UNIVERSIDADE DE LISBOA
INSTITUTO SUPERIOR TÉCNICO

Quantitative tools to aid decision-making towards Resilient Supply Chain

João Henrique Pires Ribeiro

Supervisor : Doctor Ana Paula Ferreira Dias Barbosa Póvoa

Thesis approved in public session to obtain the PhD Degree in Engineering and Management

Jury final classification: Pass with Distinction

2024

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Funding Institution - FCT: Fundação para a Ciência e a Tecnologia

2024

Abstract

Supply Chain Management is constantly evolving, and Supply Chain Resilience (SCR) appears as a recent offspring result of changes in how companies do business. Recent efforts have focused on the basic concepts of SCR, leaving a relevant research gap in the modelling and quantifying of SCR. This PhD intends to contribute to avoiding such bias and add knowledge to this challenging area. The work has one main objective: development of quantitative tools to aid decision-making in the context of SCR; and two secondary objectives: i) Understand what Resilient SC are ii) Development of an adequate Resilience Metric. From the objectives described above, a set of Research Questions are identified. Thus, this thesis presents the following contributions: i) Adequate definition of SCR. ii) Development of a comprehensive framework for the analysis and evaluation of SCR, providing a structured approach for assessing and enabling the enhancement of SCR. iii) Clarification of the distinction between SCR and risk management, highlighting the unique characteristics and objectives of SCR as a distinct field of study. iv) Compilation of a list of quantitative models and indicators that serve as a foundation for future research. v) Recognition that there is no one-size-fits-all strategy for SCR, for instance, that redundancy and flexibility have limitations in their effectiveness. vi) Empirical evidence supporting that upstream disruptions have a more significant impact on SC. vii) Development of an easy-to-use SCR metric, designed to be readily understood and implemented by stakeholders. This metric has shown to facilitate increased resilience and reduced ripple effects of disruptions. viii) Introduction of a resilient tactical and operational quantitative model. ix) Proposal of a robust optimization model for addressing uncertainty in CO2 prices.

276/300 words

Keywords

Supply Chain Management; Supply Chain Resilience; Quantitative Models; Metrics; Sustainability

Resumo

A gestão de cadeias de abastecimento (SCM) está em constante evolução, e a resiliência da cadeia de abastecimento (SCR) surge como um resultado recente das mudanças na forma como as empresas fazem negócio. Os esforços recentes têm-se centrado nos conceitos básicos da SCR, deixando uma lacuna de investigação relevante na modelação e quantificação da SCR. Este doutoramento pretende contribuir para minimizar esta lacuna. O trabalho tem um objetivo principal: o desenvolvimento de ferramentas quantitativas para apoio à decisão no contexto de Cadeias de abastecimento Resilientes; e dois objetivos secundários: i) Compreender o que são Cadeias de abastecimento Resilientes; ii) Desenvolver uma Métrica de Resiliência. A partir dos objetivos descritos, é identificado um conjunto de Questões de Investigação. Assim, esta tese apresenta as seguintes contribuições: i) Definição adequada de SCR. ii) Desenvolvimento de um quadro abrangente para a análise e avaliação da SCR, fornecendo uma abordagem estruturada para avaliar e melhorar a SCR. iii) Clarificação da distinção entre SCR e gestão de risco, destacando as características e objetivos únicos da SCR. iv) Compilação de uma lista de modelos e indicadores quantitativos que sirvam de base para futuras investigações. v) Reconhecimento de que não existe uma estratégia única para a SCR, por exemplo, que a redundância e a flexibilidade têm limitações quanto à sua eficácia. vi) Provas empíricas que sustentem que as perturbações a montante têm um impacto mais significativo na SCM. vii) Desenvolvimento de uma métrica SCR fácil de utilizar, concebida para ser facilmente compreendida e aplicada pelas partes interessadas. Esta métrica demonstrou facilitar o aumento da resiliência e a redução dos efeitos borboleta das perturbações. viii) Introdução de um modelo quantitativo tático e operacional resiliente. ix) Proposta de um modelo de otimização robusta para lidar com a incerteza dos preços do CO_2.

299/300

Palavras Chave

Gestão de Cadeias de Abastecimento; Resiliência das Cadeias de Abastecimento; Modelos Quantitativos; Métricas; Sustentabilidade

Acknowledgments

I am deeply grateful for the support and encouragement I have received throughout my PhD journey. It is with heartfelt appreciation that I acknowledge those who have been instrumental in my academic and personal growth:

To my parents, Maria João and Jorge, your unwavering love, sacrifices, and endless encouragement have been my rock. You have been my pillar of strength, and I cherish the values and resilience you instilled in me.

To my girlfriend, Inês, you have stood by me through thick and thin, and your love has been a constant source of inspiration and motivation. I treasure you all more than words can express, and I can't wait for what the future holds for us.

I extend my deepest gratitude to my supervisor, Ana Póvoa. Working with you has been an incredible journey of growth and learning. Your guidance, expertise, and unwavering belief in my abilities have been a constant source of inspiration. Thank you for your trust, availability, and for being an exceptional mentor.

To my friends, who have been a source of joy, laughter, and support throughout this challenging journey, I am immensely grateful.

I am indebted to everyone who contributed to my educational journey, from the dedicated nuns in pre-school to my Ferreira Dias and Técnico professors. Each of you has played a pivotal role in shaping my knowledge, skills, and character. Your teachings and guidance have been the foundation upon which I built my Ph.D.

I would like to express my sincere appreciation to the CEGIST team for providing me with a stimulating and collaborative research environment. Your support, resources, and vibrant research community have shaped my research and fostered academic growth. The experience of being part of CEGIST has enriched my PhD journey in countless ways.

I am deeply thankful to FCT, for the financial support provided through my grant reference, SFRH/ BD/ 148499/ 2019. This support has been invaluable in enabling me to pursue my PhD studies and carry out my research effectively.

To everyone and everything else who has made me whole and enabled me to persevere in the not-so-easy journey of a PhD, I thank you. Life is a tapestry woven with countless threads, and each experience, whether challenging or uplifting, has contributed to my growth.

I would rather have questions that can’t be answered than answers that can’t be questioned.

Richard Feynman

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Acronyms

AFSC agri-food supply chains. 44

CLSC Closed-Loop SC. 14, 35, 65, 74, 75, 80

DC Distribution Center. 49, 52

DM Decision-maker. 122

DT Digital Twins. 50

ECSL Expected Customer Service Level. xv, xix, 61–64, 66, 68–71, 81, 94, 95, 97–100, 106, 107

ENPV Expected Net Present Value. xi, xv, xix, 60–64, 66–71, 73, 81, 85, 87, 92–95, 97–100, 102, 104, 106, 107

FC Flow Complexity. 58–62, 66, 68–72

HILF high-impact and low-frequency. 51

LIHF low-impact and high-frequency. 51

MILP Mixed Integer Linear Programming. 58, 59, 61, 64–66, 68, 74, 75, 80, 87, 122

OR Operations Research. 22, 31, 32, 42, 44–47, 53, 54, 79

SC Supply Chain. xi, xv, xvi, 14, 15, 17, 18, 22, 24, 27, 29–32, 34–39, 42–54, 58–82, 84–88, 90–110, 122

SCM Supply Chain Management. ix, 14, 22, 29, 30, 37, 38, 44, 45, 50, 54, 74, 77–81, 92, 108

SCR Supply Chain Resilience. x, xi, xv, xix, 14–18, 21–24, 27–38, 42–54, 57–59, 64–66, 68, 71–81, 85–88, 91–93, 98, 104, 106–110, 122

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Introduction

Contents

1.1 Introduction

Supply Chain (SC) has emerged as the backbone of the global economy, with many economic activities heavily relying on such operations for its success. The dependency on these systems has led to the emergence of a distinct field of study, Supply Chain Management (SCM) (Oliver et al., 1982). This activity implies the study of the main concerns inside SC operations and SC Resilience, in particular, arises as a novel approach to managing the consequences of high-impact events on SC. History provides clear examples of how unforeseen circumstances can impact SC, and how different reactions can dictate profitability or, in the worst case, the dissolution of a business. This is the case of natural or anthropogenic disasters, or even economic or political decisions.

Most published articles leave the SC Resilience to qualitative interpretations (Das, 2018), and few look into quantitative analysis (Sokolov et al., 2016a; Cardoso et al., 2015), which is nowadays a research challenge. A quantitative approach is then pursued in this PhD by exploring mathematical modelling to obtain better tools for decision-makers. This is done, not only, in the design and planning of resilient SC but also in the operational decision level. To show the applicability of such approach, a mixed-integer linear programming model (MILP) is proposed, where different SC networks are studied, from only forward to closed-loop supply chains (CLSC), the latter encompassing circular economy principles.

1.1.1 Motivation

No matter the event that leads to the disruption, some lessons can be learned on how to manage and cope better with this particular kind of events (Wachtendorf et al., 2013; Wakasugi & Tanaka, 2015). Even simpler weather events, such as high gusts, heavy rain, or extreme temperatures, can induce effects on the company's operation. Minimising the risk for the whole SC is thus of great importance (Brusset & Bertrand, 2018).

On this, the relationship amongst SC actors and how they affect each other has been studied in several fields. In SC Resilience, one can study the impact of the type of contracts between suppliers and production in response to disruptions (G. Li et al., 2017, 2020). Information sharing between the different players can suffice for the appropriate SC response to disturbances (Sabahi & Parast, 2020). Positive relationships can foster responsiveness and efficiency in the SC (Goffnett & Williams, 2019), with collaboration being a relevant enabler for SCR (Scholten & Schilder, 2015); on the contrary, confrontations can have negative impacts. For example, the strike at two General Motors plants led to a gridlock in the SC, resulting in losses of millions of dollars (Snyder et al., 2006), another example of how a single event can cause a ripple effect through the system.

One of the most referred examples of the importance of resilient capabilities and information sharing amongst the SC players is the example of the fire in 2000 at a Philips' factory that impacted two big players, Nokia and Ericsson. This fire forced a stop in production, and despite being informed simultaneously, the two firms had very different responsive actions and final results. Nokia was fast to acknowledge the disruption and to seek alternatives, Ericsson failed to do so and ended up having around 400 million $ in losses (Dolgui et al., 2018). The lack of agility leads to the inability to remain competitive (Sharma et al., 2017), that is a lack of reaction after the occurrence of a stimulus (Bernardes & Hanna, 2009).

More recently, the world has faced the perfect storm in terms of disruptions, the COVID pandemic, that evidenced the need for resilient SC. The restrictions and health consequences of the coronavirus outbreak were global and spared almost no country. There is no economic sector that left unscathed from this period. If some companies had their operation left to a complete standstill, others had a massive increase in demand, and even some were in a compromised situation with some of their operations restricted.

The academic response was fast and researchers provided short publications with what could science help. The interconnected global SC were forced to face new scenarios and deal with the consequences (Baldwin & Tomiura, 2020). Hobbs (2020) focus on the Canadian food industry and how it was impacted, both for disruptions on operations but also by the panic buying that brought a considerable demand variation. Society became aware of the SCR relevance and mathematical approaches can provide useful insights and Paul & Chowdhury (2020) presents a model on the operational level where the results add validity to the relevance of SC Resilience, since SC designed with Resilience in mind had a better behaviour under stress, at least reducing costs.

Supply Chains and companies felt different levels of consequences the disruptions imposed. If on the one hand, companies must have positive economic results, on the other, the satisfaction of demand must not be neglected. Not being able to fulfil the latter during disruptions has shown to be fatal for companies and society.

The concept of SC Resilience is therefore very important and can be applied to a broad spectrum of economic activities with examples in several fields: chemical (Cardoso et al., 2015); automotive (Carvalho, Barroso, et al., 2012); agri-business sector (Stone & Rahimifard, 2018; Kirwan et al., 2017), since all sectors can be affected by disruptions which could be internal, external or a combination of both. Although, disruptions can occur in any location of a SC, most commonly the attention is centred around upstream disruptions. Transportation disruptions are often seen as one of the most frequent hurdles in SC operations. Albertzeth et al. (2020) studies such kind of scenarios and presents a metric to help find strategies to improve SCR, also tackling the difficult process of monetising in this context. A proper process of design and planning of SC can help companies to overcome vulnerabilities (Min et al., 2019).

Additionally, few works exist that address supply chain resilience and supply chain sustainability simultaneously. For instance, Giannakis & Papadopoulos (2016) studied the impact of environmental disruptions, that is, the specific environmental impact of particular scenarios. Still, this is done without considering the effects of SC disruptions on a sustainable driven SC. Current sustainability models tend to be simplistic when understanding the particular dynamics of resilience (Fiksel, 2006). The few published are fairly recent as are the case of (Fahimnia & Jabbarzadeh, 2016b; Rosič et al., 2009; Suhi et al., 2019). However, there is an expected relationship between resilience and sustainability. Resilience is often associated with redundancy or flexibility, strategies that usually imply an increased use of resources. Such strategies can lead to increased costs and waste, translating into a reduction in efficiency under steady-state conditions. This trade-off has been described by Fiksel et al. (2014). However, with the impossibility of neglecting SC Resilience, a more in-depth study on the trade-off between sustainability and resilience is of extreme relevance (Rajesh, 2019; Mohammed, 2020; Nowakowski et al., 2020; Barbosa-Povoa & Pinto, 2020).

The increased awareness of sustainable SC has led to changes in all levels of SCM, creating new challenges. One of those is how can one achieve a resilient and sustainable SC (Mari et al., 2014; Fahimnia & Jabbarzadeh, 2016a). The re-use of products is on the rise at a global scale, leading to more complex SC and with it reverse logistics/closed-loop SC (Savaskan et al., 2004; Howard et al., 2018; Özçelik et al., 2020), which can be seen as a form to guarantee SC Resilience.

However, regardless of the recent increased interest in SC resilience, there is still space for further development and to create awareness and knowledge on how companies can overcome disruptive events sustainably (Ribeiro & Barbosa-Povoa, 2018). The uncertainties around SC and Resilience, in particular, mean that decision-makers are pursuing a zone of balanced resilience (Pettit, Fiksel, & Croxton, 2013), where the trade-off between the investment in resilient capabilities and the susceptibility to vulnerabilities is best for each company. Dealing with disruptive events must be done by resorting to a holistic approach, where SC Resilience has a lot to gain by taking advantage of the knowledge and experience provided by other SC fields that handle uncertainty and risk. Examples of such benefits are the application of the concept of reliability (Ha et al., 2018) or Supply Chain Risk Management (SCRM). One can even consider SC Resilience as an offspring of SCRM (S. Y. Ponomarov & Holcomb, 2009; König & Spinler, 2016; Shekarian & Mellat Parast, 2020). Risk management consists of managing proactive practices taking into account vulnerability. Those can be prospective strategies to enhance SC Resilience (Rajesh & Ravi, 2015a).

However, to correctly face SC Resilience adaptations are needed since the traditional methods of dealing with risk rely vastly on the identification and consequent quantification of probabilities and impacts of a particular event. A challenging process that comes with its faults. For instance, in the World Economic Forum Global Risk Report of 2020 (World Economic Forum, 2019), a pandemic is not seen in the top five events in terms of likelihood, at least for the past 13 years. When discussing the impact, the term "pandemic" disappeared in 2008, and in recent years the top five global risks have been shifted towards the global trend of environmental concerns. An antagonistic approach is followed in the context of SC Resilience, where most common events can be categorised as an unknown-unknown risk and where events' probabilities are extremely difficult to obtain. The characteristics of uncertainty elements turn strategic and tactical levels of decision into a fundamental part in the process of building and maintaining a resilient SC (Sáenz et al., 2018; Sahebjamnia et al., 2015; Cohen & Lee, 2020; Kaur & Singh, 2019). Thus, macro and network decisions are a crucial factor when handling SC Resilience (Asian & Nie, 2014; Kim et al., 2015; Singh, 2020), as it already is in other fields of SCM (Farahani et al., 2013; Mota, Gomes, Carvalho, & Barbosa-Póvoa, 2015; Mota et al., 2017).

Finally, it can be said that SC Resilience is an urgent need, but it appears as a not yet mature concept. For instance, its definition is still a topic of discussion present in the work of different authors. Providing a stable interpretation is crucial to have all the involved parties discussing the issue on the same grounds, a concern recognised by several reviews on SC Resilience that devote some work to its discussion and formalisation (Ribeiro & Barbosa-Povoa, 2018; Kamalahmadi & Parast, 2016; J. Wang et al., 2016; Hohenstein et al., 2015; Tang, 2006). In this work, we will follow the definition presented by Ribeiro & Barbosa-Povoa (2018) where "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". This issue combined with the lack of a unifying tool that explores SC Resilience and SC Sustainability leave a significant research gap that practitioners and academics should address and is where this work lies its great value for the scientific as well as industrial communities.

1.2 Objectives

SC's managers face several challenges when assessing SC Resilience; most of them fall under strategic or tactical SCM decision levels. Decisions on which locations to operate, the quantities to be produced in each location, the outsourcing needs, and the flows to promote between the different possible entities in the network, are to be taken. These should guarantee operations to be cost-efficient while maintaining customer satisfaction (Lotfi & Saghiri, 2017).

As stated above, most of the works look into the SC Resilience with a qualitative interpretation (Das, 2018), and few look into quantitative analysis (Sokolov et al., 2016b; Cardoso et al., 2015). A quantitative approach is pursued in this PhD by exploring mathematical modelling to obtain better tools for decision-makers. This is done, not only, in the design and planning of resilient SC but also in the operational decision level. Additionally, few works exist that simultaneously address supply chain risk and sustainability, which is critical as resilience can not be implemented at the expense of the environment.

This work aims to reach one main objective:

- Development of quantitative tools to aid decision-making in the context of SCR

In the process of reaching such objective, two secondary objectives are defined:

- Understand what Resilient SC are

- Development of an adequate Resilience Metric

A Generic supply chain structure that involves a four-level structure will then be studied. Starting from Raw Materials and ending in markets, with Plants and Warehouses as intermediate echelons. To entail any possible SC configuration, the studied problem represents a set of different flows between tiers, from a traditional forward SC to a generic Closed-Loop SC.

1.2.1 Research Questions

From the objectives described above, a set of Research Questions are identified so as to better guide the work towards meaningful outcomes.

- RQ1 - How to define SC Resilience?
- RQ2 - Can resilient behaviour of SC be translated into a comprehensive index metric?
- RQ3 - Which challenges lie in further developments in SC Resilience for each SCM decision level ?
- RQ4 - Can environmental concerns have a symbiotic relationship with SC Resilience?
- RQ5 - What strategies can decision-makers deploy to boost the resilience of their SC?
- RQ6 - What challenges still lie for research on SC Resilience?

The relationship between the objectives and the research questions will be presented in further detail in the next section.

1.3 Thesis outline and outputs

This thesis comprises different chapters, resulting in different outputs and publications. Most of these outputs have already been published/presented (with the appropriate references identified).

1.3.1 PhD Thesis Structure

As this work is paper-based, each study has been, or will be, independently written as an article for publication and, therefore, some inevitable duplication is expected.

The overview of this thesis is presented in figure 1.1.

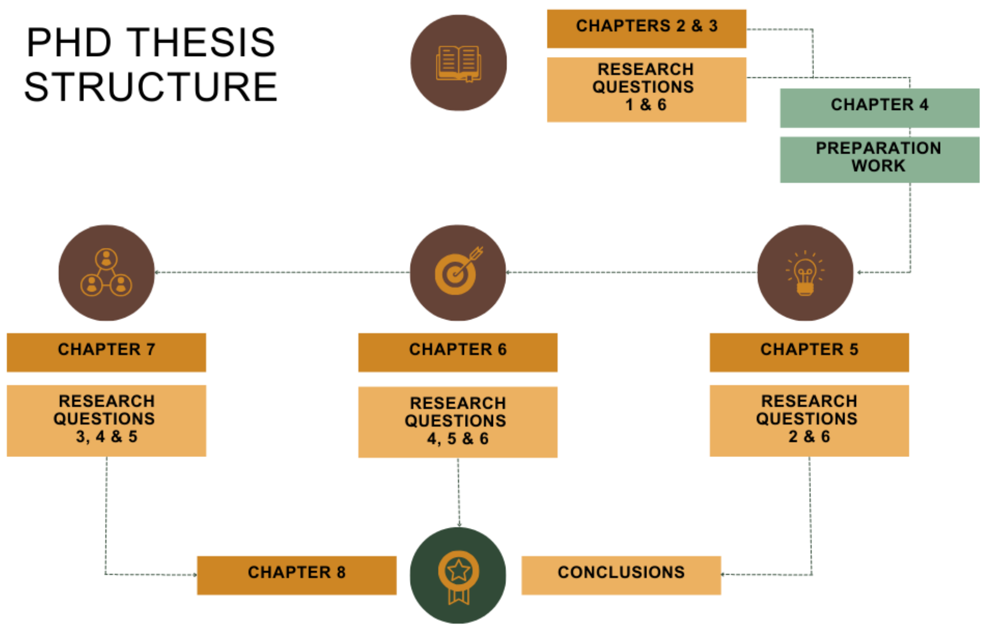


Figure 1.1: PhD Thesis Structure

Chapters 2 and 3: Literature review

Research Questions 1 and 6

Status: Published in an international journal and indexed conference proceedings

Definition and Characterisation of Resilient SC

To comprehend how the academic community has been treating such concern, we developed a systematic literature review on SC resilience, focusing on the analysis of the development of quantitative methods to support such decisions. The work is divided into two papers, in Chapter 2 focus is given to the strategic and tactical level of decision and in Chapter 3 the attention goes to the tactical and operational level. In both papers, a content analysis was performed, exploiting a solid methodology in the preparation; collection; and analysis of the information obtained.

