one. While interdependency is a bidirectional relationship between two infrastructures (Rinaldi et al., 2001)

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 details, while all the others are resumed in a table, which also presents an evaluation of these mathematical approaches using the criteria adopted by Eusgeld et al. (2008) in their article.

After the demonstration of these six modeling techniques, a discuss of them is done to explain why System Dynamics approach is chosen in this paper.

Agent-based Model

An agent-based model is a class of computational models for simulating the actions and interactions of autonomous agents with a view to assessing their effects on the system as a whole. A review of recent literature on agent-based models shows that ABMs are used on non-computing related scientific domains including Life Sciences, Ecological Sciences and Social Sciences. It is also 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).

Most agent-based models are composed of: (1) numerous agents specified at various scales; (2) decision-making heuristics; (3) learning rules or adaptive processes; (4) an interaction topology; and (5) a non-agent environment

In order to implement this approach it is important to identify every portion of the critical infrastructure 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. Fig. 2 illustrates the scheme of how it works.

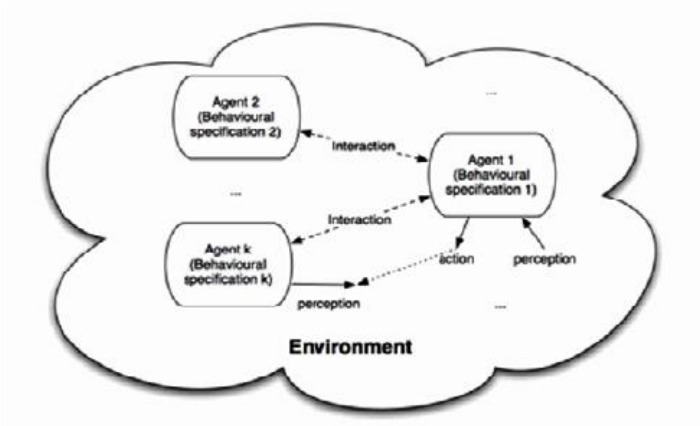


Figure 2 Agent-based modeling technique

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 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 it 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.

Fuzzy Logic and Fuzzy Cognitive Maps

Fuzzy logic is a form of many-valued logic or probabilistic logic; it deals with reasoning that is approximate rather than fixed and exact. Compared to traditional binary sets, fuzzy logic variables may have a truth value that ranges in degree between 0 and 1. Fuzzy logic has been extended to handle the concept of partial truth, where the truth value may range between completely true and completely false. Furthermore, when linguistic variables are used, these degrees may be managed by specific functions.

The term “fuzzy logic” was introduced with the 1965 proposal of fuzzy set theory by Lotfi A. Zadeh. Fuzzy logic has been applied to many fields, from control theory to artificial intelligence. Fuzzy logics however had been studied since the 1920s as infinite-valued logics notably by Lukasiewicz and Tarski; it is a popular misconception that they were invented by Zadeh.

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 Figure 3 an example of membership function is represented, but it is possible to have different shapes according to what is going to be modeld.

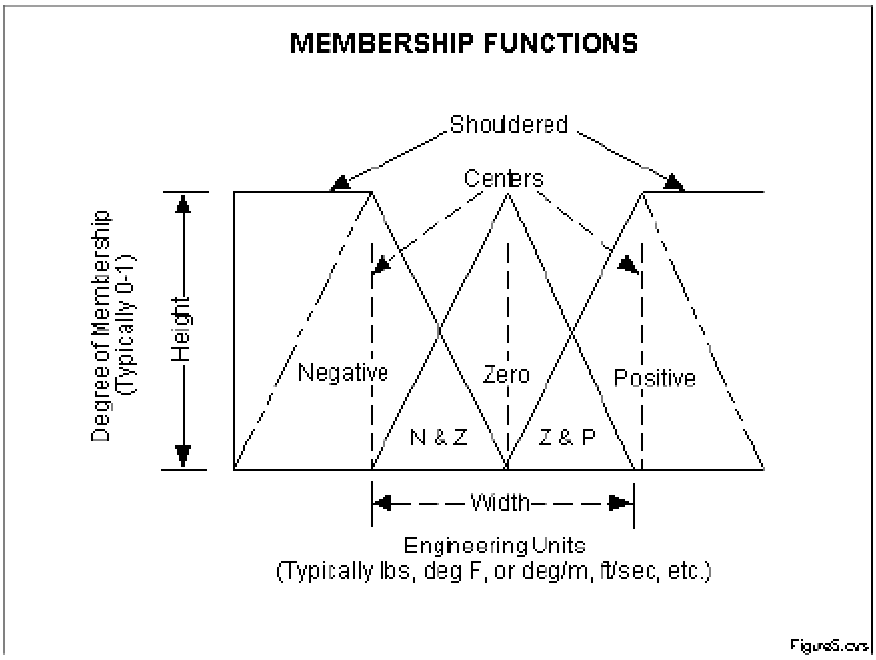


Figure 3 example of a triangular membership function (Kaehler, 2000)

Fuzzy logic and probabilistic logic are mathematically similar – both have truth values ranging between 0 and 1 – but conceptually distinct, owing to different interpretations. Fuzzy logic corresponds to "degrees of truth", while probabilistic logic corresponds to "probability, likelihood"; as these differ, fuzzy logic and probabilistic logic yield different models

Combining together fuzzy logic and neural networks, Kosko (1986) developed a 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 associate 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 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 4). 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).

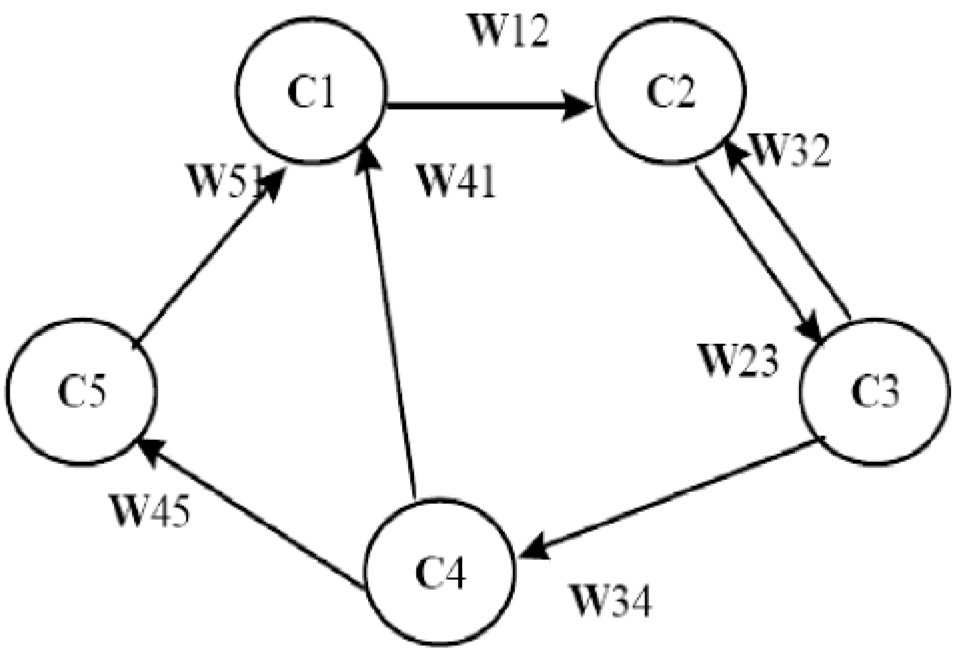


Figure 4 A simple Fuzzy Cognitive Map (Stylios et al., 1998)

High-level Architecture

A high-level architecture (HLA) is a general purpose architecture for distributed computer simulation systems. Using HLA, computer simulations can interact with other computer simulations regardless of the computing platforms. The interaction between simulations is managed by a Run-Time Infrastructure (RTI).

