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Supply Chain Resilience Metrics for Complex-Chains

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Nós somos o que fazemos. O que não se faz não existe. Portanto, só existimos nos dias em que fazemos. Nos dias em que não fazemos apenas duramos.

António Vieira

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Abstract

Resilience is currently an increasing concern in supply chain caused by their globalization, which is subject to diverse types of disturbances. These disruptions need to be handled in the right way, compelling the usage of tools that can support resilient Supply Chain (SC) decisions. To comprehend how the academic community has been treating such concern we developed a systematic literature review on Supply Chain Resilience (SCR) with the focus of analysing the development of quantitative methods to support such decisions. Additionally, SCR published definitions were analysed, where it was found that there is no consensus in the literature. A sound definition is then proposed, which is supported by a comprehensive framework that includes the four main identified SCR elements: focus event; adaptive framing or adaptive response; speed; performance level. Moreover, it is concluded that the usage of quantitative models, although recognised with a high relevance in SCR, still needs further research as most of the published work is on the conceptualization of only certain resilience elements, missing an integrated holistic approach. This should reflect simultaneously the main SC characteristics and SCR elements. Future directions for the academic community are presented, aiming to guide the future work in the area. Additionally, using a MILP model the positive influence of SC flow complexity on SCR is analysed, and is proposed a new objective function that considers simultaneously the economic return and customer service level pursuing SC resilience while guaranteeing profit and SC responsiveness.

Keywords: Supply Chain Resilience; Quantitative models; Risk; Literature review; Operations Research; Metrics

Resumo

A resiliência constitui-se como uma preocupação atual e crescente na cadeia de abastecimento, gerada pela globalização da operação, estando sujeita a diversos tipos de distúrbios que necessitam de ser tratados de forma correta. Com o intuito de melhor compreender como a comunidade académica se tem debruçado sobre tal preocupação é realizada uma revisão sistemática da literatura sobre resiliência da cadeia de abastecimento, com foco no uso de métodos quantitativos para apoiar a decisão. É desenvolvida cuidadosamente uma análise de conteúdo, garantindo a validade dos resultados e conclusões, tendo por base a criação de uma metodologia sólida de preparação, recolha e análise de dados. Como aspectos centrais, procede-se a uma discussão clarificadora sobre os principais conceitos e definições de Resiliência das Cadeia de Abastecimento e apresenta-se uma proposta de definição genérica, caracterizando os seus principais componentes. Pode-se afirmar que a Resiliência da Cadeia de Abastecimento constitui-se como um foco de atenção crescente entre académicos e profissionais, baseando-se a maioria do trabalho publicado na formulação de conceitos de certos elementos, carecendo de uma abordagem holística e integrada. A fim de orientar o trabalho futuro sobre a temática são propostas orientações para a comunidade académica. Por conseguinte, recorreu-se à utilização do Modelo MILP, com vista a analisar a relação positiva entre Complexidade e Resiliência e foi elaborada uma nova função objetivo que contempla, simultaneamente, um fator económico e com um fator de nível de serviço.

Palavras-Chave: Resiliência das Cadeias de Abastecimento; Modelos Quantitativos; Risco; Revisão da Literatura; Investigação Operacional; Métricas

Contents

List of Figures

List of Tables

Abbreviations

NPV Net Present Value

ENPV Expected Net Present Value

OR Operation Research

SC Supply Chain

SCM Supply Chain Management

SCRM Supply Chain Risk Management

SCV Supply Chain Vulnerability

SCR Supply Chain Resilience

CLSC Closed Loop Supply Chain

ECSL Expected Customer Service Level

MILP Mixed Integer Linear Programing

OF Objective Function

1

Introduction

Contents

Introduction

The world of logistics and Supply Chain (SC) represents a fairly recent field of focus for science (Barbosa-Póvoa, 2014). Not that the inherent activities did not exist, but simply were not considered foundations for the organizations and therefore did not require the effort of studying advancements and efficiency increments.

History provides several examples where, primitive, supply chain had to be implemented; from the Silk Road to the everlasting examples of human drive for armed conflict. Until 1950s, is from the military that most of the effort on the study of Supply Chain and Logistics is due (Ballou, 2007). TThe very condition of an armed conflict implies moving large quantities of personnel and goods to different locations and in such circumstances a lack of supplies, manpower or information could have tremendous consequences. Implicitly the need to address logistics as a main goal has emerged: *getting the right goods to the right place at the right time*.

After the Second World War, Logistics was also embraced by civilian's enterprises, acknowledging the fact that one's market can be much broader than its immediate surroundings. The revolutionary way of thinking business globally created concerns on how to create value. Supply Chain no longer were to be simple and a new approach to Supply Chain Management was necessary. The supply chain management concept was for the first time identified by Oliver et al. (1982), and from then on has evolved.

Supply Chain Management (SCM) definition is not however linear or absolute, since it differs between different authors (Mentzer et al., 2001).Nevertheless, it always includes the flows of goods from source to the final client, involving different tiers in between echelons. The most common definition of SCM takes into consideration that SCM not only manages the logistics side of an operation, but it is also responsible for the relationships between the different players, with data sharing having increasingly a higher importance (Christopher, 2016).

With globalization, SCM became a main organizational concern and the process of increasing SC efficiency is in constant development, turning SC structures more complex and optimized for maximum profit under normal circumstances. Decision makers are left with a high quantity of information heightening the knowledge of turning data into quantitative metrics as highly relevant, Bhagwat and Sharma (2007). Additionally, economic activities and society pressures related to environmental concerns have changed many of SCM procedures and a sustainable global business has become a mainstream enterprise strategy leading to a swift from direct flows SC to Closed Loop Supply Chain (CLSC), where not only forward but also reverse flows and activities are considered (Barbosa-

Póvoa, 2009; Salema et al., 2010). The added complexity of reverse logistics is brought from the need to better deal with e-commerce, re-use of products or customer service (Savaskan et al., 2004). This complexity of flows lead to an increased importance related to the location of individual entities and how they interact (Farahani et al., 2013; Mota et al., 2015, 2017)

Companies and academics have been involved in a joint effort to deeply study SC as a whole, including the characterization of its elements, besides the flow of goods, in what is described as Triple-bottom-line dimensions of organizations sustainability - the creation of sustainable supply chain (Elkington, 1998, 2004). The results are shown with the creation of models or frameworks applied to case studies, for example IKEA's Corporate social responsibility in global supply chain (Lindgreen et al., 2009). Different reviews on the topic have been published, showing the increased importance of the concept at both academic and industrial levels (Seuring and Müller, 2008; Brandenburg et al., 2014).

In this changing context where sustainable globalization is playing an increased role and where SC are now more exposed to disruptions, Supply Chain Resilience (SCR) has emerged, but little attention has yet received, turning this topic underdeveloped, hence creating an opportunity to further study (Tang, 2006; Kamalahmadi and Parast, 2016). Building awareness and knowledge regarding Supply Chain Risk Management (SCRM) and SCR is an important matter of interest since disruptions, even with low probability of happening, can cause severe impacts on companies if happening. Underestimate or not being able to foresee the occurrence and consequences of an event can lead to disruptions with high impact on SC operations, regardless the SC dimension or direct field of business. Complex networks for flows of goods and information lead inevitably to business being dependent of global interference. However, the focus on disruptions must be done individually to each operation, considering that the same event for disruption can cause different results on different SC. Thus addressing SCR is a key factor for a sustainable advantage.

1.1 Methodology

The approach followed to approach the topic and consequent problem is structured in five steps:

1. Problem Contextualization
2. State of the art
3. Analysis of the relationship between SC Flow Complexity and SCR
4. Construction of a new Objective Function
5. Analysis and discussion of results

This methodology allows to guide the structure of the work here presented, with each stage intended to meet a purpose:

- First Stage: Problem Contextualization consists of providing the reader enough information regarding the topic to be able to understand its relationship with other known topics, the reason and importance of studying this problem.
- Second Stage: A systematic literature review is presented to establish the state of the art and provide information to guide future work.
- Third Stage: The concepts of SC Flow Complexity and SCR are studied, recurring to the development of a quantitative model.
- Fourth Stage: An effort to reduce SCR research gap by constructing a new objective function.
- Fifth Stage: The analysis and discussion of the main results from previous stages.

1.2 Objectives

In this document, we aim at providing a state of the art on how academics working in SC have been addressing resilience and also an approach to Modelling and Analysing SCR. Two main objectives are pursued: to understand how SCR has been understood by the academic community; and to understand the development made on quantitative methods/models to support complex supply chain decisions when resilience is at stake. A set of research questions was defined where these objectives are explored. A new framework to support a sound SCR analysis is proposed, which results into a comprehensive new SC Resilience definition. The interaction of the risk concept and SCR is analysed and the work progresses by focusing on the development of quantitative SCR. A study on the methods used to build such models, the techniques used as well as the decision levels treated is presented before addressing SCR metrics and strategies.

It is also an objective to approach the challenges brought by Modelling and Analysing Supply Chain Resilience. First, by developing a quantitative model to study the relationship between SCR and SC Flow Complexity. Second, by developing a new objective function integrating not only economical concerns but also SC performance metrics.

With new information, research gaps and future directions for SCR are presented aiming to guide future work in the area.

1.3 Master Thesis Outline

Setting up a structured work contributes to the presentation of an useful document not only for authors but also for others readers, establishing a tool of knowledge dissemination.

The Mater thesis here presented follows the structure presented bellow.

- **Introduction:** Is presented an overview on the topic including the motivation for the proposed master thesis. It is also presented the project objectives and outline

- **State of the Art:** The component of this project where a systematic literature review is presented with all its intermediate sections, that include the definition of research questions and the consequent answers via the content analysis and identification of research gaps for future development.
- **Modelling and Analysing Supply Chain Resilience:** Further analysis of SCR focusing on quantitative models. Recurring to two new objective functions, one maximizing complexity and the other not focusing only on economic factors and rather on resilience factors.
- **Conclusions:** The main conclusions of the work done are presented, as well as considerations for future work.

2

State of the Art

Contents

State of The Art

Here is presented a Systematic Literature Review that aims to provide a clarification of concepts, definitions while reviewing the current state of the art for the field of SCR with a particular interest in quantitative models for Complex Supply Chains.

The work here unveiled develops a content analysis, ensuring the validity of the results and conclusions. Following a structure similar to that presented on Brandenburg et al. (2014), a systematic literature review is performed with a solid methodology regarding the preparation, collection and analysis of information collected. Previous to any result, work must be guided by a set of Research Questions that are an essential part of a literature review, guiding not only the answers provided in the end but also the efforts done throughout the whole research.

With this work we aim at providing a state of the art on how academics working in SC have addressed resilience under the change as how global economy is propelled. After setting the research questions, the work is structured firstly with an analysis of previous literature reviews and with what has been discussed, justifying the present literature review. Additionally, this literature review provides new information extracted from a new proposed framework to analyse SCR definitions, which lead to a comprehensive new SCR definition. We present a study on the interaction of risk concept and SCR. The work is then developed by focusing on quantitative SCR models. A study on the methods used to build such models, the techniques used as well as the decision level involved before addressing SCR metrics and strategies, with a comprehensive collection of resilience metrics. With such information, research gaps and future directions for the scientific field are presented in order to guide future work.

2.1 Methodology

In order to produce valid work through the literature review, the methodology proposed in Barbosa-PÃ$^3 voaet\ al.$ (2017) is adapted and the following steps are considered: research questions definition, previous literature reviews analysis, material collection, descriptive analysis, category selection and material evaluation. These are characterised generically below followed by a detailed development on each step:

1. *Research Questions definition*: first approach to the definition of research questions

2. *Previous Literature Reviews analysis*: analysis of previous literature reviews, regarding formal characteristics of the identified set and collection of information for research questions refinement.

3. *Material Collection*: material collection under defined conditions and admissibility clauses.

4. *Descriptive Analysis*: formal analysis of the set of papers identified regarding data concerning its classification, chronology and relationships.

5. *Category Selection*: identification of structural dimensions of analysis, to be applied to the collected publications. A detailed description of such dimensions is elaborated that will guide the material evaluation.

6. *Material Evaluation*: the publication set is analysed based on the dimensions defined previously, retrieving information about current and future developments for SC Resilience.

With this methodology, a new space to obtain and analyse data is available, helping to ensure the viability of the content analysis, without changing the procedures defined and validated in previous works. Coupled with this methodology the bibliometric software HistCite was used exploiting the ability to, in a short period, provide several important characteristics of a given set of references (e.g. chronology of the articles or the relationship between the citations of each element).

2.2 Research Questions

Following the motivation of the current paper, described previously, a set of research questions was defined to assess the state of the art on the topic of SCR. These are key to provide a better understanding of the topic and to guide the research to be done. Eight research questions where specified:

1. How resilience has been defined in supply chain?

2. How resilience and risk have been related in supply chain?

3. What type of supply chain structure have been considered when addressing resilience?

4. At what decision level have formal models being developed?

5. Which operations research methods are most used in modelling Supply Chain Resilience?

6. Which resilience quantitative metrics have been used?

7. What kind of risk mitigation strategies have being suggested by the current research?

8. What challenges still lie for research on resilience in supply chains and which future directions should be taken?

2.3 Previous Literature Reviews

The scientific publications here analysed and studied in further detail are the result of a search on *Web of Science* database under the terms *"supply chain" AND resilience AND review*. An initial set

Table 2.1: Publications analysed as previous literature reviews

Date / Author / Title / Journal
2016
Wang, Junwei and Muddada, Raja R and Wang, Hongfeng and Ding, Jinliang and Lin, Yingzi and Liu, Changli and Zhang, Wenjun / Toward a resilient holistic supply chain network system: Concept, review and future direction / IEEE Systems Journal 10.2 : 410-421
Kamalahmadi, Masoud and Parast, Mahour Mellat / A review of the literature on the principles of enterprise and supply chain resilience: Major findings and directions for future research / International Journal of Production Economics 171 : 116-133
2015
Hohenstein, Nils-Ole and Feisel, Edda and Hartmann, Evi and Giunipero, Larry / Research on the phenomenon of supply chain resilience: a systematic review and paths for further investigation / International Journal of Physical Distribution & Logistics Management 45.1/2 : 90-117

of 46 publications was identified, which was then refined in order to address the concerns regarding Literature Reviews on SC Resilience, resulting in three documents to be analysed, listed in Table 2.1.

The decision not to consider some publications, at this stage, was performed after a paper content analysis, removing those that did not deal specifically with SCR, were not from peer review journals or not categorized as reviews. The identified three publications are characterized in Table 2.2, regarding its objective, research methodology, focus, approach, supply chain relatives, papers and timespan of the publication sample considered. Based on these elements it is possible to infer on the currently published reviews main characteristics and consequently address the pertinence of the current review.

Hohenstein et al. (2015) performed a systematic review on the research development of SCR with special focus on the conceptualization of SCR, its definition, models and phases (readiness, response, recovery and growth). A total of 67 publications from years 2003 to 2013 were analysed.

On the systematic review from Kamalahmadi and Parast (2016) 100 publications from the years 2000-2014 are reviewed in order to state the research development on SC Resilience, it also develops a framework on the phases of SCR, different from those referred previously (Anticipation, Resistance and Recover & Response) as well as other formalization on ”Supply Chain Resilience Principles. It takes into consideration the different decision levels, from strategic to operational, and the current reality with supply chain getting more complex, with information assuming a key role when aiming at a resilient operation. An extensive conceptual analysis on SCR is presented, from its definition to the difference between risk and uncertainty, where uncertainty was seen as related with unpredictable events or in other terms unknown-unknown risks.

Wang et al. (2016) through a Systematic Review of the literature reviewed 48 publications from 1996 to 2009, considering the problematic brought by SCR with particular emphasis on the behaviour of SC Networks due to its design and organization. The focus on Network Design comes as a result of the economic development that lead to bigger and more intricate relationships between several actors, leading to the definition of a *Holistic Supply Chain* to define a ”set of SC that are interdependent”.

Table 2.2: Supply Chain Resilience Reviews Characterization

Paper	Objective	Research Methodology	Papers	Years Analysed	Focus	Approach	SC Relatives
Wang, J., Muddada, R. R., Wang, H., Ding, J., Lin, Y., Liu, C., & Zhang, W. (2016)	Identify and classify SCN and access the state of SC Resilience	Systematic Review	48	1996 - 2009	SC Network	Qualitative	-
Kamalahmadi, M., & Parast, M. M. (2016)	Research Development	Systematic Review	100	2000 - 2014	Organizational and SC Resilience Practices	Qualitative and Quantitative	Uncertainty and Risk
Hohenstein, N. O., Feisel, E., Hartmann, E., & Giunipero, L. (2015)	Research Development	Systematic Review	67	2003 - 2013	SC Resilience phases and measurement	Qualitative and Quantitative	Uncertainty and Risk

It is noticeable an evolution through time on research for SC and Resilience, with an increase in publications from 2003 and concentrated in regions where the industry is more susceptible to outsourcing risks (Kamalahmadi and Parast, 2016). The chronology is much associated with the terrorist attacks of 9/11 (Hohenstein et al., 2015) that led to a chain of events that had a disruptive effect in many economic activities. The set of events that followed resulted in a real stress test to the global economy, creating by experience the need to be better prepared for changes in steady state conditions.

From the works above, it can be concluded that a clear definition on SCR is of great importance when sharing knowledge in a global scale. The three publications approached this issue by collecting resilience definitions from several fields, comparing them and ending in a general definition of SCR. Due to this importance, the SCR definition topic is further detailed in a specific section in this document. Within such definition, SCR has to be addressed as a set of elements that interact with each other and result in the scenario of disruption or a disturbance to a scenario of normal operation. These elements must be considered in order to aid decision-making process in a disruptive state. Disruptive risks as well as recovery and reaction strategies can be categorized on the type of action and thinking it implies (Kamalahmadi and Parast, 2016). Hohenstein et al. (2015) divides the different possible strategies in two categories, proactive or reactive strategies and Wang et al. (2016) adds a third one concerning the anticipation and awareness of events. The authors approach resilience strategies in a rather qualitative manner, providing a set of strategies that can produce results on SCR without providing performance metrics to quantify the impact of a particular strategy on SC operations.

As conclusion from the analysis of these papers, it can be stated that SCR can hardly be considered as an isolated term as it is a product of industry and business evolution and needs. For many researchers, it is important to address resilience in combination with complexity, uncertainty and risk.

On the work here presented, we intend to further develop the knowledge on SCR by answering the Research Questions previously defined and differentiating from previous reviews by focusing on the use of quantitative approaches to address SCR. Additionally, a further detail study on SCR definition is performed proposing a framework to analyse and contextualise SCR definitions in its complexity and based on the varied examples from the literature studied. To do so a necessary work on the relationship between SC Resilience and Risk concepts, that are often brought up together, and a clear understanding on its interdependence is relevant and was performed.

The remaining of this review is dedicated to the measurement and quantification of SCR, by studying the quantitative models present in the literature focusing on the use of Operation Research (OR) methodologies, as well as on the strategies and metrics that can be applied in such models.

2.4 Material Collection

Publications here presented and analysed were collected as the result of a set of searches on *Web of Science* database and the following terms were explored *"supply chain" AND resilience AND*

Table 2.3: Results of the initial material collection

Term	# Initial	# Final
”supply chain” AND resilience AND Data Analysis	26	6
”supply chain” AND resilience AND Decision Analysis	35	13
”supply chain” AND resilience AND Expert Systems	5	1
”supply chain” AND resilience AND Heuristics	4	3
”supply chain” AND resilience AND Markov Decision	0	0
”supply chain” AND resilience AND Meta heuristic	2	1
”supply chain” AND resilience AND Neural Networks	1	0
”supply chain” AND resilience AND Optimization	32	15
”supply chain” AND resilience AND Queuing Theory	0	0
”supply chain” AND resilience AND Simulation	36	13
”supply chain” AND resilience AND Statistics	1	0
”supply chain” AND resilience AND Metrics	10	4
Total	152	56

Data Analysis; ”supply chain” AND resilience AND Decision Analysis; ”supply chain” AND resilience AND Expert Systems; ”supply chain” AND resilience AND Heuristics; ”supply chain” AND resilience AND Markov Decision; ”supply chain” AND resilience AND Meta heuristic; ”supply chain” AND resilience AND Neural Networks; ”supply chain” AND resilience AND Optimization; ”supply chain” AND resilience AND Queuing Theory; ”supply chain” AND resilience AND Simulation; ”supply chain” AND resilience AND Statistics and *”supply chain” AND resilience AND Metrics* resulting in a initial set of 152 publications.

To better define the papers that should be the focus of further analysis, articles with the following conditions were considered:

- Must be in English language and published in a peer-review journal until December 2016
- Publications that do not focus on Supply Chain Resilience were excluded
- Publications regarding non-technical capabilities of Supply Chain Management were excluded
- Publications with a qualitative approach were excluded

A content analysis of each paper made possible the intersection with the established conditions, consequently the relevance of each paper, resulting in a more restricted set of publications, 56 in total, see Table 2.3. From this set some publications appear in the results for more than one term of search, resulting in 39 individual publications in a timespan from 2009 until 2016.

2.5 Descriptive Analysis

One possible method to infer over a particular state is to provide an analysis regarding the factual data, independent from the content of the items. Although limited and forcibly with the need to be complemented by other means of analysis, the information provided by the temporal distribution, geographical distribution and the relative relevance for each paper can be of importance when accessing the current state of the art. The elements here described are possible to be obtained using HistCite Software.