Additionally, published SC resilience definitions were examined and, as result, 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 was concluded that the use of quantitative models, although recognised with high relevance in SC resilience, should be further researched as most of the published work explores the conceptualisation of only a limited number of resilience elements, lacking the development of integrated holistic approaches. These should simultaneously address the main supply chain characteristics and SC resilience elements.

Chapter 4: Analysing SC Resilience

Preparation work

Status: Sections 4.1 and 4.2 published independently in indexed conference proceedings

In this chapter, the focus is on understanding the key drivers of supply chain resilience before delving into more complex modelling approaches. The chapter is divided into two sections.

The first section, Section 4.1, explores the impact of redundancy and flexibility on supply chain performance, recurring to the analysis of supply chain complexity. Redundancy and flexibility are widely recognized strategies for enhancing supply chain resilience. The findings of this section indicate that while redundancy plays a significant role in improving resilience, there is a threshold beyond which further redundancy does not yield significant benefits.

The second section, Section 4.2, investigates the consequences of different types of disruptions, specifically supply disruptions, production disruptions, and transportation disruptions. The results reveal that upstream disruptions have a more substantial impact on the supply chain. Furthermore, it is observed that transportation disruptions have limited consequences on the strategic and tactical decision levels.

Overall, this chapter sets the foundation for the subsequent analysis by examining the drivers of supply chain resilience, and the impact of different disruption types.

Chapter 5: Resilience Metric

Objective 1

Research Questions 2 and 6

Status: Published in an international journal

Decision Supporting Tool for responsive Resilient SC

Recent efforts on the topic have led to a focus on the basic concepts of SCR, leaving a relevant research gap in the modelling and quantification of the SCR behaviour. Most SCR models fail to incorporate relevant characteristics of the supply chain's performance, as are the impacts perceived by downstream customers.

As a contribution to avoid such bias, an optimisation model is proposed, where economic and responsiveness objectives are maximised. This means that, as different SC goals are at stake, a multi-objective approach will be developed where a trade-off between the different objectives is pursued. An adimensional metric is proposed where economic goals are in balance with customer satisfaction, thus aiming for responsiveness in operations while being economically sound.

A case study showed that decision-makers should avoid adopting universal strategies and should instead study the best plan for their operation. Moreover, it can be concluded that there is a correlation between the SC performance and the level achieved on the proposed SCR metric, easing the process of trust in SC design and planning.

Chapter 6: Resilience at the Operational Level

Objective 3

Research Questions 4, 5 and 6

Status: Submitted to an international journal

One of the research gaps identified is related to the low incidence of published articles presenting resilience models at the operational level.

This issue poses a challenge to be addressed, not only due to its infrequent coverage in academia but also because its study is only feasible after a comprehensive understanding of the concept of resilience applied to the supply chain.

Therefore, this chapter contributes by presenting a MILP model in which operational-level resilience is studied. This model is currently under review in an international journal.

Chapter 7: Resilient and Environmental Concerns

Objective 2

Research Questions 3, 4 and 5

Status: Submitted to an international journal

Decision Supporting Tool for Sustainable and Resilient SC

The new quantitative model, presented in a paper currently under review, quantifies environmental impacts by considering CO_2 emissions as a cost. This is based on the idea introduced by the European Union Emissions Trading Scheme, where CO_2 is regarded as a commodity with a variable market price. This kind of model, a quantitative model for a resilient and sustainable supply chain, is an innovative piece of work and aims to be used by the academic and business community to gain a competitive advantage compared to not incorporating sustainable and resilient concerns.

Chapter 8: Conclusions and future research

The PhD thesis culminates into a chapter where a final discussion is presented, combining all chapters to conclude this work and present outcomes as well as suggestions for further development in the area of Supply Chain Resilience.

1.3.2 Outputs

This PhD started in September of 2018 and since then work has been done in order to fulfil the objectives identified. Bellow, Table 1.1, there is a list of the publications and conference talks, cited above, where the work was submitted to peer review and subsequently made available to the world.

For transparency, the contributions made by the PhD candidate are identified in Table 1.1 using the CRediT taxonomy, which includes 14 different roles describing each contributor's specific contribution. The roles are: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Roles/Writing - original draft; and Writing - review & editing.

Table 1.1: Current status and achieved outputs

Chapter	Objective	Research Question	Related conference presentations	Related publications (Conference proceedings, book chapters and research papers)	Ph.D. Candidate work accomplished
2	-	1, 2, 3	- (In portuguese) Pires Ribeiro, J. (2020, July 5). Resiliência, algo mais do que a soma das partes. Observador.	- Ribeiro, J. P., & Barbosa-Povoa, A. (2018). Supply Chain Resilience: Definitions and quantitative modelling approaches - A literature review. Computers & Industrial Engineering, 115, 109-122	Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Visualization;Writing - original draft; Writing - review & editing
3	-	1, 2, 3		- Bátista M., Ribeiro J.P., Barbosa-Póvoa A. (2023) Supply Chain Resilience: Tactical-Operational Models, a Literature Review. In: Operational Research. IO 2023. Springer Proceedings in Mathematics & Statistics, vol —. Springer, Cham.	Conceptualization; Methodology; Project administration; Supervision; Validation; Writing - review & editing
4	-	1, 2, 3	- Ribeiro J.P., Barbosa-Póvoa A. (2019) Supply Chain Resilience: An Optimisation Model to Identify the Relative Importance of SC Disturbances. IO 2018, Aveiro, Portugal - Cruz, L., Pires-Ribeiro, J., & Barbosa-Póvoa, A. (2019). Design and Planning of Agri-Food Supply Chains. ESCAPE 29, Eindhoven, Netherlands. [1] - Ribeiro, J. P., & Barbosa-Póvoa, A. (2018). Modelling and Analysing Supply Chain Resilience Flow Complexity. ESCAPE 28, Graz, Austria	- Ribeiro J.P., Barbosa-Póvoa A. (2019) Supply Chain Resilience: An Optimisation Model to Identify the Relative Importance of SC Disturbances. In: Alves M., Almeida J., Oliveira J., Pinto A. (eds) Operational Research. IO 2018. Springer Proceedings in Mathematics & Statistics, vol 278. Springer, Cham [1] - Cruz, L., Pires-Ribeiro, J., & Barbosa-Póvoa, A. (2019). Design and Planning of Agri-Food Supply Chains. In Computer Aided Chemical Engineering (Vol. 46, pp. 55–60) [2] - Ribeiro, J. P., & Barbosa-Póvoa, A. (2018). Modelling and Analysing Supply Chain Resilience Flow Complexity. In Computer Aided Chemical Engineering (Vol. 43, pp. 815-820). Elsevier [1]	Conceptualization[1,2]; Data curation[1]; Formal analysis[1]; Investigation[1]; Methodology[2]; Software[1]; Supervision[2]; Validation[1,2]; Visualization[1,2]; Writing - original draft[1]; Writing - review & editing[1,2]
5	1	2,3,4, 5		- Pires-Ribeiro, J., & Barbosa-Póvoa, A. (2021). A responsiveness metric for the design and planning of resilient supply chains. Annals of Operations Research.	Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Software; Validation; Visualization; Writing - original draft; Writing - review & editing

Table 1.1 continued from previous page

Chapter	Objective	Research Question	Related conference presentations	Related publications (Conference proceedings, book chapters and research papers)	Ph.D. Candidate work accomplished
6	3	4, 5, 6		- Pires-Ribeiro, J., Bátista, M., & Barbosa-Póvoa, A. (2023). Supply Chain Resilience: optimising decisions at the tactical and operational level *(Under review)*	Conceptualization; Formal analysis; Investigation; Methodology; Supervision; Visualization; Writing - review & editing
7	2	3,4,5	- Pires-Ribeiro, J., & Barbosa-Póvoa, A. (2020). First place in Best Student Research Presentation Competition - An Optimization Approach for Green Resilient Supply Chain. 5th Annual Workshopon Supply Chain & Logistics Management December 11, 2020, Rowe School of Business Dalhousie University, Halifax, Canada. - Pires-Ribeiro, J., & Barbosa-Póvoa, A. (2020). An Optimization Approach for Green Resilient Supply Chain. Enterprise and Infrastructure Resilience Workshop - 2020 - AIChE. - Pires-Ribeiro, J, Mota, B, Barbosa-Póvoa, A.P, “Resilient and Green supply chain design and planning”, XX Congress of the Portuguese Association of Operational Research (IO 2019), 22-24 July, 2019, Tomar, Portugal. - Pires Ribeiro, J., Mota, B., & Barbosa-Póvoa, A. (2020). Green and Resilient Supply Chains. Minneapolis, MN, U.S.A.: 2020 POMS Annual Conference (Accepted, event canceled due to COVID-19) - Pires Ribeiro, J., Mota, B., & Barbosa-Póvoa, A. (2019). Resilient and Green supply chain design and planning. Gothenburg: EurOMA Forum 2019	- Pires-Ribeiro, J, Mota, B, Barbosa-Póvoa, A.P, “Merging Resilience and Sustainability in Supply Chain Design”, Operational Research. IO 2019. Springer Proceedings in Mathematics & Statistics. Springer, Cham. - Pires-Ribeiro, J, Santos, D, Barbosa-Póvoa, A.P, "A step towards Green Resilient Supply Chain under Uncertainty" (under review)	Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Software; Validation; Visualization; Writing - original draft; Writing - review & editing
8	3	4,5			

2

Literature Review - A view at the strategical and tactical level

Contents

Chapter 2 is composed of an article published in 2018 as an offspring of my master's dissertation, focusing on definitions and quantitative modelling on a strategic and tactical level of decision and establishing the groundwork for the work developed in this PhD.

Ribeiro, J. P., & Barbosa-Povoa, A. (2018). Supply Chain Resilience: Definitions and quantitative modelling approaches–A literature review. Computers & Industrial Engineering, 115, 109-122.

2.1 Abstract

Resilience is currently an increasing concern in SC, caused by their globalization, which is subject to diverse types of disturbances. Such disturbances need to be handled in the right way, compelling the use of tools that can support resilient supply chain decisions. To comprehend how the academic community has been treating such concern we developed a systematic literature review on SCR, focusing on the analysis of the development of quantitative methods to support such decisions. A content analysis was performed, in an identified sample of 39 papers, exploiting a solid methodology in the preparation; collection; and analysis of the information obtained. Additionally, published SCR definitions were examined and, as result, 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 was concluded that the use of quantitative models, although recognised with high relevance in SCR, should be further researched as most of the published work explores the conceptualization of only a limited number of resilience elements, lacking the development of integrated holistic approaches. These should simultaneously address the main supply chain characteristics and SCR elements. Future directions for the academic community are presented, aiming to guide future research work in the area.

2.2 Introduction

SC represent a fairly recent field (Barbosa-Póvoa, 2014). Not that the inherent activities did not exist, but simply were not considered foundations for the organizations. The SCM concept was, for the first time, identified by Oliver et al. (1982), and from then on has evolved to meet the challenges brought by the modern economy. With globalization, SCM became a main organizational concern targeting a continuous process of increasing SC efficiency where more complex SC structures need to be optimized for maximum profit under normal circumstances.

The increased size and complexity of supply chain operations leaves decision makers with a large quantity of information, which has been treated in order to be useful, heightening the ability to turn data into quantitative metrics that can be measured and monetarized, Bhagwat & Sharma (2007). Additionally, the SCM scope has been changing not only due to an increase of society's environmental concerns but also due to objectives drawn by economic activities. To meet this new paradigm, SC have been shifting from direct flows chain to Closed-Loop SC (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 also the result of strategies created to deal with e-commerce, re-use of products or customer service (Savaskan et al., 2004). This complexity of flows leads to an increased importance of identifying the right location of individual entities and how they can interact (Farahani et al., 2013; Mota, Gomes, Carvalho, & Barbosa-Póvoa, 2015; Mota et al., 2017).

Companies and academics have been involved in a joint effort to deeply develop SC as a whole towards sustainability (Barbosa-Póvoa et al., 2017; Brandenburg et al., 2014; Seuring & Müller, 2008). This leads to the appearance of models and frameworks applied to real case studies, for example, the study of IKEA's Corporate social responsibility in a global supply chain (Lindgreen et al., 2009).

In this changing context, where sustainable globalization is playing an increasing role and where SC are now more exposed to disruptions, SCR has emerged. However, it has received little attention, turning this topic underdeveloped, hence creating an opportunity to further studies (Kamalahmadi & Parast, 2016; Tang, 2006). Building awareness and knowledge regarding SC Risk Management and SCR is an important matter since disruptions, even with low probability of happening, can, if occurring, cause severe impacts on companies. Underestimate or inability to foresee the occurrence and consequences of an event can lead to disruptions with a high impact on SC operations, regardless of SC dimension or direct field of business. Thus, addressing SCR is a key factor for a sustainable supply chain advantage.

In this paper, we aim to provide a state of the art on how academics working in SC have been addressing resilience. Two main objectives are pursued: to understand how supply chain resilience has been comprehended 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 in a comprehensive new SCR definition. The interaction of the risk concept and SCR is analysed as well as the progress on the development of quantitative SCR models. A study on the methods used to build such models, the techniques applied as well as the decision levels treated is presented before addressing SCR metrics and strategies. With the new information obtained, research gaps and future directions for SCR are presented aiming to guide future work in the area.

2.3 Methodology

In order to produce valid work through the literature review, the methodology proposed in Barbosa-Póvoa et 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 steps are developed along sections 2.4 to 2.9.

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).

2.4 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 been suggested by the current research?
8. What challenges still lie for research on resilience in supply chain and which future directions should be taken?

2.5 Previous Literature Reviews

The scientific publications here analysed and studied in detail are the result of a search performed on the 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 classify only the Literature Reviews on SCR, resulting in three documents to be analysed:

- Wang, Junwei and Muddada, Raja R and Wang, Hongfeng and Ding, Jinliang and Lin, Yingzi and Liu, Changli and Zhang, Wenjun (2016), 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 (2015), 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, 17, 116-133
- Hohenstein, Nils-Ole and Feisel, Edda and Hartmann, Evi and Giunipero, Larry (2015), 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

Table 2.1: Supply Chain Resilience Reviews

Paper	**(J. Wang et al., 2016)**	**(Kamalahmadi & Parast, 2016)**	**(Hohenstein et al., 2015)**
Objective	Identify and classify SCN and access the state of SC Resilience	Research Development	Research Development
Research Methodology	Systematic Review	Systematic Review	Systematic Review
Papers	48	100	67
Years Analysed	1996 - 2009	2000 - 2014	2003 - 2013
Focus	SC Network	Organizational and SC Resilience Practices	SC Resilience phases and measurement
Approach	Qualitative	Qualitative and Quantitative	Qualitative and Quantitative
SC Relatives	-	Uncertainty and Risk	Uncertainty and Risk

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 2.1, regarding its objective, research methodology, focus, approach, supply chain relatives, papers analysed 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 a special focus on the conceptualization of SCR, its definition 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 & Parast (2016) 100 publications from the years 2000-2014 are reviewed in order to conclude on the research development on SCR. It develops a framework on the phases of SCR, different from those referred previously (Anticipation, Resistance and Recover & Response) as well as it considers other formalization on "Supply Chain Resilience Principles". This takes into account the different decision levels, from strategic to operational, and the current reality of supply chain complexity 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 related to unpredictable events, or in other terms unknown-unknown risks.

J. 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 emphasis on the behaviour of SC Networks due to its design and organization. The focus on Network Design comes as result of the economic development that leads to bigger and more intricate relationships among 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 (Kamalahmadi & 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 caused 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 on 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 & Parast, 2016). Hohenstein et al. (2015) divide the different possible strategies into two categories, proactive or reactive strategies and J. 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 a 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 definitions is performed proposing a framework to analyse and contextualise SCR definitions in its complexity. To do so a necessary work on the relationship between SCR and Risk, concepts that are often brought up together, was developed.

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.

2.6 Material Collection

Publications here presented and analysed were collected as the result of a set of searches on the Web of Science database where the following terms were explored: "supply chain" AND resilience AND 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. This resulted in an 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 and consequently the relevance of each paper was identified. This resulted in a more restricted set of publications, 56 in total, see Table 2.2. In this set, some publications appear for more than one term of search and then a total of 39 individual publications in a timespan from 2009 until 2016 was acknowledged.

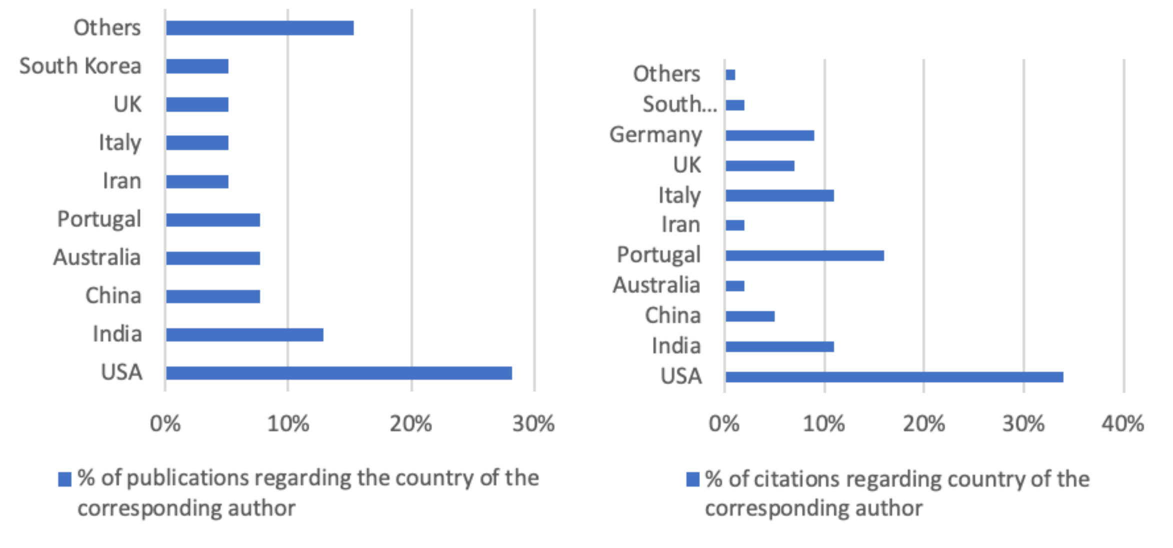
Table 2.2: Results of the initial material collection

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**

2.7 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, 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. These elements are possible to be obtained using HistCite Software. These are shown in Figure 2.1a from where 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.

When considering citations, some relevant changes are perceptible. Some publications are responsible for a vast part of the citations and on the other hand, several publications lack citations, consequently have a diminished impact. In Figure 2.1b it is observable 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



(a) **(b)**

Figure 2.1: Distribution of publications characteristics

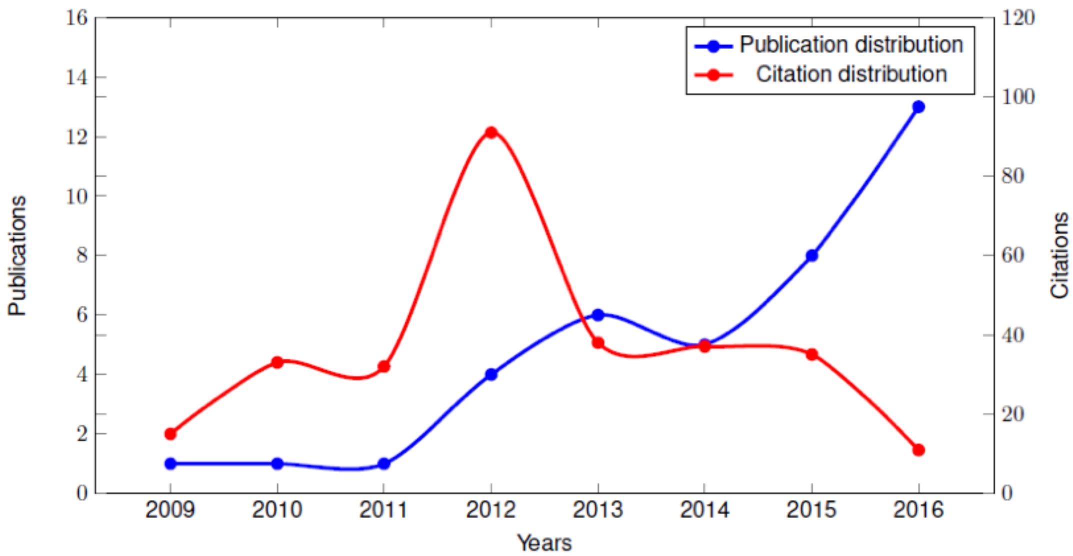


Figure 2.2: Distribution of publications and citations per year

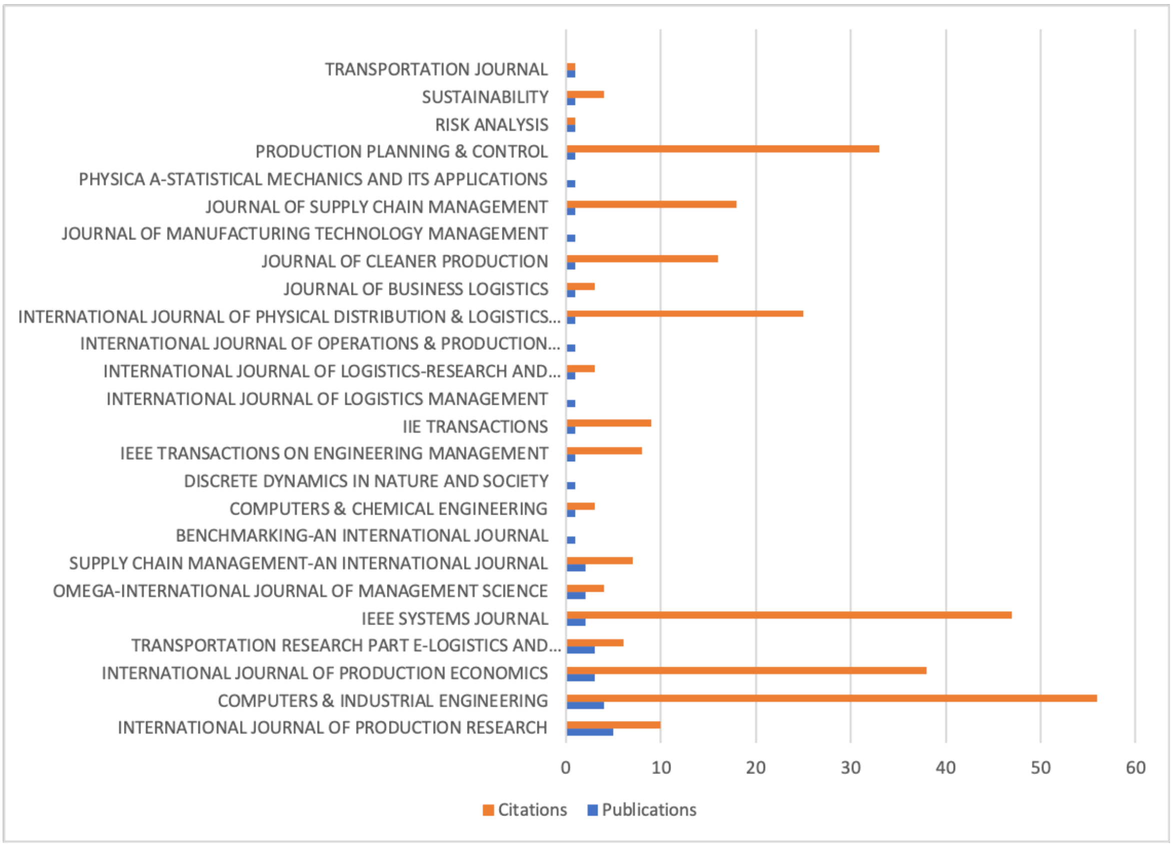


Figure 2.3: Journals present in the sample

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 & 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.