A high-level architecture consists of the following components:

- Interface specification, defines the interface between the single simulation and the RTI.
- Object model template , that specifies what information is communicated between simulations, and how it is documented
- Rules, simulations must obey in order to be compliant to the standard.

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.

Input-output Inoperability Model

The Inoperability Input-Output Model (IIM) is an analytical framework to quantify and address the risks from the intra- and inter-connectedness of economic and infrastructure sectors in the United States. Critical infrastructures are highly complex and interconnected, and they have become increasingly dependently on networked information systems for efficient operations and timely delivery of products and services. These interconnections allow flow of information, shared security, and physical flows of commodities, among others.

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).

In most cases, inoperability is referred to be a continuous value equal between 0 and 1: 0 means the system is perfectly available while 1 means the system is completely paralyzed. It may be manifested in several dimensions: geographical, functional, temporal and political.

With some simplifications and hypothesis, there is a linear equation from which we can assess the impact of a negative event on critical infrastructure system:

$$x(k+1) = Ax(k) + c$$

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 $a_{ij} = 1$, it means a complete failure of the j^{th} infrastructure will lead to a complete failure of the i^{th} infrastructure.

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):

- Identify physical connections among the infrastructure;
- Define the boundary conditions of each infrastructure and level of resolution;
- 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}.

If more and more factors, i.e. the inventory are taken into consider (Barker and Santos, 2010), the results are getting better in terms of critical infrastructure interdependencies analysis. IIM is also available when combined with other modeling techniques, for example, agent-based model and IIM approaches (Oliva et al., 2010) is designed to overcome the holistic and agent-based paradigms.

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 places, transitions, and arcs. Arcs run from a place to a transition or vice versa, never between places or between transitions. The places from which an arc runs to a transition are called the input places of the transition; the places to which arcs run from a transition are called the output places of the transition (Pye and Warren, 2006).

Graphically, places in a Petri net may contain a discrete number of marks called *tokens*. Any distribution of tokens over the places will represent a configuration of the net called a *marking*. In an abstract sense relating to a Petri net diagram, a transition of a Petri net may fire whenever there are sufficient tokens at the start of all input arcs; 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.

Since firing is nondeterministic, and multiple tokens may be present anywhere in the net (even in the same place), Petri nets are well studied for modeling the concurrent behavior of distributed systems.

System Dynamics

System Dynamics is an approach to understand the behavior of complex systems 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). It deals with internal feedback loops and time delays that affect the behavior of the entire system. What makes SD different from other approaches to studying complex system is the use of feedback loops and stocks and flows. These elements help describe how even seemingly simple systems display baffling nonlinearity.

System Dynamics is composed of two critical components: *casual loop diagram* (Figure 5a) and *stock and flow diagram* (Figure 5b).

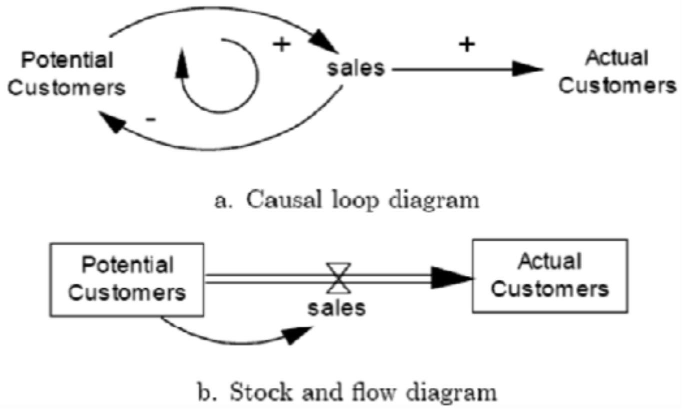


Figure 5 example of casual loop (a) and stock and flow (b) diagram (Kirkwood 1998)

In the SD methodology, a problem or a system is first represented as a causal loop diagram, which can indicate the logical relationship between every two elements in complex system.

A causal loop diagram is a simple map of a system with all its constituent elements and their interactions. By capturing interactions and consequently the feedback loops, a causal loop diagram reveals the structure of a system. By understanding the structure of a system, it becomes possible to ascertain a system's behavior over a certain period of time.

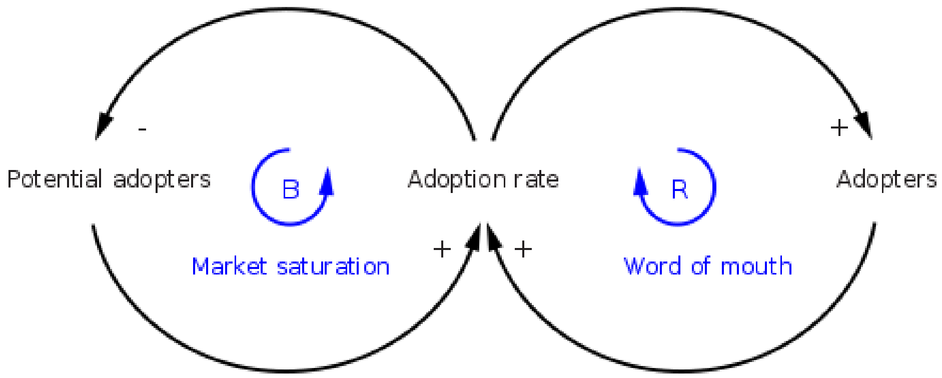


Figure 6 example of causal loop diagram

As shown in Fig.6, some symbols are used to represent certain meanings. A '+'is used if the cause increases, the effect changes in the same direction with the cause, and a '-' is used if the effect changes in the opposite direction with the cause.

From fig.6, two kinds of feedback loop are demonstrated, symbolized 'B' and 'R', which are called balancing loops and reinforcement loops respectively. 'B' loop has an odd number of '-' and it tends to produce "stable", "balance" and "equilibrium" behavior of system over time. 'R' loop has an even number of '-' and if some quantities increase, a "snowball" effect takes over and those quantities continue to increase and vice versa. Rotation direction of the symbol is the same as the causal effect relationship for both.

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

Review and discussion of the modeling techniques

In Table 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 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 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

Table 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 2 comparative evaluation of methods for CII Analysis (Eusgeld et al., 2008)

Specific objectives of the study

As discussed previously, the final objective is to protect the critical infrastructure systems and Fast Moving Consumer Goods supply chain and improve the resilience of the whole system. In 2011, one of the Master students of Professor Paolo TRUCCO did the same research through Fuzzy Logic and Fuzzy Cognitive Maps approach. The result turned out to be very convincing but it still had some drawbacks, for example, the time-discontinuity, being non-quantitative and non-univocal.

In order to overcome these drawbacks, a new interdependency modeling technique is chosen to analyze the whole system, System Dynamics. It can model the system over time, and it is also a quantitative approach. Seen from these characteristics of this modeling technique, it is reasonable to imagine that System Dynamics is able to improve the drawbacks mentioned above.