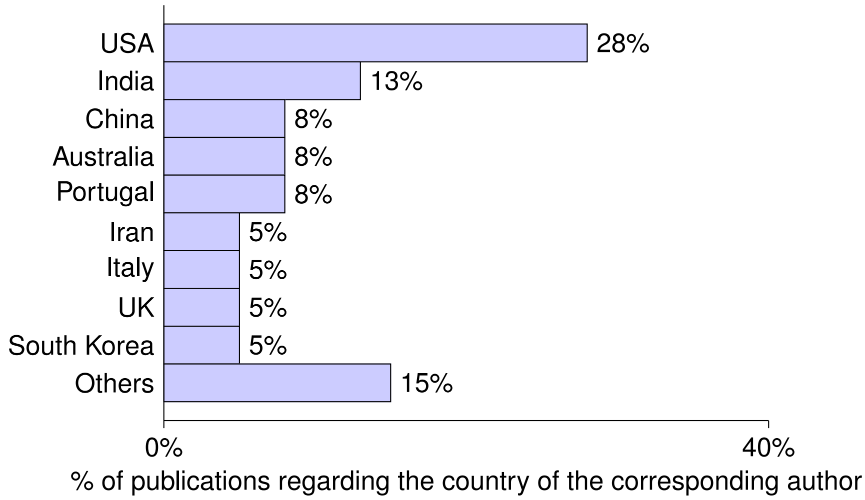

Figure 2.1: Country Distribution of identified publications

From Figure 2.1 it can be concluded that the attention given to this topic is somehow limited geographically, with a higher quantity of publications coming from a restricted set of developed countries or that its economy is dependent on Global Supply Chain, as is the case of India or China.

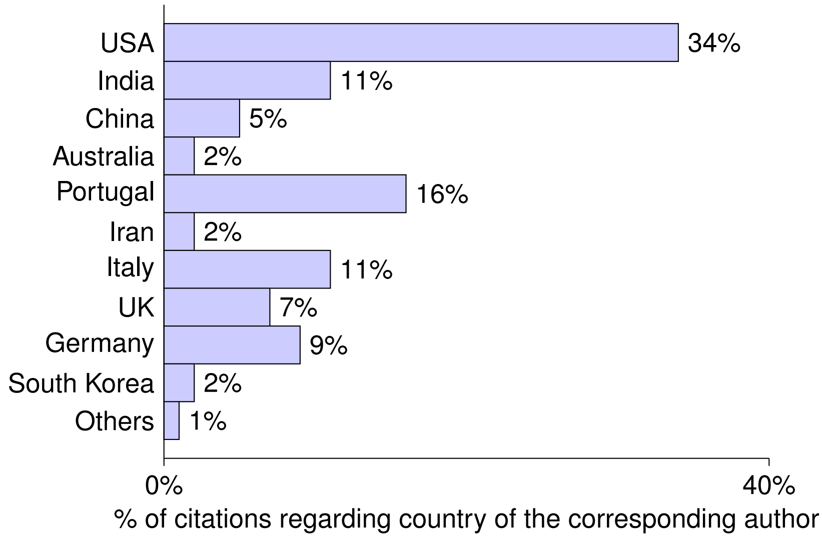

Figure 2.2: Citation Distribution of identified publications per country

When considering citations some relevant changes are perceptible. Some publications are responsible for a vast part of the citations, on the other hand several publications lack citations, consequently have a diminished impact. In Figure 2.2 it is perceptible a weight increase on publications from Portugal (from 6% of publications, 3 papers, a 16% of citations was obtained) and diminishing citations of publications from Iran, Australia or South Korea. Nevertheless, it should be mentioned that citation analysis is far from being perfect. Two defects from such process can be easily perceived. One comes from the fact that, not always, is being possible to identify negative citations or self-citations (Pilkington and Meredith, 2009) and older papers have a large lifespan to be cited. To some degree, the characteristic identified comes as no surprise, since the countries with decreased impact on citations have publications published in 2016.

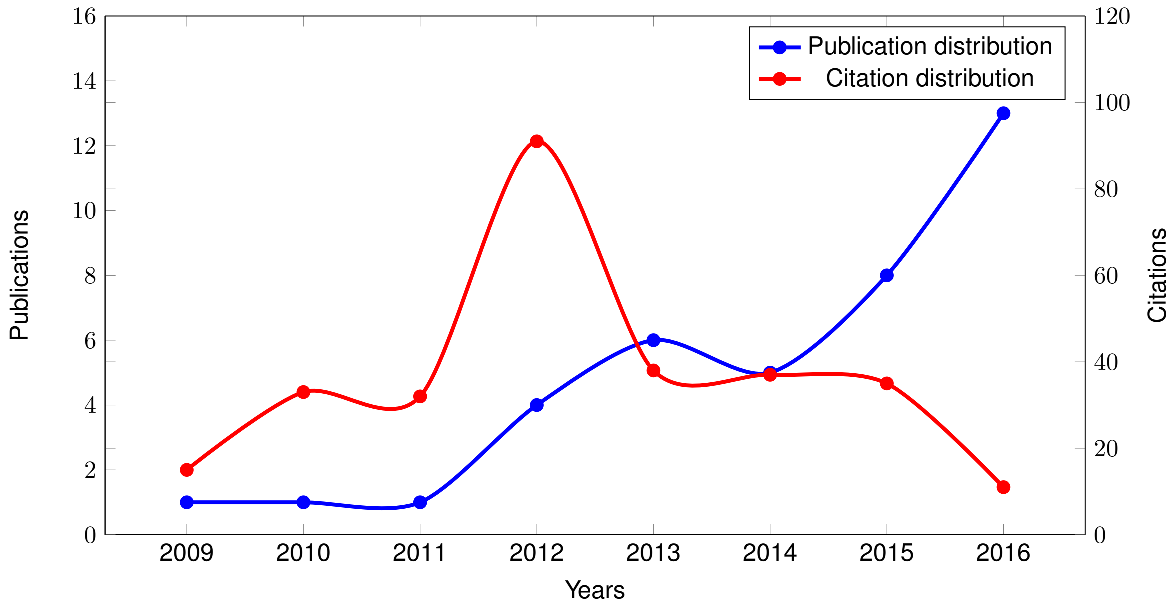

Figure 2.3: Publication and Citation Yearly Distribution

It is noticeable from Figure 2.3 (Plot) that publications regarding SCR and its quantification are on an incremental path, with 2016 being the year with most identified publications demonstrating the growing awareness regarding Resilience, its quantification and how companies can retrieve competitive advantage from embracing SCR strategies.

Regarding time line distribution of citations Figure 2.3 (Plot), a peak emerges in 2012, just after a period with fewer publications, suggesting that novelty work was created and a benchmark for publications that succeed.

The sample here collected is distributed in 25 different Journals, Figure 2.4, where a higher number of publications do not mean a higher relevance within the set. Publications are spread through several journals much due to the imprecise definition of resilience (publications on risk or sustainability journals) and the applied nature of many publications drive such publication to be done on specific journals.

Compiling the data from the analysis of publication title makes it possible to infer on most recurrent concerns for authors extrapolating from the words chosen for titles. In Figure 2.5 the most common words are listed and besides the expected ”Supply” ”Chain” and ”resilience” other words are commonly present in titles, such as ”Network”, ”risk” and ”disruption”. These three words are, to some extent, representative of the present state of the art, with resilience being applied in the context of the design of SC Networks, as well as the study on how to deal with SC disruptions and the relationship with risk management.

2.6 Category Selection

Information from the analysed publications must be compatible in order to be possible to retrieve information from a vast set of sources and positively approach the research questions. Publications were listed with its content based on four Structural Dimensions, Figure 2.6: Type of Supply Chain; Decision Level of SCM; Publication Approach; and Model, which includes the Operation Research (OR) method used; the existence of true resilience metrics and observed industry.

- Type of Supply Chain: Addressing Forward, Closed Loop Supply Chain or Reverse Supply Chain?
- Decision Level of SCM: The model takes into account decision which decision level (Strategic, Tactical or Operational)?
- Publication Approach: How does the paper approaches SC Resilience and how it collects and returns information? (Case Study, Qualitative, Quantitative and eventual description Resilience Strategies)
- Model: How is the model implemented, considering two dimensions: Operation Research methods used; and research topics such as the Resilience Metrics used and if it looks into a generic example or in a particular industry.

The paper categorization is presented in Appendix A.

2.7 Material Evaluation

2.7.1 Supply Chain Resilience Definition

Research Question 1

The study on SCR definition is somehow crucial to a correct and useful review on a concept that is somehow not yet established therefore needing a formal and recurrent study.

A primordial approach, in order to access the present and evolution on SCR definition, is to study the literature available and infer the State of the Art. There is a need to create a broader set of publications, including some that are not included in the final sample. The requisite to add papers from different sources, at this stage, is much due to the fact that these topics are much of a theoretical nature and the publication sample is focused on quantitative and applied models. A three steps approach on a collection of SCR definitions is constructed:

i) Publications present in the publication sample defined in Section 2.4, Table 2.4;

ii) Publications with relevant content present in the original publication sample defined in Material Collection, that were latter excluded of further analysis due to the conditions imposed in Section 2.3 or 2.4, Table 2.5;

iii) Cross-referencing other publications relevant in the formulation of SCR definition that are not present in any of the original search results, Table 2.6.

From this procedure a sample of 27 publications is considered, from 2003 to 2016. This will be used in the discussion on SC Resilience definition and on the relationship with Risk.

On a first analysis, it is possible to state that the definition of SCR is not well established and can differ in key elements between different authors and publications.

Table 2.4: Supply Chain Resilience Definitions present in publications retrieved on the several search iterations

Authors	Title	Definition	Year
Ponomarov, Serhiy Y and Holcomb, Mary C	Understanding the concept of supply chain resilience	The adaptive capability of the supply chain to prepare for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations at the desired level of connectedness and control over structure and function.	2009
Juttner, Uta and Maklan, Stan	Supply chain resilience in the global financial crisis: an empirical study	The apparent ability of some supply chains to recover from inevitable risk events more effectively than others, based on the underlying assumption that not all risk events can be prevented.	2011
Roberta Pereira, Carla and Christopher, Martin and Lago Da Silva, Andrea	Achieving supply chain resilience: the role of procurement	The capability of supply chains to respond quickly to unexpected events so as to restore operations to the previous performance level or even to a new and better one.	2014
Hohenstein, Nils-Ole and Feisel, Edda and Hartmann, Evi and Giunipero, Larry	Research on the phenomenon of supply chain resilience: a systematic review and paths for further investigation	Supply chain resilience is the supply chain's ability to be prepared for unexpected risk events, responding and recovering quickly to potential disruptions to return to its original situation or grow by moving to a new, more desirable state in order to increase customer service, market share and financial performance.	2015
Junwei Wang, Raja R. Muddada, Hongfeng Wang, Jinliang Ding, YingziLin,Changli Liu, and Wenjun Zhang	Toward a Resilient Holistic Supply Chain NetworkSystem: Concept, Review and Future Direction	A resilient system is a system with an objective to survive and maintain function even during the course of disruptions, provided with a capability to predict and assess the damage of possible disruptions, and enhanced by the strong awareness of its ever-changing environment and knowledge of the past events, thereby utilizing resilient strategies for defence against the disruptions.	2016
Elleuch, Hatem, E. Dafaoui, A. Elmhamedi, and H. Chabchoub	Resilience and Vulnerability in Supply Chain: Literature review	Resilience is defined as the ability of a system to return to its original state or a more favourable condition, after being disturbed.	2016
Kamalahmadi, Masoud and Parast, Mahour Mellat	A review of the literature on the principles of enterprise and supply chain resilience: Major findings and directions for future research	The adaptive capability of a supply chain to reduce the probability of facing sudden disturbances, resist the spread of disturbances by maintaining control over structures and functions, and recover and respond by immediate and effective reactive plans to transcend the disturbance and restore the supply chain to a robust state of operations.	2016

Resilience in SC context has been described in a simpler and broader terms by several authors, by implicitly stating that SCR can be described as the ability for the SC to withstand changes of steady-state and converge to the original state or to a new desirable state (Rice and Caniato, 2003; Christopher and Peck, 2004; Christopher and Rutherford, 2004; Erol et al., 2010; Carvalho et al., 2012; Xiao et al., 2012; Wieland and Marcus Wallenburg, 2013). It is important to clarify that it is not by the complexity, or depth, of a certain definition that the pertinence of such assertion can be evaluated. The definitions here listed are presented in the context of a particular publication therefore, it is normal the existence of definitions for the different scientific goals of the original publication.

There are examples of succinct definitions with interesting approaches including elements such as concept of time in terms of speed (Brandon-Jones et al., 2014) or chronology position to a disruption or disturbance (Gaonkar and Viswanadham, 2007). The explanation of the goals or performance measures under SCR has not been set in the earliest definitions however, some authors introduce the concept in short definitions (Barroso et al., 2011; Carvalho et al., 2011; Elleuch et al., 2016). Even in the identified definitions, there is no consensus on the clarification in what are the events that take the focus on SCR thought. ”Disruptions”, ”Unexpected events”, ”Risk Events” or ”Disturbances” are terms used to characterize what should be the focus on a trigger event for the SC to leave the steady state condition and consequently be the objective of SCR.

More complex and complete definitions, in its majority, are more recent and tend to combine several elements present on earlier and simpler definitions.

In the following Tables, the cited definitions are chronologically listed for convenience of interpretation and as reference for the development of upcoming Research Questions.

Considering that the purpose of this work is to advance and create knowledge on the topic, the definition to be used is aimed to be complete and clearly entail the necessary elements for a rigorous but practicable quantitative measure of SCR.

Table 2.5: Supply Chain Resilience Definitions present in the publication sample

Authors	Title	Definition	Year
Geng, Liang and Xiao, Renbin and Xie, Shanshan	Research on self-organization in resilient recovery of cluster supply chains	cluster supply chain network suffers from cascading failure when dealing with undesirable disruption, but it can conduct self-repair through adaptability and make it fast recover to a new stable state	2013
Wieland, Andreas and Marcus Wallenburg, Carl	The influence of relational competencies on supply chain resilience: a relational view	The ability of a supply chain to cope with change, if its original stable situation is sustained or if a new stable situation is achieved.	2013
Berle, Øyvind and Norstad, Inge and Asbjørnslett, Bjorn E	Optimization, risk assessment and resilience in LNG transportation systems	The ability of the supply chain to handle a disruption without significant impact on the ability to serve the supply chain mission	2013
Brandon-Jones, Emma and Squire, Brian and Autry, Chad W and Petersen, Kenneth J	A Contingent Resource-Based Perspective of Supply Chain Resilience and Robustness	The ability of a supply chain to return to normal operating performance, within an acceptable period of time, after being disturbed.	2014
Birkie, Seyoum Eshetu	Operational resilience and lean: in search of synergies and trade-offs	The ability of a business to anticipate, and adapt to sustain and recover operations against disruptions	2016