It is noticeable from Figure 2.2 (Plot in blue) 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 the timeline distribution of citations Figure 2.2 (Plot in red), a peak emerges in 2012, just after a period with fewer publications, suggesting that novel work was developed and a benchmark for publications that follow.

The sample here collected is distributed in 25 different Journals, Figure 2.3, 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 possible to infer on most recurrent concerns addressed. In Figure 2.4 the most common words are listed and besides the expected

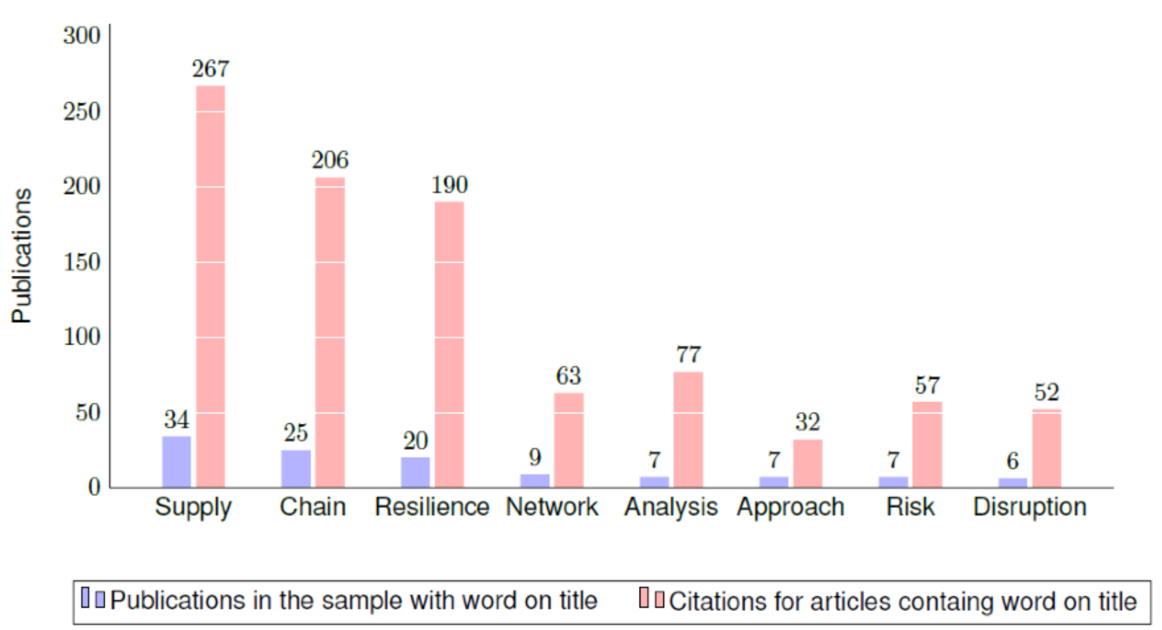


Figure 2.4: Word distribution in Title

"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 on studies that SC disruptions with risk management.

2.8 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 based on four structural dimensions, Figure 2.5: Type of Supply Chain; Decision Level of SCM; Publication Approach; and Model, which includes the Operations Research (OR) method used; the existence of resilience metrics; and observed industry.

- Type of Supply Chain: Forward, Closed Loop Supply Chain or Reverse Supply Chain
- Decision Level of SCM: What decision level was addressed in the model? (Strategic, Tactical or Operational?
- Publication Approach: How does the paper approach SCR and how it collects and returns information? (Case Study, Qualitative, Quantitative and eventual description Resilience Strategies)
- Model: How is the model implemented, considering three dimensions: Operation Research methods used; Resilience Metrics used; and if it looks into a generic example or to a particular industry.

Figure 2.5: Mind-map for Category Selection

2.9 Material Evaluation

2.9.1 Supply Chain Resilience Definition

(Research Question 1)

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

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

i Publications present in the publication sample defined in Material Collection, Table 2.3;

ii Publications with relevant content present in the original publication sample defined in Material Collection, that were later excluded from further analysis due to the conditions imposed in Previous Literature Reviews or Material Collection, Table 2.4;

iii Cross-referencing other publications relevant to the formulation of SCR definition that were not present in any of the original search results, Table 2.5.

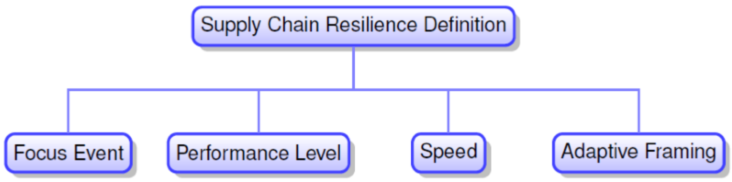


Figure 2.6: Mind-map for SCR Definition analysis framework

Applying this procedure resulted in a sample of 27 publications, from 2003 to 2016. This will be used in the discussion on SCR definition and on the relationship with Risk.

In 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. Resilience in SC context has been described in simpler and broader terms by several authors, by implicitly stating that SCR can be described as the ability of the SC to withstand changes of steady-state and converge to the original state or to a new desirable state (Rice & Caniato, 2003; Christopher & Peck, 2004; Christopher & Rutherford, 2004; Erol et al., 2010; Carvalho, Azevedo, & Cruz-Machado, 2012; Xiao et al., 2012; Wieland & 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 based on the different scientific goals of the original publication.

There are examples of succinct definitions with interesting approaches including elements such as the concept of time in terms of speed (Brandon-Jones et al., 2014) or chronology position to a disruption or disturbance (Gaonkar & 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 focus events on SCR. "Disruptions", "Unexpected events", "Risk Events" or "Disturbances" are terms used to characterize a trigger event that changed the SC from its 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 the convenience of interpretation and as a 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.

From the analysed literature is possible to purpose a new framework to understand, evaluate and create SCR Definitions. The framework proposed is presented in Figure 2.6. It relies on four pillars that should be accounted for: Adaptive Framing or Stage Adaptive Response; Speed; Performance Level; Focus Event.

Table 2.3: Supply Chain Resilience Definitions – i)

Authors	Definition	Year
Ponomarov, et al	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, et al	The apparent ability of some supply chain 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, et al	The capability of supply chain 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, et al	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, et al	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, et al	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, et al	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

Table 2.4: Supply Chain Resilience Definitions – ii)

Authors	Definition	Year
Geng, et al	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, et al	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, et al	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, et al	The ability of a supply chain to return to normal operating performance, within an acceptable period of time, after being disturbed.	2014
Birkie, et al	The ability of a business to anticipate, and adapt to sustain and recover operations against disruptions	2016

Table 2.5: Supply Chain Resilience Definitions – iii)

Authors	Definition	Year
Rice, et al	The ability to react to unexpected disruptions and restore normal supply network operations	2003
Christopher, et al	The ability of a system to return to its original state or move to a new, more desirable state after being disturbed	2004
Christopher, et al	The ability of a system to return to its original (or desired) state after being disturbed	2004
Closs, et al	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 chain quickly rebuild or re-establish alternative means of operations when the subject of an incident.	2004
Gaonkar, et al	The ability to maintain, resume, and restore operations after a disruption	2007
Priya Datta, et al	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, et al	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, et al	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, et al	Is a response to unexpected or unforeseen changes and disturbances, and an ability to adapt and respond to such changes.	2010
Carvalho, et al	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
Ponis, et al	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 favourable than the one prior to the event, thus gaining competitive advantage.	2012
Carvalho, et al	The ability of supply chain to cope with unexpected disturbances.	2012
Ponomarov	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, et al	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 supply chain show abilities on adaptability to environment and recovery.	2012
Kim, et al	As a network-level attribute to withstand disruptions that may be triggered at the node or arc level.	2015

2.9.1.A 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, SCR can be seen as a series of adaptive responses in a multi-stage approach regarding the potential events. Closs & 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 characterization of the elements to face incidents was identified, it misses the awareness on the importance to maintain a steady-state solution after the recovery from a disruption. S. Y. Ponomarov & Holcomb (2009) propose 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 & Koronis, 2012; S. Ponomarov, 2012; Hohenstein et al., 2015) or in the work presented by (Kamalahmadi & Parast, 2016) that provided a brief description of the goals for each stage to meet SCR.

It is then crucial that stakeholders involved in SCR define the concept and embrace the concern as not being a reaction in a specific individual moment but as a broader concept where the above elements are accounted for. It is therefore important to consider the presence of these elements when analysing SCR definitions.

2.9.1.B 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 & McGarrell (2004) introduce the concept of speed in SCR 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); S. Ponomarov (2012) deal with the time concern with a different approach. They do not apply the word "quick" instead, the concern relies on diminishing the time to recover, in the first, and to simply recover in a "timely manner" in the latter. Ponomorov lists two definitions accounting for time, one from 2009 and the more recent from 2012, with the main difference being the introduction of speed concerns in the SCR definition.

Concluding, it is relevant for SCR 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.

2.9.1.C 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); Kamalahmadi & Parast (2016) address SCR 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 occurs by referring the efforts on identifying, anticipating and preparing for events (S. Y. Ponomarov & Holcomb, 2009; Ponis & Koronis, 2012; S. Ponomarov, 2012; Hohenstein et al., 2015; J. 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 SCR. It is relevant to consider the consequences and how the system responds to a disturbance (Falasca et al., 2008; S. Y. Ponomarov & Holcomb, 2009; S. Ponomarov, 2012; J. Wang et al., 2016; Kamalahmadi & Parast, 2016). An objective and simple consideration that can be formulated is related to the ability of the system to maintain control during the disturbance (S. Y. Ponomarov & Holcomb, 2009; Ponis & Koronis, 2012; S. Ponomarov, 2012; J. Wang et al., 2016; Kamalahmadi & Parast, 2016) or to sustain the occurrence without significant impact (Berle et al., 2013).

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

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

2.9.1.D Focus Event

Several events are associated with SCR. 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 & McGarrell, 2004) comes as a simpler and broader term in contrast to the most frequent, in the set studied, Disruption (Falasca et al., 2008; S. Y. Ponomarov & Holcomb, 2009; Ponis & Koronis, 2012; S. Ponomarov, 2012; Kim et al., 2015; Hohenstein et al., 2015; J. 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 SCR are those that abruptly stop operations completely blocking value creation activities.

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

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

Being the lack of applied work a concern for many authors, discussed previously in Previous Literature Reviews, comes as no surprise the fact that few SCR definitions approach the level of SCM. Ponis & Koronis (2012); Kim et al. (2015) include such element by suggesting that SCR is a function of the planning and designing of the network concluding that SCR should be addressed on a Strategic Level. Although, relevant to the operationalization of SCR, 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 SCR strategies to be applied on a strategic level and on a more operational state.

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.

2.9.2 Risk on Supply Chain Resilience

(Research Question 2)

The relationship between Supply Chain and Risk is present in SCR, being this discipline derived from SC Risk Management andSCM (S. Y. Ponomarov & Holcomb, 2009; König & Spinler, 2016).

Jüttner & Maklan (2011) state that there is an already acknowledged relationship between SCR, Vulnerability (SCV) and SC Risk Management, proposing that the three concepts are complementary for a well-designed SC.

Publications focused on SC Risk Management also address SCR much due to the natural relationship between concepts. For example, Heckmann et al. (2015a) created a framework for SC Risk Management where SC Risk is represented as a 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 is 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 in SCM can be addressed through the concept of SCR, where a positive impact exists between Risk Management and the need/awareness for investment in resilience (S. Y. Ponomarov & Holcomb, 2009). This relationship can result in the use of strategies to reduce risk or the consequences related to a particular event (S. Y. Ponomarov & Holcomb, 2009). However, it is not guaranteed that a risk correction measure would benefit SCR (Jüttner & Maklan, 2011).

One relevant characteristic to be considered is the velocity for a risk event. Jüttner & 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 newly 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 2.9.1.

Conventional Risk Management relies on the 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 the risk of an uncertain and complex future (Pettit, Fiksel, & Croxton, 2013). SC Risk Management 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 & 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, Fiksel, & Croxton (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.

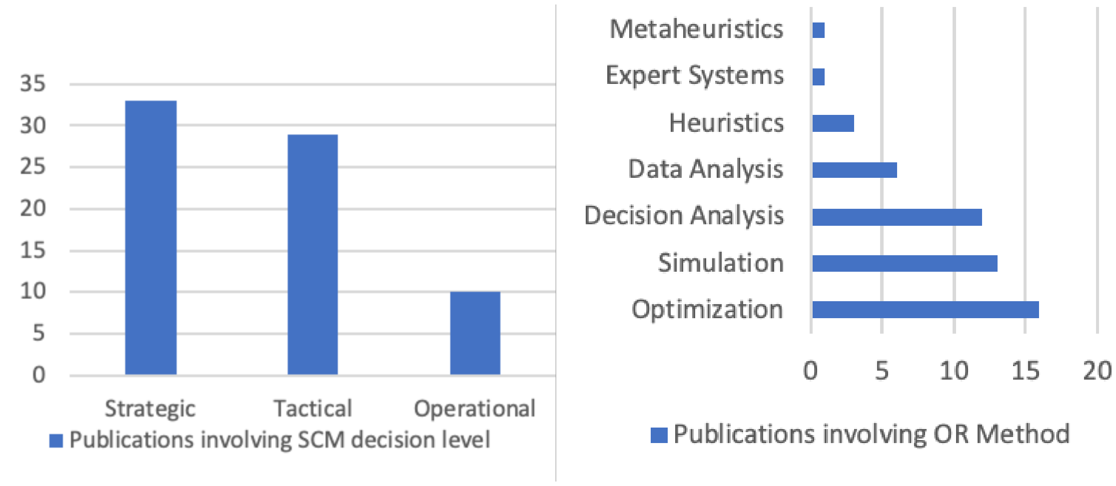
Resilience can be seen as an offspring of SC Risk Management and SCV concepts leading to the necessity of addressing such elements in combination (Pereira et al., 2014), revealing that it might not be possible to implement resilience driven actions in an isolated form. Additionally, complex SC, with 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 SC Risk Management.

Concluding and in order to address resilience, companies must be aware of their exposure to risk, which implies a continuous Risk Analysis and Assessment (S. Y. Ponomarov & Holcomb, 2009).

2.9.3 Supply Chain Resilience quantitative models and SCM 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 the SCR definition endorsed.

Models must define its scope and one relevant measure for scope is the level of the decision within the SCM framework. When the distribution of the decision level is analysed, Figure 2.7a, it provides a simple and effective way to analyse at what decision level models have been aiming to. Strategic decisions 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 to



(a) **(b)**

Figure 2.7: Model characteristics distribution

tactical decisions leads to most of the authors to consider tactical factors synchronized with strategic concerns.

The OR methods present in the different publications, Figure 2.7b, 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. 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, most in form of a case study (24 Publications). 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 some models that focus on the same industry as, for example, the case of aeronautics or the retail industry, with two representative cases each, and electronics with three examples (Rajesh & Ravi, 2015a; Rajesh et al., 2015; Rajesh & 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. With SC dealing with great distances and minimal time objectives aircrafts are often used to fulfil such objective. D. Wang & Ip (2009) deal with SC Network Resilience applied to the field of Aircraft Service, crucial for continuous flow of aircrafts, by quantifying resilience as dependent on Demand and Supply, with its redundant possibilities, thus simplifying quantification and interpretation. However, reducing the variability of inputs that real life systems suffer. Thekdi & Santos (2015) propose 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.

Authors proceed with different approaches on the construction of quantitative models, much depending on its goals regarding the scope, depth and application of the model. Harrison et al. (2013) create 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 & Khosrojerdi (2016) create 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. 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 three levels of analysis (customer, retailer and manufacturer) taking also into consideration the customer behaviour and its impact. Wu et al. (2013) propose an agent-based simulation model and Schmitt & 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 in several published works. For instance, Fahimnia & Jabbarzadeh (2016a); Mari et al. (2014) study the impact of green SC to SCR, 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. In their work, there is sustained evidence that allows for the possibility of achieving 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.

2.9.4 Strategies and Metrics applied in Supply Chain Resilience quantitative models

(Research Questions 6 and 7)

SC Resilience Strategies and Metrics vary as authors and objectives change. This is made clear in Table 2.6, where the set of factors that are explicitly applied to SCR are summarized.

From our research, only three publications (Azevedo et al., 2016; Soni et al., 2014a; D. Wang & Ip, 2009) quantify SCR in a Single Index, using a set of 21 factors to measure Resilience goals of a particular SC, Factors Ri in Table 2.6. Most of the identified publications tend to incorporate SCR factors in the models, being those factors crucial for results interpretations, but do not aim at creating a SCR Index. From the identified set of papers, it is possible to extract 48 Resilience Factors, Factors Fj in Table 2.6, which the different authors apply in order to provide better information regarding SCR.

Table 2.6: Resilience factors present in models to quantify SCR

Paper	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: Sustainability R6: Risk and revenue sharing R7: Trust R8: Visibility R9: Risk management culture R10: Adaptive capability R11: Structure
Azevedo, et al - 2016	R12: sourcing strategies to allow switching of suppliers R13: flexible supply base/flexible sourcing R14: strategic stock R15: lead time reduction R16: creating total supply chain visibility R17: flexible transportation R18: developing visibility to a clear view of own stream inventories and demand conditions R19: Agility R20: Collaboration R21: Information Sharing
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, et al - 2015	F26: Recovery F27: Impact F28: Performance Loss

Table 2.6 continued from previous page

Paper	Factors
	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, et al 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

Analysing the papers that propose a single index, it is interesting to see that the work by D. Wang & 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. (2014a) 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 a 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 2.6, 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 based on a military hierarchy. Adenso-Diaz et al. (2012) deal with reliability on SC and look 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, the authors state that supplier selection should be performed taking into consideration the resilience capabilities of the involved entities. Munoz & Dunbar (2015), recurring to Structural Equation Modelling (SEM), create a model to quantify resilience characterizing the response to a disruption of the system performance over 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 proposed. Such indicators are grouped into 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 & Barker (2016) create a Bayesian Network model to assist in the decision where resilience is a structural element characterized by a set of seven criteria related to the resilience of suppliers (see table 2.6: 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 with 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 they 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 J. Han & 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 & 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. (2016a) 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 & Marcus Wallenburg (2013) create a model involving a survey of 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, Barroso, 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 commonly addresses the minimization of SC Costs/ maximization of Net Present Value, under a more or less elaborated set of variables considering a set of 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); Y. Wang & Xiao (2016) propose a model to address SCR on SC that is keen to cascade 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 & Ravi (2015a) study the cause-effect relationships of enablers of SC Risk Mitigation (15 identified enablers) in a three-step model (Grey-DEMATEL). The work resulted 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 & Ravi (2015b) use 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, M. M. H. Chowdhury & Quaddus (2015) list 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 weight and expected capacity to mitigate disruptions.

Upstream disruptions are a particular disruptive event and can be understood as a concern regarding the supply side of a Supply Chain. Gualandris & Kalchschmidt (2015) focus 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 the 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 & 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 supply chain not only creates a supply chain 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. Colicchia et al. (2010) study such element on SC using a hub and spoke system. They implement a simulation model and identify contingency plans, mitigation actions as well as vulnerabilities that endanger the successful accomplishment of activities. 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).