This study is aimed to model the interdependencies between Critical Infrastructures (CIs) and Key Resource Supply Chain (KRSC), specifically Fast Moving Consumer Goods supply chain. Therefore it is necessary to model these two systems separately and then combine them together to analyze, first of all, concepts of the two systems must be identified:

For Critical Infrastructure and key resources the following concepts are used:

1. Electrical power
2. Oil/fuel
3. Natural gas
4. Water
5. Road transportation
6. Urban train
7. Air transportation
8. Railway transportation
9. Staff availability

For Fast Moving Consumer Goods supply chain the following concepts are used:

1. Distribution inventory
2. Retail inventory

Chapter 3: Description of Fast Moving Consumer Goods supply chain

Fast Moving Consumer Goods are products that are sold quickly at relatively low price. Examples include non-durable goods such as soft drinks, toiletries, and grocery items. Through the absolute profit made on FMCG products is relatively small, they generally sell in large quantities, so the cumulative profit on such products can be substantial.

The term FMCG refers to those retail goods that are generally replaced or fully used up over a short period of days, weeks, or months, and within one year. This contrasts with durable goods or major appliances such as kitchen appliances, which are generally replaced over a period of several years.

FMCGs have a short shelf life, either as a result of high consumer demand or because the product deteriorates rapidly. Some FMCGs, such as meat, fruits and vegetables, dairy products and baked goods, are highly perishable. Other goods such as alcohol, toiletries, pre-packaged foods, soft drinks and cleaning products have high turnover rates.

The following are the main characteristics of FMCGs (Ramanuj Majumdar 2004):

- Frequent purchase
- Low involvement
- Low price
- High volumes
- Low contribution margins
- Extensive distribution networks
- High stock turnover

The sector of FMCG 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 is significant because each category of products has different properties and these properties are the basic points from which start the development of the model. For example, 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 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 transportation can be change and this is relevant for the analysis that will be done in this work. Also the results differ if a blackout happens according to the kind of goods. In particular the case study analyzed deal only with perishable goods.

The FMCG industry is extremely competitive because it occupies 1.4% of the Italian GDP in 2009 (source: Federdistribuzione). A group of companies sell products which they purchased from the producer or the wholesalers to the consumers in order to gain profits.

Considering the sales, the most important companies in the fast moving consumer goods sector in Italy are represented in the graph in Figure 7.

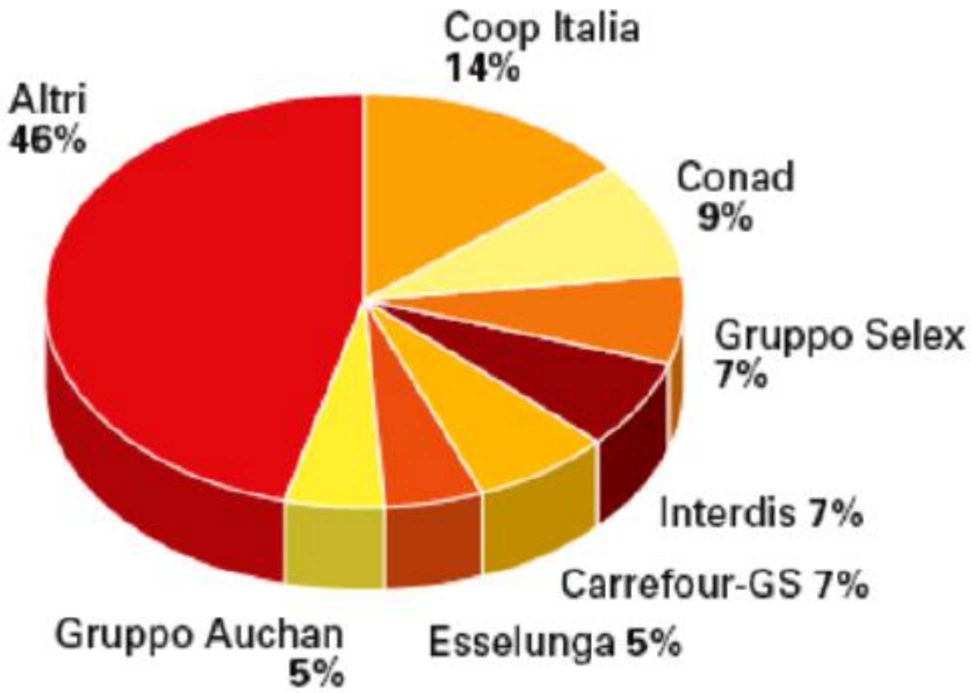


Figure 7 Most important companies in FMCG sector in Italy in 2005 (Dallari and Melacini, 2007)

In this chapter, the supply chain of this complex sector is introduced and every element of the FMCG supply chain is briefly described. 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 quite important to focus the attention on the entire sector.

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 category, the majority of goods pass directly from supplier to wholesaler, instead of being transferred in producer, in order to make the period for goods from raw material to products as short as possible due to its short shelf life. In Figure 8 shows the scheme of the fresh food supply chain, in which the dot line means those direction is not usual.

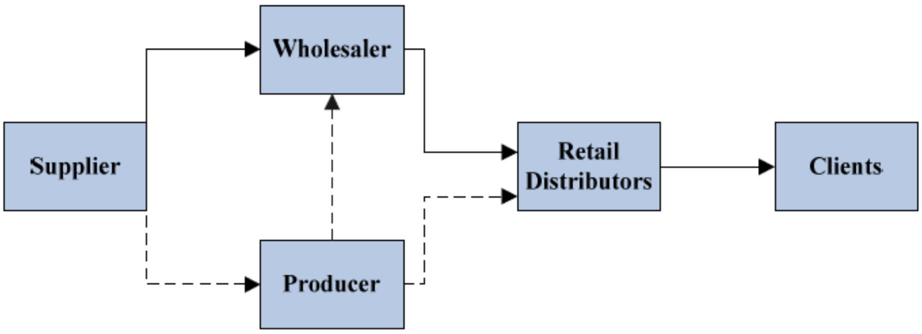


Figure 8 fresh food supply chain

The situation in no-fresh food supply chain is different. Due to the longer shelf life, the producer gets a part of the supply chain. While wholesaler sometimes does not show in the flow, it is because in some cases, the goods are directly delivered from producer to retails by skipping the wholesaler. It is reported in Figure 9.

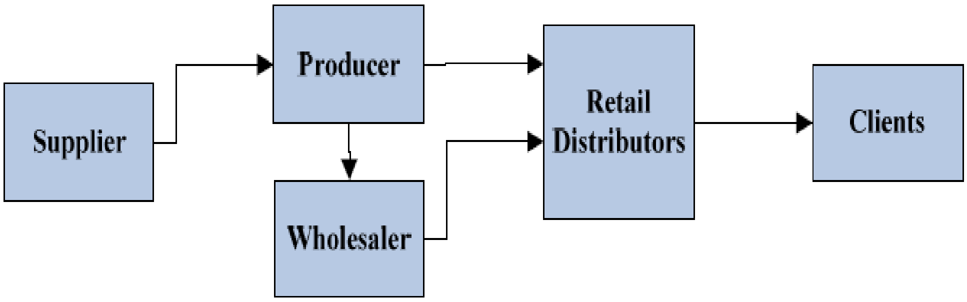


Figure 9 No-fresh food supply chain

The third category is very similar to no-fresh food supply chain and also the scheme is similar (Figure 10), but in this case the wholesaler is not present anymore in the flow.

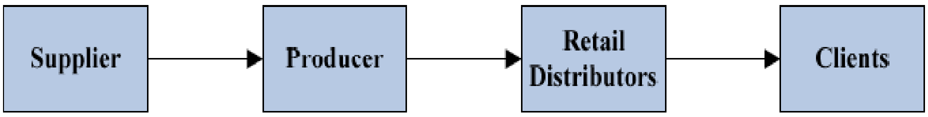


Figure 10 other grocery products supply chain

It is very necessary to introduce every single part of FMCG supply chain in order to have a better comprehension of it. In particular, in the next paragraphs the roles, objectives and activities of suppliers, producers, wholesalers and retail distributors are presented.