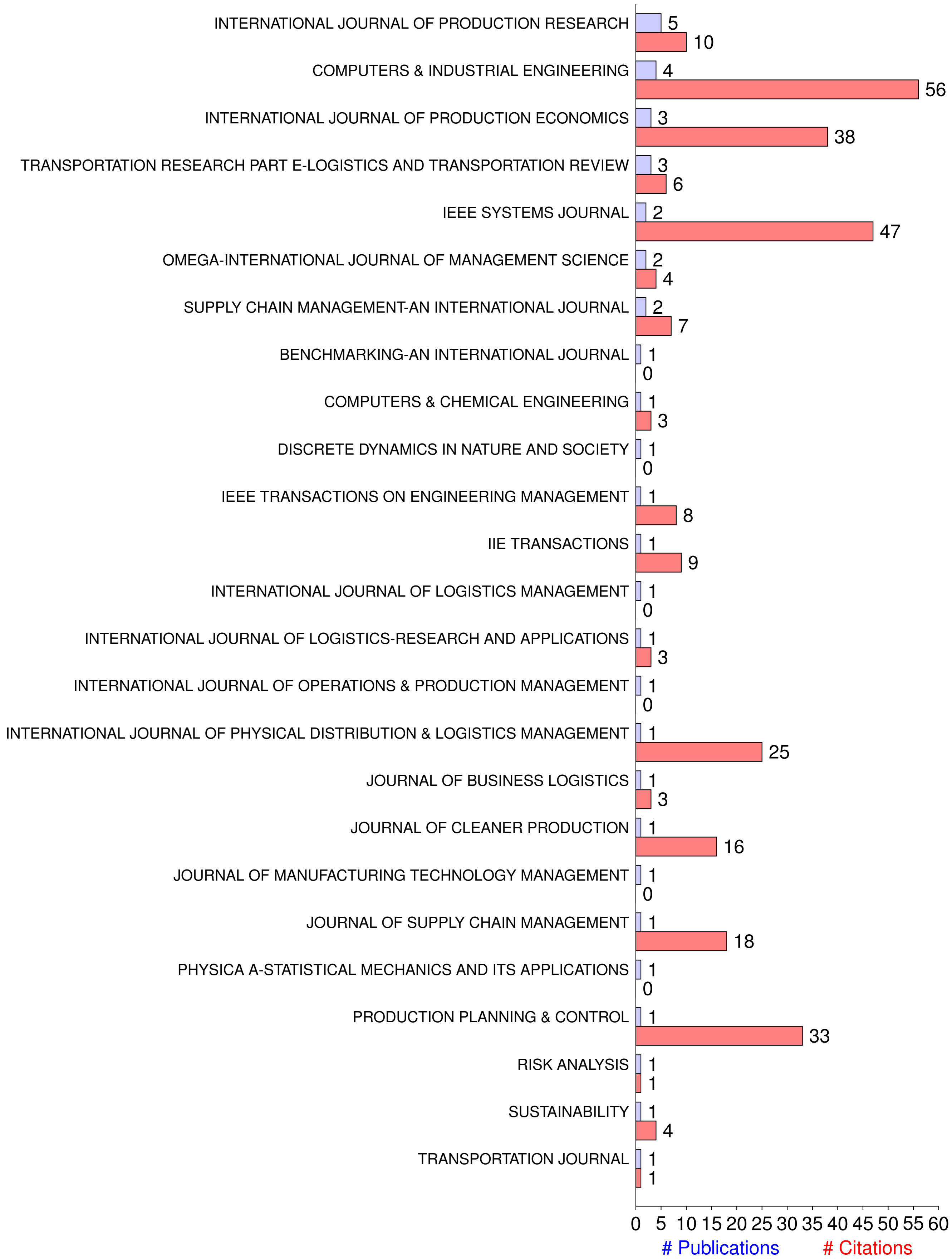

Figure 2.4: Journals present in the sample

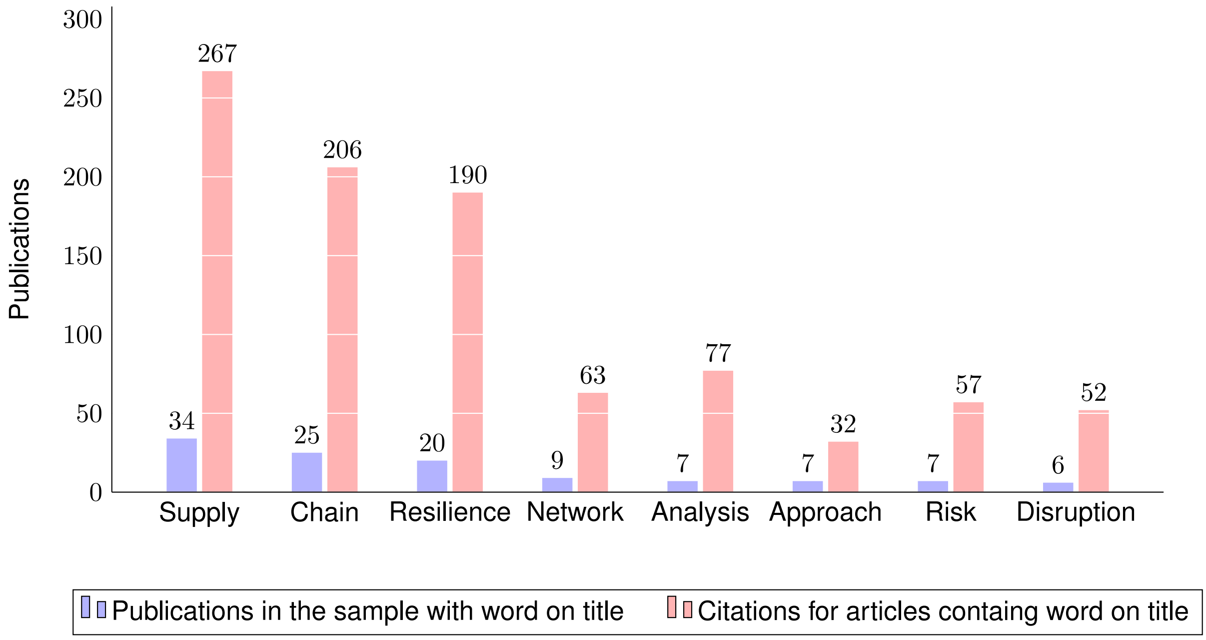

Figure 2.5: Word distribution in Title

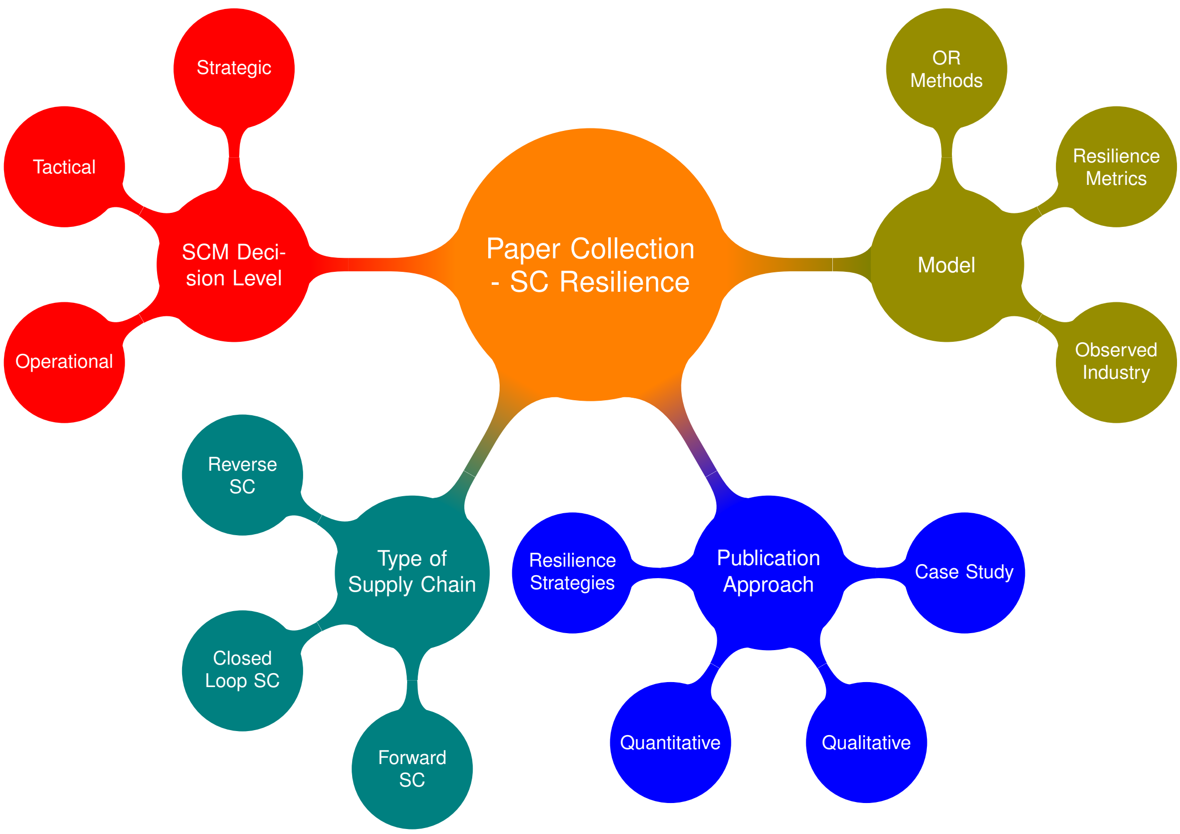

Figure 2.6: Mind-map for Category Selection

Table 2.6: Supply Chain Resilience Definitions from Cross-Referencing

Author	Title	Definition	Year
Rice, James B and Caniato, Federico	Building a secure and resilient supply network	The ability to react to unexpected disruptions and restore normal supply network operations	2003
Christopher, Martin and Peck, Helen	Building the resilient supply chain	The ability of a system to return to its original state or move to a new, more desirable state after being disturbed	2004
Christopher, Martin and Rutherford, Christine	Creating supply chain resilience through agile six sigma	The ability of a system to return to its original (or desired) state after being disturbed	2004
Closs, David J and McGarrell, Edmund F	Enhancing security throughout the supply chain	The ability to withstand and recover from an incident. A resilient supply chain is proactive-anticipating and establishing planned steps to prevent and respond to incidents. Such supply chains quickly rebuild or re-establish alternative means of operations when the subject of an incident.	2004
Gaonkar, Roshan S and Viswanadham, Nukala	Analytical framework for the management of risk in supply chains	The ability to maintain, resume, and restore operations after a disruption	2007
Priya Datta, Partha and Christopher, Martin and Allen, Peter	Agent-based modelling of complex production/distribution systems to improve resilience	Not only the ability to maintain control over performance variability in the face of disturbance, but also a property of being adaptive and capable of sustained response to sudden and significant shifts in the environment in the form of uncertain demands	2007
Falasca, Mauro and Zobel, Christopher W and Cook, Deborah	A decision support framework to assess supply chain resilience	The ability of a supply chain system to reduce the probabilities of disruptions, to reduce the consequences of those disruptions, and to reduce the time to recover normal performance.	2008
Barroso, AP and Machado, V Cruz and Machado, VH	Supply chain resilience using the mapping approach	The ability to react to the negative effects caused by disturbances that occur at a given moment in order to maintain the supply chain's objectives.	2010
Erol, Ozgur and Sauser, Brian J and Mansouri, Mo	A framework for investigation into extended enterprise resilience	Is a response to unexpected or unforeseen changes and disturbances, and an ability to adapt and respond to such changes.	2010
Carvalho, Helena and Duarte, Susana and Cruz Machado, Virgilio	Lean, agile, resilient and green: divergencies and synergies	Concerned with the system ability to return to its original state or to a new one, more desirable, after experiencing a disturbance, and avoiding the occurrence of failure modes.	2011

Continued on next page

Table 2.6 – continued from previous page

Author	Title	Definition	Year
Ponis, Stavros T and Koronis, Epaminondas	Supply chain resilience: definition of concept and its formative elements	The ability to proactively plan and design the Supply Chain network for anticipating unexpected disruptive (negative) events, respond adaptively to disruptions while maintaining control over structure and function and transcending to a post event robust state of operations, if possible, more favorable than the one prior to the event, thus gaining competitive advantage.	2012
Carvalho, Helena and Azevedo, Susana Garrido and Cruz-Machado, Virgilio	Agile and resilient approaches to supply chain management: influence on performance and competitiveness	The ability of supply chains to cope with unexpected disturbances.	2012
Ponomarov, Serhiy	Antecedents and consequences of supply chain resilience: a dynamic capabilities perspective	The adaptive capability of a firm's supply chain to prepare for unexpected events, respond to disruptions, and recover from them in a timely manner by maintaining continuity of operations at the desired level of connectedness and control over structure and function.	2012
Xiao, Renbin and Yu, Tongyang and Gong, Xiaoguang	Modeling and simulation of ant colony's labor division with constraints for task allocation of resilient supply chains	The supply chain's ability of returning to the original or ideal status when this supply chain system has been disturbed by external interruption, and resilient supplys chain show abilities on adaptability to environment and recovery.	2012
Kim, Yusoon and Chen, Yi-Su and Linderman, Kevin	Supply network disruption and resilience: A network structural perspective	As a network-level attribute to withstand disruptions that may be triggered at the node or arc level.	2015

From the analysed literature is possible to purpose a new framework to understand, evaluate and create Supply Chain Resilience Definitions. The framework here presented, Figure 2.7, relies on four pillars Adaptive Framing or Stage Adaptive Response; Speed; Performance Level; Focus Event.

- **Adaptive Framing or Stage Adaptive Response**

  As described before, there are authors that simply address resilience as the ability to react, or to withstand a disruption or disturbance. However, SC Resilience can be seen as a series of adaptive responses in a multi-stage approach regarding the potential events. Closs and McGarrell (2004) take into consideration such elements by stating that a Resilient SC must *"withstand and recover from an incident. (...) proactive-anticipating and establishing planned steps to prevent and respond to incidents. (...) quickly rebuild or re-establish alternative means (...)"*. Birkie (2016) suggests a simpler approach on the actions required before, during and after the disruption "*Anticipate, and adapt to sustain and recover* (...)"

  Although a solid characterization on the elements to face incidents, it misses the awareness on the importance to maintain a steady-state solution after the recovery from a disruption. Ponomarov and Holcomb (2009) proposes a definition that accounts for these concerns: "*(...) prepare* *for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations (...)*" . The four stages here presented (Prepare, Respond, Recover and Maintain) are also described in subsequent definitions (Ponis and Koronis, 2012; Ponomarov, 2012; Hohenstein et al., 2015) or the work presented by Kamalahmadi and Parast (2016) that provides a brief description on the goals for each stage to meet SC Resilience.

It is then crucial that stakeholders involved in SC resilience define the concept and embrace the concern as not being a reaction in a specific individual moment. When analysing SC Resilience definitions, it is important to check the presence of these elements.

- **Speed**

  When facing a change that has an impact on the way a firm is operating, producing harm to its results, the time needed to halt such harmful act is of crucial analysis. Closs and McGarrell (2004) introduces the concept of speed in SC Resilience by allowing two possibilities: "*(...) quickly rebuild or re-establish alternative means (...)*". The concept of urgency in re-establishing steady state is also present in Geng et al. (2013); Pereira et al. (2014); Hohenstein et al. (2015) by stating the need for a quick/fast response.

  Falasca et al. (2008) and Ponomarov (2012) deal with the concern regarding time with a different approach, not applying the word "quick", instead the concern rely on diminishing the time to recover, in the first, and to simply recover in a "timely manner" in the latter. Ponomorov lists two definitions in the set here presented, one from 2009 and the more recent from 2012, with the main difference being the introduction of speed concerns in SC Resilience definition.

  It is relevant for SC Resilience definition to include the specific concern regarding the speed on which the system returns to a positive steady state, even if the notion of quick might change depending on the specific case.

- **Performance Level**

  The definition of a certain property should include the concerns that could be the target of evaluation or quantification of such comprehensive definition. Authors have presented, in previous definitions, several elements that can be the root cause to measure resilience.

  Falasca et al. (2008) and Kamalahmadi and Parast (2016) address SC Resilience as an adaptive ability to *reduce the probability of disruptions/disturbances*. On the other hand several authors deal with the period before the disturbance event by referring the efforts on *identifying, anticipating and preparing for events* (Ponomarov and Holcomb, 2009; Ponis and Koronis, 2012; Ponomarov, 2012; Hohenstein et al., 2015; Wang et al., 2016).

  Concerning the period when an event, that negatively influences operations, is active, there are key items that can be identified when defining SC Resilience. It is relevant to consider the *consequences and how the system responds to a disturbance* (Falasca et al., 2008; Ponomarov and Holcomb, 2009; Ponomarov, 2012; Wang et al., 2016; Kamalahmadi and Parast, 2016). An objective and simple consideration that can be formulated is related to the ability for the system to *maintain control during the disturbance* (Ponomarov and Holcomb, 2009; Ponis and Koronis, 2012; Ponomarov, 2012; Wang et al., 2016; Kamalahmadi and Parast, 2016) or to sustain the occurrence *without significant impact* (Berle et al., 2013).

The *time required by the system to return to steady-state* is fundamental when studying the resilience of a particular system (Falasca et al., 2008; Ponomarov, 2012; Pereira et al., 2014; Hohenstein et al., 2015; Kamalahmadi and Parast, 2016).

It is then crucial to consider the period consequent to the disturbance and how the system reach steady state, where a position *equal or better than the original* is relevant for a resilient supply chain (Ponis and Koronis, 2012; Pereira et al., 2014; Hohenstein et al., 2015).

- **Focus Event** Several events are associated with the focus of SC Resilience. This is a point in definitions that must be clearly identified since it allows for a narrower or broader set of events to influence resilience.

  The term *incident* (Closs and McGarrell, 2004) comes as a simpler and broader term in contrast to the most frequent, in the set presented, *Disruption* (Falasca et al., 2008; Ponomarov and Holcomb, 2009; Ponis and Koronis, 2012; Ponomarov, 2012; Kim et al., 2015; Hohenstein et al., 2015; Wang et al., 2016). Disruption although the most frequent term is also the event classification that narrows the set of possible events; it implies that the events that can be the focus of SC Resilience are those that abruptly stop operations completely blocking value creation activities.

  Other terms are used such as *disturbance* (Priya Datta et al., 2007; Kamalahmadi and Parast, 2016), *Unexpected Events* (Ponomarov and Holcomb, 2009; Ponomarov, 2012) and *Risk Events* (Jüttner and Maklan, 2011; Hohenstein et al., 2015) and come as much broader terms that enable SC Resilience to be influenced by simpler events that can produce negative impacts on operations, without disrupting it.

  In matter of fact, the balance between the two perspectives on focus events is perceptible from the fact that several authors (Ponomarov and Holcomb, 2009; Ponomarov, 2012; Hohenstein et al., 2015) include *Disruption* alongside a broader term.

  Being the lack of applied work a concern for many authors, discussed previously in Section 2.3, comes as no surprise the fact that few SC Resilience definitions approach the level of SCM. Ponis and Koronis (2012) and Kim et al. (2015) include such element of characterization by suggesting that SC Resilience is function of the planning and designing of the network, concluding that SC Resilience should be addressed on a Strategic Level. Although relevant to the operationalization of SC Resilience, the strict definition of the decision level involved can be restrictive on the use of a definition.

  The term *disturbance* can be presented as a broader term, not only regarding the focus event, but also in relation to the different SCM decision levels. It can easily allow for SC Resilience strategies to be applied on a strategic level and also on a more operational state.

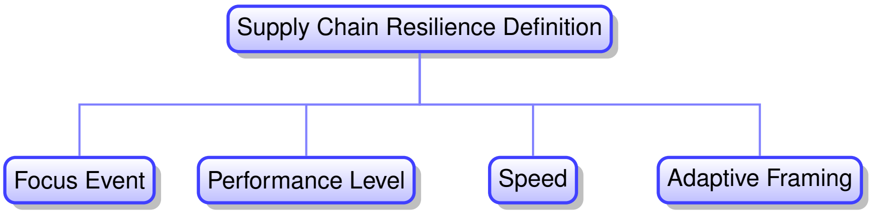

Figure 2.7: Mindmap for SC Resilience Definition analysis framework

From the framework analysis, a comprehensive but simple new definition is proposed, resulting from the discussion of the five pillars defined before:

A resilient supply chain should be able to prepare, respond and recover from disturbances and afterwards maintain a positive steady state operation in an acceptable cost and time.

2.7.2 Risk on Supply Chain Resilience

Research Question 2

The relationship between Supply Chains and Risk is present in SCR, being this discipline derived from SCRM and SCM (Ponomarov and Holcomb, 2009; König and Spinler, 2016).

Jüttner and Maklan (2011) states that there is an already acknowledged relationship between Supply Chain Vulnerability (SCV) and SCRM, proposing that the three concepts are complementary for a well-designed SC.

Publications focused on SCRM also address SCR much due to the natural relationship between concepts. For example, Heckmann et al. (2015) creates a framework for SCRM where SC Risk is represented as primary concept, whereas vulnerability and resilience appear aggregated when it refers to the effects of risk on SC. The two terms appear related, however a difference in connotation can be found. Resilience is perceived with a good connotation unlike vulnerability that has a negative connotation (Elleuch et al., 2016). Therefore, resilience might be relevant when other concepts fail in empowering firms and academics to study the several elements under risk management.

Following the dogma of considering variability in steady-state conditions as a constant possibility in operations, decisions on actions to be introduced in SCM can be addressed through the concept of SCR, where a positive impact can be stated between Risk Management and the need/awareness for investment in resilience (Ponomarov and Holcomb, 2009). This relationship can result in the use of strategies to reduce risk or the consequences related with a particular event (Ponomarov and Holcomb, 2009). However it is not guaranteed that a risk correction measure would benefit SCR (Jüttner and Maklan, 2011).

One relevant characteristic is the velocity for a risk event. Jüttner and Maklan (2011) categorize velocity of risk events in three different approaches: the rate that the event happens; the rate that the event fades; how quickly the event is discovered. Then they propose a new added factor for velocity regarding SCR: the rate that the SC can recover from a disruption into a new steady-state condition, a concept with increasing impact on SCR definition as discussed in Section 2.7.1.

Conventional Risk Management relies on identification and quantification of risk events and consequences, appearing as step-backs when there is no data available in an ever-changing world, thus leading resilience thought as a key process for SCM in handling risk of an uncertain and complex future (Pettit et al., 2013). SCRM presents several challenges and insufficient information that disables the traditional methods of managing risk, SCR can provide the tools and knowledge to complement traditional risk management techniques (Kamalahmadi and Parast, 2016). It is this incomplete study, on the interaction between several SC concerns, which generates the need for a greater investment in the study and awareness regarding the several possible approaches for SCR.

The concept *Zone of Balanced Resilience* is proposed by Pettit et al. (2013), as the optimal location for firms to choose. This goal is met by finding an equilibrium between the exposure to risk, and consequent increase in vulnerabilities, and the increasing capabilities that can cause erosion of profits.

Resilience can be seen as an offspring of SCRM and SCV concepts leading to the necessity of addressing such elements in combination (Pereira et al., 2014), revealing that it might not be possible to implement resilience driven actions in an isolated form. Additionally, complex SC, with several tiers, constituted by elements representing several different economic actors, allow partnerships to occur with companies sharing benefits but also risks and creating dependency. This divided stake can, and must, be addressed via resilience strategies that rely on knowledge already created in SCRM.

Concluding and in order to address resilience, companies must be aware of exposure to risk that implies continuous Risk Analysis and Assessment (Ponomarov and Holcomb, 2009).

2.7.3 Supply Chain Resilience quantitative models and Supply Chain Management decision level

Research Questions 3, 4 and 5

SC Resilience quantitative models are a fairly new effort for academics and practitioners, appearing as a consequence of the growing concern on SCR. With the growth in knowledge, quantitative models went in consonance with the concepts discussed, adding particular relevance to SCR definition endorsed.

Models must define its scope and one relevant measure for scope is the level of decision within the SCM framework. The distribution of decision level involved, Figure 2.8, provides a simple and effective way to analyse at what decision level models are aiming to. Decisions related to Strategic thought are the most common, with SCR being a property of the network as a whole. Therefore, consequences on SCR quantification come from upper levels of decision. The intricate relationship leads to most of the authors to consider tactical factors synchronized with strategic concerns.

The methods present in the different publications, Figure 2.9, are concentrated in three main modelling approaches: Optimization, Simulation and Decision Analysis. This distribution reflects the preferred methods to quantify SCR, with models that can provide easy construction and understanding being those that decision makers can trust with ease. Thus, models are getting more complex keeping up with the consolidation of SCR concepts and relevance to SC operations.

From the set of 39 publications a high number of models apply some kind of numeric confirmation,

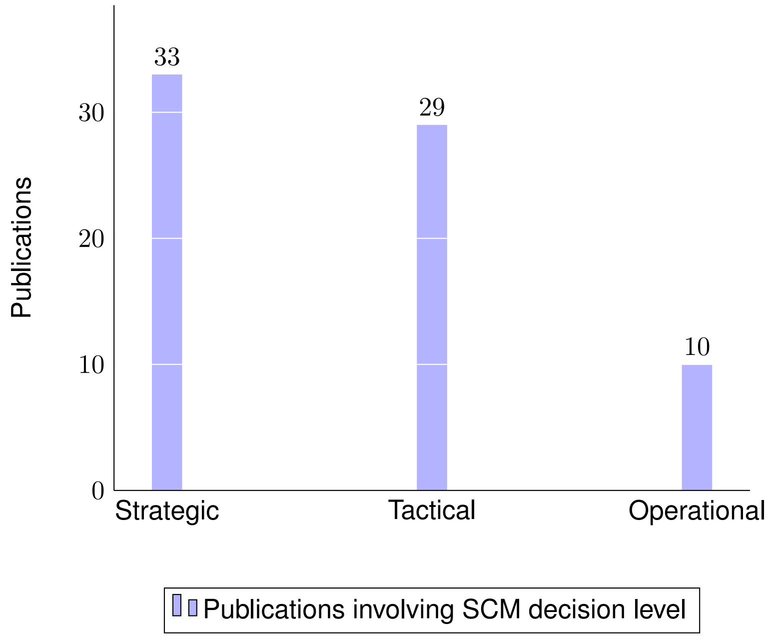

Figure 2.8: SCM Decision Level

most in form of a case study (24 Publications) applying the model. From the set of papers that deploy a model on a case study it is not possible to identify any prominent field of application, with nine publications not identifying specifically the industry of the presented example. It is possible to identify multiple models that focus on the same industry as, for example, the case of aeronautics or retail industry, with two representative cases each, and electronics with three examples (Rajesh and Ravi, 2015a; Rajesh et al., 2015; Rajesh and Ravi, 2015b). Using case studies is the preferred method to test the model with real life scenarios and it can provide information to meet its objectives and ultimately aid decision making on improving SCR.

Authors proceed with different approaches on the construction of quantitative models, much depending on its goals regarding the scope, depth and application of the particular model.

Harrison et al. (2013) creates a simple model where it optimizes a SC network by iteratively removing a node from the SC and re-optimize the remaining structure thus being possible to create several disruptions scenarios. Contrasting from simple models, Hasani and Khosrojerdi (2016) creates a fairly complex, but complete, model combining classic OR methods with Heuristics in order to study network design under uncertainty applying resilience strategies to the context of global SC.

With SC dealing with great distances and minimal times objectives aircrafts are often use to fulfil such objective. Wang and Ip (2009) deals with SC Network Resilience applied to the field of Aircraft Service, crucial for continuous flow of aircrafts, by quantifying resilience as dependent to Demand and Supply, with its redundant possibilities, thus simplifying quantification and interpretation. However, reducing the variability of inputs that real life systems suffer. Thekdi and Santos (2015) proposes a model regarding the specific context of port operations where interdependence of different infrastructure and the risk of operations disruptions are measured, reaching suggestions regarding decision making under several types of disruption scenarios. Maritime transport disruptions are also addressed by Berle et al. (2013) with a Monte Carlo simulation with quantity delivered being the performance metric for comparison.