2.10 Research Gaps and Future Directions

From the literature analysed it can be stated that the scientific field of SCR is on a positive path with more knowledge and applications being developed recently. This is advancing SCR and its applicability to real-life situations. Regardless, further research is needed, which should follow some important directions, as below discussed.

The recurrent need for the extensive characterization of the term Resilience in a SC context comes from the inexistence of a clear definition of SCR, which can be used in different possible contexts. At the current stage of research, the work already done with such objective is significant. However, further developments are required to consolidate the work already performed on SCR definition. Researchers should converge to a stable SCR definition, embracing the fact that SCR is an aggregating concept, involving expertise already created on other fields of SCM, such as Risk Management. In this paper, we have proposed a new definition that encompasses the different concerns listed and discussed in the analysed papers.

Within the analysed literature, a relationship between risk and resilience is perceptible when considering a chronological evolution. SCR comes 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 the low impact and frequent risks, often neglecting high impact risks as is the case of low probability disruptions (Z. Li & Gulati, 2015). Resilience awareness can mitigate such neglect and the combination of such concepts should than be further researched.

As seen in this paper, 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 many of these networks representing a global operation. The ability to acquire knowledge of already implemented strategies to cope with such kind of scenarios is of greater importance. The complexity of real-life systems is something still to be explored. Quantitative models can help in this study and can act as tools to 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 done in order to measure comprehensively SCR, not focusing on a concrete part of a SC operation but adopting a global view. It is crucial that new OR methods are implemented, exploring the development of artificial intelligence like the deployment of Expert Systems supported by optimization tools. Created models are often limited as they often fail to represent reality. Thus, the creation of more holistic models regarding complex SC that incorporate reverse flows and account for the SCR elements is essential. The integration of different OR methods should also be explored, as for instance decision analysis methods combined with optimization would allow the translation of qualitative concepts, often present in SCR problems, into quantified forms that can be tackled by optimization.

The construction of more realistic models may lead to an increase in complexity, which can reveal difficulties in their solution. Thus, the research community should explore the development of faster alternative solution methods such as meta-heuristics.

Within the models, performance metrics assume a key role. However, these are only appropriate if they accurately measure the transient results along several tiers of the SC in different disruptive scenarios. This is still an area in need of further research due to its relevance when applying SCR models in real decision making, as it ultimately allows an increased knowledge on the complete SC functioning.

Additionally, developing efforts on SCR strategies at 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 imperative.

2.11 Conclusion

In this paper, a systematic literature review was performed, aiming to identify the existent definitions of supply chain resilience and to understand the development progress of quantitative models to support SCR decisions. This is a topic of 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 on the use of quantitative models. Our paper contributes to reducing such gap.

We start by presenting a study on SCR definition, identifying the different authors' approaches and conceptualizations proposed. This lead to the development of a novel framework, that translates the pertinence and scope of SCR and supports a new, proposed, sound definition for SCR, which 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.

From the work developed, it can be stated that the implementation of resilience practices can be one efficient and important strategy for enterprises to create competitive advantage. Also, the relationship between resilience concerns and risk events was acknowledged.

The use of quantitative models to support decisions when building and operating resilient supply chain was shown to be prominent and a set of challenges was presented to further develop and implement SCR using quantitative models. A clear need for the improvement of decision-making tools so as 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.

SC Resilience is, in 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

Literature Review - A view at the tactical and operational level

Contents

In Section 3 the literature review for the tactical and operational level of decision is presented. This article was created in collaboration with Márcia Batista under her work to obtain a MSc. The article is currently accepted and awaiting publication in Operational Research to be published in a book of Conference Proceedings.

3.1 Abstract

The field of SCR has been growing in recent years but has become particularly relevant during the pandemic. Modern SC, characterised by their global presence and complex structure, are increasingly vulnerable to disruptions. As a result, companies are shifting from a reactive approach to building resilience. As resilience has been mainly analysed at the strategic level, this work aims to assess the current state of the art on SCR quantitative models that support tactical-operational decisions. This is done through a comprehensive literature review where the SC's main activities were considered, as well as the use of OR methods to build quantitative approaches. It is also studied how these publications model risk and uncertainty and which resilience metrics have been used since these might be highly influenced by the context in which the models are developed. The results make a set of outcomes available to the community: a set of approaches to deal with the tactical-operational problems; and a list of SCR indicators to measure and monitor SCR. Finally, a research framework for tactical-operational resilient SC is proposed, where the main problems that still require further research attention are identified.

3.2 Introduction

Modern SC have become increasingly exposed to unpredictable events due to globalisation and complex structures involving multiple dispersed nodes (Christopher & Peck, 2004; Kamalahmadi & Parast, 2016; Saha et al., 2020). Supply chain risk management struggles to deal with these disruptive events, highlighting the need for resilience management (Fiksel, 2015). Recent history has shown that these events will continue to occur, making it essential to plan for them to maintain a competitive advantage (Munoz & Dunbar, 2015). Although SC faced several disruptive events before, the COVID-19 pandemic (Golan et al., 2020a; Modgil et al., 2021) and, more recently, the war in Ukraine (Valtonen et al., 2023; Faggioni et al., 2023) have further highlighted the need for resilient SC as companies shift their focus from efficiency to resilience (Lund et al., 2020).

Historically, SC have been designed for a narrow range of conditions, leaving them vulnerable to unpredictable events (Alicke & Strigel, 2020; Christopher & Peck, 2004). SC have also become more complex, involving relationships with multiple actors who play vital roles in each other's SC, making it crucial to consider these relationships (Lau et al., 2008; Ghosh & Jaillet, 2022). The current pandemic has increased awareness of the importance of resilience in SC management (S. Y. Ponomarov & Holcomb, 2009; T. Nguyen et al., 2018). However, existing literature on SCR focuses heavily on qualitative insights, with limited quantitative contributions, especially at the tactical-operational level (Ribeiro & Barbosa-Povoa, 2018). This gap is important to address, as these quantitative models can provide valuable aid to decision-makers in evaluating and adopting strategies towards resiliency.

This work aims to construct a reliable assessment of the state of the art of SCR operations research with a focus on the tactical-operational level through a literature review methodology. Relevant content is retrieved, reflecting the established research questions, which are then thoroughly analysed. Insights that can be drawn from recent research on the effects of the current pandemic are discussed. The focus is then directed to four general categories (distribution, inventory, production, and generic SC). Finally, the metrics used are identified, and the results are discussed, proposing a framework for future research.

The remainder of this work is organised as follows: Section 3.3 describes the methodology adopted throughout the review. Section 6.4 reviews previous literature in this field of research, positioning and distinguishing this review from existing ones. Following the analysis, a set of research questions are established in Section 6.5 to guide the present work. The material collection procedure is described in Section 6.6, followed by selecting categories to attribute structural dimensions to the sample in Section 6.8. The content of the retrieved papers is then evaluated to answer the research questions in Section 6.9, which are then discussed in Section 3.9 to provide future research paths. Finally, Section 3.10 concludes this paper with final considerations and presents the main outcomes.

3.3 Methodology

The methodology adopted in this work follows an adapted form of the one presented by Ribeiro & Barbosa-Povoa (2018), consisting in six main steps, which will constitute sections of this paper in the following order: Previous literature reviews; Research questions; Material collection; Descriptive analysis; Category selection; Material evaluation.

3.4 Previous literature reviews

In order to position the present paper, a search on the Web of Science core collection database was performed for literature reviews on "supply chain" and "resilience" published in English from 2010 (when the number of papers published on the theme increased as presented in Ribeiro & Barbosa-Povoa (2018)) up to December 2021. An initial dataset of 236 results was obtained, then refined to 22 by excluding those that did not specifically address SCR or focus on analysing a particular event.

All authors have acknowledged that research on SCR has been steadily increasing in recent years, with the early 2000s being identified as the starting point and 2003 as a turning point due to the increased focus on developing solutions after highly disruptive events such as the 9/11 attacks, however with scarce publications overall (Hohenstein et al., 2015; Ribeiro & Barbosa-Povoa, 2018). The work by Katsaliaki et al. (2021) sheds light on the diverse nature of SC disruptions and offers a deeper understanding of their root causes and consequences, providing a comprehensive list of SC disruptions and their mitigation strategies. Despite the increasing attention towards SCR in light of the COVID-19 pandemic, there is still a gap in addressing low-demand products as most papers are regarding high-demand products (P. Chowdhury et al., 2021).

The literature reviewed has acknowledged that there is a lack of a clear definition of SCR in the literature due to the multidisciplinary nature of the term resilience and the ambiguity surrounding SCR elements and their interdependence. This issue has also been identified as hindering the development of a single definition of SCR (Hosseini et al., 2019). As a result, earlier literature reviews have focused on developing and clarifying conceptual terms such as SCR principles, elements, and strategies, intending to propose well-founded definitions of SCR. The earliest reviews, in 2015, (Hohenstein et al., 2015; Tukamuhabwa et al., 2015), where both proposed a solid definition for SCR. The former focused on identifying SCR phases (readiness, response, recovery and growth), elements and metrics, while the latter assessed the most cited strategies. Additional to these reviews, Kamalahmadi & Parast (2016) focus on SCR principles, proposing a framework incorporating major components of a resilient SC.

Later on, surged works that pursued other qualitative objectives. A. Ali et al. (2017) took the constructs of the existing SCR definitions to develop a concept mapping framework to provide clarity on the subject of SCR for both managerial and research implications, identifying: phases (pre-disruption, during disruption and post-disruption), strategies and capabilities. Ribeiro & Barbosa-Povoa (2018) propose a framework for a holistic approach towards SCR (Focus event, Performance Level, Adaptive Framing, Speed). Posteriorly, Zavala-Alcívar et al. (2020) extended on previous works by presenting three building blocks as a framework, whose goal is to integrate key components for analysis, measurement and management of resilience to enhance sustainable SC.

In fact, there is a three-way attention that still has to be given to SCR. As seen above, conceptualization is still a topic of interest, but academics and practitioners should also devote attention to implementation methods and the measurement of SCR (Negri et al., 2021). By doing that, further relationships with other fields of SCM can be established, thus positively affecting SC performance.

It can be seen that there are context-specific literature reviews, such as those that propose specific definitions for SCR in third-party logistics providers (Gkanatsas & Krikke, 2020) and agri-food supply chains (AFSC) (Stone & Rahimifard, 2018). Despite some papers presenting quantitative approaches, the depth of these approaches is limited in most cases (Hohenstein et al., 2015; Kamalahmadi & Parast, 2016; Kochan & Nowicki, 2018; Centobelli et al., 2020; Zavala-Alcívar et al., 2020). There is a lack of literature on quantitative models and metrics for SCR (A. Ali et al., 2017; Hosseini et al., 2019; Kamalahmadi & Parast, 2016; Ribeiro & Barbosa-Povoa, 2018). Further research on this topic is important as it can aid decision-makers in adopting effective strategies and assessing performance (Gkanatsas & Krikke, 2020; Ribeiro & Barbosa-Povoa, 2018; Y. Han et al., 2020).

Ribeiro & Barbosa-Povoa (2018) conducted a content analysis to study OR methods and metrics used in SCR models. The authors found that the models were scarce and mostly focused on the strategic level. Hosseini et al. (2019) later explored analytical approaches to SCR and clarified the significance of three capacities (absorptive, adaptive and restorative), presenting an analysis of the key drivers for each capacity. The findings were categorized based on the capacities. Y. Han et al. (2020) aimed to connect SCR capabilities to performance metrics, identifying 11 capabilities and associating them with three dimensions of SCR, but literature was lacking for three capabilities. The three previous reviews provide a foundation for understanding the integration of resilience into mathematical models within SCM. However, there is still a gap in assessing the key constructs required for tactical-operational models. The current paper aims to reduce this gap; therefore, a set of research questions to support such work is presented in the next section.

3.5 Research questions

Five research questions were established to attain this paper's goal, which will serve as a guide throughout this work. Considering the recent Covid-19 as a worldwide disruption, and in order to understand how it was treated within SC, the following research question is defined:

1. What insight can be withdrawn on SCR from COVID-19 pandemic responses?

Having the context and focusing on the analysis of SCR quantitative approaches to the tactical-operational problems, the following questions aim to be answered:

2. How has tactical and operational resilience been tackled in SC?
3. How have OR methods been used to support tactical and operational decisions?
4. How have uncertainty and risk been modelled in tactical and operational problems?
5. Which resilience quantitative metrics have been used in tactical and operational problems?

3.6 Material collection

With the goal of retrieving significant articles, a set of keywords was established to conduct a search on the Web of Science collection database. The keywords considered were "supply chain" and "resilience" with the combination of each of the following terms: "tactical"; "operational"; "quantitative"; "optimization"; "simulation"; "heuristics"; "metrics"; "routing"; "scheduling"; "statistics" and "COVID-19". All searches were restricted to publications in peer-reviewed journals, written in English, and published between 2010 and December 2021. Further refinements were applied, guaranteeing relevance by meeting the following selection criteria: Articles must have SCR as the main focus; purely qualitative approaches were excluded; articles that focus solely on a strategic-level problem were excluded. After removing the duplicates, a set of 385 papers was obtained, which was reduced to 42 articles, following the rules above. An exception was made to publications addressing the current pandemic, thus retaining six papers for that sole purpose.

3.7 Category selection

Considering the span of the collected material, it is pertinent to define structural dimensions in order to guide the following material evaluation and appropriately answer the established research questions. Hence, the papers are categorized following the logic depicted in Figure 3.1, accounting

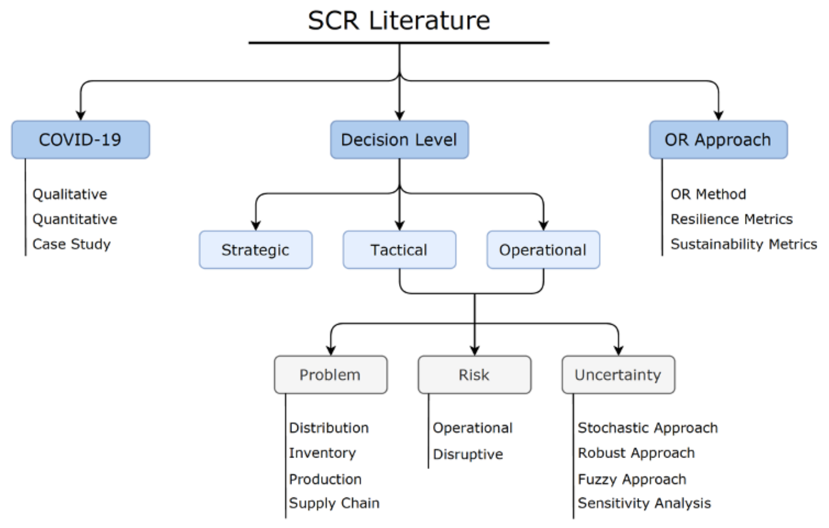


Figure 3.1: Mind-map for category selection

for three main dimensions: COVID-19 outbreak; Decision level; OR approach. COVID-19 is included because it acts as a disruptive event without precedents; Decision level as this describes in an aggregate form the decisions taken in the SC; OR approach is taken as the basis to build quantitative tools.

3.8 Material evaluation

3.8.1 Insights on SCR from COVID-19 outbreak responses (Research Question 1)

On March 11th, 2020, the World Health Organization (WHO) declared COVID-19 a global pandemic, causing worldwide disruptions that lasted longer than expected. Even as the health effects of the pandemic have improved, the crisis's further evolution and impacts remain uncertain. The severity of this crisis on SC mostly derives from the simultaneous impact on supply and demand due to forces reshaping the business environment, as explored in the previous section. Despite verifying many commonalities across sectors on the caused effects, overall disruptions are essentially industry-specific (Marzantowicz, 2020). Hobbs (2020); Zhu et al. (2020) address food and medical SC, respectively, where a Just-In-Time philosophy is adopted and concluded that these were not able to withstand unpredictable spikes in demand fully, be it from panic buying of groceries or increased necessity for high volumes of personal protective equipment, which led to short-run stockouts.

Marzantowicz (2020); Rapaccini et al. (2020) report disruptions to SC operations due to protective regulations, decreased orders, and longer transport times. Many managers had to delay deliveries because of difficulties filling and securing transportation. Remko (2020) found that companies are reducing reliance on single suppliers and increasing the use of local and nearshore options. de Assunção et al. (2020) concluded that shorter SC were less impacted by transport restrictions due to closer proximity to regional suppliers. Technological investments in digitization and cooperation between entities have been identified as crucial for improving SCR (Remko, 2020; Marzantowicz, 2020; Zhu et al., 2020). Inventory management changes and strengthened relationships have also been highlighted as key strategies (Hobbs, 2020; Zhu et al., 2020). However, more data is needed for further study at the tactical and operational level (Zhu et al., 2020).

3.8.2 SCR quantitative models on the tactical and operational level (Research Questions 2 and 3)

In this section, we review studies that address the impact of disruptive events on SC strategies and the use of OR models to facilitate decision-making. Firstly, we examine studies that validate strategies present in qualitative literature and provide insights that can benefit tactical and operational decisions. Secondly, we analyse papers focusing on tactical and operational problems and develop OR models to support decision-making.

Collaboration between entities can be crucial during disruptive events and can aid in increasing the responsiveness of the entire SC. Using agent-based simulation Lohmer et al. (2020) show that implementing blockchain technology can increase collaboration and agility but require suitable expertise and depend on the length of the disruption. Additionally, Aggarwal & Srivastava (2019) use a grey-based Decision Making Trial and Evaluation Laboratory (DEMATEL) approach to study how to build collaborative, resilient SC and find that top management commitment is the most prominent factor. However, they also find that collaboration culture and design resilience in operations strongly influence the remaining success factors.

Various strategies have been proposed to improve SCR in the literature. The work of Azadeh et al. (2014) found that redundancy and visibility were effective strategies for a transportation system in a 3-echelon SC. Salehi et al. (2020) also found that redundancy was important in a pharmaceutical SC, specifically in the form of additional storage capacity. Zhao et al. (2019) studied the impact of reactive and proactive strategies in a complex adaptive system and concluded that proactive strategies were overall superior. M. M. H. Chowdhury & Quaddus (2015) identified eight strategies for improving SCR, including backup capacity, building relationships with buyers and suppliers, and adopting technology. Gholami-Zanjani, Jabalameli, & Pishvaee (2021); H. Nguyen et al. (2021); J. Chen et al. (2021) and Moosavi & Hosseini (2021) study the impact of different strategies under SC disruptions, either by MILP or simulation approaches with similar conclusions that profit losses can be reduced by proactively looking at SCR. Overall, the literature suggests redundancy, visibility, and proactive strategies can effectively improve SCR.

Models that tackle SCR problems and support decisions at the tactical-operational level are now separated into four general categories: **Distribution problems**: regard coordination of product flows through optimization of supply lead time and routing assignments; **Inventory problems**: solutions for inventory management decisions; **Production problems**: planning and scheduling considerations for production; **Generic Supply Chain problems**: models that tackle the implementation of recovery policies and timely allocation of resources in more than one SC activity.

The literature review revealed that production issues are underrepresented in quantitative SCR research, while distribution, inventory, and integrated activities in the recovery process are more

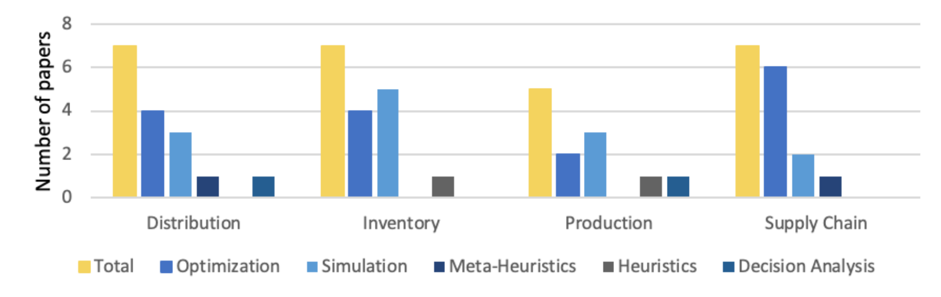


Figure 3.2: OR methods employed in tactical-operational problems

prevalent. This is evident in the graph shown in Figure 3.2 (yellow bars), which also shows the most commonly used OR method for each problem. Optimization and simulation are the preferred methods, with the occasional use of meta-heuristics, heuristics, and decision-analysis methods.

3.8.2.A Distribution Problems

In the face of disruptions to a SC, various strategies and methods have been proposed to enhance resilience. Harrison et al. (2013) proposed the READI optimization model, which iteratively deletes a component from the network and inserts mitigation strategies, such as re-routing product flow for short-term resilience. X. Wang et al. (2016) focus on disruptions specifically to supplier nodes and investigate how changes in Decision Makers' preferences for suppliers affect the coordination of product flows. Ayoughi et al. (2020) propose a four-objective model for a Closed-Loop Supply Chain that balances sustainability and risk minimization, relying on meta-heuristic algorithms for the solution approach.

Studies on SCR to natural hazards can be found for the New York motor-fuel SC and New Zealand's forestry SC. Beheshtian et al. (2017) address distribution routing in a bi-stage integer non-linear stochastic model as a planning tool for decision-making in New York. Childerhouse et al. (2020) evaluate the New Zealand case through a two-tier modelling approach, using optimization and micro discrete event simulation for port closure scenarios.