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.

Producers

The producer 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 producer; 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.

Wholesalers

Wholesale is defined as the sale of goods to retailers; to industrial, commercial, institutional, or other professional business users; or to other wholesalers and related subordinated services. In general, it is the sale of goods to anyone other than a standard consumer.

Traditionally, wholesalers are closer to the markets they supply than the producer from whom they get the products.

The wholesalers has two possible functions, one of them is to stock material and then sell these products to the retail distributors; the other one is to process the raw material in particular for the fresh foods.

In recent years, wholesalers is taking producer's place and getting closer and closer to retail distributors because the retailers want to reduce the costs and also the risk in the supply chain.

Retailers

Retail trade is divided roughly evenly into grocery trade (primarily food and certain household items) and non-grocery trade (clothing and footwear, household furnishings and electronic goods). These two parts of the sub-sector differ substantially in terms of their main economic characteristics, with grocery trade being somewhat more homogeneous than non-grocery trade. Most consumers obtain the basic necessities required for daily living, such as food and household goods, in the grocery market. However, although the goods sold here may be broadly similar across countries, there are notable differences across countries in terms of, for example, store format, the degree of internationalization, market penetration by hard discounters and private label brands, and the role of buying groups. (Robert A. et al., 2011)

Retail is the sale of goods and services from individuals or businesses to the end-users. Retailer is a very important part of a supply chain. A retailer purchases goods in large quantities from producers directly or through wholesaler, and then sells smaller quantities to the consumer for a profit. Retailing can be done in either fixed locations like stores or markets or malls, door-to-door or by delivery.

The principal operators in the FMCG sector in Italy are:

- "Mass Organized Retailers" (MOR) or "Large Organized Retailers" (LOR). This class is mainly referred to large retailers, which have a large central structure and they have a direct control on the distribution centers and the sales network. Some example can be: GS, Esselunga, Metro, Auchan.

- 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

Distribution Centers

A distribution center for a set of products is a warehouse or other specialized building, often with refrigeration or air conditioning, which is stocked with products to be redistributed to retailers, wholesalers, or directly to consumers. A distribution center is a principal part, the order processing element, of the entire order fulfillment process.

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 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 Distribution Centers of the large organized retailers in the MLR

Chapter 4: Development of the System Dynamics model for interdependency

analysis between the system of CIs and the FMCG Supply Chain

As discussed previously, in this work, the modeling technique used to analyze the interdependencies between CIs and FMCG supply chain is System Dynamics in order to make the research time-continuous, univocal and quantitative compared to the work done by Ferrari (2011)

In this chapter, detailed introduction of SD approach and the procedure of model construction will be given.

Detailed introduction of System Dynamics modeling approach

System Dynamics (SD) is a powerful system analysis methodology combined with qualitative and quantitative methods and based on feedback control theory. It is created by Forrester from MIT, aiming to apply industry simulations to enterprise management fields. Its main objectives are to analyze the disruption or deviation of system and find the drawbacks by creating and simulating the models. In nature, it is composed of a series of first order differential time-lag equations. The core theory of SD is the causal relationship and structure of system. With over 40 years' growth and development, SD approach is used in many fields and the results turn out to be very convincing.

What makes System Dynamics different with other modeling techniques is that SD approach creates standard mathematical model from the inner microstructure and meanwhile analyze the system function and dynamic actions. Generally speaking, SD has characteristics as following:

- Focused on the casual relationship. Casual relationship is very common in a system with related parts. Reaching a good understand on casual relationship helps to analyze the interdependencies of CIs and FMCG supply chain.

- Start with system structure. SD approach thinks that system structure is the motive power of system developing. Only with knowing well the system structure is possible to forecast the deviation of system actions.

- Be able to simulate. Simulation is aimed to get more detailed information in order to find a solution to a certain problem, also to analyze the interdependencies between CIs and FMCG supply chain.

Two diagrams are used to capture the structure of systems: (1) causal loop diagrams; and (2) stock and flow diagrams. A causal loop diagram consists of variables connected by arrows; it captures the causal influence among the variables. Each loop has an associated identifier, which shows whether the loop is positive (reinforcing) or negative (balancing) feedback. The causal loop diagram provides a high-level view of relationships, interactions, and feedback processes. Consequently, it is hard to see the physical buildup and flow of information and products through the system. For this, we need stock and flow diagrams which consist of stocks (integrals or state variables), flows (derivatives or rates), valves (controlling the flows), and clouds (sources and sinks for the flows). The stock and flow diagrams can be used to generate the differential equations that govern the evolution of the system. The modelers can start with either of the diagrams (which complement each other) to build a SD model.

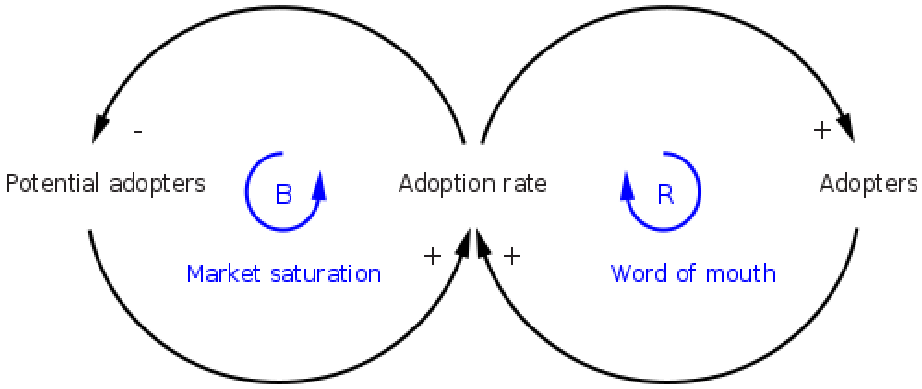
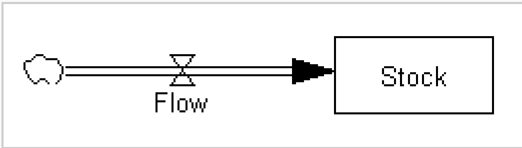


Figure 11 casual loop diagrams

As shown in Fig. 11, some symbols are used to represent certain meanings. A '+'is used if the cause increases, the effect changes in the same direction with the cause, and a '-' is used if the effect changes in the opposite direction with the cause.

From fig.6, two kinds of feedback loop are demonstrated, symbolized 'B' and 'R', which are called balancing loops and reinforcement loops respectively. 'B' loop has an odd number of '-' and it tends to produce "stable", "balance" and "equilibrium" behavior of system over time. 'R' loop has an even number of '-' and if some quantities increase, a "snowball" effect takes over and those quantities continue to increase and vice versa. Rotation direction of the symbol is the same as the causal effect relationship for both.

The causal 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 (Fig. 12).



A flow is the rate of accumulation of the stock

Figure 12 stock and flow diagram

As shown in Fig. 12, 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).

The procedure of model construction

In this paragraph, the complete model and its procedure of construction will be given. As discussed previously, the concepts for critical infrastructure are as follows:

1. Electrical power
2. Oil/fuel
3. Natural gas
4. Water
5. Road transportation
6. Urban train
7. Air transportation
8. Railway transportation
9. Staff availability

The concepts for Fast Moving Consumer Goods supply chain are:

1. Distribution inventory
2. Retail inventory

To complete this model some hypothesis should be made:

1. The system of systems is isolated from outer environment, which means it can only be affected by inner concepts. Other concepts not mentioned are not taken into considered.