There are approaches on the specific concern of inventory management and disruptions caused by stock-outs. Boone et al. (2013) provides a case study where inventory is managed under a system approach rather than focusing on individual items and Spiegler et al. (2016) proposes an elaborated non-linear model, with objective to control inventory and reduce stock-out situations, representing the dynamic relationship between errors of knowledge, variability and eventual inventory disruptions. There are simulation models to study resilience in terms of inventory stock-out at 3 levels of analysis (costumer, retailer and manufacturer) taking also into consideration the costumer behaviour and its impact. Wu et al. (2013) proposes an agent-based simulation model and Schmitt and Singh (2012) not only implement a simulation model for the case study at hand, but also proposes a set of strategies to mitigate the consequences of inventory stock-out.

It is perceptible a concern regarding the sustainability of SC, Fahimnia and Jabbarzadeh (2016) and Mari et al. (2014) study the impact of green SC to SC Resilience, creating a multi-criteria model combining Environmental and Social performance score with SC Cost under a set of disruption scenarios recurring to a goal programming approach to compare the conflicting objectives, sustaining that it is possible to achieve a "*resiliently sustainable SC*".

Lean practices take on as a more usual principle for operations and Birkie (2016) uses Bayesian Networks on the consequences of integrating lean and resilience strategies on system performance under disruptions, concluding that Lean is not a constraint for resilience practices implementation.

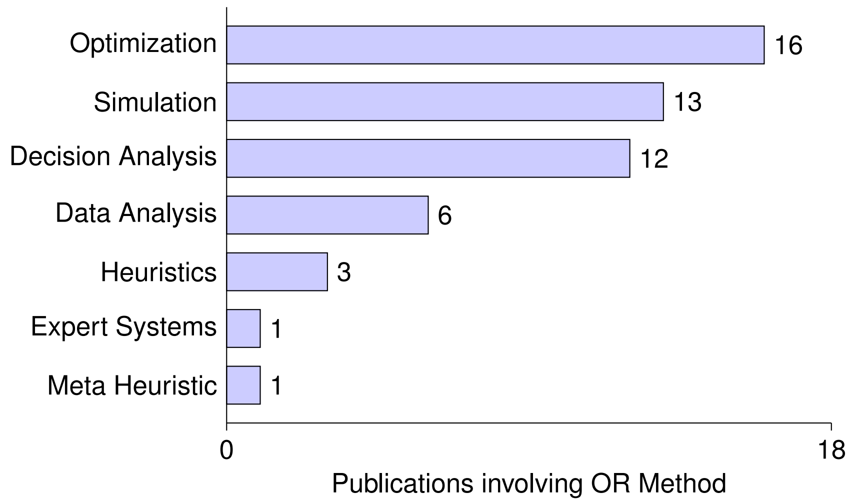

Figure 2.9: Operations Research Method distribution

2.7.4 Strategies and Metrics applied in Supply Chain Resilience quantitative models

Research Questions 6 and 7

SCR Strategies and Metrics are much variable as authors and objectives change, with some authors following the conceptualization proposed by earlier publications. This is made clear in Table 2.7, where the set of factors that are explicitly applied to SC Resilience are summarized.

From our research, only three publications (Wang and Ip (2009); Soni et al. (2014); Azevedo et al.

(2016)) quantify SCR in a Single Index *per si* and using a set of 21 factors to measure Resilience goals of a particular SC, Factors Ri in Table 2.7.

Table 2.7: Resilience factors present in models to quantify SC Resilience

Publication	**Factors**
Wang and Ip (2009)	*Resilience for each node* R1: Supply Reliability R2: Edge Reliability R3: Factor between (Demand, Supply and transport capacity) and demand *Network Resilience* R4: Weighted sum of each node resilience
Soni et al. (2014)	R5: Agility R6: Collaboration R7: Information sharing R8: Sustainability R9: Risk and Revenue sharing R10: Trust R11: Visibility R12: Risk Management Culture R13: Adaptive capability R14: Structure
Azevedo et al. (2016)	R15: sourcing strategies to allow switching of suppliers R16: Flexible supply base/flexible sourcing R17: Strategic stock R18: Lead time reduction R19: Creating total supply chain visibility R20: Flexible transportation R21: Visibility to a clear view of own stream inventories and demand conditions

Most of the identified publications tend to incorporate SCR factors in the models, being those factors crucial for results interpretations, however do not aim at creating a SCR Index. From the identified set, it is possible to extract 48 resilience factors, Factors Fj in Table 2.8, that the different authors apply in order to provide better information regarding SCR.

Analysing the papers that propose a single index, it is interesting to see that the work by Wang and Ip (2009) departs from a study of an Aircraft service. The authors access, in this operation, the most relevant metrics and establish a resilience metric for each node involved and provide a network resilience metric by performing a weighted sum of each node resilience. Soni et al. (2014) create an Index to measure and compare SCR. This relies on several enablers of resilience, which were identified via a survey with practitioners and academics. From the identified enablers, a study on its interdependence is presented through a matrix involving 10 chosen enablers. More recently, Azevedo et al. (2016) propose an index to classify SC in combination of four vectors (Lean, Agile, Resilient and Green), presenting a set of resilience metrics and its relative weights to SCR. An automotive SC is studied.

When analysing that papers that incorporate SCR factors into the models developed but not aiming at a single index, several papers were identified, where it can be seen the diversity of factors considered (see Table 2.8, Factors Fj). Zhao et al. (2011) address the network design problem using a simulation approach. The authors analyse the obtained results recurring to three resilience new metrics (availability, connectivity and accessibility) and propose a new approach to resilient SC Design

Table 2.8: Resilience factors present in models to characterize SC Resilience

Publication	Factors
Zhao et al. (2011)	F1: Availability: percentage of demand nodes that have access to supply nodes F2: Connectivity: Size of the largest functional sub-network F3: Accessibility: Maximum supply path length and average supply-path length
Adenso-Diaz et al. (2012)	F4: Node Complexity F5: Suppliers Complexity F6: Sources Criticality F7: Density F8: Variance Density F9: Node Criticality F10: Flow Complexity F11: Node Reliability F12: Flow Reliability F13: Cluster Reliability F14: Variance Node Reliability F15: Variance Flow Reliability F16: Variance Cluster Reliability
Brandon-Jones et al. (2014)	F17: SC Connectivity F18: Information Sharing F19: SC Visibility F20: SC Resilience F21: SC Robustness F22: Environmental Dynamism F23: Scale Complexity F24: Differentiation F25: Delivery Complexity
Munoz and Dunbar (2015)	F26: Recovery F27: Impact F28: Performance Loss F29: Profile Length F30: Weighted Sum of F26 to F29
Cardoso et al. (2015)	Network Design F31: Node Complexity F32: Flow Complexity F33: Density F34: Node Criticality Network Centralization F35: Quantity of inbound and outbound flows F36: Intensity of inbound and outbound flows Operational F37: Expected Net Present Value F38: Expected Customer Service Level F39: Investment
Hosseini and Barker (2016)	F40: Geographical Segregation F41: Surplus Inventory F42: Backup Supplier Contracting F43: Physical Protection F44: Rerouting F45: Restoration Budget F46: Technical Resource Restoration
Dixit et al. (2016)	F47: Percentage of unfulfilled demand post-disaster F48: Total transportation cost post-disaster

based on a military hierarchy. Adenso-Diaz et al. (2012) deals with reliability on SC also looking into the SC network design problem. A Monte Carlo simulation model is developed considering thirteen factors that influence reliability, while identifying its relative importance in a particular case.

Brandon-Jones et al. (2014) study the SC supply-side by considering visibility as a key capability. The authors justify such importance through an empirical evidence by developing a survey to practitioners, and a consequent data analysis on the measure of several parameters (SC connectivity, information sharing, SC visibility and geographic dispersion). SCR is assumed as a result of the restoration of material flow and operating performance, recovery of the supply chain, and the speed with which disruptions would be dealt with. As main conclusion, supplier selection should be performed taking into consideration the resilience capabilities of the involved entities.

Munoz and Dunbar (2015) recurring to Structural Equation Modelling (SEM) create a model to quantify resilience characterizing the response to a disruption by the system performance along time, visually and with a rationale associated (five dimensions: Recovery time, Impact, Profile Length, Performance Loss and Weighted Sum).

For the first time, Cardoso et al. (2015) study the design and planning of a CLSC developing an optimisation model where 11 indicators to measure SCR are considered. Such indicators are grouped in two main types: Network design; and Operational indicators. The CLSC characteristics expressed into the network design indicators denote the level of resilience achieved amongst different CLSC networks. Using a survey with practitioners Hosseini and Barker (2016) create a Bayesian Network model to assist on the decision where resilience is a structural element characterized by a set of seven criteria related to the resilience of suppliers (see Table 2.8: F40 to F46). Finally, Resilience is also a subject for models with concise and simple performance measures such as the model formulated by Dixit et al. (2016) where Percentage of unfilled demand and Total transportation cost post-disaster are seen as fundamental.

As resilience is a concept with ambiguity on its definition, it is expected to find resilience quantification on models not identified as SCR indicators, as are the publications that are to be referred next. There are models that do not comprehensively present a set of quantitative metrics with the goal to address SCR. Rather present models that contain, what we now can infer as, resilience concerns, not providing enough information to replicate the quantification of such concern. Therefore, these publications are not present in the previous table providing, however, relevant information, that is analysed next.

This is the case of Han and Shin (2016) that created a model that analyses resilience by measuring robustness including the concepts of risk propagation after a disruptive event, taking into consideration not only risk but also network configuration. Nooraie and Parast (2016) provide a model to study the relationship between SC Risk Drivers, investment and consequence costs when applying SCR strategies, by studying the overall maximization of revenues and minimization of costs. Sokolov et al. (2016) propose a model assuming SC Design as the focus of analysis with the interaction of a static model (Network Constants) and a dynamic model (Variable under uncertainty) with Service Level and Delivery Reliability as performance indicators. Wieland and Marcus Wallenburg (2013) create a model involving a survey with practitioners with the main objective of measuring the SC Customer Value due to resilience, assuming it in two dimensions (Agility and Robustness). Taking into consideration resilience concerns.

Carvalho et al. (2012) elaborate a simulation model applied to SC Network Design in the context of automotive industry, correcting ”Supply delay” as the main goal, analysing Lead Time and Total Cost as performance measures. Sadghiani et al. (2015) perceives total system cost seen as fundamental for the analysis of disruptive scenarios. Under the above publications, the objective function is commonly addressed by the minimization of SC Costs/ maximization of Net Present Value (NPV) under a more or less elaborated set of variables under disruption scenarios. However, Ehlen et al. (2014) create a model where the objective function is to minimize a sum of two penalizing terms (Deviation of optimal state and Producing or consuming products with no actual demand).

Geng et al. (2013); Wang and Xiao (2016) propose a model to address SCR on SC that are keen to cascading failures, due to internal or external factors. The authors conclude that the cooperative and inherent relationships between several players naturally leads to having the capability of flexibility with the latter presenting the model based on ant colonies. Rajesh et al. (2015); Rajesh and Ravi (2015a) study the cause effect relationships of enablers of SC Risk Mitigation (15 identified enablers) in a three step model (Grey-DEMATEL), resulting in the identification of a set of strategies that represent the highest significance in the model (*Dynamic Assortment Planning, Accurate Demand Forecasting, Supply Chain Visibility, Collaborative Partner Relations and Integrated Supply Chain*).

Rajesh and Ravi (2015b) uses Grey Theory to address the action of choosing suppliers, considering 13 attributes relevant for resilient SC, divided into four groups of factors (Primary performance factors, Supplier’s responsiveness, Supplier’s risk reduction, Supplier’s technical support, Supplier’s sustainability). With the objective of identifying bundles/portfolios of strategies to better cope with SC disruptions, Chowdhury and Quaddus (2015) lists a set of vulnerability factors, SCR capabilities and its dependency culminating in the listing of strategies to meet the issues identified. However, the determination process for the resilience value is through a particular weight and expected capacity to mitigate disruptions.

Upstream disruptions are a particular disruptive event and can be understand as a concern regarding the supply side of a SC. Gualandris and Kalchschmidt (2015) focuses on the interaction between risk management, disruptive events and competitive advantage via a misfit analysis, trying to establish a balanced-resilience logic. The referred misfit was measured based on a Euclidian distance between experimental unit and a risk profile taking into consideration not only risk conditions but also the implementation of mitigation practices. Dabhilkar et al. (2016) address supply-side resilience performing a case-study analysis of actual disruptions and interviews stakeholders involved, creating a link between qualitative to quantitative through statistical analysis creating 4 bundles of resilience practices (from the interaction of Proactive-Reactive and Internal-External practices), concluding that such groups are complementary. Saghafian and Van Oyen (2012) produces a particular work on the supply side, analysing the introduction of a secondary flexible backup supplier to compensate any fluctuation in production in case of disruption, the model created does not quantify resilience per si, being the financial indicator, ”money that a risk-neutral firm should be willing to invest to implement” one of the two strategies at stake: Value of Generalized capacity reservation and the value of analysis suppliers to enhance awareness of disruption risks, the final comparative element.

Global SC not only create structures with an increased number of agents, but also it can increase distances between origin and destination. This paradigm takes lead times to a concept that cannot be ignored and Colicchia et al. (2010) studies such element on SC using hub and spoke system, implementing a simulation model and identifying contingency plans, mitigation actions as well as vulnerabilities that endanger the successful accomplishment of activities. Transportation delays can also be seen as a particular issue that can have impacts along the different tiers of the SC. Azadeh et al. (2014) studies the effects of flexibility, redundancy, velocity and visibility in face of SC Disruptions by using simulation and Fuzzy Data Envelopment Analysis (FDEA) to create a method to order individual, or groups of, resilience practices applied to different scenarios characterized by a particular state (pessimistic, most likely, optimistic).

2.8 Research Gaps and Future Directions

The scientific field of SC Resilience is on a positive path with more knowledge and applications being developed therefore advancing SC Resilience and its applicability to real life situations. Regardless, future research should follow some important directions.

The recurrent need for the extensive characterization of the term Resilience in SC context comes from the fact of not existing a clear definition of SC Resilience, for its different possible uses. However, at the current stage of research, the work already done with such objective is significant, but further developments were identified as required so as to consolidate the work already done on Supply Chain Resilience definition. Researchers should converge to a stable SC Resilience definition, embracing the fact that SC Resilience is an aggregating concept, involving expertise already created on other fields of SCM, such as Risk Management. In this literature review we have proposed a new definition that encompass the different concerns listed and discussed on the analysed papers.

Within the analysed literature is noticeable a relationship between risk and resilience that is perceptible when addressing chronological evolution. SC Resilience come as the latter term, appearing as an aggregation term allowing further development in the specific field. Classical Risk management can be seen as a procedure to mitigate low impact and frequent risks, often neglecting high impact risks as is the case of low probability disruptions (Li and Gulati, 2015), resilience awareness can mitigate such neglect. The combination of such concepts should be further researched.

As seen along this review, SCR is a concern that is relevant for SC operations and consequently for economic activity. Modern complex SC represent a greater set of elements, interactions and intricate flows with the majority of these networks representing a global operation. The ability to acquire knowledge, of already implemented strategies to cope with such kind of scenarios, becomes of greater importance. The need to tackle the issue imposed by the complexity of real life systems is something still to be explored. Quantitative models can help on this study and can act as tools that aid the implementation of resilience practices, providing the necessary insight to acknowledge requirements, objectives and consequences. However, this area is not yet fully explored thus investment on the development of quantitative models should be performed in order to measure comprehensively SCR, not focused on a concrete part of a SC operation but adopting a global view. It is crucial that new OR methods are implemented, following the developments of artificial intelligence as the deployment of Expert Systems supported by optimization tools. Created models are often limited as they often fail to represent the reality, thus it is essential the creation of more holistic models regarding complex SC that incorporate reverse flows. The integration of different OR methods should also be explored as for instance decision analysis methods combined with optimization will allow translation of qualitative concepts often present in SC resilience models into quantified forms that then can be tackled by optimization.

Additionally, the creation of more realistic models may lead to an increase in complexity that may reveal difficulties in the solution of such decision tools. Thus, the research community should explore the exploration of faster alternative solution methods such as meta-heuristics.

Within the models, performance metrics take a key role but are only appropriate if they accurately measure the transient results along several tiers of the SC and for different disruptive scenarios. This is still an area for further research due to its relevance for the use of SC Resilience models in real decision making and ultimately it allows for a increased knowledge on the complete SC functioning. Furthermore, develop efforts on SCR strategies on the different SC decision levels to mitigate the lack of strategies focusing on the operational level is also a path to follow, that should be covered in future models.

Finally, the treatment of real cases should be further explored as although most of the papers claim to have dealt with case studies the current state of the art does not provide nor a vast and broad spectrum nor a particular investment of an individual industry in SCR quantitative models. Therefore, moving to meet such gap is of great importance.

2.9 Literature Review Conclusions

In this systematic literature review, focused on the main existent definitions of supply chain resilience and on the development of quantitative models to support SCR decisions. This is a topic with growing interest for academics and practitioners however, from our research, only three publications were identified as reviews on the SCR and none of them was focused in the use of quantitative models. Our review contributes to reduce such gap.

We start by presenting a study on SCR definition, identifying the different authors' approaches and conceptualizations proposed, leading to the development of a novel framework to analyse the pertinence and scope of SCR. This analysis created the requisite for the establishment of a new sound definition for SCR that can meet the current and future challenges.

Additionally, a content analysis was performed on quantitative SCR models in a set of 39 publications, retrieving with special relevance resilience metrics, OR methods and SCM decision level addressed. As conclusions, it can be stated that the implementation of resilience practices can be one efficient and important strategy for enterprises to create competitive advantage, along with the acknowledgement of the relationship between resilience concerns and risk events. The usage of quantitative models to support the decision in building and operating resilient SC was shown to be of great importance. A set of challenges is presented in order to further develop and implement SCR using quantitative models. A clear need on the improvement of decision making tools in order to provide better and trustworthy information to decision makers was identified, which can only be achieved by developing more comprehensive quantitative models that represent real scenarios, including SC with reverse flows, and make use of effective OR methods.

Supply Chain Resilience is, as conclusion, a field of study that can have a positive impact on companies, needing more thorough studies so as to meet the identified challenges and explore the potential of such interesting field.

3

Modelling and Analysing Supply Chain Resilience

Contents

Modelling and Analysing Supply Chain Resilience

3.1 Problem Description

Nowadays, SC represent an increased role on a company's performance, both economically and on customer service. There is no absolute strategy on which decision makers are to follow to better prepare each SC to the challenges of today and tomorrow. This distinctive element leads to the necessity of providing tools that accurately represent not only the current situation but also a margin of variation on its elements.

In such context, the interest in a deeper understanding of SCR has led academics and companies to pursuit efforts regarding such objective. It is on the best interest of real life SC the increase in knowledge on the topic as it is fundamental to better understand not only the resilience concept, challenge met on the previous chapter, but also how susceptible SC are to events that can endanger their steady state operation. To achieve this goal, we will focus on a strategic level of decision and analysis, regarding the decisions at study to be regarded with SC Design. With this concern as orientation, the main decisions to be set are related with SC network structure. Network configuration has a great impact on operations since it is, usually, an investment with an economic return in a large period of time and therefore its adaptation to the managerial view is fulcrum. Decisions with such relevance are usually associated with the definition of locations to operate and which flows to allow between the different possible entities.

In order to be able to discuss how different SC networks behave towards resilience, a five echelons SC was considered (Figure 3.1) where reverse flows are also be possible to occur. Such echelons involve: Raw Material Suppliers; Plants that can also function as Disassembling Centres with end of life products; Warehouses with added value activities as reconditioning non-conforming products; Outsourcing contractors as alternative to plants production and finally Markets. To plants and warehouse there are technologies that can be implemented modulating production, assembly and disassembly processes. These technologies can be fitted to the entities or upgraded, providing bigger capacity.

Taking as point of origin Cardoso et al. (2015) work, a set of cases are to be studied allowing to compare and construe results. Five cases are studied regarding how the SC network can be designed to achieve higher resilience:

- "Case A - a forward supply chain;

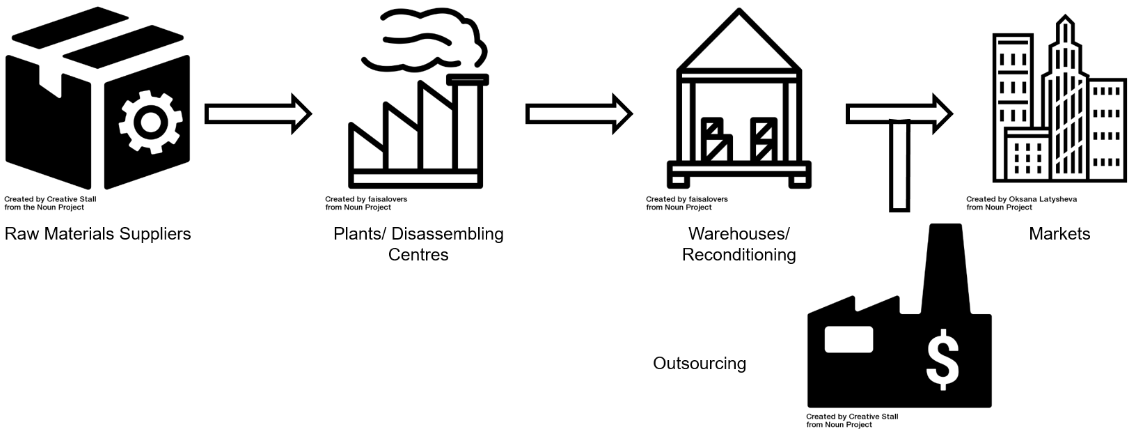

Figure 3.1: Possible SC echelons to consider

- Case B - similar to A, but now integrating also reverse flows between consecutive echelons;
- Case C - similar to B, but plants and markets can directly exchange products, thus bypassing the warehouses;
- Case D - similar to B, but with the possibility of transhipment at plants, disassembling centers and warehouses;
- Case E - the most general case, encompassing all the previous ones. It is a closed-loop supply chain where plants send directly products to markets and can also receive directly from markets the end-of-life products. Transhipment is allowed at plants, warehouses and disassembling centers."