A major concern in optimizing product flow is the potential impact of lead time on SC operations. Researchers have used supplier lead time variability as a proxy for SCR, as seen in the work of Colicchia et al. (2010); Chang & Lin (2019). These studies test different contingency plans and mitigation strategies to address lead time issues.

Figure 6.6 proposes an approach to SCR in distribution problems at the tactical-operational level, highlighting key considerations. Two main approaches to studying SCR are reactive, where re-routing is the most common strategy, and proactive, where representative longer-term contingency plans are implemented.

Inventory Problems

Unexpected spikes in demand can cause companies to fail to meet customer needs. Schmitt & Singh (2012) use the percentage of immediately satisfied customers as a performance metric in

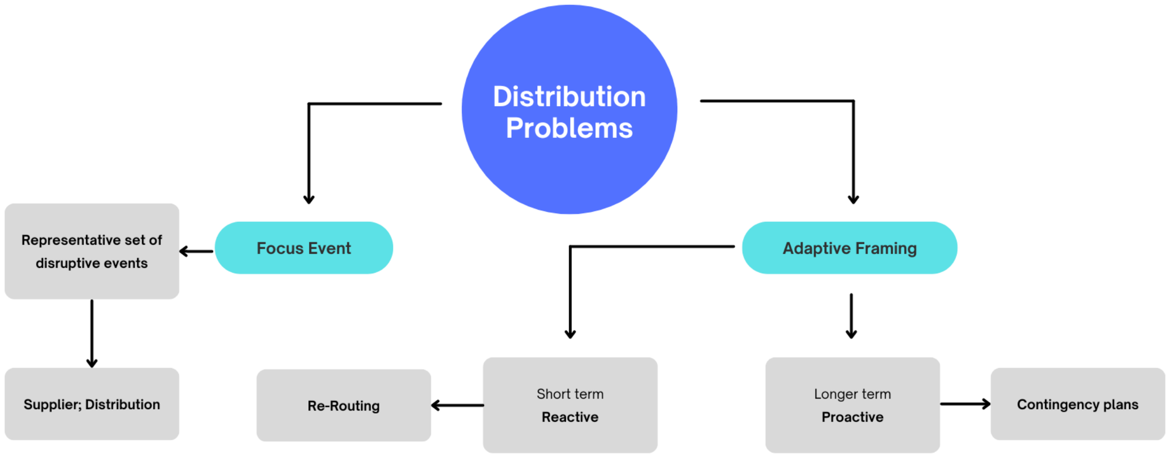


Figure 3.3: Proposed generic approach toSCR in distribution problems

their discrete-event simulation to analyse inventory placement and backup capabilities for improved system resilience. Similarly, Wu et al. (2013) study the effects of stockouts on consumer response, market share, and stockout duration through agent-based simulation. Lücker & Seifert (2017) use stockout quantity and time as SCR metrics to determine optimal risk mitigation inventory levels. To prevent supply-demand mismatches, Spiegler et al. (2016) use a simulation model with non-linear control theory to assess the SCR of a grocery SC's Distribution Center (DC) replenishment system. Gholami-Zanjani, Jabalameli, Klibi, & Pishvaee (2021) study a Robust Location-Inventory Problem, taking into account the decision-maker's level of risk aversion.

Recent research on inventory management in SCR has yielded novel approaches, such as the simulation-based optimization model developed by Yang et al. (2017), which determines inventory decisions and cost reductions in the event of disruptions to an interconnected network to enhance SCR. Similarly, Gružauskas et al. (2019) examine how information sharing and collaboration can improve forecasting accuracy and market integration. They use agent-based simulation with machine learning algorithms to enhance system resilience.

When dealing with inventory problems in SCR, it is important to consider several factors, as outlined in Figure 6.7. The speed linked with SC reaction is crucial to its scope and should include the stock-out duration to examine the trade-off between waiting and investment. The expected client behaviour should also be considered, as different types of client reactions can have varying consequences. For example, in some industries, not ensuring immediate service may lead to a lost customer, whereas customer loyalty and willingness to wait are higher in others. To study the level of collaboration and transparency in the SC, one should also consider the timespan, as it should allow for complex bullwhip effects to be felt between different entities.

Production Problems

In addition to inventory management, decision-making systems that can dictate production decisions in response to unexpected events are necessary to enhance SCR. It is important to note that production systems can operate under different strategies, influencing how they must be modelled.

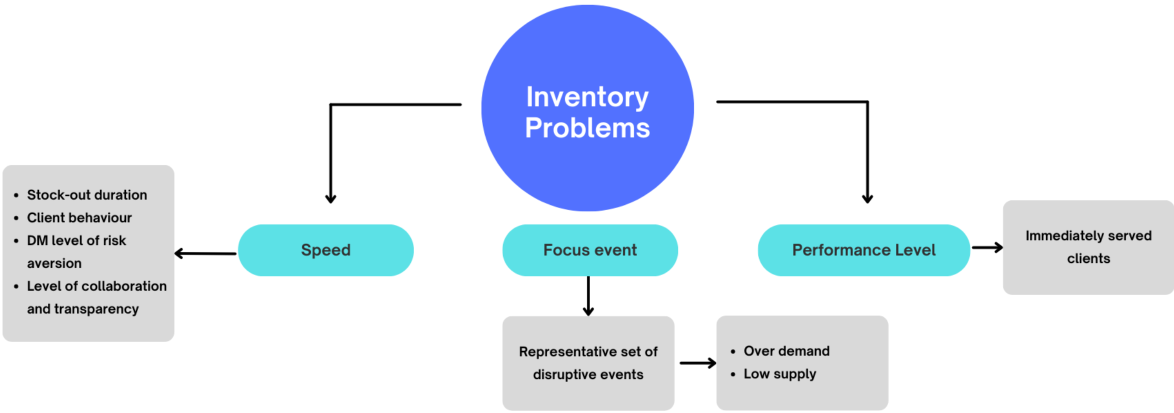


Figure 3.4: Proposed generic approach toSCR in inventory problems

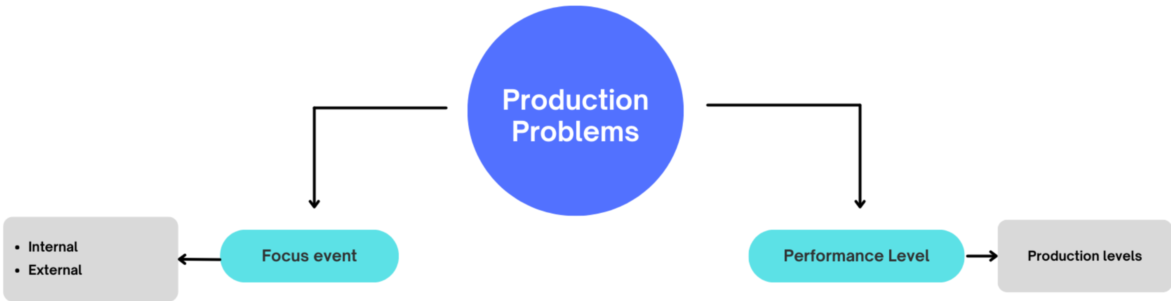


Figure 3.5: Proposed generic approach toSCR in production problems

For example, Thomas & Mahanty (2019) developed a 2-part model for Make-to-Stock environments, where firstly, an analytical investigation based on control engineering techniques and system dynamics. The second part is a simulation of an Inventory and Order-Based Production Control System. For Make-to-Order environments, which involve personalized production, Park et al. (2021) propose a novel approach for applying Cyber-Physical Structure and Digital Twins (DT) to SC, using DT simulation to predict and coordinate production of various agents and achieving resilient planning in operation stages in SC production, able to handle disruptions such as the bullwhip effect and ripple effect. DT are also present in Kalaboukas et al. (2021) defending that DT are a good option for studying SCR at the tactical/operational level.

In context-specific scenarios, such as the impact of a hurricane on a butanediol SC, Ehlen et al. (2014) use a large-scale agent-based simulation to address production scheduling, chemical buying, selling and shipping, and obtain ideal production levels by solving a collection of Linear Programming constrained problems.

From Figure 3.5, two main elements should be considered to optimize the approach to production problems in SCR: the focus event and the performance level. The focus event can be internal, such as a production line malfunction, or external, such as suppliers not meeting their obligations.

Generic Supply Chain Problems

To maintain or acquire a competitive advantage, resilient SCM needs to react quickly and coordinate available resources efficiently during disruptions. Researchers have proposed various models and tools to address this issue. Mao et al. (2020) propose a model that optimizes restoration schedules and work crew assignments by a bi-objective non-linear programming model solved by a simulated annealing algorithm. Ivanov et al. (2016) develop a dynamic model using optimal program control theory, implemented through simulation, to aid operations and SC planners in adopting reactive recovery policies. Ivanov (2018b) use attainable sets and optimal control theory to develop two scheduling models for material flow and recovery actions of SC resources. Goldbeck et al. (2020) propose a multi-stage stochastic programming model that considers multiple operational adjustments for recovery strategies. Ivanov et al. (2019) propose a feedback-driven framework that integrates functional level recovery control with structural recovery control. Ivanov & Dolgui (2020) uses discrete-event simulation to investigate efficient recovery policies and redundancy allocation by considering SC overlays of disruptions. Khalili et al. (2017) tackle a production-distribution planning problem by developing a two-stage scenario-based mixed stochastic-probabilistic programming model with SCR enhancing options.

3.8.3 Risk and uncertainty in tactical and operational models (Research Question 4)

When addressing SCR problems, considering risk events, whether operational and/or disruptive, is inevitable. These events are distinguished by their level of impact and frequency, with low-impact and high-frequency (LIHF) events and high-impact and low-frequency (HILF) ones (Khalili et al., 2017; Namdar et al., 2018). As expected, disruptive risks are the most considered, given the value of resilience in dealing with HILF events. However, given that these works focus on the tactical-operational level, eight papers were identified that addressed SCR in the face of LIHF events, while five addressed both risks simultaneously.

However, in terms of how these risks are modelled, simple approaches are adopted in the majority of cases. For example, some works that address the occurrence of severe disruptions model such events within a pre-specified time frame (Ehlen et al., 2014; Chang & Lin, 2019; Mao et al., 2020). Other works consider that suppliers are disrupted from the beginning (X. Wang et al., 2016) or select which node of the network to be disrupted within a given time length (Harrison et al., 2013; Lücker & Seifert, 2017; Childerhouse et al., 2020).

Another approach is setting different risk profiles that may arise (Schmitt & Singh, 2012; Wu et al., 2013; Beheshtian et al., 2017; Singh, 2020). These risk profiles are based on interviews with operational personnel and literature (Schmitt & Singh, 2012), historical data (Das & Lashkari, 2017), or models defined in the extant literature (Yang et al., 2017).

In terms of uncertainty, a few papers have been identified that integrate this condition into their models. Khalili et al. (2017) adopt a stochastic approach, taking the production and distribution of new products as imprecise parameters formulated in the form of triangular fuzzy numbers. This approach is also adopted by Ayoughi et al. (2020) for dealing with demand, facility costs, and inventory costs parameters, which are taken as uncertain. Goldbeck et al. (2020) also adopt a stochastic approach, generating a scenario tree with an input-output method to account for the propagation of

Table 3.1: Resilience indicators in tactical-operational models

Paper	Problem addressed	Resilience indicators	Formula
Khalili et al., (2017)	Supply Chain	Availability of production capacity (PR)	$PR_s = \sum_j \sum_t (K_j + w_j - up^s_{jt})$
		Availability of transportation capacity (DR)	$DR_s = \sum_j \sum_c \sum_m \sum_l \sum_t (z^{ml}_{jc} K^l_m - ut^s_{jct})$
		Availability of emergency inventory (IR)	$IR_s = \sum_k \sum_c \sum_t (w_{kc} - ub^s_{kct})$
Lücker & Seifert, (2017)	Inventory	Stockout surface	$S = -\int_{t_1}^{t_2} I(t)\, dt$
		Mitigation surface	$M = \int_0^{t_2} I(t)\, dt + \int_{t_D}^{\tau} (td)dt + \int_{\tau}^{t_2} t\,(d+p)\, dt$
Mao et al., (2020)	Supply Chain	Cumulative loss	$R_u = 1 - \frac{\int_{t_e}^{t_e+M} [\varphi(t_0) - \varphi(t)]dt}{M_{max} \times \varphi(t_0)}$
		Restoration rapidity	$R_m = 1 - \frac{M}{M_{max}}$

risk and interdependency between assets. Lastly, (Gholami-Zanjani, Jabalameli, Klibi, & Pishvaee, 2021) address uncertainty in selected parameters through a robust approach, using a Monte Carlo method to generate plausible scenarios.

3.8.4 SCR metrics (Research Question 5)

Relative to resilience metrics that are applied in the context of SCR, it can be said that these are greatly influenced by the end goal of the paper in which they are proposed and/or used, presenting diverse forms. Table 3.1, where it is represented the main indicators identified in tactical-operational models, confirms this affirmation, where it is possible to verify that there is no unique approach to SCR quantitative models and each application leads to different indicators being used.

Khalili et al. (2017) suggest three indicators that are relevant for each activity of the SC, and their weighted sum provides the resilience of the SC as a whole. They compute the Production Resilience as the sum of the initial production capacity and the difference between the decision variables of the additional initial production capacity and the production capacity that is available in a given scenario. Transportation Resilience is calculated based on the difference between the transmission capacity of the transportation mode and the transportation capacity that is available under a scenario. The Inventory Resilience is computed by the difference between the additional capacity of a DC and the emergency inventory level available under a scenario. Nayeri et al. (2021) works on inventory location problem with minimum levels of responsiveness as a resilience enabler thus, fostering SCR. Suppliers have to be seen as relevant actors in tactical-operational SCR, as their relationship with the downstream echelons is vital in the short term (Mohammed, Naghshineh, et al., 2021).

Mao et al. (2020) propose normalized indicators in terms of resilience, where the range of its value is between 0 and 1. The resilience of cumulative loss is calculated as the ratio of the area between the SC's performance and the restoration strategy's maximum makespan value. Lücker & Seifert (2017) construct a resilience metric based on both the stockout quantity and time. The successfully mitigated area and the stockout surface are used as components of the resilience metric. Chang & Lin (2019) assess the stability of the net inventory level by observing the time variation between critical inventory

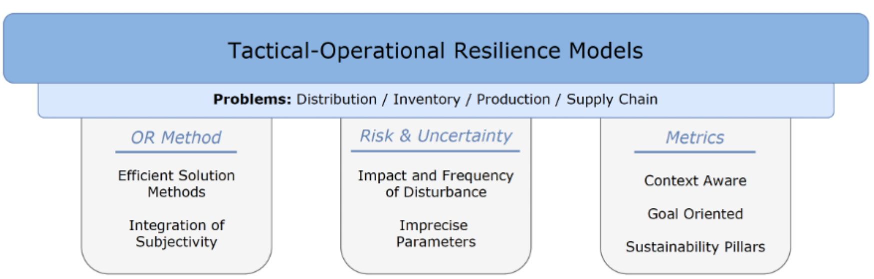


Figure 3.6: Research framework on tactical-operationalSCR models

points and define impact propagation as the ratio between the stockout duration and the duration of the initial disruptive event.

G. Li et al. (2017) proposed two metrics related to end-customer satisfaction and delivery requirements, while Dixit et al. (2016) propose metrics related to order fulfilment and transportation costs. Taghizadeh et al. (2021) perform a simulation approach to the impact on SCR in deep-tier SC, with the resilience metric being based on the demand lost. L. Chen et al. (2020) focus on economic interests, proposing three cost-related indicators and one for sales revenue. Gupta et al. (2021) uses fuzzy multi-objective linear programming in an Agri-food SC to optimise the operational objective of minimizing costs while maximizing long-term resilience. Zokaee et al. (2021) focuses on the reconstruction of SC after a disruption caused by a catastrophe, aiming at providing a balanced solution between different objectives, namely minimizing costs and keeping the high efficiency of the SC. In fact, taking into account costs is an approach many authors follow. However, due to the high impact of disruptions might lack the trade-off necessary coming from acknowledging the need for profits. Other approaches mitigate that by analysing the Return on Assets and Return on Equity (Azadegan et al., 2021; Baghersad & Zobel, 2022).

Ahmadian et al. (2020) developed a general quantitative model to assess physical networks' resilience and identify components that require improvements. They measure the resilience of individual components and define criticality as the ability of the network to perform in case of component failure. Sprecher et al. (2017) establish resilience indicators for the SC of critical materials, while Sharma et al. (2017) focus on the characteristics of trucking companies' SC. Lastly, Ramezankhani et al. (2018) use a hybrid method that combines QFD methodology with DEMATEL to determine the most influential resilience and sustainable factors. Table 3.2 lists other papers that present resilience indicators.

3.9 Discussion and future research directions

The field of SCR is rapidly growing and is expected to continue expanding. We propose a framework for future developments in Figure 6.10, which encapsulates a future research agenda where three main topics within the development of Tactical-Operational Resilience models should be considered: OR methods; Risk and Uncertainty; Metrics.

Models for tactical-operational decisions in SCR mostly rely on optimization and simulation, while the use of heuristics and decision analysis is under-explored. Future research should focus on both methods, with heuristics particularly valuable for their ability to deliver quick results.

As SCR research advances, common risk management methods are becoming more frequent, but they may not capture the unique aspects of SCR. Further study is needed to understand the impact and frequency of disturbances. Most research has been deterministic, neglecting uncertainty and other parameters. Stochastic approaches should be considered to better reflect real-world dynamics and randomness.

Selecting appropriate performance metrics for SCR is critical for accurately reflecting model objectives. Inadequate metrics can lead to inconsistent results, and there is a gap in the literature regarding resilience metrics. Research is needed to bridge this gap by adapting strategies from the strategic level to the tactical-operational level.

3.10 Conclusions

The literature review presented in this paper aims to review the current state of the art on SCR quantitative models, focusing on the tactical and operational decision levels. By conducting a thorough analysis of previous literature reviews, the authors found that SCR is a rapidly growing research field, but quantitative approaches are scarce. To address this gap, the present work focuses on the tactical and operational decision level of SCR.

An overview of the literature developed addressing the COVID-19 pandemic was also executed, and some insights were drawn, although these are limited to early assessments. The developed models were divided into four categories (distribution, inventory, production, SC), and the OR method used within each category was analysed. The category with the least dedicated research was identified as production. The authors then analysed how risk and uncertainty have been modelled and what resilience metrics have been used.

The authors intend to provide useful information that can be used by practitioners and academics alike. To that end, they have identified a list of quantitative resilience indicators, associated mathematical formulas, and the problems where they can be used. They have also provided the most relevant issues to consider when dealing with resilience in specific problems in SCM, which can be used as a checklist for constructing new models that can support decision-makers in building resilience at the tactical and operational levels.

3.11 Annex 1

Resilience indicators

Paper	Resilience indicators
Munoz & Dunbar, (2015)	Recovery Performance loss Impact Profile Length
Dixit et al., (2016)	Percentage of unfulfilled demand Total transportation cost post-disaster
R. Li et al., (2017)	Amount of product delivered Average delivery distance
Sprecher et al., (2017)	Time lag Response speed Maximum magnitude
Sharma & George, (2018)	Dimensions of resistive capacity: Maintenance Fuel price variability hedging Skilled labour and management Communication and coordination Security Insurance Mode flexibility Dimensions of restorative capacity: Risk assessment Budget availability
Ramezankhani et al., (2018)	Average inventory Economic: Cost Part unit profit Social: Number of employees Employee satisfaction Environmental: Waste Recyclable waste
Chen et al., (2020)	Cost of order loss Cost of order backlog Sales revenue Cost of resilience ability
Ahmadian et al., (2020)	Probability of disruption Impact of the disruption Recovery to normal state Criticality
Y. Li & Zobel, (2020)	Robustness at initial impact Robustness at full impact Recovery time Average performance retained over time

4

Analysing SC Resilience - Flow complexity and SC Disturbances

Contents

The content of this section is published in the Proceedings of two international conferences, combined in one section due to its smaller size and related outcomes. The former analyses the impact of SC Flow complexity, a commonly identified resiliency driver. The latter explores the impact of different types of disruptions in the SC. These analyses ease the understanding of the following papers.

The first sub-section of this section is the work published in 2018 aiming at studying the influence of redundancy in SCR, by studying the impact of Flow Complexity (FC) in SC performance.

Ribeiro, J. P., & Barbosa-Póvoa, A. (2018). Modelling and analysing supply chain resilience flow complexity. In Computer Aided Chemical Engineering (Vol. 43, pp. 815-820). Elsevier.

The second sub-section provides a brief study on the types of disruptions namely on what each one affects the most on SC operation.

Ribeiro, J. P., & Barbosa-Póvoa, A. (2019). Supply Chain Resilience: An optimisation model to identify the relative importance of sc disturbances. In Operational Research: IO 2018, Aveiro, Portugal, September 5-7 19 (pp. 189-198). Springer International Publishing.

4.1 Modelling and Analysing Supply Chain Resilience – Flow complexity

Globalization has increased the exposure of SC to higher uncertainties that call for adequate strategies, thus supporting the creation of SCR. There is, however, no absolute strategy that decision makers can follow to guarantee such resilience and the knowledge on how to characterise SCR (SCR) is still an open issue. This work focuses on a strategic level of decision and analyses the relationship between SCR and SC complexity, aiming to conclude how SC FC reflects SCR. The design and planning of a multi-product, multi-period SC are addressed through a Mixed Integer Linear Programming (MILP) model where demand uncertainty is considered. A set of disruptions is studied for different SC structures and as main conclusions, it can be stated that SC FC leads to an increase in SC resilient performance and appears as a good indicator of SCR.