2. The effect from one CI to another is linear. For example, if 100t fuel happened to fulfill 100% requirement of power plant, then 80t fuel could fulfill 80% requirement of power plant.

3. Fuel is divided into two groups: one is transported through pipeline, the other is transported by road and rail. Furthermore, fuel through

pipeline is used for airport and power generation, while fuel through road and rail is used for road, rail, and supply chain.

4. The amount of demand is constant. For example, every day the requirement of fuel demand for supply chain is constant.

5. Staff availability only affects distribute rate and purchase rate. Since most of the concepts are automatic, staff may not be the priority on site, thus the effect of staff availability can be neglected in those automatic concepts.

It has been made very clear that there are interdependencies between CIs (Fig.1). In our particular case, based on the hypothesis above, electrical power plant needs fuel and natural gas for power generation and airport also needs fuel and natural gas for daily usage. Furthermore, fuel is also used for railway system, road transportation and FMCG supply chain. The power is used for fuel and gas production, urban train functioning, supply chain, water supply, road, rail and air transportation. Staff to work station (staff availability) is determined by the status of urban train, road, and railway transportation. As to the FMCG sector, the production rate is influenced by power and fuel, while the distribution parts are affected by staff availability and three kinds of transportation: road, railway and air. At last the purchase rate is influenced by staff and power (e.g. a shopping mall cannot function when power or staff is unavailable). Thus, the interdependencies between CIs and FMCG in this case have been found. The next step is to create sub-models and then assemble them as a whole. (The software used is called Anylogic 6.0)

1. Sub-model of FMCG supply chain sector

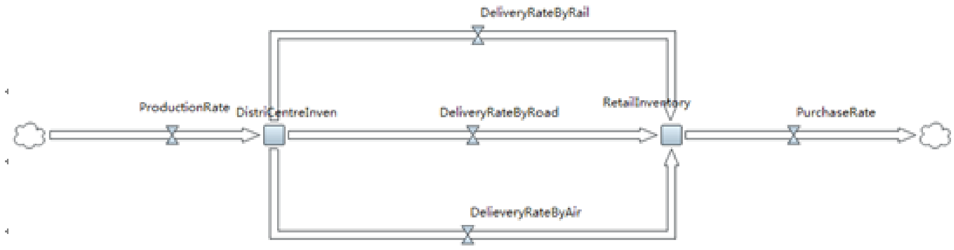


Figure 13 *sub-model of FMCG supply chain sector*

The elements in a FMCG supply chain are defined as two stocks and five flows: distribution center inventory and retail inventory for stocks and production rate, delivery rate by rail, road, air, and purchase rate for flows.

The FMCG supply chain products are stored in distribution center in the first place after production. Then are transported via three methods: rail, road and air to retails. At last the goods are purchased at a purchase rate and consumed by consumers.

The production rate is influenced by water usage for supply chain, power usage for supply chain and fuel usage for supply chain. The transportation rates are influenced by the functioning status of rail, road and air systems. The purchase rate is determined by retail staff availability and power supply.

2. Sub-model of fuel through pipeline for its specific usage fields

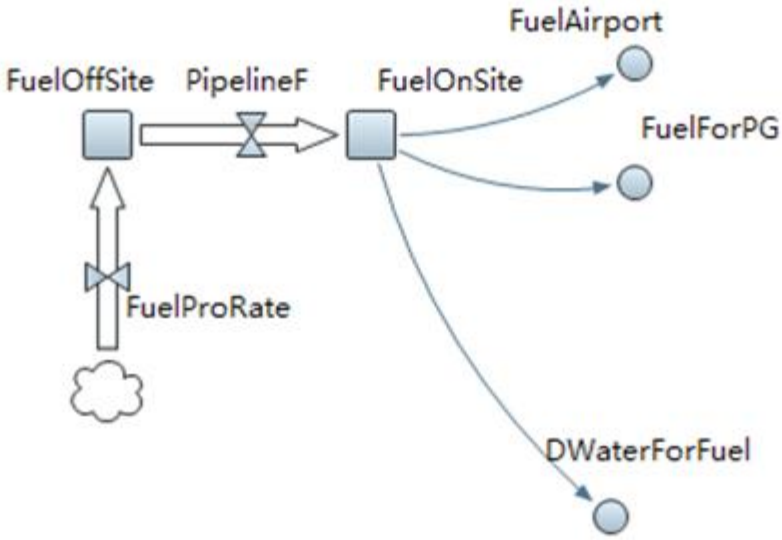


Figure 14 Sub-model of fuel through pipeline

After produced from crude oil, fuel is transported by pipeline to be used. The usage fields of fuel through pipeline are divided into 2 parts: airport usage and power generation. Water is needed to produce fuel, so it is possible to calculate how much water is needed to produce a certain amount of fuel.

3. Sub-model of fuel through road and rail for its specific usage fields

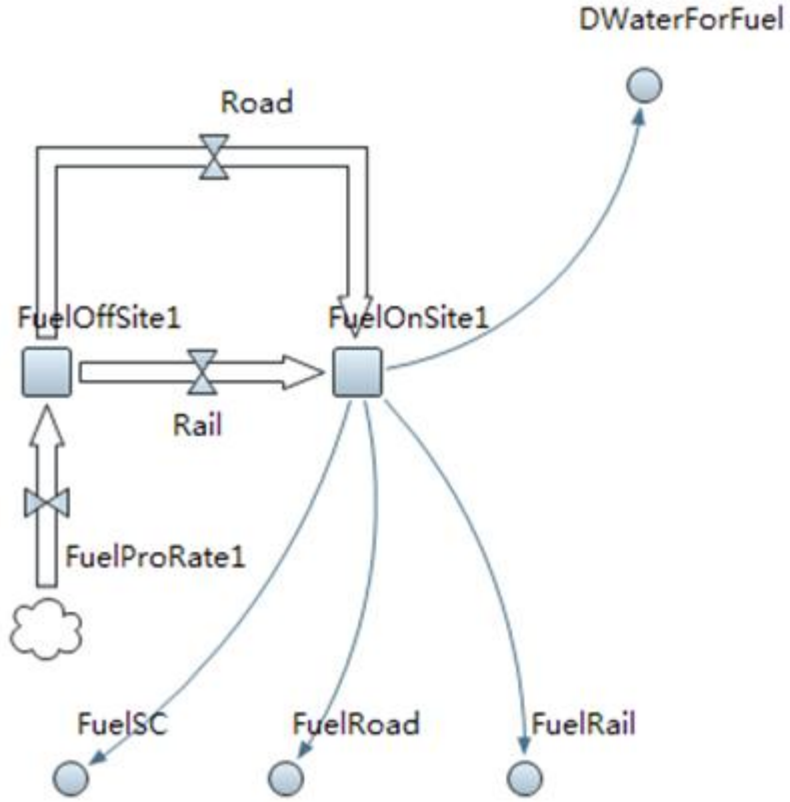


Figure 15 Sub-model of fuel through road and rail

Different with pipeline, fuel transported by road and rail is used in 3 fields which are supply chain, road system, rail system. Similarly, the amount of water for a certain amount of fuel can be calculated.