Whilst considering strategic decisions, it is not needed to possess meticulous control on time details but rather consider large periods of time, a timespan of 15 years is considered with intervals of five years.

Uncertainty was also considered in the SC demand and on Disruptions. A scenario tree is then constructed combining the two sources of uncertainty. Demand variability is introduced by generating a scenario on each period from a set of three possibilities (Pessimistic, Realistic or Optimistic). The result probabilistic nodes are then combined with the variability from the disruption that can only assume two options, or it occur or it does not occur on a specific time period to consider. With this, each scenario probability is given by the probabilities of the path, with all stages, between the root node and each final leaf node. In Figure 3.2 an example is given of a scenario tree considering the analysis of a disruption in time period two, generating 18 different scenarios.

3.2 Model Description

The Mixed Integer Linear Programing (MILP) model developed by Cardoso et al. (2015) is taken as base to the work here presented and was adapted to this work goals. This is applied to the problem above described where the multi-product, multi-period model considering demand uncertainty.

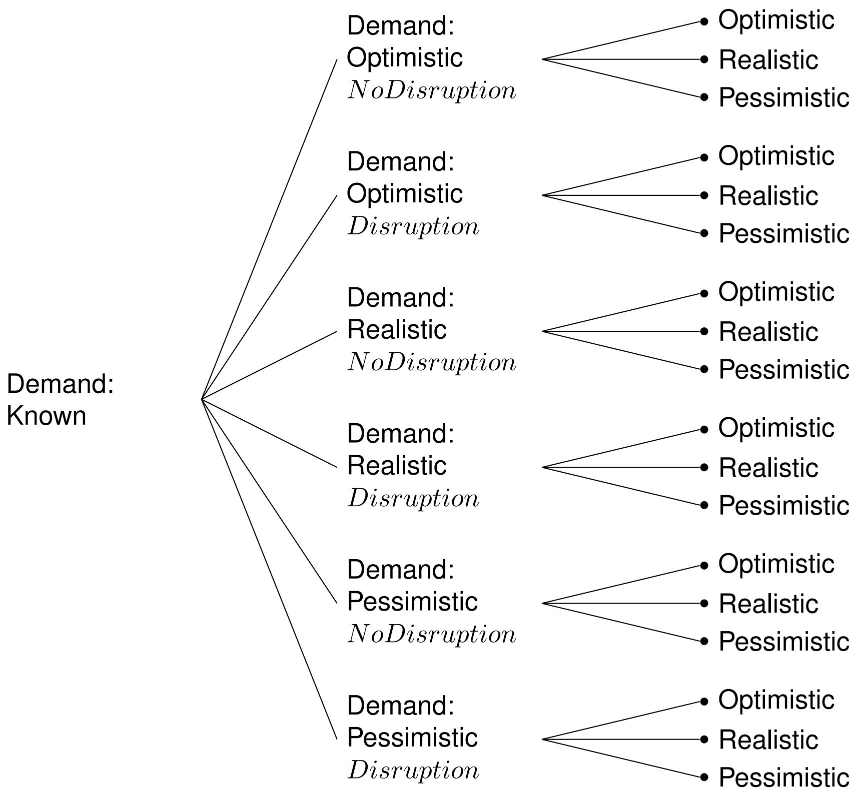

Figure 3.2: Example of a Scenario Tree

As seen previously, the task to measure Resilience is challenging and far to be an accomplished task by the academia. Here we will not present a SCR Index, however an approach to the concept will be made based on relevant performance metrics, allowing to infer on the resilience performance.

3.2.1 Parameters

From the model proposed by Cardoso et al. (2015), a set of important parameters describing the SC performance are chosen to represent and compare the several runs.

For each equation there are a set of independent variables represented in subscript. This variables are further presented:

- v and w - Physical entities, origin and destiny respectively
- s - The scenario s
- t - Time period t
- p - Product p
- i - Technology i
- **Flow Complexity** - Total number of material flows in the network;

$$FC_t = \sum_v \sum_w (Y_{vwt} + YNC_{vwt} + YEL_{vwt}) \forall t \tag{3.1}$$

Where Y stands for forward flows, YNC reverse flows of non-conforming products and YEL represents the reverse flows of end of life products.

- **NPV** - Expected Net Present Value (ENPV) (€) - Calculated for each scenario and time period;

$$NPV_s = \sum_t \frac{CF_{st}}{(1+ir)^t} \tag{3.2}$$

Where CF_{st} stands for Cash Flow and ir represents an interest rate.

Cash Flows can be determined by:

$$CF_{st} = NE_{st} - FDC_t \qquad t = 1, ..., NT-1 \tag{3.3}$$

Where NE_{st} stands for Net Earnings, FDC_t the fraction of depreciable capital and NT represents the total periods of time considered, therefore the last period must take into consideration the part of fixed investment that can be recovered, defining a salvage value sv.

$$FDC_t = \frac{FCI}{NT} \qquad \forall t \epsilon T \tag{3.4}$$

$$CF_{st} = NE_{st} - FDC_t + sv \times FCI \qquad t = NT \tag{3.5}$$

$$\begin{aligned} NE_{st} = (1-tr) \Bigg[& \sum_{v\epsilon V_m} \sum_p fp_{pvt} \times S_{vpst} - \sum_{v\epsilon V_m} \sum_{w:(v,w)\epsilon R} \sum_p QNC_{vwpst} \times fp_{pvt} - \sum_{v\epsilon V_g} \sum_p \\ & rm_{pvt} \times Pu_{pvst} - \sum_i \sum_{v\epsilon V_h} \sum_p Oc_{ivt} \times Out_{ivpst} - \sum_{v\epsilon V_z} ci_{vt} \times IL_{vst} \\ & - \sum_v \sum_w \sum_p dt_{vw} \times (Q_{vwpst} + QNC_{vwpst} + QEL_{vwpst}) \times dc_{vwt} \Bigg] + (tr \times DP_t) \forall s \epsilon K \end{aligned} \tag{3.6}$$

The Net Earnings come as result of the difference between the income ($\sum_{v\epsilon V_m} \sum_p fp_{pvt} \times S_{vpst}$) and the costs as are: the refunds from non-conforming products ($\sum_{v\epsilon V_m} \sum_{w:(v,w)\epsilon R} \sum_p QNC_{vwpst} \times fp_{pvt}$); purchasing products ($\sum_{v\epsilon V_g} \sum_p rm_{pvt} \times Pu_{pvst}$); operational ($\sum_i \sum_{v\epsilon V_h} \sum_p Oc_{ivt} \times Out_{ivpst}$); Inventory ($\sum_{v\epsilon V_z} ci_{vt} \times IL_{vst}$); Transportation ($\sum_v \sum_w \sum_p dt_{vw} \times (Q_{vwpst} + QNC_{vwpst} + QEL_{vwpst}) \times dc_{vwt}$); depreciation of invested capital ($tr \times DP_t$).

It possible to calculate the depreciation value by:

$$DP_t = \frac{(1-sv)FCI}{NT} \forall t \epsilon T \tag{3.7}$$

- **FCI** - Fixed Capital Investment (€);

$$FCI = \sum_i \sum_v im_{iv} \times in^p_{iv} + \sum_i \sum_{v \epsilon V_h} \sum_t (v^p_{ivt} \times CE^p_{ivt}) + \sum_v is_v \times in^s_v \\ + \sum_{v \epsilon V_z} \sum_t (v^s_{vt} \times CE^s_{vt}) + \sum_v \sum_w \sum_t lk_{vwt} \times (Y_{vwt} + YNC_{vwt} + YEL_{vwt} \tag{3.8}$$

FCI assumes the summation of different costs associated with strategic decisions, with each parcel representing different investments: the occurrence of each process ($\sum_i \sum_v im_{iv} \times in^p_{iv}$), the eventual expansion of processes capacity ($\sum_i \sum_{v \epsilon V_h} \sum_t (v^p_{ivt} \times CE^p_{ivt})$), the cost of storage entities ($\sum_v is_v \times in^s_v$), the eventual storage expansion ($\sum_{v \epsilon V_z} \sum_t (v^s_{vt} \times CE^s_{vt})$) and the investment needed to implement new links between entities ($\sum_v \sum_w \sum_t lk_{vwt} \times (Y_{vwt} + YNC_{vwt} + YEL_{vwt}$).

- **Investment** (€) - The total investment in the SC infrastructure, not including transportation costs;

$$Investment = \sum_i \sum_v im_{iv} \times in^p_{iv} + \sum_i \sum_{v \epsilon V_h} \sum_t (v^p_{ivt} \times CE^p_{ivt}) + \sum_v is_v \times in^s_v + \sum_{v \epsilon V_z} \sum_t (v^s_{vt} \\ \times CE^s_{vt}) \tag{3.9}$$

- **Inventory** - Inventory present in warehouses (€);

$$Inventory_t = \sum_{v \epsilon V_h} pb_s \times Cinv_{vt} \times IL_{vst} \tag{3.10}$$

Inventory values are represented in monetary terms, taking into account the probability of all scenarios (pb_s), the unitary cost of holding inventory ($Cinv_{vt}$) and the amount of inventory present in each entity at each scenario for each time period (IL_{vst}).

- **Purchases** - Total purchases (€);

$$Purchases_t = \sum_{v \epsilon V_g} \sum_p pb_s \times rm_{pvt} \times Pu_{pvst} \tag{3.11}$$

Purchases values are represented taking into account the probability of all scenarios (pb_s), the unitary cost of acquiring certain good (rm_{pvt}) and the amount of products bought in each entity at each scenario for each time period (Pu_{pvst}).

- **Sales** - Total sales (€);

$$Sales_t = \sum_{v \epsilon V_m} \sum_p pb_s \times SPrice_{pvt} \times Sa_{pvst} \tag{3.12}$$

- **Expected Customer Service Level (ECSL)** - The percentage of demand not met.

$$ESC = \frac{\sum_t \left(1 - \sum_s pb_s \left[\frac{\sum_{v \epsilon V_m} \sum_p ID_{pvst}}{\sum_{v \epsilon V_m} \sum_p D_{pvst}}\right]\right)}{NT} \tag{3.13}$$

With ECSL as the relationship between the unsatisfied demand ($\sum_{v\epsilon V_m}\sum_{p} ID_{pvst}$) and the total demand ($\sum_{v\epsilon V_m}\sum_{p} D_{pvst}$). Unsatisfied demand has to be calculated as a result of the decisions made during the three time periods that influence the difference between actual demand and the flows sent to each market ($\sum_{w:(w,v)\epsilon F} Q_{wvpst}$).

Unsatisfied demand is given by Equation 3.14, representing the difference between the demand for each market and product, for each scenario and time period (D_{pvst}), and the quantity of product delivered to such market ($\sum_{w:(w,v)\epsilon F} Q_{wvpst}$).

$$ID_{pvst} = D_{pvst} - \sum_{w:(w,v)\epsilon F} Q_{wvpst} \qquad \forall p\epsilon G \wedge v\epsilon V_m \wedge (s,t)\epsilon S \tag{3.14}$$

3.2.2 Objective Function

Building an Objective Function (OF) is an exercise of establishing a guideline for the behaviour of the particular system. In this case, we will follow our problem description and provide enough information to infer on the impact of SC Network Complexity and its behaviour when faced with a disruptive scenario. Two objective functions will be studied, Equations 3.15 and 3.16.

A first one will consider the maximization of the network flow complexity (Equation 3.15), as this would return a network configuration with maximum flow complexity (FC) under the feasibility space generated by problem constraints.

$$Max \sum_{t} FC_t \tag{3.15}$$

This model formulation, although returning a SC with the maximum amount of flows feasibly possible do not take into consideration economic concerns, leading to solutions that may have a low performance in financial terms. This issue can be tackled by setting additional constraints, for instance setting up a minimum profit to be extracted from the model. However, this method was not followed due to two reasons;

First, restrictions had to apply to all cases and scenarios, which involves setting up conditions that can not interfere with the feasibility of the model, a task that can be very specific for each SC.

Second, by setting up new conditions there is the possibility of endangering the established relationship and compatibility with the original model could be compromised.

Therefore, a two-step approach is followed, primarily the model is run based on Equation 3.15 to retrieve the maximum flow complexity within the model feasibility. The second step is to retrieve the network configuration and then study how much such network configuration maximize the economic return.

The economic return is based on the Expected Net Present Value and by proceeding using this method and its maximization (Equation 3.16) it is ensured a network with maximum flow complexity with the most advantageous economic performance to the company.

$$MaxENPV = \sum_s pb_s \times NPV_s \tag{3.16}$$

By fixing the network configuration there is no capability for the SC network to change, however it can adapt to the variability introduced on each situation by investing in technologies and upgrades to existing facilities.

3.3 Case Study

The presented model is implemented on a Case Study, the same as the original work (Cardoso et al. (2015)) in order to allow for comparison of results. An European SC is considered with the values associated scaled down, due to confidentiality reasons.

"The existent supply chain is formed by one plant in Hamburg (P11) with twelve production technologies (il to i12) and six disassembling technologies (i19 to i24), one warehouse in Munich (W1) with six assembly lines (i13 to i18) and a storage capacity for 500 units. All the existing technologies have an initial capacity of 600 t. There are four raw materials suppliers in Frankfurt, Prague, Birmingham and Copenhagen (S1 toS4) and three final products suppliers located in Riga, Minsk and Warsaw (01 to 03), meaning that the supply chain can outsource part or all of the production. The supply chain supplies eighteen markets located in different European countries."

In order to improve SC's capacity to withstand disruptive events, while expanding its business, the company is studying several possibilities and acquire the best information possible to make an informed decision. In broad terms, the company is willing to reconfigure the existent SC by upgrading the technologies used on the current entities or invest in the introduction of new elements; Plants, Suppliers or Warehouses.

There is the possibility to include two new plants with its set of raw material suppliers:

- Bilbao (Pl2)
  - Badajoz (S5)
  - Toledo (S6)
  - Barcelona (S7)
  - Marseille (S8)
- Milan (Pl3)
  - Ljubljana (S9)
  - Lausanne (S10)
  - Linz (S11)
  - Florence (S12)

Table 3.1: Case Study costs table

Costs		
Inventory Costs		0.3€/t period
Transportation Costs		
	Fixed Costs	200€/forward transportation link 150€/reverse transportation link
	Variable Cost	0.1€/t km for forward flow 0.2€/t km for reverse flow
Outsourced final production costs per ton		P29=250€, P30=270€, P31=240€, P32=290€, P33=255€and P34=265€
Plants' investment cost		1€/t
Warehouses' investment cost		0.5€/t
Disassembling Centres' investment cost		0.1€/t

And the prospective warehouse locations are Portsmouth (W2), Lyon (W3), Bologna (W4) and Salamanca (W5).

"At each plant there are twelve technologies that can be used to manufacture twelve products (from P16 to P27). There are fifteen raw materials (from P1 to P15) and one intermediate product, P23."

The activities associated with reverse logistics are associated with Warehouses in the case of assembling (i13-i18) producing the final products (P29-P34) and with plants in the case of disassembling end of life products (i19-i24) allowing the salvage of products (P16-P27).

The costs associated with the case study are as follows in Table 3.1:

A set of relevant restrictions and conditions also exist and must be considered.

- Capacity expansions lower than 400 000 t/entity
- Flow between entities lower than 5000 t
- Warehouses turnover ratio is equal to 20 and no initial inventories are considered
- 20% of products sent to markets each period are non-conforming
- Minimum of 10% of products to be collected at markets, 20% of collected goods are sent to disposal
- Demand is assumed to be known for first period. For the second period the optimistic scenario has a probability of 0.25 with an increased demand of 10%, the realistic scenario with a probability of 0.5 and an increase of 3% and finally the pessimistic scenario has a probability of 0.25

causing a decrease in demand of 2%. In the third period the scenarios have the same probability as in the second period but with different effects on the demand, the optimistic causes an increased demand of 5%, the realistic 2% and finally the pessimistic causing a decrease in demand of 2%

- Interest rate = 10%, Salvage Rate = 20%, Tax Rate = 30%
- All costs are penalized by 5% in the consequent periods of time

The above characterization and model formulation allows for the introduction of changes on the way that the model is run, providing relevant results to an effective analysis of a SC performance. Further in this document, the SC will perform under four operational conditions; one reference case with perfect operational conditions and three examples of disruptions. The three disruptions where chosen following failure modes defined by Rice and Caniato (2003) therefore generating a set of scenarios relevant for analysis.

- Disruption 1 (Production Facilities)- " 100% decrease in the production capacity of the most important plant (plant Pl3), in time period 2, caused, for example, by a major natural catastrophe";
- Disruption 2 (Supply)- "The most important raw materials suppliers (s3, s5, s8, s9 and s10) have their supply suspended in time period 2, due to an assumed industrial action";
- Disruption 3 (Transportation)- "The 3PL hired to operate those transportation links, between plants and warehouses, that carry the highest quantity of products (links between Pl3 and warehouses W1, W2 and W4), goes out of business in time period 2."

3.4 Results

Following the need to further develop the understanding on how network complexity influences SCR, the original case study is developed with such goal in sight. As possible disruptions to a SC usually are Known-Unknown risks, or even Unknown-Unknown, therefore the strategic decision must be based on an option to cope with a set of scenarios to be better prepared for such events.

Thus for each SC case, as described in section 3.1, two configurations are established based on the SC network provided for the two objective functions: maximization of ENPV; and maximization of complexity, when there is no disruption. These network designs are then implemented for each disruption and its results are analysed and discussed.

The MILP model is develop using GAMS software, and is run for a gap of 5%.

3.4.1 Case A

Case A represents a simple SC structure allowing only forward flows, represented in Figure 3.1. When maximizing ENPV, under disruptions, the network losses some of its capacity to meet customer demand and consequently reduces its financial performance, see Table 3.2. When maximizing complexity, with no disruption, there is a slight decrease of ENPV and a slight increase of ECSL when

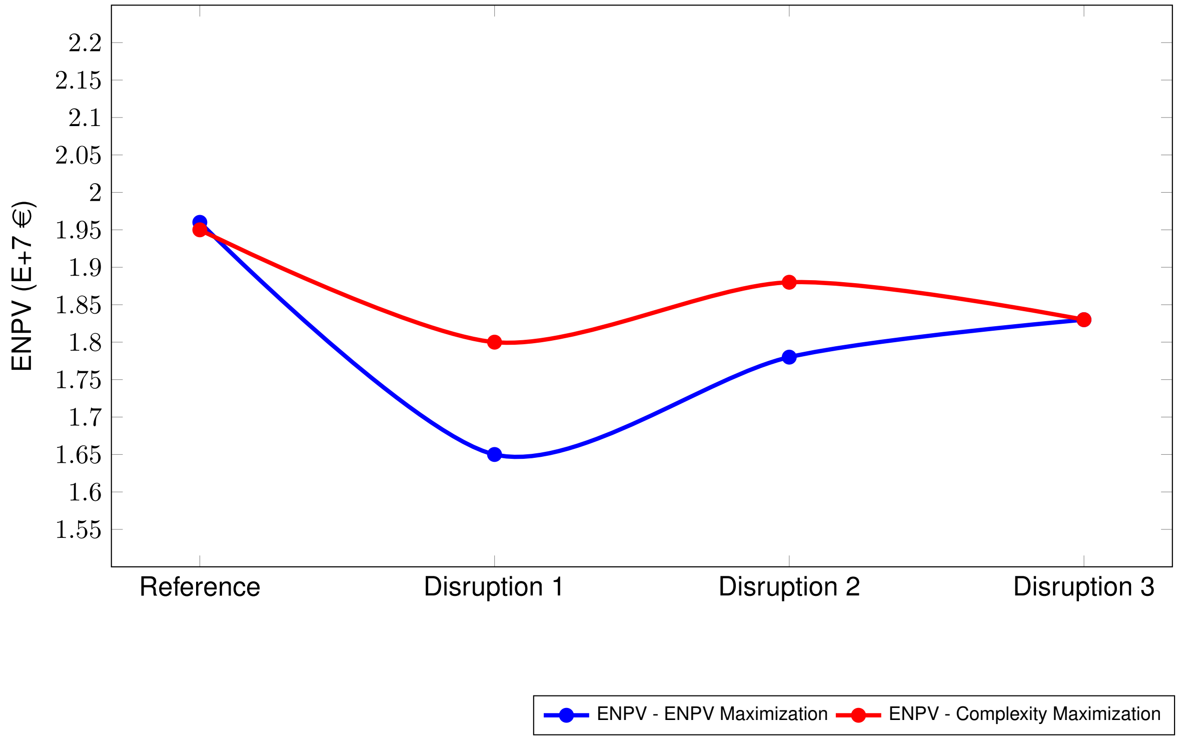

Figure 3.3: Comparison between reference and max complexity models - Expected Net Present Value (Case A)

comparing to the results from maximizing ENPV, see Table 3.3. However, when disruptions do occur the more complex configuration returns better performance, than the previous configuration under the same circumstances.

