Supply Chain Resilience

Impact of Quantitative Resilience Metrics for Complex Supply-Chains

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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

1. Introduction

The world of logistics and Supply Chain (SC) represents a fairly recent field of focus for science [1]. 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 [2]. The 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 (SCM) was necessary. The SCM concept was for the first time identified by [3], and from then on has evolved.

Supply Chain Management (SCM) definition is not however linear or absolute, since it differs between different authors [4].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 [5].

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, [6]. 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 [1], [7]. The added complexity of reverse logistics is brought from the need to better deal with e-commerce, re-use of products or customer service [8]. This complexity of flows lead to an increased importance related to the location of individual entities and how they interact [9]–[11]

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 [12], [13]. 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 [14]. Different reviews on the topic have been published, showing the increased importance of the concept at both academic and industrial levels [15], [16].

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 [5], [17]. 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.

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

Taken as basis the review performed, that identified quantitative models as crucial to better understand and to provide useful information to decision makers concerning SCR, a model to analyse the SCR is also explored in this work. The work by Cardoso et al [41] was taken as basis and the study was developed considering two main research goals, which aim to understand: how maximizing SC complexity may contribute to SCR; and how a resilient SC can also be designed towards more responsiveness (e.g. high service levels) considered at the design stage. This was achieved by working on the definition of the adequate Objective Function and several case-studies were studied. Following this objective, a MILP model was applied to GAMS. Firstly, to test the SC complexity against resilience performance by maximizing SC Flow Complexity, and then test such configurations against the disruptive events allowing an analysis and comparison of SC performance under disruptive events. Then, the results from deploying a new objective function are presented aiming to reach a higher level of responsiveness.

In the end of this paper, conclusions and suggestions for future work are presented.

2. LITERATURE REVIEW

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 [16], a systematic literature review is performed with a solid methodology regarding the preparation, collection and analysis of information collected. The following steps are considered: research questions definition, previous literature reviews analysis, material collection, descriptive analysis, category selection and material evaluation.

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. 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. 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 such information, research gaps and future directions for the scientific field are presented in order to guide future work.

Research Questions

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.

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?

Previous Literature Reviews

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

[18] 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 [17], 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.

[19] 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”.

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. A clear definition on SCR is of great importance when sharing knowledge in a global scale.

Disruptive risks as well as recovery and reaction strategies can be categorized on the type of action and thinking it implies [17]. [18] divides the different possible strategies in two categories, proactive or reactive strategies and [19] 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.

Material Collection

Table 1 - Material collection results

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

The material collection procedures resulted in an initial set of 152, Table 1, that due to exclusions and duplicates was reduced to 39 individual publications in a timespan from 2009 until 2016.

Descriptive Analysis

Some publications are responsible for a vast part of the citations, and 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. 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. 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. 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.

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 4 Structural Dimensions 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.

Supply Chain Resilience Definition (Research Question 1)

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 [20]–[26]. There are examples of succinct definitions with interesting approaches including elements such as concept of time in terms of speed [27] or chronology position to a disruption or disturbance [28]. 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 [29]–[31]. More complex and complete definitions, in its majority, are more recent and tend to combine several elements present on earlier and simpler definitions.

From the analysed literature is possible to purpose a new framework to understand, evaluate and create SCR Definitions. The framework here presented, Figure 1, relies on four pillars: Adaptive Framing or Stage Adaptive Response; Speed; Performance Level; Focus Event. From the framework analysis, a comprehensive but simple new definition is proposed, resulting from the discussion of the five pillars defined before:

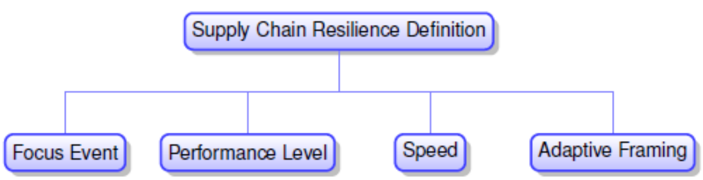

Figure 1 Mindmap for SC Resilience Definition analysis framework

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.

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 [32], [33]. [34] 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. [35] creates a framework for SCRM where SC Risk is represented as primary concept, whereas vulnerability and resilience appear aggregated. The two terms appear related, however Resilience is perceived with a good connotation unlike vulnerability that has a negative connotation [31]. [34] 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. SCR can provide the tools and knowledge to complement traditional risk management techniques [17]. The concept Zone of Balanced Resilience is proposed by [36], 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.

Supply Chain Resilience quantitative models and Supply Chain Management decision level (Research Questions 3, 4 and 5)

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.

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. 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. The methods present in the different publications are concentrated in three main modelling approaches: Optimization, Simulation and Decision Analysis. 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.

Strategies and Metrics applied in Supply Chain Resilience quantitative models (Research Questions 6 and 7)

From our research, only three publications [37]–[39] quantify SCR in a Single Index per si and using a set of 21 factors to measure Resilience goals of a particular SC. 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. Most of the strategies and metrics can be described as a concern from economic or customer demand performance, as well as SC network parameters.