4. Sub-model of gas through pipeline for its specific usage fields

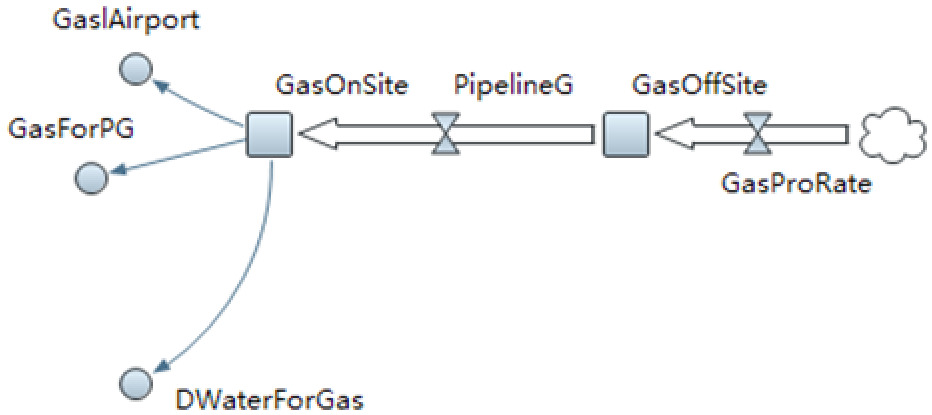


Figure 16 Sub-model of gas through pipeline

The natural gas is transported only via pipeline and its usage fields are airport and power generation.

5. Sub-model of water through pipeline for its specific usage fields

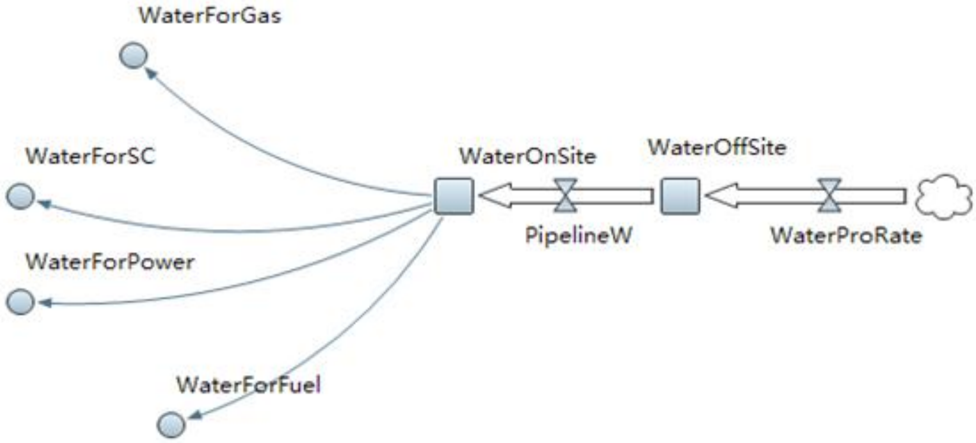


Figure 17 Sub-model of water through pipeline

Water is transported only via pipeline and its usage fields are gas production, fuel production, power generation and supply chain.

6. Sub-model of power for its specific usage fields

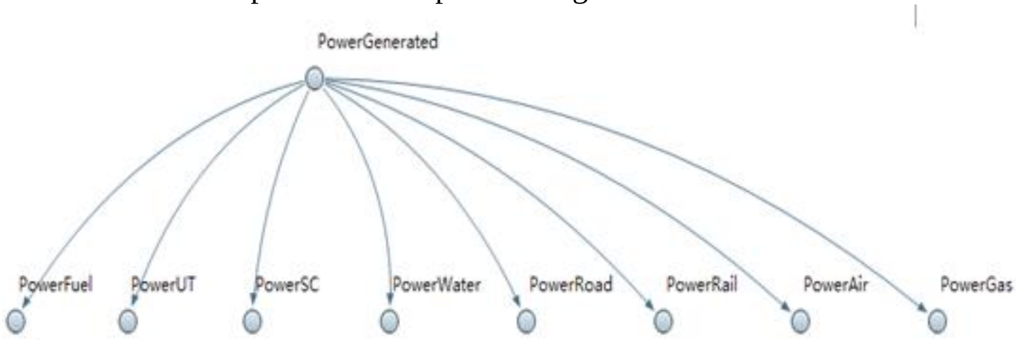


Figure 18 Sub-model of power

The power system is used to most fields than others, including fuel production, gas production, urban train, supply chain, water production, road system, railway system and airport.

7. Sub-model of staff availability

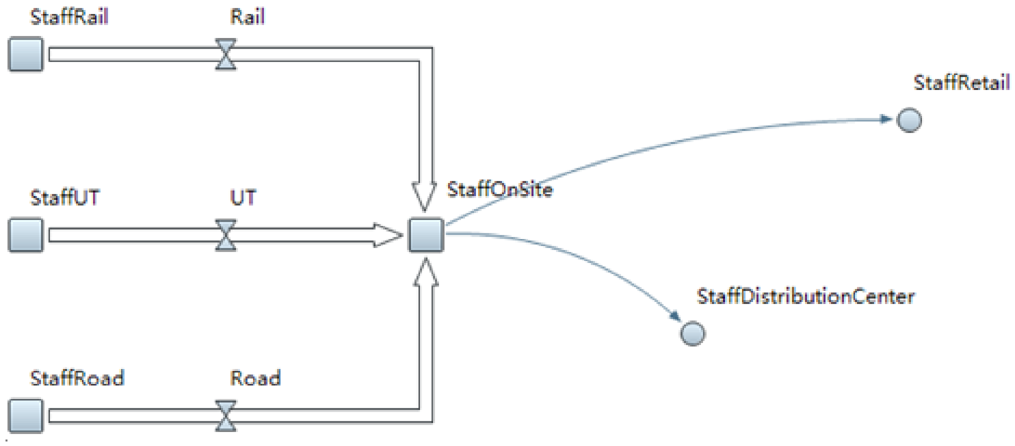


Figure 19 Sub-model of staff availability

The ways of staff transportation to work are defined as three ways: railway, urban train and road. From the hypothesis point 5, the staff availability is only considered in distribution center and retail shop (because these two work station is less automatic).

8. The introduction of the concept *availability*

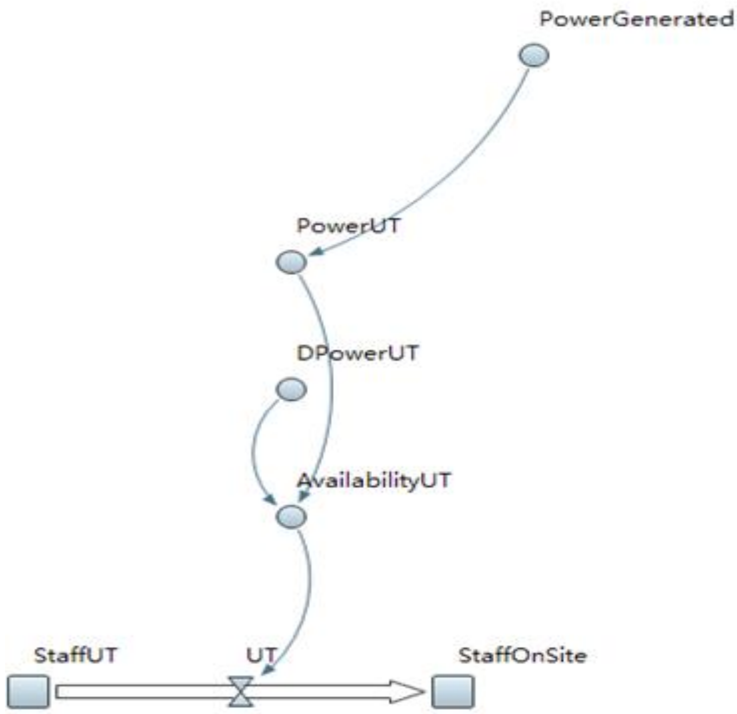


Figure 20 availability concept

The availability variable is defined as the ratio between actual value and demand value (marked with "D"). This definition is based on the hypothesis point 1. As shown in Fig. 20, the availability UT directly influences the urban train transportation system, and so do the other availability variables.