Table 3.2: Case A - ENPV Maximization

Case A	Complexity	ENPV	FCI	Investment	Inventory	Purchases	Sales	ECSL
Reference	46	1.96E+07	7.61E+05	7.32E+05	1450.707	342670	50563000	85.7%
Disruption 1	46	1.65E+07	8.10E+05	7.81E+05	1084.072	356550	43821000	63.3%
Disruption 2	44	1.78E+07	1.06E+06	1.03E+06	1231.576	373537.712	47473000	72.1%
Disruption 3	44	1.83E+07	7.80E+05	7.52E+05	1278.613	313616.662	48435000	75.7%

Table 3.3: Case A - Complexity Maximization

Case A	Complexity	ENPV	FCI	Investment	Inventory	Purchases	Sales	ECSL
Reference	156	1.95E+07	8.30E+05	7.32E+05	1451.691	342800	50572000	85.8%
Disruption 1	156	1.80E+07	9.54E+05	8.56E+05	1305.564	316095.608	48831000	76.9%
Disruption 2	151	1.88E+07	9.56E+05	8.61E+05	1409.266	333077.386	50058000	83.1%
Disruption 3	154	1.83E+07	8.78E+05	7.81E+05	1392.458	328540	49883000	82.2%

Comparing both configurations (see figures 3.3 and 3.4), it is perceptible that, for this SC and for these disruptions, the interruption of production (Disruption 1) produces the bigger impact, both economically and on fulfilling customer demand.

The variation on ENPV between the different operational conditions, for the SC maximizing ENPV, is relevant and is enough reason to address better ways to cope with this kind of events. Facing Disruption 1 operation faces a loss of 15% in ENPV, Disruption 2 a loss of 9% and Disruption 3 a loss of 7%.

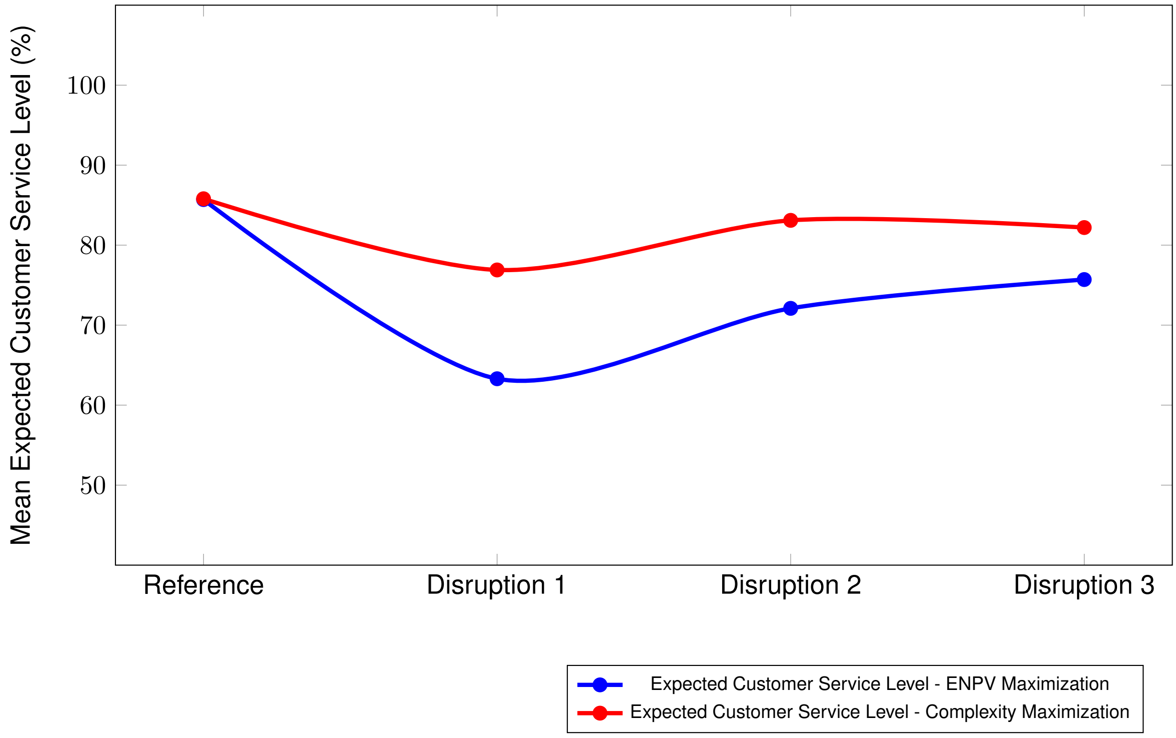

Figure 3.4: Comparison between reference and max complexity models - Customer Service Level (Case A)

One relevant analysis can be made regarding the delta of ENPV value between the two options, maximizing ENPV versus maximizing complexity. This metric represents economically the impact of the different decisions on the SC performance thus representing one important model applicability factor. So, the ENPV results from ENPV maximization, Plot, are always lower than the results from the more complex network, Plot. For Disruption 1, where the system reacts the worst, is where that gap is higher, becoming a candidate justification for investment regarding SCR concerns. The loss in ENPV by incrementing complexity (-0.01E7€) is easily compensated by the gains in disruption 1 and 2 (0.15E7€and 0.1E7€), representing gains of 9% and 5% respectively.

When considering mean ECSL, Figure 3.4, an improvement is perceptible amplified in case of disruption events. This element might be important to consider when, for instance, disruption 2 and 3 where for a similar value of ENPV the more complex network provides a higher value of ECSL. The disruptive scenarios cause severe impacts on service level with reductions of 26%, 16% and 12% for disruptions 1, 2 and 3 respectively. Adopting a more complex network provides significant increases in ECSL for the different disruptive events: 21%, 15% and 9% for disruptions 1, 2 and 3 respectively.

3.4.2 Case B

Case B represents a SC structure where reverse flows are allowed between consecutive echelons adding complexity to the operation, Figure 3.5.

It is expected an increase in flow complexity in order to cope with such requirement. When maximizing ENPV disruptions cause negative impacts in the several performance metrics, see Table 3.4. Similar to Case A there is an improved performance regarding ECSL and also, in most cases, in

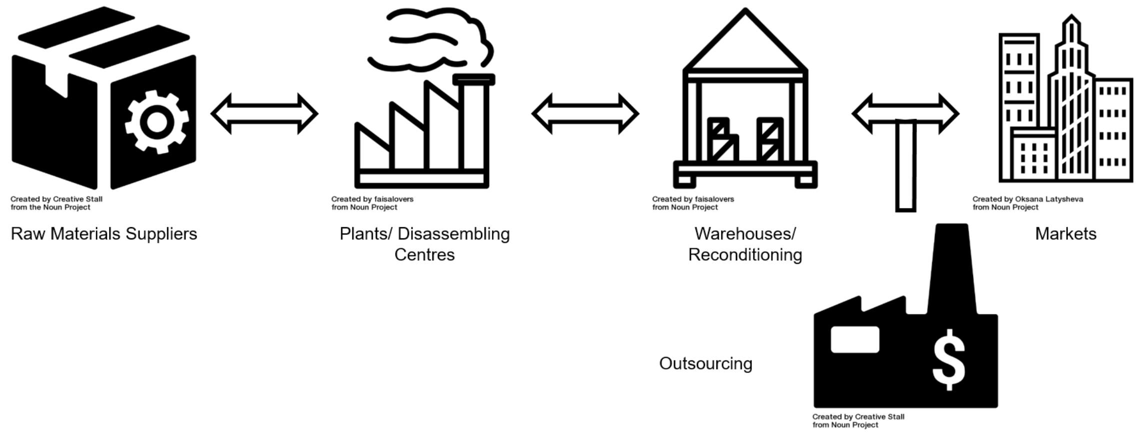

Figure 3.5: Schematic configuration of flows allowed in Case B

ENPV, see Table 3.5.

Table 3.4: Case B - ENPV Maximization

Case B	Complexity	ENPV	FCI	Investment	Inventory	Purchases	Sales	ECSL
Reference	89	1.91E+07	7.65E+05	7.20E+05	1449.68	334490	50548000	85.6%
Disruption 1	84	1.64E+07	7.99E+05	7.56E+05	1091.136	346070	44301000	63.8%
Disruption 2	87	1.77E+07	1.04E+06	9.92E+05	1229.269	302462.827	47672000	72.0%
Disruption 3	87	1.79E+07	7.89E+05	7.45E+05	1301.026	304995.435	48744000	77.0%

With the reference network configuration, disruptions cause a decrease on ENPV of 14%, 7% and 6% for disruptions 1, 2 and 3 respectively.

Table 3.5: Case B - Complexity Maximization

Case B	Complexity	ENPV	FCI	Investment	Inventory	Purchases	Sales	ECSL
Reference	346	1.89E+07	9.01E+05	7.19E+05	1451.139	334770	50564000	85.7%
Disruption 1	343	1.75E+07	1.01E+06	8.30E+05	1320.152	310323.917	49012000	76.9%
Disruption 2	341	1.83E+07	1.03E+06	8.47E+05	1409.159	324379.133	50053000	83.1%
Disruption 3	344	1.78E+07	9.41E+05	7.61E+05	1390.301	320275.72	49855000	82.1%

Comparing the several model runs, for the different SC configurations and for the different disruptive events, Disruption 1 produces the most negative impact, similarly with Case A. When no disruption is present a variation of -0.03E7€ in ENPV is expected, when the SC shifts to a more complex network the ENPV variation in Disruptions 1 and 2 are positive, 7% and 3% respectively, compared with the reference configuration. This gain is more than the double of the cost if no disruption is present, see Figure 3.6.

If the difference in ECSL is small when no disruption is present, the same does not happen in the case of a disruption happening. Again, the more complex structure allows for a better performance in responding to customer demand, Figure 3.7, even if that entails an increase in costs as is the case of disruption 3. If the SC does not acquire a more complex configuration, disruptions cause a decrease of service level of 26%, 16% and 10% for disruptions 1, 2 and 3 respectively. In a more complex configuration the SC can have that performance improved by 21%, 15% and 7% for disruptions 1, 2 and 3 respectively.

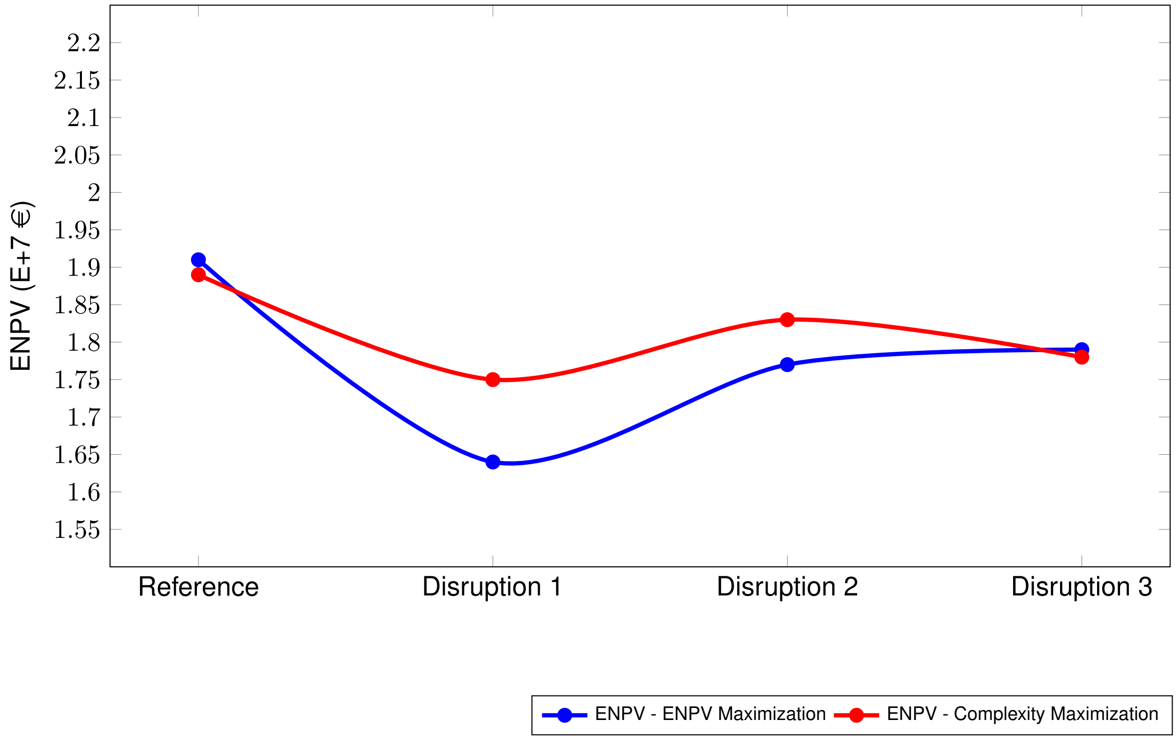

Figure 3.6: Comparison between reference and max complexity models - Net Present Value (Case B)

3.4.3 Case C

Case C introduces a different kind of flexibility to the network, it allows the same flows as Case B and also allows for plants and markets to exchange products without any warehouse intervention, Figure 3.8 .

In this configuration, the results become somehow distinct to Case A and B. For instance, results are different from previous runs in the sense that there is not the same trend, being Disruption 2 the one that causes a bigger impact, instead of Disruption 1, see Tables 3.6 and 3.7. However, this configuration still provides better results than SC configurations from Cases A and B. The increased susceptibility to Disruption 2 in Case C, is much related with the non existence of transhipment between entities in the same echelon. The failure in supply and not having the possibility to allow transhipment, turns the consequence inevitable since it does not allow for other entities to compensate the lack of goods which will eventually impact ECSL and ENPV.

Table 3.6: Case C - ENPV Maximization

Case C	Complexity	ENPV	FCI	Investment	Inventory	Purchases	Sales	ECSL
Reference	110	2.05E+07	8.45E+05	7.90E+05	913.478	380870	52937000	99.4%
Disruption 1	109	1.66E+07	9.58E+05	9.03E+05	791.844	377550	45538000	83.4%
Disruption 2	108	1.45E+07	9.84E+05	9.30E+05	720.256	374369	40396400	71.8%
Disruption 3	108	1.84E+07	9.31E+05	8.77E+05	885.054	457070	51674000	98.4%

ENPV results leave the reference configuration in disruption 2 as the lower expected value for the different disruptive events. The leaner SC has a decrease in ENPV of 19%, 30% and 10% for disruptions 1, 2 and 3 respectively. The more complex network still provides higher ENPV when a

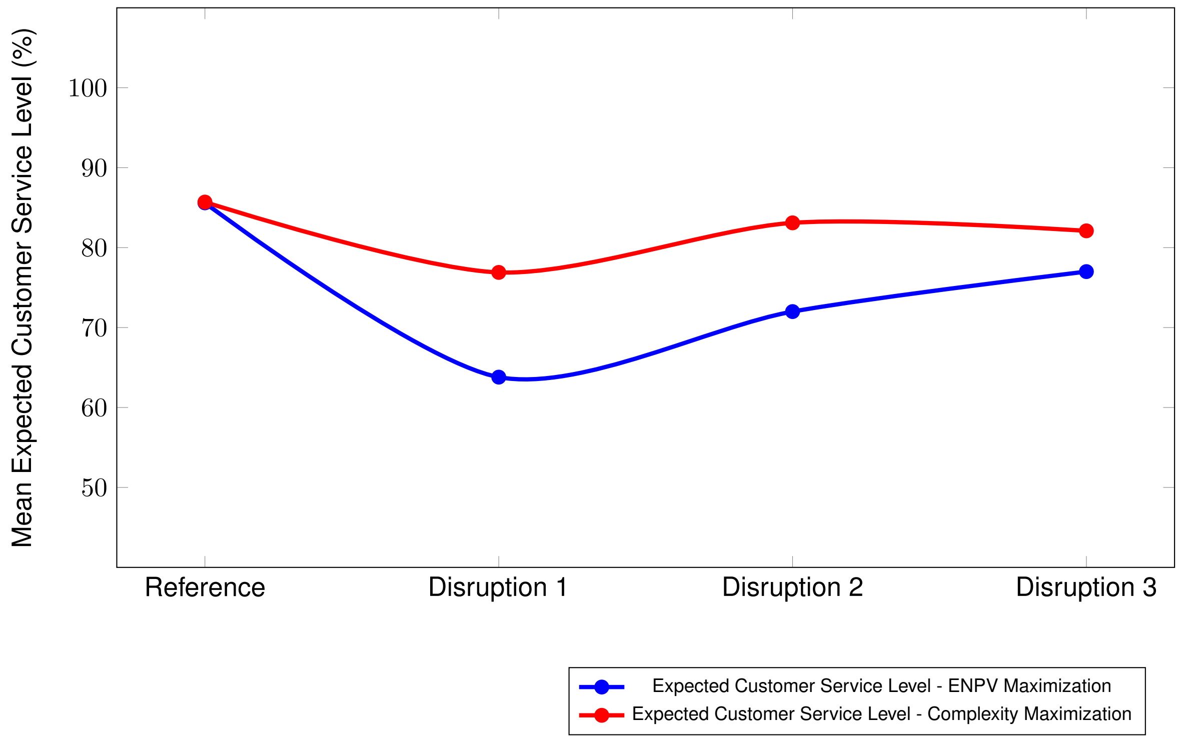

Figure 3.7: Comparison between reference and max complexity models - Expected Customer Service Level (Case B)

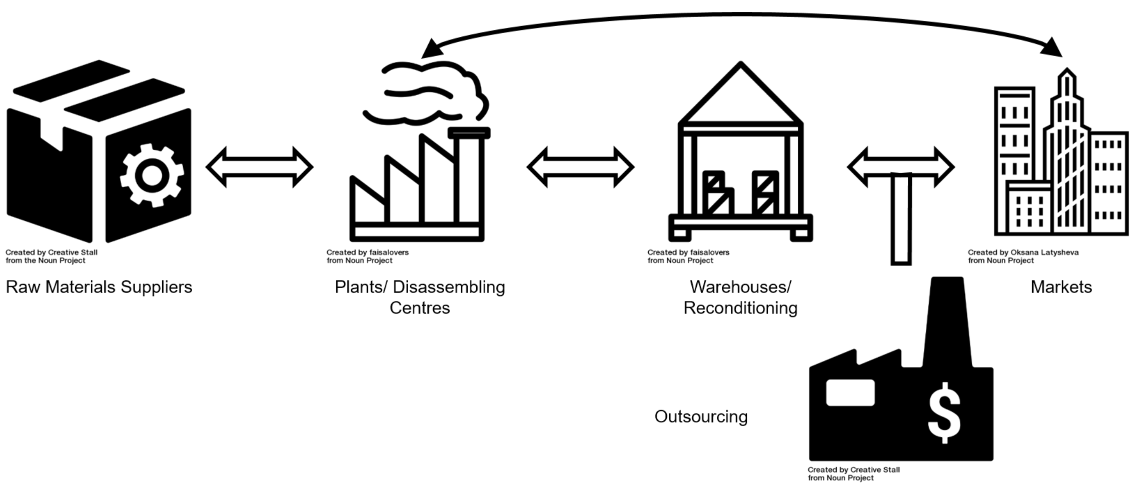

Figure 3.8: Schematic configuration of flows allowed in Case C

Table 3.7: Case C - Complexity Maximization

Case C	Complexity	ENPV	FCI	Investment	Inventory	Purchases	Sales	ECSL
Reference	495	2.03E+07	1.05E+06	7.90E+05	914.547	381050	52933000	99.4%
Disruption 1	495	1.89E+07	1.22E+06	9.59E+05	915.528	364530	52193000	95.1%
Disruption 2	491	1.83E+07	1.29E+06	1.03E+06	918.789	345240	51382000	90.1%
Disruption 3	493	1.94E+07	1.09E+06	8.29E+05	914.66	378400	52886000	98.9%

disruption does occur, improving the performance in 14%, 27% and 5% for disruptions 1, 2 and 3 respectively. The absolute difference between ENPV performance of the two network options, for Disruptions 1 and 2, is greater than the loss in ENPV if no disruption occur.