4.1.1 Introduction

The concept of Supply Chain Management was for the first time introduced in the XX century by Oliver et al. (1982) and since then has evolved. The need to guarantee competitiveness in a global market has lead SC to expand geographically and consequently, SC structures have been facing an increased exposure to risks due to a larger set of uncertainties that they have to deal with. This has created the necessity of deeply analysing the concept of SCR as a way to deal with such uncertain context. This is critical in the case of process supply chain as this type of systems are frequently global chains, whose business spreads around the globe, and whose products with great importance to society have to be continuously available, as is the case of pharmaceuticals, food, chemicals, energy, amongst others (Barbosa-Póvoa, 2014).

SCR is one of the newer concepts in SC and it comes as a need to better prepare SC for challenges brought by global SC operations. As stated by Ribeiro & Barbosa-Povoa (2018) in a recent review on the topic, «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».

In such setting, the interest in a sound understanding of SCR has led academics and companies to pursuit efforts regarding such objective (Tang, 2006; Kamalahmadi & Parast, 2016). It is on the best interest of real SC the increase in knowledge in SCR as it is fundamental to better understand not only the resilience concept but also how this can help SC to deal with disruptive events that can endanger their steady-state operation (Cardoso et al., 2015). Several authors have been recently studying SCR but there is still a lack of understanding on how to quantify SCR (Ribeiro & Barbosa-Povoa, 2018). Cardoso et al. (2015) studied SCR and proposed a set of SC indicators that could be used to analyse SCR. SC FC was identified as one of the most promising indicators and further studies on this should be performed to confirm such result.

Based on these results, the present work focus on the design and planning of SC where decisions taken on the SC network structure are analysed. A design and planning multi-product, multi-period MILP model is developed where demand uncertainty is considered. Five different supply chain structures are analysed and the associated complexity optimized. The resulted SC structures are subject to a set of disruptive events and their resilience is analysed.

4.1.2 Problem and Model Description

In order to be able to discuss how different SC networks behave towards resilience, a five echelons supply chain was considered, where reverse flows are also possible to occur. Such SC involves: 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 an alternative to plants production and finally Markets. In the plants and warehouses, technologies can be installed, which influence production, assembly and disassembly processes. These technologies can be fitted to the entities, or upgraded, to provide better performance.

Based on this generic SC structure five different SC cases are studied where different SC structures are considered and allow to compare and construe results on SCR: 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, forming 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 centres.

The MILP model developed by Cardoso et al. (2015) is taken as a base and was adapted to this work goals, providing a new objective function and a set of constraints to study SC FC. Uncertainty was considered in the SC demand and on Disruptions. A scenario tree is 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 occurs 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.

4.1.2.A Objective Function

Two objective functions are studied, Equations 4.1 and 4.2. A first one considers the maximization of the network FC (Equation 4.1), as this would return a network configuration with maximum FC under the feasibility space generated by problem constraints, being FC_t the summation of all positive flows present in the SC for each time period.

$$Max \sum_t FC_t \tag{4.1}$$

This model formulation, although returning a SC with the maximum amount of feasible possible flows does not take into consideration economic concerns, leading to solutions that may have a low performance in financial terms. This issue can, however, be tackled by setting additional constraints in the model, as is the case of establishing a minimum profit that must be obeyed. However, this method was not followed due to two reasons. First, restrictions had to apply to all cases and scenarios, which involve setting up conditions that cannot interfere with the feasibility of the model. Second, by setting up new conditions there is the possibility of endangering the established relationship and compatibility with the original model.

Therefore, a two-step approach is followed. Primarily the model is run based on Equation 4.1 to retrieve the SC with maximum FC within the model feasibility. The second step is used to retrieve the obtained network configuration and then study how much such network configuration maximizes the economic return. The economic return is based on the ENPV, Equation 4.2 (where CF stands for the Cash flow for each scenario and time period, and ir for a defined interest rate). Trough this method it is ensured a network with maximum FC and with the most advantageous economic performance to the company.

$$MaxENPV = \sum_s pb_s \times NPV_s \tag{4.2}$$

$$pb_s = Probability\ scenarios \tag{4.3}$$

$$NPV_s = \sum_t \frac{CF_{st}}{(1+ir)^t} \tag{4.4}$$

By fixing the network configuration there is no capability for the SC network to change, however, it can adapt to the variability introduced in each situation by investing in new technologies, or upgrades to the existing facilities as well as optimize the supply chain flows.

4.1.3 Case Study

The presented model is tested in a Case Study of an European Chemical Process SC. The values associated are scaled down, due to confidentiality reasons. The initial SC configuration comprises a set of European locations, with one plant in Hamburg, one warehouse in Munich, four raw materials suppliers, 3 suppliers of final products and 18 Europeans cities as markets. In broad terms, the company is studying the existent SC in order to access the investment necessary in technologies for current entities, or the implementation of new facilities, to improve the SC's resilient capability. Four operational conditions are studied; one reference case with perfect operational conditions and three examples of disruptions. The disruptions were chosen following failure modes defined by Rice & Caniato (2003). **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". The scenario tree responsible for the uncertainty in the demand is built based on the assumption that the demand in the beginning is known and that there are three possible branches for time period 2 and 3, with the same probability in both periods; Optimistic 0.25, Realistic 0.5 and Pessimistic 0.25. (Time period 2: Optimistic with an increase of 10%; Realistic with an increase of 3%; Pessimistic with a decrease of 2%. Time period 3: Optimistic with an increase of 5%; Realistic with an increase of 2%; Pessimistic with a decrease of 2%)

For each SC case, two configurations are established based on the SC network provided by the two objective functions: maximization of ENPV and maximization of FC, when there is no disruption. These network designs are then subject to the disruptions and the results are analysed and discussed. The MILP model is developed using the GAMS software. The results when applying a network configuration for ENPV maximization can be seen in Table 4.1, whereas the results for a SC with its FC maximized are presented in Table 4.2.

4.1.3.A Case A

Case A represents a simple SC structure allowing only forward flows. One relevant analysis can be made regarding the delta of ENPV value between the two options, maximizing ENPV versus maximizing complexity. Comparing the results from both configurations, respectively in Tables 4.1 and 4.2 it can be seen an increase in service quality (ECSL) and that 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. During Disruption 3 the leaner SC network is able to provide the same economic return than the network with increased complexity, however, it does so with a decreased service quality.

Table 4.1: Combined results for 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%
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%
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%
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%
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%

4.1.3.B Case B

Case B represents a SC structure where reverse flows are allowed between consecutive echelons adding complexity to the operation. It is expected an increase in FC in order to cope with such requirement. The SC configuration with ENPV maximization has an increased impact from disruptions causing a decrease in ENPV of 14%, 7% and 6% for disruptions 1, 2 and 3 respectively. 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 are positive, with a gain more than the double of the cost if no disruption is present. The service quality is also impacted by a more complex configuration with improvements of 21%, 15% and 7% for disruptions 1, 2 and 3 respectively.

4.1.3.C 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. There is an increased susceptibility to Disruption 2 in Case C and this is much related with the non-existence of transhipment between entities in the same echelon. The leaner SC has a decrease in ENPV of 19%, 30% and 10% for disruptions 1, 2 and 3 respectively, while the more complex SC shows improvements of 14%, 27% and 5% for disruptions 1, 2 and 3 respectively. In terms of service quality it is perceptible an increase in ECSL for the more complex structure, maintaining levels of above 90% even during disruptions.

Table 4.2: Combined results for 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%
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%
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%
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%
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%

4.1.3.D 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. Applying the leaner configuration, disruptions cause an 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. In terms of ECSL 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.

4.1.3.E Case E

Case E represents a network that includes all 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. ENPV variations between steady-state operation and disruptive scenarios are visible, resulting in a decrease of 20%, 20% and 10% for disruptions 1, 2 and 3 respectively on the network provided by the ENPV maximization. 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.

4.1.4 Conclusions and Discussion

From the above study, it can be concluded that the obtained results vary not only with the SC complexity but also with the SC structure (e.g. forward or closed-loop) as well with the different types 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 to aid decision making.

Considering the behaviour on ENPV caused by the increased complexity, when no disruption occurs, is observed an increment on costs, due to the obligations that come from opening and maintaining more facilities and flows. However, if disruptions occur, there is an evident benefit of operating a more complex SC. The difference in ENPV in disruptive scenarios between the more complex and a leaner SC is always positive, in comparison with not investing in preventive strategies.

There is a more evident benefit from deploying a more complex SC in terms of ECSL. The notable shift is made possible by the increased flexibility and redundancy allowed by the higher amount of entities and flows involved resulting in an increased SC responsiveness. 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 should be always met by a specific analysis of each SC and to its, perceptible, vulnerabilities.

As a final analysis, it is relevant to compare the results of this paper with those from the original publication of Cardoso et al. (2015), aimed at maximizing ENPV for each SC structure and scenario. As expected, our results produce a network with lower ENPV but with a trade-off for better ECSL.

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 a positive outcome in case of some disruptions, as suggested by Cardoso et al. (2015) in their study.

4.2 SCR: An Optimisation Model to Identify the Relative Importance of SC Disturbances

SC have been facing a vast set of events that can endanger their operations and produce permanent damage, which are unknown until its occurrence. This led to an increased awareness of SCR to deal with such SC uncertainty. This work uses a MILP model to study the relative importance of the different types of events that threaten SC operations exploring the use of two indicators ENPV and ECSL. From this work, it can be said that upstream disturbances are of greater importance and because of that should be more efficiently managed, generating value and ultimately a competitive advantage to companies that deploy resilience concerns to their operations.

4.2.1 Introduction

SC are an essential system of enterprises and have been receiving increased importance with globalisation. However, globalisation has also exposed such systems to high levels of uncertainty and risk. In this setting, SCR should be a main SC concern, as this allows such systems to be able to react to unforeseen events Tang (2006). As proposed by Ribeiro and Barbosa-Povoa Ribeiro & Barbosa-Povoa (2018): «A resilient supply chain should be able to prepare, respond and recover from disturbances and afterwards maintain a positive steady state operation at an acceptable cost and time.» Such definition appears as a coherent and comprehensive definition of SCR that should be followed when managing SC. The risk of occurring an event causing significant damages to the SC is today a reality, proven by recent events as stated in the SC literature Hohenstein et al. (2015); Kamalahmadi & Parast (2016); J. Wang et al. (2016).

In this context, the importance of studying SCR is today a requisite. However, SCR is still far from being thoroughly studied, and there is still the need to understand SCR main characteristics comprehensively. Most published SCR models have been presenting and studying the resilient concerns by modelling the SC response against a set of disruptions. However, little attention has been given to which kind of disruptions companies should devote efforts and so improve its resilience capabilities. Here the importance of the different types of SC disruptions is the motivation for the study on the particular impacts of such events so as to understand how companies should design their SC to better respond to disruptive events, thus improving the operations' resilience. For that, a MILP model for the design and planning of SC was developed considering uncertainty in demand. A case study of a European CLSC is solved to provide useful information regarding the relationship between different SC configurations and different types of disruptions (Production facilities, Supply and Transportation), aspect not compreenshive addressed in the literauture, but very important to support the supply chain managers when managing scarce resources in the design of resiliente supply chain.

This paper is structured as follows. In Section 4.2.2 a brief contextualization on SC disturbances is presented. In Sections 4.2.3 and 4.2.4 the problem is defined and the case study is presented. Section 4.2.5 presents the results of the application of the model on the case study. Finally, Section 4.2.6 presents the discussion and conclusions.

4.2.2 Supply Chain Disturbances

The primary relevance brought by this work is to aid in SC decision making regarding which events should efforts be directed. This is studied by exploring the framework proposed by Ribeiro & Barbosa-Povoa (2018), constituted by four pillars (Performance Level, Speed, Focus Event, Adaptive Framing) and where the Focus Event is the central element, given its importance in SCR. Deciding on what are the type of events that should be primarily considered in SCR is a topic of discussion S. Y. Ponomarov & Holcomb (2009); S. Ponomarov (2012); Hohenstein et al. (2015); Ribeiro & Barbosa-Povoa (2018).

The categorisation of such events is essential and should embrace the SCM challenges and provide the most useful channels to face such uncertainties. The work presented by Rice & Caniato

(2003) proposes five categories of disturbances (Supply, Transportation, Production Facilities, Communications, Human Resources) as the summarisation of all the events that can cause harm to SC and should be dealt as SCR concerns. However, one can consider that the impact of the latter two types of failures ultimately leads to failures in the first three categories and thus we can focus on the first three types of disruptions (Supply, Transportation and Production Facilities). Based on this, these disturbances are the events to be studied along this paper, making use of the model developed.

4.2.3 SC Model Characterisation

The primary goal of this paper is to examine the extent of the impact caused by several types of disturbances in SC operation, while considering different SC design strategies, so as to identify where should a supply chain manager invest primarily the available resuources when designing resiliente supply chains. For that an optimisation model for the design and planning of SC is applied, for model details see Cardoso et al. (2015). The model is a multi-product and multi-period MILP model where uncertainty in demand is considered. This allows the study of SCR under different SC structures: forward, reverse or closed-loop supply chain.

Following the conclusions on the SCR metrics of Cardoso et al Cardoso et al. (2015) where FC is the most adequate SCR metric two objectives functions are studied: the ENPV, considering the probability of each scenario occurence (Pb_s) (Equation 4.2); and the SC FC (Equation 4.1). Additionally, and in order to ensure the best financial result while generating comparable results when considering the maximisation of SC FC, a two step approach is followed: First the SC network configuration in retrieved, considering the model with an objective function maximising SC FC, for all time periods. Second, the SC network configuration found previously is imposed to the objective function where ENPV is maximised (Equation 4.2). This procedure ensures two sets of results. A first one obtained when only only financial concerns are considered and a second one, wich results from the application of the the two step approach, where FC is maximized.

The SC FC (FC) was adapted as it is identified in the literature as a natural mean to provide resilience to SC S. Y. Ponomarov & Holcomb (2009); Cardoso et al. (2015); Adenso-Diaz et al. (2012), since it provides more flexibility and redundancy to the SC therefore is seen as an appropriate method to test SC resilient behaviour.

The model, apart from the objective functions involves a diverse set of constraints related to: entities capacities; material balances; demand and supply needs. Providing this model, it is possible to assess the impact of disruptions analysing the SCR through the obtained ECSL while considering investments in technology and facilities as well as flow and inventory allocation.

4.2.4 Case Study

The case study of a European SC is here analysed, the same SC operation presented by Cardoso et al. (2015), with the values associated scaled down due to confidentiality reasons. The original SC is distributed throughout Europe, with one production facility and one warehouse in Germany and the remaining entities (4 raw materials suppliers, 3 possible final products suppliers, considered as outsourcing, and 18 cities acting as markets) broadly distributed in the continent. The company has the possibility of expanding the current SC by installing new plants in Spain and Italy, with each one of the plants with a set of specific suppliers and new warehouses in the UK, France, Italy and Spain. With the introduction of new facilities the company is also considering the expansion or the upgrade of the existent facilities.

Uncertainty in demand is introduced using a scenario tree, based on the assumption that demand is known in the beginning and in the consecutive branches a probability is assumed to each of the three possibilities (Optimistic, Realistic and Pessimistic), Figure 4.1.

Within the case study, different SC structures can be designed: 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, forming a closed-loop supply chain where plants send products directly to markets and can also receive directly from markets the end-of-life products. Transhipment is allowed at plants, warehouses and disassembling centres.

For each SC network configuration case, from Case A to Case E, four operational conditions are studied. One reference case, representing the steady state operation and where the SC network is defined. The defined SC are then faced with three examples of different SC disturbances:

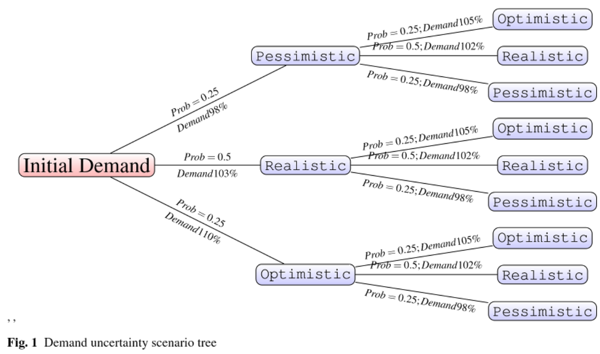


Figure 4.1: Demand uncertainty scenario tree

- **Disturbance 1** - Production facilities: A production disturbance is studied by assuming the occurrence of an event causing all production to stop in the most important plant for one time period.
- **Disturbance 2** - Supply: A failure in the supply of raw materials is considered. This is implemented by stopping all production of most important suppliers for one time period.
- **Disturbance 3** - Transportation: A transportation disturbance is introduced by unexpectedly stopping the biggest existent flow between plants and warehouses.

Such disturbances are studied considered the two objective functions, above defined, resulting in four different series of results for each case. The first two series are related with ENPV maximisation, the solid blue line when only the ENPV maximisation is considered, and in the dashed light blue line the ENPV result in the twostep approach considering the FC maximisation. The remaining two series are the result of the ECSL, the percentage of demand met, where the solid red line represents the ECSL result obtained with the ENPV maximising objective function and the dashed line in red represents the result from the two-step approach. The MILP model is implemented in the GAMS software, and the results are presented in Section 4.2.5.

4.2.5 Results

4.2.5.A Disturbance 1

As mentioned, in Disturbance 1, a production failure is considered. From Figure 4.2 it can be seen that when comparing the SC network with increased complexity (Figure 4.2, Plots dashed in blue and red), for all configurations studied, against a SC designed for maximum economic return (Figure 4.2, Plots in solid blue and red), an improvement in performance is observed both on the economic return and as well on customer service. Cases A and B present similar results for both objective functions. The difference between such cases is represented by the introduction of reverse flows which are of no use to improve ECSL. With the increased complexity, the ENPV of Case B decreases slightly, when compared with Case A, due to the added cost of implementing more complexity without providing additional economic return or increased responsiveness to meet customer demand. For cases C and E the economic and service level outcomes are very much identical since the infrastructures are very similar. The added flexibility in Case E is of great benefit, since it adds better responsiveness without implying costs if those options are not used by the SC. Case D presents itself as the worst performing case since its added complexity (allowing transhipment) comes as no use when facing a disruption in the production facility. When maximising FC in the SC the results for this SC configuration improve. Particularly ENPV results move from being the weaker performer in the simpler strategy to an ENPV in line with Case B when SC FC is maximised. This can be seen as a result of the increased responsiveness of all tiers of the SC that, possiblely by increased redundancy better meet customer demands leading to an improvement in the economic return. Is important to mention that this improvement, brought by increased FC, is not a consequence of the different characteristics between Case B and Case D (transhipment). In fact the ECSL is in line with case B allowing to consider the contribution of transhipment to SCR to be small.

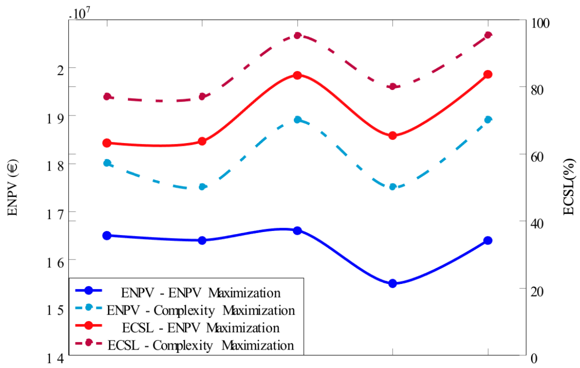


Figure 4.2: Results of ENPV and ECSL for Disturbance 1

4.2.5.B Disturbance 2

Supply-side disturbances are tested in this case, by assuming a failure in suppliers such that production facilities do not receive upstream goods. In this case, Cases C and E (Figure 4.3, Plot in solid blue), that have lower FC, appear with the worst ENPV when suffering the disturbance. However for the same cases when maximising FC there is an increase in economic and service quality performance for all types of SC Figure 4.3, Plots in dashed blue and red.

When designing the SC to maximise profit under steady-state conditions there is the danger of producing severe consequences under a disturbance event, Case C during disturbance 2 is an excellent example of such. There is a noticeable drop in ENPV much because the added complexity (plants and markets being able to communicate directly) does not provide any enhanced solution for the lack of raw materials upstream. With increased redundancy, the SC can increase inventory thus better coping with the changes in operational conditions. Taking advantage of the risk pooling between the different entities, the SC can reduce purchases, developing the responsiveness to meet customer demand while simultaneously improving economic return. On the other hand, Case E provides the SC that can return higher ECSL when facing disturbances. Also, a significant improvement in ENPV between the profit-driven strategy and when designing the SC with increased FC is observed. This added value in ENPV comes from the added flexibility, brought by the increment in possible flows, that combines the possibility to add inventory and to take advantage of the communication between entities allowing for a higher amount of sales, compensating the increased costs of a more complex network.

Cases A, B and D show very similar performance, both in ENPV and ECSL. While the three cases reach the same level of sales, the increased SC responsiveness observed in Cases B and D, with higher costs of investment allows for a decrease in the use of outsourcing, thus improving control, margins and economic return.