9. A overall scheme of the model

After sketching all the sub-models, it is possible to put all of them together to obtain an overall scheme (Fig. 21)

(after obtaining the license of the software)

Chapter 5: Data requirements, collection and fusion

As seen in the concepts used in the above System Dynamic model, many categories of data in different terms are required such as *liter gas per year*, *kilogram fuel per year*, *kWh electricity per year*, *liter water per year* and so on. Since the data required are in different unit terms, it is very convenient and also necessary to convert them to a single unit term for the simulation. From economic point of view, one of the ultimate goals of this model is to analyze the economic loss due to disruption of any critical infrastructures, so it is well-reasoned to define this single unit term as ***euro per year***. Now the task is to convert all the data in different terms to ***euro per year***. Fortunately the Joint Research Center (JRC) has done some research about the data. The following is the procedure of data collection aided by JRC.

NACE_R1	Share elec	Share gas	Share water
GEO/TIME			
European Union (27 countries)			
Belgium	76.2%		
Bulgaria	72.4%	8.4%	19.3%
Czech Republic			
Denmark	53.2%	29.0%	17.8%
Germany (including former	75.5%	20.2%	4.3%
Estonia			31.2%
Ireland			
Greece		0.0%	
Spain	77.4%	11.6%	11.0%
France	58.5%	23.4%	18.1%
Italy	68.5%	26.4%	5.0%
Cyprus		0.0%	
Latvia	64.1%		
Lithuania	62.6%	6.8%	30.5%
Luxembourg			
Hungary	61.1%	9.2%	29.7%
Malta		0.0%	
Netherlands			
Austria	77.0%	17.4%	5.6%
Poland	59.9%	20.2%	19.9%
Portugal		2.5%	
Romania	75.5%	11.4%	13.1%
Slovenia	79.2%	3.3%	17.5%
Slovakia			
Finland	87.8%	0.1%	12.1%
Sweden	77.0%	0.7%	22.3%
United Kingdom	69.0%		
Norway	96.2%	0.8%	3.0%

Figure 22 European shares of electricity, gas and water supply (source: JRC)

A	G	H	I
INDIC_SB			
NACE_R1	Share rail	Share road	Share pipeline
GEO/TIME			
European Union (27 countries)			
European Union (25 countries)			
Belgium		74.2%	0.6%
Bulgaria	21.7%	78.3%	0.0%
Czech Republic			
Denmark	3.6%	64.9%	
Germany (including former GDR from 1991)	26.4%	70.0%	3.6%
Estonia	14.0%	86.0%	0.0%
Ireland			
Greece		95.7%	
Spain	5.6%	94.4%	0.0%
France	24.7%	72.9%	2.3%
Italy	10.5%	85.9%	3.6%
Cyprus	0.0%	100.0%	0.0%
Latvia		75.5%	
Lithuania	15.2%	84.7%	0.1%
Luxembourg	25.9%	74.1%	0.0%
Hungary	18.1%	75.0%	6.9%
Malta	0.0%	100.0%	0.0%
Netherlands	8.7%	90.6%	0.7%
Austria	11.6%	83.6%	4.9%
Poland	19.3%	76.9%	3.8%
Portugal		90.7%	
Romania		73.1%	
Slovenia		85.4%	
Slovakia		47.3%	
Finland		89.5%	
Sweden	10.0%	90.0%	
United Kingdom	16.3%	82.6%	1.2%
Norway	7.1%	89.7%	3.2%
Switzerland			

Figure 23 European shares of railway, road and pipeline transportation (source: JRC)

INDUSTRIES (NACE)	Manufacture of coke, refined petroleum products and nuclear fuels	Electricity, gas, steam and hot water supply	Land transport; transport via pipelines	Air transport
Manufacture of coke, refined petroleum produ	2 950	1 382	5 510	1 152
Electricity, gas, steam and hot water supply	474	9 223	857	10

Figure 24 Input-output data related to our needs (source: JRC)

(Note: figure 22, 23 and 24 are cut out from full figures provided by JRC which are shown in full version in annexes at the end of this thesis)

Turnover per *sector* in Italy			
Concept	**Q_i^* (in million**	**Year**	**Source**
Electrical Power	86,224.2	2005	Eurostat, structural business statistics database
Oil/Fuel	93,136.2	2005	Eurostat, structural business statistics database
Natural Gas	7,188.3	2005	Eurostat, structural business statistics database
Water	4,883.0	2005	Bardelli & Robotti (2009), p.24
Road Transport	40,553.3	2005	Eurostat, structural business statistics database
Air Transport	10,016.3	2005	Eurostat, structural business statistics database
Railway Transport	5,804.1	2005	Eurostat, structural business statistics database
Telephone Network	35,000.0	2005	Eurostat, structural business statistics database + Swedisch Trade Council, 2008
Data Network	16,257.5	2005	Eurostat, structural business statistics database + Swedisch Trade Council, 2008
Staff Availability	0.0	-	
Production	99,754.7	2005	Eurostat, structural business statistics database
Dist. Centers	0.0	-	
Retail Dist.	113,623.3	2005	Eurostat, structural business statistics database

Figure 25 *Total turnover per infrastructures sector in Italy (source: JRC)*

In 2005, the GDP at market prices in Italy is 1436379 million euro. (Source: Eurostat:http://epp.eurostat.ec.europa.eu/portal/page/portal/national_accounts/data/main_tables). In the same year, the input value of Fast Moving Consumer Goods supply chain is 80760 million euro. (Source: Dallari & Melacini, 2005). Based on the assumption that inputs are proportionally used by FMCG SC, we can conclude that the total turnover of the FMCG industry in Italy in 2005 is 5.6% (80760/1436379) of GDP in 2005.

Therefore, to obtain the input value of infrastructures sector in FMCG SC in Italy, we can multiply the coefficient (5.6%) with the corresponding values in Fig. 25. For example, the input value of Electrical Power in FMCG SC is:

$$86224.2 \times 5.6\% = 4847.9\text{million euro}$$

The input value of Oil/Fuel in FMCG SC is:

$$93136.2 \times 5.6\% = 5236.6\text{million euro}$$

The input value of Natural Gas in FMCG SC is:

$$7188.3 \times 5.6\% = 404.2\text{million euro}$$

The other values are calculated through the same method, therefore Fig. 26 is obtained.