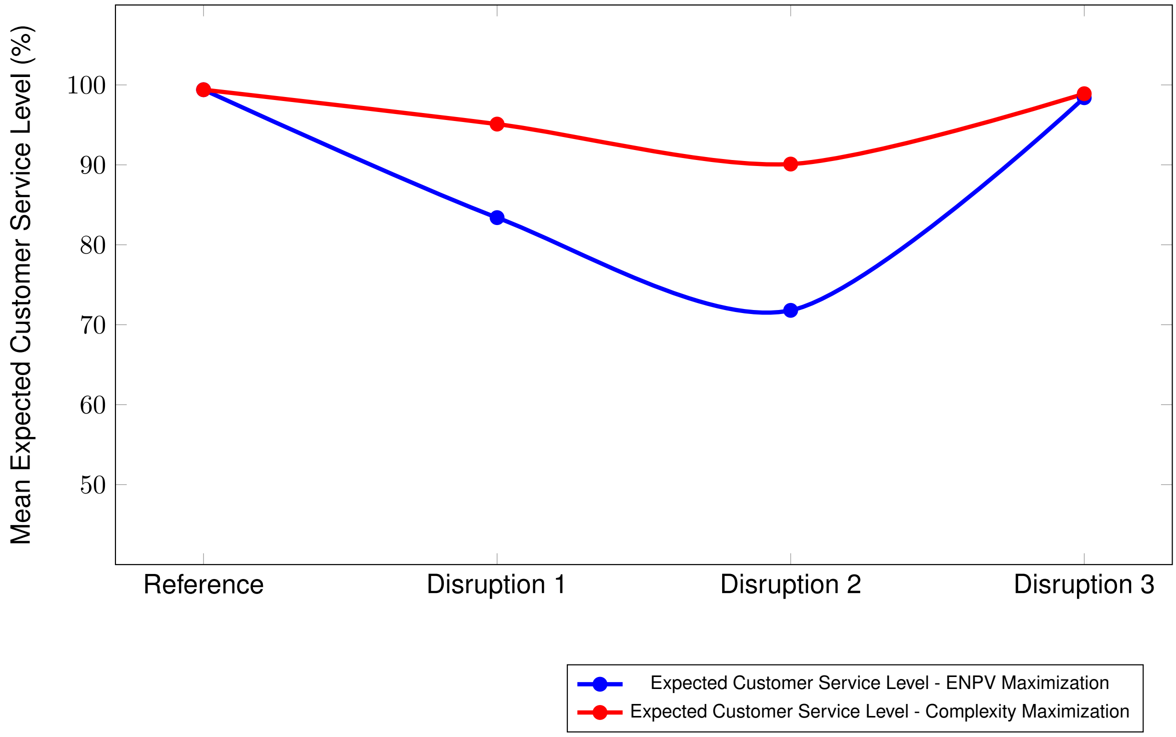

Figure 3.9: Comparison between reference and max complexity models - Expected Customer Service Level (Case C)

Disruption 3 seems to cause small impact on results from both design configurations, much due to the fact that plant 3, the one affected by the disruption, has always an available flow to the warehouse that work smoothly. There is an interesting result concerning that FCI is higher for the complex configuration and investment reaches higher amounts in the leaner design. The reason for that might be that the complex network relies on providing itself the transportation of goods, whereas the leaner has to purchase more goods to third parties to fulfil the demand.

Allowing a more complex network creates a more agile network in meeting customer demand, Figure 3.9. While the leaner SC leads to a decrease in ECSL (16%, 28% and 1% for disruptions 1, 2 and 3 respectively), a more complex network can help mitigating that effects by improving such results by 14%, 25% and 1% for disruptions 1, 2 and 3 respectively.

3.4.4 Case D

Case D allows forward and reverse flows between consecutive echelons and adds a new set of possibilities by allowing transhipment at plants, disassembling centres and warehouses, Figure 3.10.

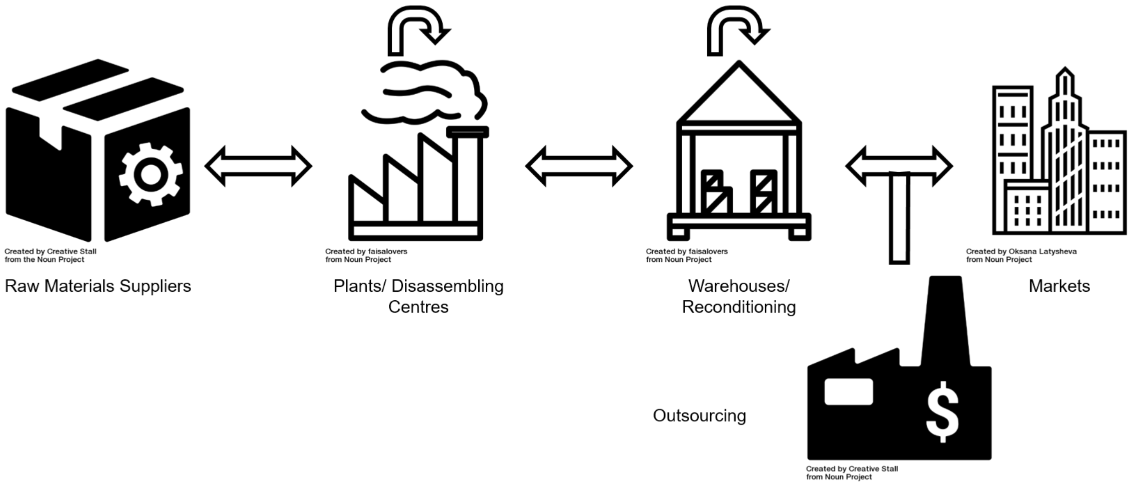

Figure 3.10: Schematic configuration of flows allowed in Case D

With this configuration, the results are similar to Cases A and B, the more complex SC allowing a higher ENPV and better ECSL when a disruption occur, except for Disruption 3 where there is a small decrease of ENPV, see Tables 3.8 and 3.9. Disruption 1 is, again, the event that causes the most stress to the operation and its objectives.

Applying the reference configuration, disruptions cause a ENPV decrease of 19%, 7% and 6% for disruptions 1, 2 and 3 respectively. These results can be improved by 13% and 3% for disruptions 1 and 2 respectively, if a more complex network is deployed.

Table 3.8: Case D - ENPV Maximization

Case D	Complexity	ENPV	FCI	Investment	Inventory	Purchases	Sales	ECSL
Reference	90	1.91E+07	7.65E+05	7.20E+05	1452.711	334880	50586000	85.8%
Disruption 1	83	1.55E+07	8.28E+05	7.86E+05	1123.564	266442.058	42559300	65.5%
Disruption 2	89	1.77E+07	1.04E+06	9.95E+05	1227.958	302704.653	47651000	72.0%
Disruption 3	88	1.79E+07	7.88E+05	7.44E+05	1301.334	304860.924	48747000	77.0%

Table 3.9: Case D - Complexity Maximization

Case D	Complexity	ENPV	FCI	Investment	Inventory	Purchases	Sales	ECSL
Reference	376	1.89E+07	9.21E+05	7.20E+05	1456.127	335370	50607000	85.9%
Disruption 1	373	1.75E+07	1.03E+06	8.28E+05	1355.382	314110.778	49432000	79.9%
Disruption 2	372	1.82E+07	1.07E+06	8.75E+05	1381.246	316696.483	49723000	81.5%
Disruption 3	374	1.78E+07	9.59E+05	7.59E+05	1391.087	319616.258	49853000	82.1%

ECSL is also hit by the disruptive events imposed to the SC operation. While the leaner configuration leads to a decrease of 24%, 16% and 10% for disruptions 1, 2 and 3 respectively, the more complex network allows for a steady service level of around 80%, improving the alternative configuration by 22%, 13% and 7% for disruptions 1, 2 and 3 respectively.

3.4.5 Case E

The last case in our study represents a network that includes the possibilities from previous cases. This closed-loop SC can perform transhipment at all levels, except for markets, and flows bypassing intermediate entities are also allowed, Figure 3.11.

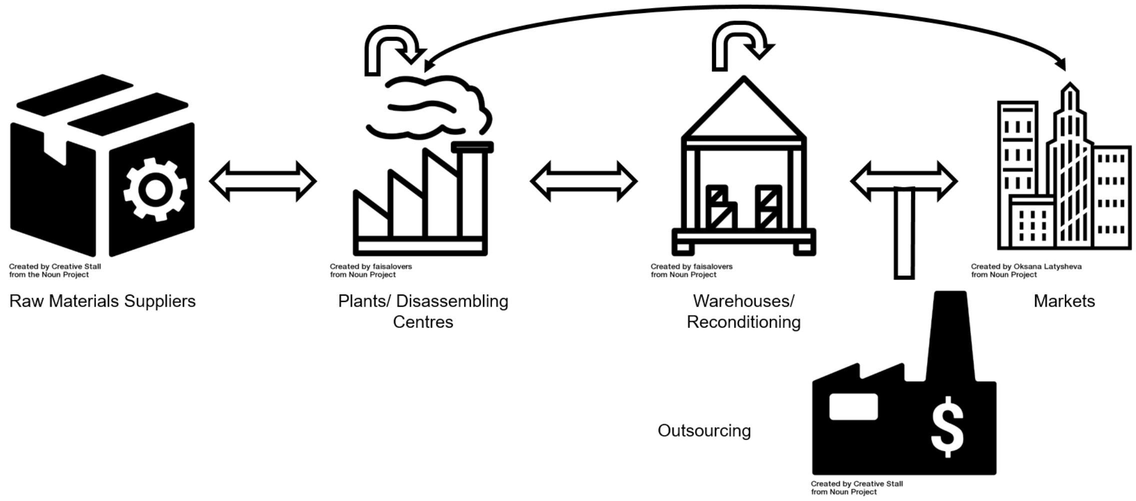

Figure 3.11: Schematic configuration of flows allowed in Case E

From the results, Tables 3.10 and 3.11, it is perceptible that for both network configurations ENPV and complexity are impacted in different magnitudes for the different disruptions. Disruption 1 is the event that influences ENPV the most, whereas Disruption 2 is the scenario that affects ECSL with an increased impact.

If in other cases disruption 3, presented as a case where a trade-off between ENPV and ECSL had to be made, in this case the max complexity network provides better results in both ENPV and ECSL.

Table 3.10: Case E - ENPV Maximization

Case E	Complexity	ENPV	FCI	Investment	Inventory	Purchases	Sales	ECSL
Reference	106	2,05E+07	8,46E+05	7,91E+05	913,478	380670	52940000	96,4%
Disruption 1	102	1,64E+07	9,68E+05	9,14E+05	796,152	379080	45463000	83,7%
Disruption 2	104	1,65E+07	1,00E+06	9,47E+05	805,425	348862,167	44065000	77,8%
Disruption 3	104	1,84E+07	9,31E+05	8,77E+05	885,033	4,55E+05	51674000	98,4%

For the network with fewer flows allowed, the ENPV variations between steady-state operation and disruptive scenarios are discernible, resulting in a decrease of 20%, 20% and 10% for disruptions 1, 2 and 3 respectively. On the other hand, applying the more complex network the results of ENPV during the disruptive events are improved by 15%, 16% and 5% for disruptions 1, 2 and 3 respectively.

It is also perceptible some characteristics that distinguish this case with the previous ones. With the maximization of complexity, the SC can return ECSL higher than 90% in all scenarios, even when a disruption does occur. When a leaner network is implemented disruptive scenarios cause a decrease in service level of 13% and 19% for disruptions 1 and 2 respectively. Applying the network with a higher amount of permitted flows leads to an improvement of 14%, 19% and 1% for disruptions 1, 2

Table 3.11: Case E - Complexity Maximization

Case E	Complexity	ENPV	FCI	Investment	Inventory	Purchases	Sales	ECSL
Reference	525	2,03E+07	1,07E+06	7,89E+05	915,493	380820	52933000	99,4%
Disruption 1	516	1,89E+07	1,23E+06	9,51E+05	916,495	365270	52210000	95,2%
Disruption 2	520	1,92E+07	1,25E+06	9,80E+05	975,706	354997,874	51803000	92,8%
Disruption 3	523	1,94E+07	1,10E+06	8,26E+05	915,648	377860	52886000	99,0%

Table 3.12: Absolute variations between ENPV from reference and maximized complexity configurations

	△ No disruption	**Mean △ Disruptions**
Case A	-9.20E+04 €	8.11E+05€
Case B	-1.48E+05 €	5.50E+05 €
Case C	-2.12E+05 €	2.39E+06 €
Case D	-1.66E+05 €	8.32E+05 €
Case E	-2.30E+05 €	2.05E+06 €

and 3 respectively.

3.5 Discussion - Flow complexity on SC Resilience

After running the model for five types of SC design, considering forward and closed-loop SC, the presence of uncertainty in the demand and the cases with and without disruptions, it is possible to address the question at hand: Does network complexity allows for better resilience?

From the above study, it can be concluded that the obtained results vary not only with the SC complexity but also with its base structures (e.g. forward or closed-loop) as well with the different type of disruptions. Different disruptions cause different results and so decision makers should have enough information to make the most acceptable decision considering model results and available information. It is in this line that, studying SCR factors gain importance, as it allows the development of better models thus better aid in decision making.

The model developed was run on a 15 year period with demand uncertainty, allowing to be robust in aiding strategic decision, as is the case of defining a SC network design. The vast majority of results provide benefits, in ENPV and ECSL.

Considering the behaviour on ENPV caused by the increased complexity, when no disruption occurs, it is expected to show some kind of increase in costs, due to the obligations that come from opening and maintaining more facilities and flows. Such impact is noticeable in Table 3.12 (△ No disruption), where it can be seen that a more complex SC implies lower values of excepted NPV (negative values). However, if disruptions occur, there is an evident benefit of operating a more complex SC. The difference in ENPV return, in disruptive scenarios between the more complex and a leaner SC is always positive, Table 3.12 (Mean △ Disruptions), providing better return than not investing in preventive configuration.

Also, there is a more evident benefit, from deploying a more complex SC, in terms of ECSL. An

Table 3.13: Percentage variation of Expected ENPV and ECSL between the reference and maximized complexity configuration

Disruption 1	ENPV	ECSL	Disruption 2	ENPV	ECSL	Disruption 3	ENPV	ECSL
Case A	9%	21%	Case A	5%	15%	Case A	0%	9%
Case B	7%	21%	Case B	3%	15%	Case B	0%	7%
Case C	14%	14%	Case C	27%	25%	Case C	5%	1%
Case D	13%	22%	Case D	3%	13%	Case D	0%	7%
Case E	15%	14%	Case E	16%	19%	Case E	5%	1%

improvement, percentually, higher than that obtained in ENPV, Table 3.13. The notable shift is made possible by the increase flexibility and redundancy allowed by the higher amount of entities and flows involved.

The investment made in increasing complexity is completely overcome by the resilience created in the supply chain structures as they are able to better react to disruptions guaranteeing higher service levels and higher profit values. However, this characteristic must be always met by a specific analysis of each SC and to its, perceptible, vulnerabilities.

Concluding in more detail for each disruption it can be said that:

Disruption 1, fail of production facilities, has transversally the greatest negative impact in operation's quality and consequently on economic return. It is also the disruption where the company can retrieve the most economical gains from applying a more complex network. This results characteristic might be from the lack of alternatives in the production side, with the SC not being able to present enough final products to its network causing a cascading effect.

In a supply disruption, Disruption 2, there is a steady increase of CSL but the results of ENPV depend on the type of SC involved. It is fundamental an increase in flexibility to cope with the lack of raw materials upstream, otherwise is where leaner SC can suffer the most, much due to the lack of alternative options downstream to manage the units available in the SC as a whole.

On the other side, a transportation failure, represented by Disruption 3, is the one that produces the smaller impact on performance levels. This disruption is based on the elimination of a particular set of flows between entities. Flows that can be essential, or not, to the SC. Therefore, this result must be interpreted concerning the particular flows that were disrupted. In this case having a SC with more flow options allowed for higher quantities of products to find alternative routes thus improving ECSL.

Comparing the behaviour of the different SC cases, Table 3.13, it is evident which have a better resilience performance, both in absolute values and in the advantage brought by maximizing complexity. Cases C and E, Figures 3.8 and 3.11, provide SC networks that are more flexible thus providing better ways of mitigating disruptions, results that can be further improved by maximizing the flow complexity, a conclusion in line with Cardoso et al. (2015) work.

As final analysis, it is relevant to compare these results with those from the original publication, aimed at maximizing ENPV for each SC structure and scenario. As expected, since it is not maximized for ENPV in every scenario, our results produce a network with lower ENPV but with a trade-off for better ECSL turned possible for the multiple possible flows. In the original publication, Disruption 3 caused results far from the reference scenario and in our result it was the opposite. The justification might come from the very nature of the imposed disruption, a limitation in flows, that is easily suppress by increased complexity and devastating if no other option exists.

As main conclusions, it can be said that investing in proactive resilient Supply Chain Design can reduce losses, generate value to companies and reduce the need for reactive strategies, in case of facing a disruptive event. With this work, we are also capable of attesting the positive correlation between the increased SC complexity with positive outcome in case of some disruptions, as suggested by Cardoso et al. (2015) in their study.

3.6 Resilience and Economic Objective Function

Most common objective functions rely on maximizing only one type of factors, usually financial or some kind of SC SC performance metric. Such approach restricts what is considered to be relevant to shape the model output. It also fails to incorporate the multitude of human decision, where rarely one can base a decision solely on a single element and most commonly a decision is made based on multiple elements.

From our literature review an extensive list of resilience metrics was presented and that work can now be put into practice with the objective of designing a new OF within our model. It is our objective to generate a new function that takes into consideration not only economic concerns but also SC performance.

In the previous section, the OF developed takes an economic element as the maximizing term leaving other concerns to be modulated via constraints. It presents it self as a robust formulation since it realistic represents ENPV return for the different scenarios. However, another element that should be considered into the objective function relies on the resilience quantification based on what was described by several authors Wang and Ip (2009); Dixit et al. (2016); Sokolov et al. (2016),as the need of meeting costumers demand, meaning guaranteeing customer service level.

Based on these two concerns a new approach on the original problem is to be presented, merging economic and resilience concerns into one OF.

3.6.1 New Objective Function

The new objective function, Equation 3.17, is the maximization of the summation of two factors.

$$Max \frac{\sum_s pb_s \times NPV_s}{NPVref} - \frac{\sum_s pb_s \left[\frac{\sum_{v\epsilon V_m} \sum_p ID_{pvst}}{\sum_{v\epsilon V_m} \sum_p D_{pvst}}\right]}{NT} \tag{3.17}$$

The first term, $\frac{\sum_s pb_s \times NPV_s}{NPVref}$, represents the economic concern by creating a variation rate between the new found solution and ENPV return from running the model with the original objective function, in the scenario without disruption. This element will vary, for any positive number, smaller than one if

ENPV values are smaller than the reference. However, it is not expected for this value to go above the unitary value since that would imply an increase in ENPV return when that metric is not the only one being maximized. Generically, this parcel is responsible for penalizing deviations to the best ENPV possible, with values closest to one as those that most positively impact SC performance.

The second term, $\frac{\sum_s pb_s \left[\frac{\sum_{v \epsilon V_m} \sum_p ID_{pvst}}{\sum_{v \epsilon V_m} \sum_p D_{pvst}}\right]}{NT}$, allows for the introduction of the concern of meeting Customer demand as a key decision factor when a strategic decision is to be made, regarding the definition a new SC network. This parcel varies from zero to one, as it represents the mean value for the fraction between the unsatisfied demand and total demand. Generically, this parcel is responsible for not letting the Customer service level drop in complete favour of economic return and will generate the most benefit to the OF as close to zero as possible.

The relationship between the two parcels implies that the model will value equally the increase of 1% in ENPV as the decrease of 1% in unsatisfied demand, implying that percentage variations are equally relevant to the decision at stake. It is expected that this characteristic will lead to an increase in Customer service level and an decrease of ENPV when compared with reference values.

3.6.2 Model Description

The model is based on the one described previously. Parameters and constrains remain similar and to accommodate the new objective function a new scalar has to be defined, regarding the reference value for ENPV.

For each type of SC (Case A to E - leading to Cases NA to NE), the same OF is to be used in all scenarios however, the network configuration will be fixed by that which come as a result of the model run when there is no disruption. Following this methodology it is possible to compare the obtained results with the ones from previous model runs, including those with different OF described before, and test its resilient behaviour.

3.6.3 Case NA

Table 3.14: Case NA - New objective function

Case NA	Complexity	ENPV	FCI	Investment	Inventory	Purchases	Sales	ECSL	Obj. Function
Reference	49	1.91E+07	8.39E+05	8.08E+05	1688.807	395200	52868000	100.0%	0.976
Disruption 1	49	1.47E+07	9.46E+05	9.15E+05	1458.818	1015990	50039000	85.6%	0.608
Disruption 2	47	8.30E+06	8.90E+06	8.87E+06	2229.688	1172260	50760000	89.2%	0.315
Disruption 3	47	1.64E+07	8.48E+05	8.18E+05	1560.005	871100	51675000	92.3%	0.762

The results to Case NA, Table 3.14, are substantially different to those from the model using only the economic term as maximizing term, see Table 3.2. OF values are lower for Disruption 2, where ENPV is the lowest of all disruptions. In the eventuality of no disruption occurring OF value stays close to 1, revealing the similarity between the Reference case and the new SC network configuration, providing a slightly smaller return in ENPV but mean ECSL moves to 100%.

From Table 3.14 it can be seen that between disruptions there are significant ENPV variations, with Disruption 3 returning the higher value and with the smallest percentual variation to the results from ENPV maximization, 10%. Other disruptions also negatively affect the ENPV, with reductions of 11% and 53% for Disruptions 1 and 2 respectively.

With this new OF there is a relevance being given to ECSL that did not exist in previous examples. This new element leads to significant improvement in service quality leading to an ECSL of above 85% for all disruption, a value better than that returned by the reference case, where the mean ECSL for Case A is 70.37% (See Table 3.2). Comparatively there are variations of 35%, 24% and 22% for Disruptions 1, 2 and 3 respectively (From Tables 3.2 and 3.14). This effort to meet customer demand comes from added complexity but also from an increased amount of purchases of final products from outsourcing, which allows for an increase in sales and consequently in ECSL.

3.6.4 Case NB

Table 3.15: Case NB - New objective function

Case NB	Complexity	ENPV	FCI	Investment	Inventory	Purchases	Sales	ECSL	Obj. Function
Reference	95	1.87E+07	8.53E+05	8.07E+05	1695.532	383610	53045000	100.0%	0.979
Disruption 1	94	1.39E+07	9.13E+05	8.67E+05	1554.218	950520	51169000	91.4%	0.641
Disruption 2	94	1.59E+07	1.09E+06	1.05E+06	1589.617	671200	51856000	93.6%	0.769
Disruption 3	93	1.69E+07	8.68E+05	8.23E+05	1642.735	530850	52543000	97.0%	0.853

In Case NB results, Table 3.15, the values for the OF are always higher to those from Case NA, meaning less deviation to the ENPV and an improvement in ECSL, from the reference case (see Table 3.4).