Research Gaps and Future 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. 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. Develop efforts on SC Resilience strategies on the different SC decision levels to mitigate the lack of strategies focusing on the operational level is a path to follow. The need to tackle the issue imposed by the complexity of real life systems is something still to be explored.

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 [40], resilience

awareness can mitigate such neglect. The combination of such concepts should be further researched. 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.
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.

3. Modelling and Analysing Supply Chain Resilience

In order to be able to discuss how different SC networks behave towards resilience, a five echelons SC was considered, Figure 2, 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. Taking as point of origin [41] work, a set of cases are to be studied allowing to compare and construe results.

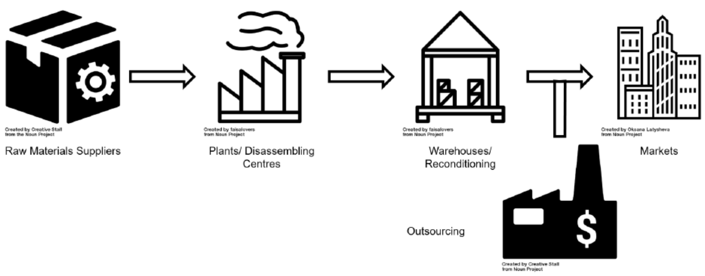

Figure 2: Possible SC echelons to consider

Five cases are studied regarding how the SC network can be designed to achieve higher resilience: Case A - a forward supply chain; 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 centres and warehouses; Case E - the most general case, encompassing all the previous ones. It is a closed-loop SC 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 centres."
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.

Model description

The Mixed Integer Linear Programming model developed by [41] 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.

Parameters

A set of important parameters describing the
SC performance are chosen to represent and compare the several runs. Flow Complexity - Total number of material flows in the network; NPV - Net Present Value - Calculated for each scenario and time period; FCI - Fixed Capital Investment; Investment - The total investment in the SC infrastructure, not including transportation costs; Inventory - Inventory present in warehouses; Purchases - Total purchases; Sales - Total sales; Expected Customer Service Level (ECSL) - The percentage of demand not met.

Objective Function

In this case, we will follow our problem description and will provide enough information to infer on the impact of SC Network Complexity and its behaviour when faced with a disruptive scenario. Two objective functions are studied.

$$Max \sum_{t} FC_t \quad (1)$$

$$MaxENPV = \sum_{s} pb_s \times NPV_s \quad (2)$$

A first one will consider the maximization of the network flow complexity,(1), as this would return a network configuration with maximum flow complexity (FC). 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. However, this method was not followed due to its implication on reality representaiton.
The second step is to retrieve the network configuration and then study how much such network configuration maximize the economic return, based on the Expected Net Present Value (2). By proceeding using this method and its maximization it is ensured a network with maximum FC with the most advantageous economic performance to the company.

Case Study

The presented model is implemented on a Case Study, the same as the original work [41] in order to allow for comparison of results. An European SC is considered with the values associated scaled down, due to confidentiality reasons. The initial SC is formed by one plant, one warehouse, four raw material suppliers, three final products suppliers and 18 markets. 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 a set of costs, restrictions and characteristics that shape the model and its feasibility space.
Model formulation allows for the introduction of changes in the model scenario, allowing for the SC to perform under

four operational conditions; one reference case with perfect operational conditions and three examples of disruptions, chosen following failure modes defined by Rice & Caniato, (2003) [Disruption 1 (Production Facilities), Disruption 2 (Supply) and Disruption 3 (Transportation)].

4. RESULTS

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, two configurations are established based on the SC network provided for the two objective functions. These network designs are implemented for each disruption scenario and its results are analysed and discussed. The MILP model is develop using GAMS software, and is run for a gap of 5%.

Case A

Table 3.2: Case A - NPV Maximization

Case A	Complexity	NPV	FCI	Investment	Inventory	Purchases	Sales	Customer Service
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	NPV	FCI	Investment	Inventory	Purchases	Sales	Customer Service
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%

The variation on expected NPV (ENPV) between the different operational conditions, Table 2, 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%. ENPV results from ENPV maximization, Table 3, are always lower than the results from the more complex network. For Disruption 1, where the system reacts the worst, is where that gap is higher, becoming a candidate justification for investment regarding SC Resilience concerns. The loss in ENPV by incrementing complexity (-0.01E7€) is easily compensated by the gains in disruption scenario 1 and 2 (0.15E7€ and 0.1E7€), representing gains of 9% and 5% respectively.

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 scenarios: 21%, 15% and 9% for disruptions 1, 2 and 3 respectively.