Input value of sectors in FMCG SC in Italy

Concept	**Q_i^* (in million €)**	**Year**	**Source**
Electrical Power	4,847.9	2005	Eurostat, structural business statistics database
Oil/Fuel	5,236.6	2005	Eurostat, structural business statistics database
Natural Gas	404.2	2005	Eurostat, structural business statistics database
Water	274.5	2005	Bardelli & Robotti (2009), p.24
Road Transport	2,280.1	2005	Eurostat, structural business statistics database
Air Transport	563.2	2005	Eurostat, structural business statistics database
Railway Transport	326.3	2005	Eurostat, structural business statistics database
Telephone Network	1,967.9	2005	Eurostat, structural business statistics database + Swedisch Trade Council, 2008
Data Network	914.1	2005	Eurostat, structural business statistics database + Swedisch Trade Council, 2008
Staff Availability	0.0	-	
Production	99,754.7	2005	Eurostat, structural business statistics database
Dist. Centers	0.0	-	
Retail Dist.	113,623.3	2005	Eurostat, structural business statistics database

Figure 26 Input value of infrastructures sector in Fast Moving Consumer Goods supply chain in Italy (source: JRC)

From the figures given by Fig.22-26, a matrix with all considered critical infrastructure can be obtained. Some of the figures are obtained through calculation, and some of them are acquired from literatures or researches directly (details are presented in Annexes). The matrix is shown as following (unit: million euro):

	Electricity	FMCG SC	Urban Train	Road syst.	Rail syst.	Airport	Gas	Fuel	Water
Electricity	x	4847.9	65.1	504.8	61.5	6.7	254.7	324.5	525.4
FMCG SC	x	x	x	x	x	x	x	x	x
Urban Train	x	x	x	x	x	x	x	x	x
Road syst.	x	x	x	x	x	x	x	x	x
Rail syst.	x	x	x	x	x	x	x	x	x
Airport	x	x	x	x	x	x	x	x	x
Gas	1667.9	x	x	x	x	2.6	x	x	x
Fuel	947.1	5236.6	x	4735.8	577.3	1152.0	x	x	x
Water	315.9	274.5	x	x	x	x	121.7	23.8	x

Figure 27 the matrix showing economic interdependencies between CIs

Fig.27 shows the matrix in an economic term to illustrate the interdependencies between CIs. What are written in column is exactly the same as row, but the column means requirement while the raw means objectives. For example, the element *4847.9* means that to fulfill year Fast Moving Consumer Goods supply chain's normal function in Italy for entire year, it needs *4847.9* million euro of electricity.

Another important factor in our case is the number of staff. For relatively high level of automatic of infrastructure such as power generation plant, gas production plant and so on, the effect of staff is very small to be neglected. For relatively low level of automatic such as distribution center and supermarkets, the effect of staff is prominent. In our data requirement procedure, we must acquire the approximate overall number of staffs who work in FMCG supply chain distribution centers and retailers.

The concept retailer includes supermarket, store and hypermarket. So it is possible to collect the overall staff needed in these kinds of working place in entire Italy. Fortunately, data are acquirable in literature searching: 173,248 staffs for supermarket, 27,346 for stores and 84,674 for hypermarket, which makes 285,268 in total (2011).

In Italy, there are about 250 distribution centers, and the average employees in each DC is about 435 working staff (Fabrizio D & Gino M, 2008). So the overall number of working staff in distribution centers is:

$$250 \times 435 = 108{,}750$$

With these two overall employee numbers in DCs and retailers, it is possible to calculate that how many workers go to work in DCs or retailers through road, rail and urban train. Since distribution centers are usually located in remote area, most of workers prefer to use road service rather than urban train. So it is reasonable to assume the percentages of usage of road, rail and UT are 70%, 25% and 5% respectively. While supermarkets and stores are normally located inside city or town, so using urban train as transport tool is more convenient and popular. Therefore the percentages are assumed to be 30%, 20%, 50% respectively.

With all the data shown above, it is obviously easy to calculate the daily number of staffs who choose different transportation systems to go to work:

$$\text{DC workers through road: } 108{,}750 \times 70\% = 76{,}125$$
$$\text{DC workers through rail: } 108{,}750 \times 25\% = 27{,}187$$
$$\text{DC workers through UT: } 108{,}750 \times 5\% = 5{,}438$$
$$\text{Retailer workers through road: } 285{,}268 \times 30\% = 85{,}580$$
$$\text{Retailer workers through rail: } 285{,}268 \times 20\% = 57{,}054$$
$$\text{Retailer workers through UT: } 285{,}268 \times 50\% = 142{,}634$$

The Fast Moving Consumer Goods supply chain in Italy has two resources: import and domestic production. According to Fig.25 and Fig.26, in 2005, the domestic production value of FMCG is 99,754.7 million euro and the total value of FMCG is 113,623.3 million euro, so the import value is the difference between these two values: 13,868.6 million euro.

There are 4 transportation ways to import goods from other countries: air, ship, railway and road. For domestic production goods, they are transported via 2 means, which are railway and road. In our case, ship transportation system is not considered separately. When goods through ship arrives the dork, railway and road systems are needed for further transportation to distribution centers or supermarkets. Air system is not used in domestic production transportation but in importing. Railway and road systems are used in both sectors including the usage from shipping in importing as discussed previously.

Since we know the overall input value of each infrastructure related to FMCG supply chain, it is quite important to split each of them into specific usage field.

Therefore, percentages of transportation methods in importing and internal production are necessary for data requirement. In the literature, it is possible to find the total import mass data through air, ship, railway and road. (Benchmark, 2011.Source:http://www.bancaditalia.it/statistiche/rapp_estero/altre_stat/trasporti/documenti/indagine-trasporti11.pdf) (Fig. 28)

	kiloton per year	percentage
Ship	223,034	72.6%
Rail	29,603	9.6%
Road	54,266	17.7%
Air	335	0.1%
Total	307,238	

Figure 28 Total goods mass through air, ship, railway and road

As discussed above, ship transportation is not considered separately but with rail and road, so we should convert the ship percentage into rail and road under the assumption that rail and road service after shipping are used proportionally as importing goods directly. Following is the algorithm:

$$\text{Rail: } 9.6\% + 72.6\% \times \frac{9.6\%}{9.6\% + 17.7\%} = 35.1\%$$

$$\text{Road: } 17.7\% + 72.6\% \times \frac{17.7\%}{9.6\% + 17.7\%} = 64.8\%$$

Air: 0.1% (because air transportation is only used for importing)

The total import value was already calculated in previously paragraph, equal to 13,868.6 million euro. With the percentage of three transportation means in importing, we can easily get the economic value related to each single sector (1):

$$\text{Rail: } 13868.6 \times 35.1\% = 4867.9$$
$$\text{Road: } 13868.6 \times 64.8\% = 8986.9$$
$$\text{Air: } 13868.6 \times 0.1\% = 13.9$$

Till now, the import part is finished. What we have already known is the overall service value of each critical infrastructure related to FMCG supply chain, so it is important to split the overall service value as import and domestic production to analyze the effect due to a specific disruption of any infrastructure.

In the literature it can be found that the ratio between usage of rail and road in internal production and transporting goods from distribution center to retailers in Italy is approximately 1:9. As we know the overall values of goods in internal production and distribution centers are 99754.7 million euro and 113623.3 million euro respectively, it is quite easy to obtain the value of goods in each step:

$$\text{Road used for internal production: } 99754.7 \times 0.9 = 89779.2$$
$$\text{Road used for distribution centers: } 113623.3 \times 0.9 = 102261.0$$
$$\text{Rail used for internal production: } 99754.7 \times 0.1 = 9975.5$$
$$\text{Rail used for distribution centers: } 113623.3 \times 0.1 = 11362.3$$

With the transportation value of importing we got previously (1), also with the assumption that service value is proportional to goods value while transporting, it is possible to calculate the service values of these three transportation ways in each phase. See Fig. 29.

	overall service value(million €)	use	goods(million €)	percentage	service value due to each usage
Road Transport	2,280.10	internal production	89,779.23	45%	1,018.42
		import	8,963.66	4%	101.68
		Distribution Center to Retailers	102,260.97	51%	1,160.00
Air Transport	563.16	import	15.12	100%	563.16
Railway Transport	326.33	internal production	9,975.47	38%	124.12
		import	4,889.82	19%	60.84
		Distribution Center to Retailers	11,362.33	43%	141.37

Figure 29 Service values of road, air and rail in each phase

Chapter 6: Simulations campaign

Chapter 7: Discussion of results and conclusions

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