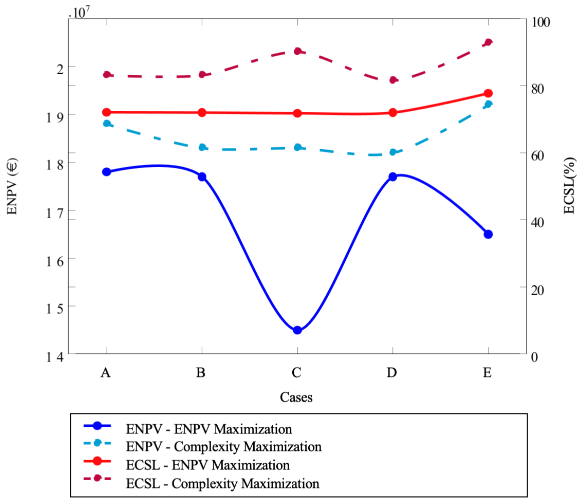


Figure 4.3: Results of ENPV and ECSL for Disturbance 2

4.2.5.C Disturbance 3

Transportation failures are a permanent risk for SC managers, delays or even complete failures in the transport of goods can occur. When studying such disturbance and comparing it to the previous events it is observed a weaker impact on SC performance. Higher ENPV and ESCL values close to 100% in both strategies of SC design, Figure 4.4. Cases A, B and D have very similar results between them and with small improvements when a more complex network is deployed, a behaviour caused by the same considerations as in Disturbance 2, Section 4.2.5.B.

For this type of disturbances, the SC configurations provided by Cases C and D are more resilient. These two cases return a performance very similar between them and can also improve the economic return while increasing FC. The better performance is due to the ability of plants and markets being able to communicate directly, bypassing warehouses. With this relevant characteristic, the operation can avoid the disruptive effects of the transportation failure passing through intermediate entities.

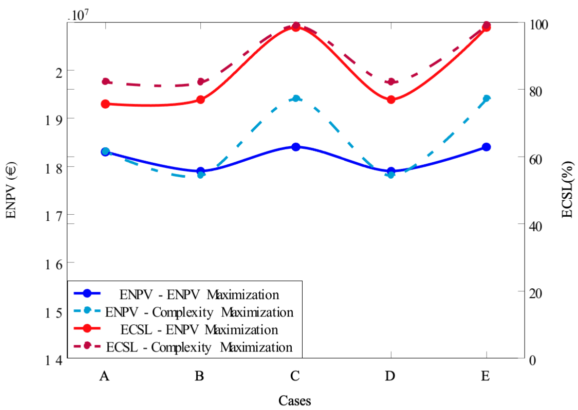


Figure 4.4: Results of ENPV and ECSL for Disturbance 3

4.2.6 Discussion and Conclusions

Accounting for the results previously analysed, in Figure 4.5 is represented the mean relative variation between maximising ENPV or ECSL when FC is accounted for (by the two-step approach) and the ENPV without FC consideration (Equation 4.2), for each type of disturbance considered. When analysing such results it can be observed an improvement in the resilient behaviour brought by the increased SC FC on economic (Squares) and customer service level (Triangles) for the different types of disturbances - a positive variation in %.

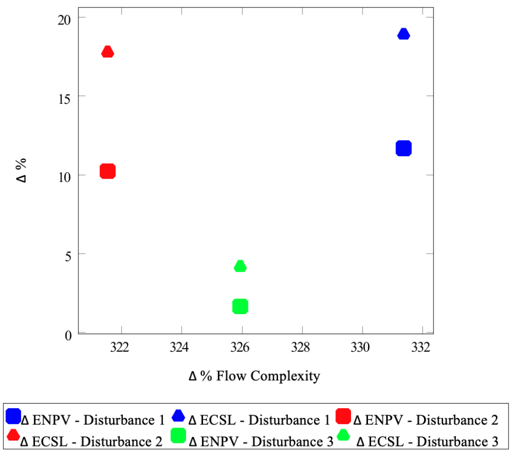


Figure 4.5: Delta representation for the diferent runs

In conclusion, it can be said that companies can retrieve beneficial outcomes if considering and investing in a SC with resilient behaviour by increasing SC FC. The increased observed responsiveness introduces significantly different ways for the SC to face disturbances when compared to the scenario of deciding just based on steady-state conditions. Additionally, it is seen that the results of ENPV and ECSL are different between the disturbances in study, Figure 4.5. For all scenarios, there is a better performance associated with the SC structures that provide a higher SC FC. Also, when disturbances occur, there is a more prominent gain in ECSL than ENPV, since the SC can better respond to the challenges of meeting customer demand.

Transportation failures, represented by Disturbance 3 (Figure 4.5 in green), is the scenario where there is a smaller gain from the increased FC, whereas response to Disturbance 1 and 2 (Figure 4.5 in blue and red respectively) can be profoundly enhanced if a SC design with resilience concerns is deployed, especially the capability to meet customer demand while improving economic return. This behaviour comes as a result of the impact of the type of disturbance impacting the SC. Production and raw materials supplier are upstream entities that influence all the players downhill since there are fewer ways of compensating such failure in a leaner SC. With an increased amount of possible flows, there is increased flexibility and better responsiveness to changes in steady-state conditions.

From the above analysis, it can be concluded that upstream disturbances are critical and should be the ones where decision-makers should consider investing resources towards SCR. Also as managerial insights, companies should invest in contingency plans involving the different players in the SC enhancing communication and collaboration between entities thus advancing through a more resilient

SC.

Future work should continue to pursue the challenge of identifying and understanding SCR drivers and the relationship between those. There should be efforts to understand better the disturbances that influence SC performance and can be dealt with more efficiently. The relationship between SC FC and the positive impact on SCR should be the focus of more significant attention.

5

A responsiveness metric for the design and planning of resilient supply chains

Contents

This chapter is the work published in 2023 aiming at providing a quantitative metric for SCR.

Ribeiro, J. P., & Barbosa-Póvoa, A. P. F. (2023). A responsiveness metric for the design and planning of resilient supply chains. Annals of Operations Research, 324(1-2), 1129-1181.

5.1 Abstract

SCM is in constant evolution, and SCR appears as a recent offspring result of changes in how companies do business. Research efforts on the topic have led to a focus on the basic concepts of SCR, leaving a relevant research gap on the modelling and quantification of the SCR behaviour. In fact, there is not yet a consensus on SCR metrics or on how to quantify SCR. Most SCR models fail to incorporate relevant characteristics of the supply chain's performance, as are the impacts perceived by downstream customers. This work addresses such gaps, and a new resilient SC metric is proposed, which is incorporated into a developed optimisation model, where economic and responsiveness objectives are maximised when designing and planning resilient SC considering all SC entities. The model is applied to a case study that shows that decision-makers should avoid adopting universal strategies when managing their SC and instead should define the best plan for their SC operation. The impacts perceived by downstream customers are analysed. Moreover, it can be concluded that there is a correlation between the SC performance and the new SCR metric, easing the process of designing and planning the SC when resilience concerns are at stake.

5.2 Introduction

SC has emerged as the backbone of the global economy, with many economic activities heavily relying on such operations for its success. The dependency on these systems has led to the emergence of a distinct field of study, SCM (Oliver et al., 1982). This activity implies the study of the main concerns inside SC operations and SCR, in particular, arises as a novel approach to manage the consequences of high-impact events on SC. History provides us with clear examples of how unforeseen circumstances can impact SC, and how different reactions can dictate profitability or, in the worst case, the dissolution of a business. This is the case of natural or anthropogenic disasters or even economic or political decisions.

In this work, we aim to address an adequate SCR metric to be used in a model that can support the design and planning of SC. Thus, meeting one research gap in this field (Ribeiro & Barbosa-Povoa, 2018). Most published articles leave the SCR to qualitative interpretations (Das, 2018), and few look into quantitative analysis (Sokolov et al., 2016a; Cardoso et al., 2015). A quantitative approach is pursued in this paper by exploring financial aspects coupled with service level goals, modelled as a SCR metric that is used in the design and planning of resilient SC when uncertainty is present. To show the applicability of such approach, a MILP is proposed, where different SC networks are studied, from only forward to CLSC, the latter encompassing circular economy principles. The results show the justifiability of such approaches towards the incorporation of resilience into supply chains, providing decision-makers with a broader insight into SCR as well as a means to improve SC operations.

The features that distinguish this paper from the existing literature include the quantitative study of SCR on a strategic-tactical level of decision, focusing on designing and planning a resilient global CLSC. A generic multi-product, multi-period and multistage MILP model is presented, accounting for uncertainty in demand and disruptive scenarios. This includes the development of a new metric, meeting in this way a relevant research gap identified by academics and practitioners – the need to find adequate measures to supply chain resilience. This metric combines the profit goal with the capacity of guaranteeing high service levels under disruptive scenarios. The application of this metric and the promising results are illustrated in Section 5.7.

The novel approach provides a new path for SCR, providing not only a new tool to be used on the design and planning of resilient supply chains but a quantitative model that explores prior conceptualisations of SCR, such are the four pillars of SCR presented by (Ribeiro & Barbosa-Povoa, 2018) (Focus Event, Performance Level, Speed and Adaptive Framing). The developed tool allows for the study of different disruptive events, providing the usage of a new performance level that leads to the presentation of alternative adaptive framing solutions to each SC/disruptive scenario. Due to the nature of a strategic model, the speed on how the SC responds to disruptive scenarios is not considered in this work.

The outcomes of this paper, namely the new SCR metric, the mathematical model and the managerial insights, can be used by both academics and practitioners when looking at their operations. The features of SCR here explored, as is the case of meeting customer demand or economic return, have been traditionally presented individually. This work is one of the few attempts that integrate these aspects to provide a more holistic and usable tool for SCR.

The remainder of this paper is structured as follows: Section 5.3 presents the work being done in SCR modelling; Section 5.4 presents the problem description; Section 5.5 characterises the mathematical model; Sub-Section 5.5.2 presents the new SCR metric; Section 5.6 presents the disruptive scenarios; Section 5.7 presents and solves a case study; Section 5.8 performs discussion and conclusion of results; Section 5.9 presents managerial insights. Finally, Section 5.10 concludes the work and proposes future directions.

5.2.1 Resilience in SC

Natural disasters are one example of events that can severely impact SC Duhamel et al. (2016). The consequences of Hurricane Katrina were far more persistent than the natural phenomenon. The destruction it caused culminated in stoppages in the oil refining industry and on the production of products like fruit or lumber (Snyder et al., 2006; Vigdor, 2008).

Areas prone to earthquakes are also an example of how severe the SC consequences of an unpredictable event can be. The auto industry, partially due to high investment in lean practices, is highly sensitive to changes in the steady-state operation, with disturbances being able to cause long-lasting adverse effects. This sensitivity was verified in 2011 when Japan's auto industry was severely affected by an earthquake. The resulting stoppages cost millions of dollars, and 11 months were required to restore production levels (Takahashi, 2011).

No matter the event that leads to the disruption, some lessons can be learned on how to manage and cope better with this particular kind of events (Wachtendorf et al., 2013; Wakasugi & Tanaka, 2015). Even simpler weather events, such as high gusts, heavy rain, or extreme temperatures, can induce effects on the company's operation. Minimising the risk for the whole SC is thus of great importance (Brusset & Bertrand, 2018).

On this, relationship amongst SC actors and how they affect each other has been studied in several fields. In SCR, one can study the impact of the type of contracts between suppliers and production in the response to disruptions (G. Li et al., 2017, 2020). Information sharing between the different players can suffice for the appropriate SC response to disturbances (Sabahi & Parast, 2020; Tao et al., 2020). Positive relationships can foster responsiveness and efficiency in the SC (Goffnett & Williams, 2019); on the contrary, confrontations can have negative impacts. The strike at two General Motors plants led to a gridlock in the SC, resulting in losses of millions of dollars (Snyder et al., 2006), another example of how a single event can cause a ripple effect through the system.

One of the most referred examples of the importance of resilient capabilities and information sharing amongst the SC players is the example of the fire in 2000 at a Philips factory that impacted two big players, Nokia and Ericsson. This fire forced a stop in production, and despite being informed at the same time, the two firms had very different responsive actions and final results. Nokia was fast to acknowledge the disruption and to seek alternatives, Ericsson failed to do so and ended up having around 400 million $ in losses (Dolgui et al., 2018). The lack of agility leads to the inability to remain competitive (Sharma et al., 2017), which is a lack of reaction after the occurrence of a stimulus (Bernardes & Hanna, 2009).

The concept of SCR is therefore very important and can be applied to a broad spectrum of economic activities with examples in several sectors, including: chemical (Cardoso et al., 2015); automotive (Carvalho, Barroso, et al., 2012); agri-business (Stone & Rahimifard, 2018; Kirwan et al., 2017; Mwangi et al., 2021), since all sectors can be affected by disruptions which could be internal, external or a combination of both. Although, disruptions can occur in any location of a SC, most commonly the study is centred around upstream disruptions. Transportation disruptions are often seen as one of the most frequent hurdles in SC operations. Albertzeth et al. (2020) studies such kind of scenarios and presents a metric to help find strategies to improve SCR, also tackling the difficult process of monetising in this context.

One of the dangers of improperly addressing SCR is failing to acknowledge the ripple effect that different events can have in the SC (Dolgui et al., 2018; Pires Ribeiro & Barbosa-Póvoa, 2019). The ripple effect is associated with the occurrence of one seemingly harmless event which can cause a complete shutdown in a domino effect. Despite possibly starting under the radar, companies must be capable of stopping and mitigating its propagation and for that should have resilient SC.

Recently, the world has faced the perfect storm in terms of disruptions, the COVID-19 pandemic, that evidenced the need for resilient SC. The restrictions and health consequences of the coronavirus outbreak were global and spared almost no country. There is no economic sector that left unscathed from this period. While some companies had their operation left to a complete standstill, others had a massive increase in demand. Moreover, some were in a compromised situation with part of their operations restricted.

The academic response was fast and researchers provided short publications aimed at exploring how science could help. The interconnected global SC were forced to face new scenarios and deal with the consequences (Baldwin & Tomiura, 2020). Hobbs (2020) focus on the Canadian food industry and how it was impacted, both for disruptions on operations but also by the panic buying that brought a considerable demand variation. Mathematical approaches provide useful insights and Paul & Chowdhury (2020) presents a model on the operational level where the results add validity to the relevance of SCR, since SC designed with Resilience in mind had a better behaviour under stress, at least reducing costs.

The shortages of essential medical goods, eg. Personal Protective Equipment (PPE), in western countries are an evidence of policies that failed to implement a strategic resilient SC in-place (Gereffi, 2020). This wake-up is leading to an increased concern on the topic and on the study of Resilient SC. Until now, re-shoring was seen as an option that would yield lower profits, companies are now considering it to mitigate shortages of essential products (L. Chen & Hu, 2017). Regardless, the works on SCR its modelling and quantification have not reached a consensus on the best approach for resilience metrics (Golan et al., 2020b). However, SCM with a strong resilience drive is an option for decision makers to empower their companies. For that to be possible, academics must present concise, simple, and reliable models and metrics to provide useful managerial insights for decision makers.

5.2.2 Relationship with other fields of SC

In recent years, the world has been witnessing a shift in the way business is performed, enabled by higher connectivity along with advances in technology, shaped by new intense societal challenges such as the case of sustainability. This new paradigm for doing business brought a spotlight to activities not used to be the focal point of SCM. It calls for high SC effectiveness and responsiveness, a continuous challenge for companies (Ralston & Blackhurst, 2020; Mohammed, Harris, et al., 2021).

The increased awareness of sustainable SC leads to changes in all levels of SCM, creating new challenges. One of those is how can one achieve a resilient and sustainable SC (Mari et al., 2014; Fahimnia & Jabbarzadeh, 2016a). The re-use of products is on the rise at a global SCale, leading to more complex SC and with it reverse logistics/closed-loop SC (Savaskan et al., 2004; Howard et al., 2018; Özçelik et al., 2020).

Regardless of the recent increased interest in SCR, there is still space for further development and to create awareness and knowledge on how companies can overcome disruptive events (Ribeiro & Barbosa-Povoa, 2018). Dealing with disruptive events must be done resorting to a holistic approach, where SCR has a lot to gain by taking advantage of the knowledge and experience provided by other SC fields that handle uncertainty and risk. Examples of such benefits are the application of the concept of reliability (Ha et al., 2018) or Supply Chain Risk Management (SCRM). One can even consider SCR as an offspring of SCRM (S. Y. Ponomarov & Holcomb, 2009; König & Spinler, 2016; Shekarian & Mellat Parast, 2020). Risk management consists of managing proactive practices taking into account vulnerability. Those can be prospective strategies to enhance SCR (Rajesh & Ravi, 2015a). Inspired by the biological immune system Srinivasan & Tew (2017) present a SCRM framework that can be adapted to SCR.

However, to correctly face SCR adaptations are needed since the traditional methods of dealing with risk rely vastly on the identification and consequent quantification of probabilities and impacts of a particular event. An antagonistic approach is followed in the context of SCR, where most common events can be categorised as an unknown-unknown risk and where events' probabilities are extremely difficult to obtain. The characteristics of uncertainty elements turn strategic and tactical levels of decision into a fundamental part in the process of building and maintaining a resilient SC (Sáenz et al., 2018; Sahebjamnia et al., 2015; Cohen & Lee, 2020; Kaur & Singh, 2019). Thus, macro and network decisions are a crucial factor when handling SCR (Asian & Nie, 2014; Kim et al., 2015; Singh, 2020), as it already is in other fields of SCM (Farahani et al., 2013; Mota, Gomes, Carvalho, & Barbosa-Póvoa, 2015; Mota et al., 2017).

With SCR appearing as a not yet mature concept, its definition is still a topic of discussion present in the work of different authors. Providing a stable interpretation is crucial to have all the involved parties discussing the issue on the same grounds, a concern recognised by several reviews on SCR that devote some work to its discussion and formalisation (Ribeiro & Barbosa-Povoa, 2018; Kamalahmadi & Parast, 2016; J. Wang et al., 2016; Hohenstein et al., 2015; Tang, 2006). In this work, we follow the definition presented by Ribeiro & Barbosa-Povoa (2018) where "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".

5.3 SC Resilience - Models and Metrics

As in other areas of SCM, quantitative studies have been applied to SCR so as to provide the best insight possible for decision-making. However, due to its particular characteristics, discussed in Section 7.2, its modelling varies in scope, approach and metrics involved.

5.3.1 Models

A straightforward way to think about SCR is establishing what should be done prior and after a disruption (Birkie, 2016; Gaonkar & Viswanadham, 2007; J. Han & Shin, 2016). It is possible to identify four steps (Prepare, Respond, Recover and Maintain) that are used frequently in the literature with different degrees of description (Hohenstein et al., 2015; Ponis & Koronis, 2012; S. Ponomarov, 2012; Kamalahmadi & Parast, 2016). Ribeiro & Barbosa-Povoa (2018) summarise SCR in a mind-map of 4 elements (Focus Event, Performance Level, Speed and Adaptive Framing). It is by combining these different elements that one should consider how to evaluate SCR for each particular case properly.

The need for tailored attention to the specification of the focus event and the requirements in terms of speed and adaptive framing lead to a broad set of examples on the SCR metrics used in the literature. The resilience of the whole SC is the result of the resilience of each element and the interactions between them. The design and planning of SC networks is of extreme relevance since it affects different groups of decision. For instance, it will influence inventory costs, production and transportation costs, but it can also imply in what is the growth capability of a company (Song & Sun, 2017). Modelling could provide the tools to make better decisions, identifying the weakest links and work with them as best as possible (Adobor, 2019).

Moving from acknowledging the core principles of SCR to a requisite model is a challenge. Firstly, one has to generate or acquire a set of elements to be representative of the reality to be translated into a mathematical language. The literature provides few examples on how to apply such constructions into models that vastly differ on the OR method used, and in its scope.

SCR particularities guide authors to follow OR methods that are well-established in the field of SCM, with optimisation being the most frequently used approach, closely followed by simulation or decision analysis (Ribeiro & Barbosa-Povoa, 2018). While Carvalho, Barroso, et al. (2012) or Schmitt & Singh (2012) face the challenge of designing a resilient SC through a simulation model, Cardoso et al. (2015) explored optimisation, which is recurrently used and recognised as an appropriate method to study the problem of SC design and planning under uncertain conditions, where different objectives are at stake (Ivanov et al., 2017; Ning & You, 2018).

5.3.2 Metrics

The most common quantitative resilience approaches rely on maximising only one type of factor, usually financial. On the other hand, the introduction of goals and performance measures is a method used to better describe the model intentions (Barroso et al., 2011; Carvalho et al., 2011; Elleuch et al., 2016). Recognising this, Munoz & Dunbar (2015) quantifies resilience in five dimensions (recovery time, impact, profile length, performance loss and weighted sum). Another approach is the development of a single index, as presented by Azevedo et al. (2016); Soni et al. (2014b); D. Wang & Ip (2009); Hosseini et al. (2019). The latter method leads to a more straightforward and more intuitive way to understand the results and allows a simple comparison between the different cases where the model is to be implemented.

The primary objective of a location problem is to establish a SC network that can fulfil its demand efficiently (Farahani et al., 2014). Being able to meet a pre-established customer service level, even under disruptions, can be a way to study the resilient behaviour of SC (Jahani et al., 2020). Such idea is to be explored in the present work, by combining financial measures with service level leading to a responsive metric for the design and planning of resilient SC.

5.4 Problem Description

SC's managers face several challenges when assessing SCR; most of them fall under strategic or tactical SCM decision levels. Decisions on which locations to operate, the quantities to be produced in each location, the outsourcing needs, and the flows to promote between the different possible entities in the network, are to be taken. These should guarantee operations to be cost-efficient while maintaining customer satisfaction (Lotfi & Saghiri, 2017). The design and planning of resilient SC are the objects studied in this article.