Case B

Table 3.4: Case B - NPV Maximization

Case B	Complexity	NPV	FCI	Investment	Inventory	Purchases	Sales	Customer Service
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%

Table 3.5: Case B - Complexity Maximization

Case B	Complexity	NPV	FCI	Investment	Inventory	Purchases	Sales	Customer Service
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%

With the reference network configuration, disruptions cause a decrease on expected ENPV of 14%, 7% and 6% for disruptions 1, 2 and 3 respectively, Table 4 and 5.

Comparing the several model runs, Disruption 1 produces the most negative impact, similarly with Case A. When no disruption is present a variation of -0.03E7e 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.

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. If the SC does not acquire a more complex configurations 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.

Case C

Table 6: Case C - NPV Maximization

Case C	Complexity	NPV	FCI	Investment	Inventory	Purchases	Sales	Customer Service
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%

Table 7: Case C - Complexity Maximization

Case C	Complexity	NPV	FCI	Investment	Inventory	Purchases	Sales	Customer Service
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%

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 6 and 7. However, this configuration still provides better results than SC configurations from Cases A and B. 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 expected ENPV. 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 disruption does occur, improving the performance in 14%, 27% and 5% for disruptions 1, 2 and 3 respectively. 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.

Case D

Table 3.8: Case D - NPV Maximization

Case D	Complexity	NPV	FCI	Investment	Inventory	Purchases	Sales	Customer Service
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	NPV	FCI	Investment	Inventory	Purchases	Sales	Customer Service
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%

From the results provided, Tables 8 and 9, 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.

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.

Case E

Table 10: Case E - NPV Maximization

Case E	Complexity	NPV	FCI	Investment	Inventory	Purchases	Sales	Customer Service
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%

Table 11: Case E - Complexity Maximization

Case E	Complexity	NPV	FCI	Investment	Inventory	Purchases	Sales	Customer Service
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%

From the results, Tables 10 and 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 scenario that influences ENPV the most, whereas Disruption 2 is the scenario that affects CSL with an increased impact. If in other cases disruption 3, presented as a case where a trade-off between ENPV and CSL had to be made, in this case the max complexity network provides better results in both ENPV and CSL. For the network with fewer flows allowed, the NPV variations resulted 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.

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 and 3 respectively.

5. Discussion

After running the model with the two types of network configurations for four different scenarios and for five types of SC design 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 obtained results vary not only from SC complexity but also due to its base structures (e.g. forward or closed-loop) and with the different type of disruption. 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.

The model developed was run on a 15 year period, 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 Costumer Service Level.

The difference in ENPV return, in disruptive scenarios between the more complex and a leaner SC is always positive, Table 12 (Mean Δ Disruptions), providing better return than not investing in preventive configuration.

Table 12: Absolute variations between NPV from reference and maximized complexity configurations

	Δ No disruption	Mean Δ 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 €

There is a more evident benefit, from deploying a more complex SC, in terms of ECSL. An improvement, percentually, higher than that obtained in ENPV, Table 13. The notable shift is made possible by the increase flexibility and redundancy allowed by the higher amount of entities and flows involved.

Table 13: Percentage variation of NPV and Customer Service Level (CSL) between the reference and maximized complexity configuration

Disruption 1	NPV	CSL	Disruption 2	NPV	CSL	Disruption 3	NPV	CSL
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%

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 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.

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. 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. 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 [41] in their study.

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 performance metric. Besides ENPV maximization, another element to be inserted into the new objective function relies on the resilience quantification based on what was described by several authors [37], [42], [43], where resilience is quantified by 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 objective function.

New Objective Function

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

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

The first term 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. The second term, allows for the introduction of the concern of meeting customer demand by using a fraction of the unsatisfied demand. It is expected that this characteristic will lead to an increase in ECSL and an decrease of ENPV when compared with reference values.

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), the same objective function 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. In this way it is possible to compare the obtained results with the ones of the previous model runs and test its resilient behaviour.

Case NA

Table 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

From Table 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. The 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. Comparatively there are variations of 35%, 24% and 22% for Disruptions 1, 2 and 3 respectively. This effort to meet customer demand comes from added complexity but also from an increased amount of purchases of final products from outsourcing.

Case NB

Table 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

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 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. 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.

Case NC

Table 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 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 stands out with a higher impact on ENPV, with variations of -1%, -28% and 2% for Disruptions 1, 2 and 3 respectively. This means that, for Disruption 3, this new OF provided a network that provides a better economic return, interestingly with a lower value for complexity. 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. 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 to meet the demand.

Case ND

Table 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

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. 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.

Case NE

Table 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

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 the added benefit of the new OF providing a maximum value for ECSL. 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. 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.

Discussion

Considering that during the decision making process, there must be 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. From the results obtained 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. 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 19.

Table 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%

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 given to high ECSL the system has to adjust in accordance by incrementing the purchase of final products in order to meet the gap left bt the disruptive event. 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 in study and the particular disruption.

7. Conclusions and 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 concerns, SCR 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, as suggested [41] 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. 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 a 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 an relationship between the work done in Computer Science and this kind of SC optimization problems.

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