Due to the OF elements, ENPV values are expected to be lower than those from the reference configuration to all cases, a result perceptible in Table 3.15, with Disruption 1 returning the lowest value and Disruption 3 the higher for the new SC network configuration. These decreases in value represent a variation of -15%, -10% and -6% for Disruptions 1, 2 and 3 respectively when compared to the reference results (see Tables 3.15 and 3.15).

On the other hand, there is a significant increase in the SC responsiveness, with ECSL being always above 90%, even during disruptions, representing values higher than those provided by the original model when no disruption was present. Comparatively it produces better results than the reference configuration by 43%, 30% and 26% for Disruptions 1, 2 and 3 respectively.

3.6.5 Case NC

Table 3.16: Case NC - New objective function

Case NC	Complexity	ENPV	FCI	Investment	Inventory	Purchases	Sales	ECSL	Obj. Function
Reference	103	2.05E+07	8.59E+05	8.05E+05	913.377	383260	53045000	100.0%	1.074
Disruption 1	102	1.63E+07	1.02E+06	9.69E+05	949.88	773300	51244000	94.0%	0.795
Disruption 2	101	1.04E+07	4.58E+06	4.52E+06	1041.83	983980	48807000	87.4%	0.418
Disruption 3	101	1.87E+07	9.58E+05	9.04E+05	912.987	502350	49245000	100.0%	0.98

In Case NC, Table 3.16, there is an interesting result when no disruption occur, the new OF reaches an value above one, which means that for a small decrease in NPV the responsiveness of the SC can be improved to levels that almost reach the plenitude of meting customer demand.

Disruption 2 is the event that gave an higher impact on the SC operation, even comparatively with the reference results Disruption 2 stands out with a higher impact on ENPV, with variations of -1%, -28% and 2% for Disruptions 1, 2 and 3 respectively (see Tables 3.6 and 3.16). This means that, for Disruption 3, this new OF provided a network that guarantees a better economic return, interestingly with a lower value for complexity. This dissonant result is the consequence of imposing the same disruption to two different SC configurations, where one might be more susceptible to that particular disruption. However, the differences in complexity, from 108 in the reference Case C to 101 in Case NC and the gap of 5% associated to the model, are not enough to put into question the assertions made before.

ECSL is beneficed by the new SC network configuration providing higher levels of service, with variations of 13%, 22% and 2% for Disruptions 1, 2 and 3 respectively (see Tables 3.6 and 3.16). With this, Disruption 2 is not only the event that cause the most damage but also the one that provides the higher percentual increase in service quality. The improvement in ECSL is much due to the increase in investment but also due to the increment in purchase activity from outsourcing to meet the demand.

3.6.6 Case ND

Table 3.17: Case ND - New objective function

Case ND	Complexity	ENPV	FCI	Investment	Inventory	Purchases	Sales	ECSL	Obj. Function
Reference	99	1.87E+07	8.53E+05	8.04E+05	1694.754	382910	53045000	100.0%	0.98
Disruption 1	91	1.33E+07	8.95E+05	8.49E+05	1479.319	717760	46344000	86.6%	0.564
Disruption 2	97	9.30E+06	9.03E+06	8.98E+06	1582.006	693940	51227000	91.3%	0.4
Disruption 3	97	1.62E+07	9.25E+05	8.77E+05	1665.886	666800	52755000	98.4%	0.834

Results in Case ND, Table 3.17, when no disruption occur the results, between the reference configuration and the new SC network, a small decrease in ENPV is perceptible with an increase in ECSL to total demand fulfilment.

Concerning the present OF, Disruption 2 returns the lowest value. This result is due to the high decrease of ENPV, representing a negative variation of nearly 50%, which is not compensated by the increase in ECSL. The other disruptions also lead to lower economical returns however, with smaller proportions representing -14%, -47% and -9% for Disruptions 1, 2 and 3 respectively (see Tables 3.8 and 3.17).

In line with other cases, ECSL is higher in this model with costumer demand being met nearly 90% of the times of all the disruptions represented. This represents an improvement from the reference case of 32%, 27% and 28% for Disruptions 1, 2 and 3 respectively (see Tables 3.8 and 3.17).

3.6.7 Case NE

For this case, when no disruption is present, the OF value is higher than one, which means a SC network very similar to that present in the reference case, with parameters values related between the two situations, with the added benefit of the new OF providing a maximum value for ECSL.

Disruption 2 is the event that causes the lowest value in the OF, it also returns an ENPV significantly lower than the one provided by the reference case. On the contrary, Disruption 3 is able

Table 3.18: Case NE - New objective function

Case NE	Complexity	ENPV	FCI	Investment	Inventory	Purchases	Sales	ECSL	Obj. Function
Reference	110	2.05E+07	8.61E+05	8.05E+05	913.966	383440	53045000	100.0%	1.001
Disruption 1	107	1.61E+07	1.02E+06	9.66E+05	945.353	642790	49620000	93.7%	0.722
Disruption 2	108	5.09E+06	1.36E+07	1.35E+07	1138.429	777240	50559000	92.3%	0.171
Disruption 3	108	1.90E+07	9.61E+05	9.06E+05	913.887	447640	53045000	100.0%	0.927

to provide a solution that improves the result from the reference case, although only slightly. While Disruptions 1 and 3 provide a limited impact on ENPV, -2% and 3% respectively, Disruption 2 causes a variation of -69% if compared with the reference case (see Tables 3.10 and 3.18).

Although the new SC network provides better ECSL, with all disruptive events reaching values above 92%, it is the case where the percentual variation between new and reference OF is smaller, with 12%, 19% and 2% for Disruptions 1, 2 and 3 respectively (see Tables 3.10 and 3.18).

3.7 Discussion - New Objective Function

The new OF appears as an effort to meet the challenge of generating a quantitative model that better encapsulates the strategic decisions to be made, regarding SC network, in a uncertainty environment and with the concerns brought by SCR. In this process, two parcels are defined; one regarding the economic return and penalizing negative deviations to the result in optimal condition and the other a parcel that is responsible for penalizing increased amounts of unsatisfied demand. With this process the responsiveness of the SC is considered and consequently improved, if compared towards the reference results.

Considering that during the decision making process, there should be pursued a trade-off between the gains in ECSL and losses in ENPV a balance achieved in this trade-off procedure ensures a better fit between the model results and the challenges created by a real scenario decision. Failure in this process would lead to solutions that might not be acceptable for companies, due to low economic results (as the case of maximizing complexity) or low service quality.

From the obtained results one can conclude that it is possible to improve normal and under disruption operations with an acceptable amount of money, valuing the trade-off that lead to an increase in the SC responsiveness and consequently in the quality of service provided to customers.

However it is important to relate these results with this case study and with these disruptions. While some general conclusions can be drawn there are some results that come from the particular nature of the combinations between SC network, case study and disruption.

As expected, the main improvement is seen on ECSL, with an orientation to the SC responsiveness that leads to better ECSL in all conditions generated, with or without disruptive events, Table 3.19.

It is also evident that Disruption 2 causes the biggest impact on ENPV, for all the Cases considered. The disruption, a lack of supplies, is compensated based on the objective function, where a high importance is given to high ECSL the system has to adjust in accordance by incrementing the purchase of final products from outsourcing in order to meet the gap left bt the disruptive event.

Table 3.19: Percentage variation of Expected ENPV and ECSL between the reference and the new objective function configuration

No Disruption	ENPV	ECSL	Disruption 1	ENPV	ECSL	Disruption 2	ENPV	ECSL	Disruption 3	ENPV	ECSL
Case NA	-2%	17%	Case NA	-11%	35%	Case NA	-53%	24%	Case NA	-10%	22%
Case NB	-2%	17%	Case NB	-15%	43%	Case NB	-10%	30%	Case NB	-6%	26%
Case NC	0%	1%	Case NC	-1%	13%	Case NC	-28%	22%	Case NC	2%	2%
Case ND	-2%	17%	Case ND	-14%	32%	Case ND	-47%	27%	Case ND	-9%	28%
Case NE	0%	4%	Case NE	-2%	12%	Case NE	-69%	19%	Case NE	3%	2%

Table 3.20: Mean Objective Function Values for Cases NA to NE

	Mean Objective Function Value
Case NA	0.665
Case NB	0.811
Case NC	0.817
Case ND	0.695
Case NE	0.705

Disruption 3 is the event that causes the less amount of variation regarding ENPV, even in two cases it is possible to combine the increase of economic return with a better performance. In case NC it is even possible to meat that objective with a SC with a lower flow complexity, a result due to the unique characteristics of the SC and the particular disruption. However, an example that leaves space for more work regarding the elements of SCR.

With this new OF it is also created a new resilience metric, from the combination of the two factors (economic and operational). This resilience metric allows for a comparison between the several possible cases and infer on what are the cases that are more resilient.

From the mean value of the OF, Table 3.20, it is possible to infer that the SC with the lower resilience value is also the simpler one, Case NA - Figure 3.1, closely followed by Case ND, Figure 3.10, that in the pursuit of improving SC responsiveness reaches higher levels of ECSL with a greater reduction of ENPV, which penalizing the overall OF value.

Better performances are achieved by Cases NB and NC, Figures 3.5 and 3.8, with very similar results with the latter reaching a higher value. Case NB provides a network that leads to a significant increase in ECSL, many times with significant drops in economic return. Case NC, allowing direct flows between plants and markets adding flexibility to the network on the demand side thus increasing ECSL with little impact, or improving ENPV. Exception being made with Disruption 2, an event that disrupts the supply side of the SC, but still with an increase in ECSL.

4

Conclusions and Future Work

Conclusions and Future Work

The work here presented was developed along two main research lines along Resilience in Supply Chains: first a systematic literature review on supply chain resilience SCR was performed with the focus of analysing the development of quantitative methods to support such decisions; secondly a MILP model was developed to analyse the influence of SC flow complexity on SCR, and how the simultaneously consideration of economic return and customer service level could affect SCR. The work developed allowed to retrieve some conclusions and provide directions for future work.

From the developed work, it can be concluded that SCR is a concept that still needs a consolidation on its definition as there is an evident diversity in the definitions present and used. This issue leads to the dispersion on what is resilience and how should be dealt with, where fundamental concerns regarding its quantification exist. As a newer branch of SC, SCR concerns will only gain by taking advantage of work already done in other fields, such as SCRM and SCV, and through the creation of SC quantitative models that will support the associated decision making process. In such models the objective function has to be representative of the decision maker perspective. However, aligning the mathematical and practical objectives in a functional and useful way is a challenge. In SCR context there must be identified not only the decision maker preferences but also all the SC characteristics, including its operation, costs, revenues, risks and future directions.

The increment in the SC responsiveness can be one key element for decision. The work developed shows that investing in a proactive resilient Supply Chain Design can reduce losses, generate value to companies and reduce the need for reactive strategies, in case of facing a disruptive event. It is also possible to attest the positive correlation between the increased SC complexity with positive outcome in case of some disruptions, SC with increased flexibility in managing flows between all echelons lead the SC to acquiring more resilient behaviour (Cases C and E), as suggested by Cardoso et al. (2015) in their study.

Additionally, is important to note that a SCR analysis has to be a customized work for each SC, due to the direct impact of disruptions dependent on the type of SC operation and network. In the proposed new OF, the most resilience SC is also the one provided in Case NC with added flow flexibility between echelons. This consequence, brought to light in the results, makes the quality of information a key factor for success.

The work already done leaves research gaps that still must be addressed in order to better understand SCR its consequences and relevant parameters. Future work can provide useful and relevant advances to SC field of study in several lines of study:

- The model used in this work did not take into consideration any negative aspects of low responsiveness leading to the failure of fulfilling demand and consequently to the original results with low ECSL. This issue was tackled by the new proposed OF, with the introduction of an operational performance parcel leading to a Resilience Metric. However, there is still the need to better represent the impact of lost orders both economically and to the company's awareness by customers.
- The relationship between SC Flow Complexity, ENPV and ECSL is one of relevant interest and still has space for more study, for instance establishing the boundaries where incrementing Flow Complexity or ECSL lead to an increase of ENPV.
- In OF with several elements there is an evident need for defining weight that represent faithfully the objective of companies, crucial to representative and acceptable model results.
- Prospection of more recent OR methods, taking advantage of more recent work done in other fields of Science. For instance an effort to establish a relationship between the work done in Computer Science and this kind of SC optimization problems.

As final note, is important to mention that the current work lead to the submission of a paper to an International Indexed Journal that is now with minor revisions.

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A

Article Collection Database

Article Identification								Type of Supply Chain		Decision Level			Paper Aproach			
Nr	Year	Author	Title	Journal	University Corre	Nº de Citações	Search Term	FSC	CLSC	Strategic	Tactical	Operational	Case Study	Qualitative	Quantitative	Resilience Strategies
1	2009	Wang, Dingwei a	Evaluation and a	IEEE Systems Jo	China	15	2	1	0	1	1	0	1	0	1	1
2	2010	Colicchia, Claudi	Increasing suppl	Production plan	Italy	33	1	1	0	0	1	1	1	0	1	1
3	2011	Zhao, Kang and	Analyzing the re	IEEE Systems Jo	USA	32	1	1	0	1	0	0	1	0	1	1
4	2012	Saghafian, Sorou	The value of flex	IIE Transactions	USA	9	1	1	0	1	0	0	0	0	1	1
5	2012	Schmitt, Amand	A quantitative a	International Jo	USA	32	1	1	0	1	1	0	1	0	1	1
6	2012	Carvalho, Helen	Supply chain rec	Computers \& In	Portugal	44	1	1	0	1	0	0	1	0	1	1
7	2012	Adenso-Diaz, Be	The impact of su	Supply Chain Ma	Spain	6	1	1	0	1	1	0	1	0	1	0
8	2013	Wieland, Andrea	The influence of	International Jo	Germany	25	1	1	0	1	1	0	0	1	1	0
9	2013	Boone, Christop	Implementation	Journal of Busin	USA	3	1	1	0	1	1	0	1	0	1	1
10	2013	Geng, Liang and	Research on self	Discrete Dynam	China	0	1	1	0	1	0	0	0	0	1	0
11	2013	Berle, {\O}yvind	Optimization, ris	Supply Chain Ma	Norway	1	3	1	0	1	1	0	0	0	1	0
12	2013	Wu, Teresa and	Supply chain risk	IEEE Transaction	USA	8	1	1	0	0	1	0	1	0	1	0
13	2013	Harrison, Terry	Supply chain dis	Transportation J	USA	1	1	1	0	1	1	0	1	0	1	1
14	2014	Azadeh, A and A	Modelling and in	International Jo	Iran	3	3	1	0	0	1	0	0	0	1	1
15	2014	Brandon-Jones,	A Contingent Re	Journal of Suppl	UK	18	1	1	0	1	0	0	0	1	1	0
16	2014	Soni, Umang an	Measuring supp	Computers \& In	India	9	1	1	0	1	0	0	1	1	1	1
17	2014	Mari, Sonia Irsh	Sustainable and	Sustainability	Republic of Kore	4	1	1	0	1	1	0	0	0	1	0
18	2014	Ehlen, Mark A a	Chemical supply	Computers \& C	USA	3	2	1	0	1	1	1	1	0	1	0
19	2015	Gualandris, Jury	Supply risk man	The Internationa	Ireland	0	2	1	0	1	1	0	0	0	1	0
20	2015	Munoz, Albert a	On the quantific	International jou	Australia	4	3	1	0	1	1	1	0	0	1	0
21	2015	Rajesh, R and Ra	Modeling enable	Computers \& In	India	3	1	1	0	1	1	1	1	1	1	1
22	2015	Rajesh, R and Ra	Selection of risk	International Jo	India	4	1	1	0	1	1	1	1	1	1	1
23	2015	Rajesh, R and Ra	Supplier selectio	Journal of Clean	India	16	1	1	0	1	1	0	1	1	1	1
24	2015	Chowdhury, Md	A multiple objec	Omega	Australia	1	1	1	0	1	1	0	1	0	1	1
25	2015	Sadghiani, N Sal	Retail supply ch	Transportation R	USA	4	1	1	0	1	1	0	0	0	1	0
26	2015	Cardoso, S{\'o}n	Resilience metri	Omega	Portugal	3	1	1	1	1	0	0	1	0	1	1
27	2016	Thekdi, Shital A	Supply Chain Vu	Risk Analysis	USA	1	1	1	0	0	1	0	0	0	1	1
28	2016	Dabhilkar, Mand	Supply-side resil	International Jo	Swedden	0	1	1	0	0	1	1	1	1	1	1
29	2016	Birkie, Seyoum E	Operational resi	Journal of Manu	Italy	0	1	1	0	1	1	1	1	0	1	0
30	2016	Hosseini, Seyedr	A Bayesian netw	International Jo	USA	0	2	1	0	1	1	1	0	0	1	0
31	2016	Han, Jihee and S	Evaluation mech	International Jo	Republic of Kore	1	2	0	0	1	0	1	0	0	1	0
32	2016	Sokolov, Boris a	Structural quant	International Jo	Russia	0	2	1	0	1	0	0	0	0	1	0
33	2016	Azevedo, Susana	LARG index: A b	Benchmarking: A	Portugal	0	1	1	0	1	1	1	1	0	1	0
34	2016	Fahimnia, Behna	Marrying supply	Transportation R	Australia	0	1	1	0	1	1	0	1	0	1	0
35	2016	Dixit, Vijaya and	Performance me	Computers \& In	India	0	2	1	0	1	1	0	0	0	1	0
36	2016	Wang, Yingcong	An ant colony ba	Physica A: Statis	China	0	1	1	0	1	1	0	1	0	1	0
37	2016	Spiegler, VLM ar	The value of nor	International Jo	UK	1	1	1	0	0	1	0	1	0	1	0
38	2016	Hasani, Aliakbar	Robust global su	Transportation R	Iran	2	3	1	0	1	1	0	1	0	1	1
39	2016	Nooraie, S Vahid	Mitigating suppl	International Jo	USA	6	2	1	0	1	0	0	1	0	1	1

Model														
OR Method												Research		
Data Analysis	Decision Analysi	Expert Systems	Heuristics	Markov Decision	Metaheuristics	Neural Network	Optimization	Queuing Theory	Simulation	Statistics	Other	Resilience Metrics	Observed Industry/(	Original Definition
0	1	0	0	0	0	0	1	0	0	0		1	Aircraft Services	0
0	0	0	0	0	0	0	0	0	1	0		0	Global	0
0	0	0	0	0	0	0	0	0	1	0		1	Military	0
0	1	0	0	0	0	0	0	0	0	0		0	Generic	0
0	0	0	0	0	0	0	0	0	1	0		0	Generic	0
0	0	0	0	0	0	0	0	0	1	0		0	Automotive	0
0	0	0	0	0	0	0	0	0	1	0		1	Generic	0
1	0	0	0	0	0	0	0	0	0	0		0	Generic	1
0	0	0	0	0	0	0	1	0	0	0		0	Aircraft Services	0
0	0	0	0	0	0	0	1	0	0	0		0	Generic	1
0	0	0	1	0	0	0	1	0	1	0		0	Maritime	1
0	0	0	0	0	0	0	0	0	1	0		0	Retail	0
0	0	0	0	0	0	0	1	0	0	0		0	Generic	0
1	0	0	0	0	0	0	1	0	1	0		0	Transportation	0
1	0	0	0	0	0	0	0	0	0	0		1	Generic	1
0	1	0	0	0	0	0	0	0	0	0		0	Generic	0
0	0	0	0	0	0	0	1	0	0	0		0	Garment	0
0	0	0	0	0	0	0	1	0	1	0		0	Chemistry	0
1	1	0	0	0	0	0	0	0	0	0		0	Generic	0
0	1	0	0	0	0	0	0	0	1	0		1	Generic	0
0	1	0	0	0	0	0	0	0	0	0		0	Eletronic	0
0	1	0	0	0	0	0	0	0	0	0		0	Eletronic	0
0	1	0	0	0	0	0	0	0	0	0		0	Eletronic	0
0	0	0	0	0	0	0	1	0	0	0		0	Garment	0
0	0	0	0	0	0	0	1	0	0	0		0	Retail	0
0	0	0	0	0	0	0	1	0	0	0	Metrics	1	Generic	0
0	0	0	0	0	0	0	0	0	0	0	Metrics	0	Port Operations	0
1	0	0	0	0	0	0	0	0	0	0	0	0	Generic	0
1	0	0	0	0	0	0	0	0	0	0	Baysian Net	0	Lean	1
0	1	1	0	0	0	0	0	0	0	0	Baysian Net	1	Generic	0
0	1	0	0	0	0	0	0	0	0	0	Metrics	0	Generic	0
0	1	0	0	0	0	0	1	0	0	0		0	Generic	0
0	1	0	0	0	0	0	0	0	0	0		1	Generic	0
0	0	0	0	0	0	0	1	0	0	0		0	Generic	0
0	0	0	0	0	0	0	1	0	1	0		1	Generic	0
0	0	0	0	0	0	0	0	0	1	0		0	Cluster	0
0	0	0	0	0	0	0	0	0	1	0		0	Grocery/Retail	0
0	0	0	1	0	1	0	1	0	0	0		1	Generic	0
0	0	0	1	0	0	0	1	0	0	0		0	Generic	0