The most common SC can be depicted in a four-level structure. Starting from Raw Materials and ending in Markets with Plants and Warehouses as intermediate echelons. To entail any possible SC configuration, the problem here studied represents a set of different flows between tiers, from a traditional forward four levels SC to a generic CLSC.

Uncertainty is considered in the SC demand and on disruptions, where a scenario tree is constructed, combining the outcomes of these two sources of uncertainty. Demand variability is introduced by generating a scenario for each period from a set of three possible outcomes (Pessimistic, Realistic or Optimistic). The disruptions only assume two options, it either occurs, or it does not, in a specific period to consider. The probabilistic binary distribution for the occurrence of disruptions is due to the impracticable definition of probabilities of occurrence of each event (Ivanov & Dolgui, 2018), as discussed in Section 7.2. Resulting in a set of scenarios where each scenario probability is given by the probabilities of the path, with all stages between the root node and each leaf node.

5.5 Mathematical Model

The model here presented is a strategic-tactical model that supports the design and planning of SC considering a new resilience metric is incorporated to build a resilient SC. This was based on the MILP model developed by Cardoso et al. (2015), here the most relevant elements are presented, and the new model is provided with detail in the Annex made available in Section 5.11. The main decisions are summarised below and are further detailed in Section 5.5.1.

- Defining the supply chain network ($XNodes_{vt}$ - Binary variable equal to 1 if entity $v \in V$ opens in period $t \in T$ and 0 otherwise)
- Defining the flows between entities (Y_{vwt} - Binary variable equal to 1 if the forward link between entity $v \in V$ and entity $w \in V$ is established at time period $t \in T$ and 0 otherwise; YNC_{vwt} - Binary variable equal to 1 if the reverse link between entity $v \in V$ and entity $w \in V$ is established at time period $t \in T$ and 0 otherwise; YEL_{vwt} - Binary variable equal to 1 if the end-of-life reverse link between entity $v \in V$ and entity $w \in V$ is established at time period $t \in T$ and 0 otherwise)
- Defining the supply chain network, the characteristics of production and the technologies involved (im_{iv} - production capacity of technology $i \in I$ in facility $v \in V$ and CE^{p}_{ivt} - the capacity

expansion of technology $i \in I$, in facility $v \in V$ and in time period $t \in T$) and those related with storage (in^s_v - the initial capacity of facility $v \in V$ and CE^s_{vt} - the expansion of storage capacity of facility $v \in V$ in time period $t \in T$)

Consider the following sets:

$$
\begin{aligned}
V&, \; set\ of\ entities/locations \\
V_{wh} &\subseteq V, \; set\ of\ entities\ with\ warehousing \\
V_m &\subseteq V, \; set\ of\ markets \\
V_g &\subseteq V, \; set\ of\ suppliers \\
V_c &\subseteq V, \; set\ of\ entities\ with\ technologies \\
F_{v,w}&, \; set\ of\ pairs\ (v,w)\ such\ that\ a\ forward\ flow\ is\ allowed\ between\ v\ and \\
& \quad w,\ v,w\ \in V \\
R_{v,w}&, \; set\ of\ pairs\ (v,w)\ such\ that\ a\ reverse\ flow\ is\ allowed\ between\ v\ and \\
& \quad w,\ v,w\ \in V \\
S&, \; set\ of\ nodes\ in\ scenario\ tree \\
P&, \; set\ of\ products \\
P_f &\subseteq P, \; set\ of\ final\ products \\
I&, \; set\ of\ available\ technologies \\
T&, \; set\ of\ time\ periods
\end{aligned}
$$

This work focuses on the definition of a new SCR metric, which aims to account not only for economic return but also for customer service level.

5.5.1 SC Management Key Performance Indicators

A set of SCM performance metrics is here considered to express SCR and can be used for a more in-depth analysis of the problem. This is based on commonly used network design resilience metrics. Flow complexity adds flexibility and redundancy to the SC, being already proved to be a very good indicator of SCR (Cardoso et al., 2015). These strategies are, however, far from being feasible "plug and play" solutions in real applications (Ribeiro & Barbosa-Póvoa, 2018). For instance, back-up suppliers might lead to performance degradation if the SC is still reliant on unreliable suppliers(Demirel et al., 2018). Two operational metrics are often used: Expected ENPV and ECSL have been shown to drive supply chain management. It is natural for a new metric to emerge, combining the two operational indicators aiming to be a more comprehensive SCR metric. In this new metric, both economic and responsiveness goals of the supply chain are achieved while guaranteeing supply chain resilience. Although the forehand listed metrics can be present as resilience metrics, it is impossible to retrieve any conclusion regarding the resilience of a given SC solely from an individual parameter. Thus, these metrics must be used in combination and relative to each other to provide useful information.

The mentioned base metrics are modelled as follows:

5.5.1.A Flow Complexity

Total quantity of flows between entities, including forward flows (Y), reverse flows of non-conforming products (YNC) and the reverse flows of end of life products (YEL);

$$FC_t = \sum_{v \in V} \sum_{w \in V} (Y_{vwt} + YNC_{vwt} + YEL_{vwt}) \qquad \forall t \in T \tag{5.1}$$

5.5.1.B ENPV

The Expected Net Present Value (€) is calculated for each scenario and period, considering cash flows (CF_{st}) and an interest rate (ir), eq. (7.2);

$$NPV_s = \sum_{t \in T} \frac{CF_{st}}{(1+ir)^t} \qquad \forall s \in S \tag{5.2}$$

$$CF_{st} = NE_{st} - FDC_t \qquad t = 1, ..., |T| - 1, \quad \forall s \in S \tag{5.3}$$

The cash flows are given by eq. (7.3) represented by the difference between the net earning and the fraction of the depreciated capital. Net earnings (NE_{st}), eq. (7.4), come as result of the difference between the income (Eg. Sales revenue (S_{vpst}) and the refunds from non-conforming products ($RQNC_{vwpst}$)) and the costs (Eg.: purchasing products (Pu_{pvst}), operational (Op_{ivpst}), inventory (IC_{vst}), transportation (TC_{vwt}) and depreciation of invested capital (DP_t) considering taxes (tr). $|T|$ stands for the number of time periods involved in the model;

$$\begin{aligned} NE_{st} = (1-tr) \Bigg[& \sum_{v \epsilon V_m} \sum_{p \in P} S_{vpst} - \sum_{v \in V_m, w \in V : (v,w) \in R_{v,w}} \sum_{p \in P} RQNC_{vwpst} \\ & - \sum_{v \epsilon V_g} \sum_{p \in P} Pu_{pvst} - \sum_{i \in I} \sum_{v \in V} \sum_{p \in P} Op_{ivpst} - \sum_{v \epsilon V_{wh}} IC_{vst} - \sum_{v \in V} \sum_{w \in V} TC_{vwt} \Bigg] \\ & + (tr \times DP_t) \qquad \forall t \in T \quad \forall s \in S \end{aligned} \tag{5.4}$$

5.5.1.C ECSL

Expected Customer Service Level (%) is the percentage of demand met, as the relationship between the unsatisfied demand ($\sum_{v \epsilon V_m} \sum_{p \in P} ID_{pvst}$) and the total demand ($\sum_{v \epsilon V_m} \sum_{p \in P} D_{pvst}$). Unsatisfied demand has to be calculated as a result of the decisions made during the time periods that influence the difference between the actual demand and the flows sent to each market ($\sum_{v \in V_m, w \in V : (v,w) \in F_{v,w}} Q_{wvpst}$);

$$ESC = \frac{\sum_{t\in T}\left(1-\sum_{s\in S} pb_s\left[\frac{\sum_{v\epsilon V_m}\sum_{p\in P} ID_{pvst}}{\sum_{v\epsilon V_m}\sum_{p\in P} D_{pvst}}\right]\right)}{|T|} \tag{5.5}$$

Unsatisfied demand is given by Equation 7.22, representing the difference between the demand recognised for each market and product, for each scenario and period (D_{pvst}), and the quantity of product delivered to such market ($\sum_{w:(w,v)\epsilon F} Q_{wvpst}$). P_f represents the set of final products and S represents the nodes of the scenario tree;

$$ID_{pvst} = D_{pvst} - \sum_{v\in V_m, w\in V:(v,w)\in F_{v,w}} Q_{wvpst} \qquad \forall p \in P_f \ \wedge \ v\epsilon V_m \ \wedge \ \forall t \in T\, \forall s \in S \tag{5.6}$$

5.5.1.D Auxiliary variables

- **FCI** (€) - Fixed Capital Investment is the summation of costs associated with strategic decisions, in which each parcel represents different investments: the occurrence of each process ($\sum_{i\in I}\sum_{v\in V} im_{iv}\times in^p_{iv}$), the eventual expansion of processes capacity ($\sum_{i\in I}\sum_{v\epsilon V_c}\sum_{t\in T}(v^p_{ivt}\times CE^p_{ivt})$), the cost of storage entities ($\sum_{v\in V} is_v\times in^s_v$), the eventual storage expansion ($\sum_{v\epsilon V_{wh}}\sum_{t\in T}(v^s_{vt}\times CE^s_{vt})$) and the investment needed to implement new links between entities ($\sum_{v\in V}\sum_{w\in V}\sum_{t\in T} lk_{vwt}\times (Y_{vwt} + YNC_{vwt} + YEL_{vwt})$);

$$\begin{aligned} FCI = \sum_{i\in I}\sum_{v\in V} im_{iv}\times in^p_{iv} + \sum_{i\in I}\sum_{v\epsilon V_c}\sum_{t\in T}(v^p_{ivt}\times CE^p_{ivt}) \\ + \sum_{v\in V} is_v\times in^s_v + \sum_{v\epsilon V_{wh}}\sum_{t\in T}(v^s_{vt}\times CE^s_{vt}) \\ + \sum_{v\in V}\sum_{w\in V}\sum_{t\in T} lk_{vwt}\times (Y_{vwt} + YNC_{vwt} + YEL_{vwt} \end{aligned} \tag{5.7}$$

Where:

$im_{i,v}$	$Capacity\ of\ technology\ i\ \in I\ in\ entity\ v\ \in V$
$in^p_{i,v}$	$Initial\ investment\ associated\ with\ each\ technology\ i\ \in I\ in\ each\ entity\ v\ \in V$
$CE^p_{i,v,t}$	$Technology\ i\ \in\ I\ capacity\ expansion\ in\ entity\ v\ \in\ V\ over\ time\ period\ t\ \in\ T$
$v^p_{i,v,t}$	$variable\ investment\ associated\ with\ each\ technology\ i\ \in\ I\ in\ each\ entity\ v\ \in\ V\ in\ each\ time\ period\ t\ \in\ T\ in\ euros$
in^s_v	$initial\ capacity\ of\ each\ entity\ with\ storage,\ v\ \in\ V_{wh}$
is_v	$initial\ investment\ associated\ with\ each\ entity\ with\ storage,\ v\ \in\ V_{wh}$
$CE^s_{v,t}$	$Storage\ expansion\ of\ entity\ v\ \in\ V\ over\ time\ period\ t\ \in\ T$
$v^s_{v,t}$	$variable\ investment\ associated\ with\ each\ entity\ v\ \in\ V\ with\ storage\ in\ time\ period\ t\ \in\ T\ in\ euros$
$lk_{v,w,t}$	$contract\ cost\ of\ a\ carrier\ to\ make\ a\ journey\ from\ one\ entity\ v\ \in\ V\ to\ another\ w\ \in\ V\ in\ the\ period\ t\ \in\ T\ in\ euros$

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

$$Investment = \sum_{i \in I} \sum_{v \in V} im_{iv} \times in^p_{iv} + \sum_{i \in I} \sum_{v \epsilon V_c} \sum_{t \in T} (v^p_{ivt} \times CE^p_{ivt}) + \sum_{v \in V} is_v \times in^s_v + \sum_{v \epsilon V_{wh}} \sum_{t \in T} (v^s_{vt} \times CE^s_{vt}) \quad (5.8)$$

- **Inventory** (€) - Inventory present in warehouses is 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}) are considered;

$$Inventory_t = \sum_{s \in S} \sum_{v \epsilon V_c} (pb_s \times Cinv_{vt} \times IL_{vst}) \qquad \forall t \in T \quad (5.9)$$

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

$$Purchases_t = \sum_{s \in S} \sum_{v \epsilon V_g} \sum_{p \in P} pb_s \times rm_{pvt} \times Pu_{pvst} \qquad \forall t \in T \tag{5.10}$$

- **Sales** (€) - Total sales are given by the price of products ($SPrice_{pvt}$) and the amount of goods sold (Sa_{pvst});

$$Sales_t = \sum_{s \in S} \sum_{v \epsilon V_m} \sum_{p \in P} pb_s \times SPrice_{pvt} \times Sa_{pvst} \qquad \forall t \in T \tag{5.11}$$

5.5.2 New SC Resilience performance metric

As identified by Ribeiro & Barbosa-Povoa (2018); J. Wang et al. (2016); Kamalahmadi & Parast (2016); Hohenstein et al. (2015) there is a need to develop more comprehensive SCR metrics. In this work, we pursue this goal and a SCR metric involving economic goals and service level is developed. This is considered in the model as an objective function (OF) and is defined as follows in equation 5.12.

$$Max \frac{\sum_{s \in S} pb_s \times NPV_s}{NPV_{ref}} - \frac{\sum_{s \in S} pb_s \left[\frac{\sum_{v \epsilon V_m} \sum_{p \in P} ID_{pvst}}{\sum_{v \epsilon V_m} \sum_{p \in P} D_{pvst}} \right]}{|T|} \tag{5.12}$$

The first term represents the economic concern modulated through a variation rate between the resilient SC ENPV and the ENPV obtained for the SC network that maximises ENPV when no disruption occurs NPV_{ref}. This term will vary, for any positive number smaller than one if ENPV values are lower than the reference. However, it is not expected for this value to go above the unitary value since the NPV_{ref} is the best economic performance when compared to a situation where disruptions occur. Generically, this parcel is responsible for penalising deviations from the best ENPV possible, with the values closest to one being those that most positively impact SC performance.

The second term, introduces the concern of meeting customer demand as a key decision factor when a strategic decision is to be made. This term assumes values between zero and 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 the increase of ENPV equally as the decrease of unsatisfied demand, implying that the percentage variations are equally relevant to the decision. The definition of monetary values for non-satisfied demand introduce deviations that change from case to case and can be challenging to obtain when considering a longer time span, as is this case. Defining a target service level, in the context of disruptions can also mislead results, due to its relationship with steady-state and disruptions. Therefore, in the context of measuring the resilient behaviour of a SC, this approach returns appropriate information to decision-makers on how will the SC respond to disruptive scenarios and easily allows for comparisons between different SC.

5.5.3 Model main constraints

As the design and planning of resilient supply chains are at stake, it is crucial to consider different problem characteristics that arise when focusing on generic supply chain networks. This involves a set of constraints as: mass balances; demand levels; capacity restrictions; flow definition; transportation links. This are described in detail in the Annex made available in Section 5.11.

5.6 Disruptive scenarios

The quest for the identification of events that cause disruptions in SC is not new. Most authors identify representative episodes that could be implemented in models. The results of the COVID-19 pandemic shows us that this is a sound approach, since most events that occurred could have been prepared following such strategy. Works already published are consistent with such idea (Azad et al., 2013; Elluru et al., 2019), most retaining information from pandemic case studies. Hobbs (2020) identified two types of disruptions for the Canadian food industry, the lack of raw materials and transportation disruptions brought by the restrictions on movements of goods and people. Production and raw materials can be affected, as there was a global effort to maximise production on essential items, as toilet paper or medical provisions, that can lead to stoppages in production of the usual items (Paul & Chowdhury, 2020).

In order to properly understand how the results of the new metric and the presented model impact on the SCR, three failure modes are identified (Production, Supply, Transportation), adapted from (Rice & Caniato, 2003), and are to be studied.

- **Disruption 1 - Production facilities**

  This disruption is representative of all the failures that can cause factories to cease production. The COVID-19 pandemic showed us several examples of this. Some, due to imposed lock-down which in consequence forced factories to stop. Some parts of Italy closed theirs factories in an effort to contain the outbreak (RTE, 2020). In the area of Milan, the mandatory shutdown lasted for months and the return to normal was done gradually, depending on the type of service (Jewkes & Amante, 2020).

  Production could also stop if for some reason there was no workforce available. The traditional example of labour strikes had similar consequences to factories that had to stop operations due to infections of SARS-COV-2 amongst their workers. This forced stop could happen in all kinds of factories, since regardless of the relevance of the product being made, keep on working could pile up infections inside and outside the factory. An example of this occured in a meat processing plant in the United States (US), that was forced to close even after initial efforts to remain open due to its relevance in food production (Lussenhop, 2020).

- **Disruption 2 - Supply**

  Shortages of raw materials represent a fairly common event in SC. The COVID-19 pandemic brought it to a completely different level. This type of events were fairly brief, in contrast to recent shortages that lasted for months. This was particular evident in the pharmaceutical industry, with raw materials distribution halted which in turn lead to shortages of medical drugs (Mullin, 2020; Fitch Solutions, 2020).

- **Disruption 3 - Transportation** Even for industries that were able to keep working and producing some had a new hurdle, the transportation of goods to their final destination. Many countries prohibited non-essential movements, most often international ones. In some cases it also included transportation of goods (*Covid-19 is closing borders and attitudes as globalisation slows down*, 2020). Even traditionaly interconnected countries had their exchanges halted as was the case of the border between the US and Canada (Hobbs, 2020). Who would ever thought that the Schengen space would close completely in such a small period of time (Wimmer, 2020)? Thus, transportation disruptions are representative and give an insight into how prepared a SC must be to be resilient.

With this interpretation for the generation of a representative set of disruptions, previously used and presented in the literature, it is possible to establish a simple and replicable methodology not only for comparison with previous publications but also for new developments in the field of SCR. It enables the study of the resilient behaviour of the SC while providing relevant data, facilitating the improvement of the responsiveness of the SC while easing the dissemination of managerial insights for practitioners and academics alike.

5.7 Maximising SC ENPV Vs Maximising SCR Performance

For a comprehensive and valid process of results acquisition and discussion, a structured methodology is followed, represented schematically in Figure 5.1. For each SC case, defined later on in Sub-Section 5.7.2, the network configuration is established based on the SC network provided by the objective function when no disruption occurs. The obtained network design is then tested under a disruption scenario, as characterised in Section 5.6, and the SCR results are analysed and discussed.

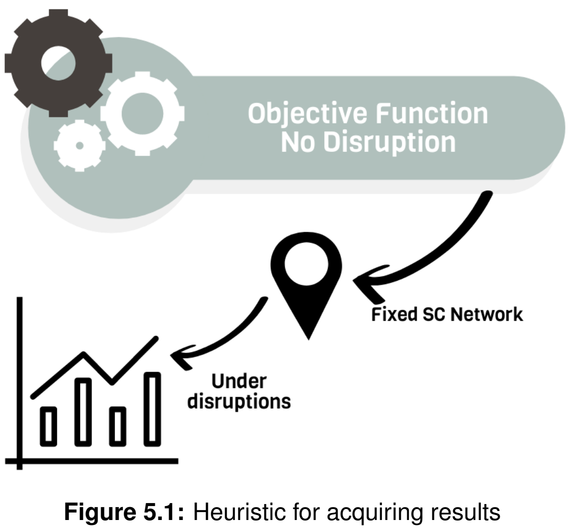


Figure 5.1: Heuristic for acquiring results

The MILP model is implemented in GAMS software and solved with CPLEX.

With this study, it is possible to compare the SCR in terms of different metrics and understand the relevance of the new proposed SCR metric and its impact on the SC network design.

5.7.1 Case Study Description

The presented model is tested in a case study. This case study is based on a European SC with the associated data scaled down due to confidentiality reasons.

To improve SC's capacity to withstand disruptive events, while expanding its business, the company is studying several possibilities and acquiring 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 new entities; Plants, Suppliers or Warehouses.

As mentioned, the data is modified to respect company confidentiality, but this does not affect the SC characteristics.

5.7.1.A Supply Chain characteristics

The initial SC is supplying 17 European markets. Final products can be manufactured in a plant in Hamburg or be bought in outsourcing suppliers located in Riga, Minsk and Warsaw. When produced in-house, the SC relies on raw materials sourced from suppliers in Frankfurt, Prague, Birmingham and Copenhagen. The raw materials are then brought to the plant where twelve production technologies and six disassembling technologies are used in the production of products. The latter technologies are allocated to the reserve flows of used products, if existing. There is an intermediate echelon constituted by one warehouse in Munich, with a capacity of 500 units, that creates value not only by managing the inventory but also by being able to assemble goods with six technologies.

With an expansion strategy, the SC is considering the possibility of including two new plants with the following set of raw material suppliers:

- Bilbao
  - Badajoz, Toledo, Barcelona, Marseille
- Milan
  - Ljubljana, Lausanne, Linz, Florence

The prospective warehouse locations are Portsmouth, Lyon, Bologna and Salamanca.

The possible structure of the SC considered in the case study is represented in Figure 5.2.

Production of products is associated with the implementation of technologies in each plant. Raw materials and intermediate products are also considered. The activities associated with reverse logistics are associated with Warehouses in the case of assembling or re-producing the final products. In plants, there is the case of disassembling end of life products allowing the salvage of products, and the exploration of circular economy concepts.

The costs associated with the case study are expressed in Table 5.1:

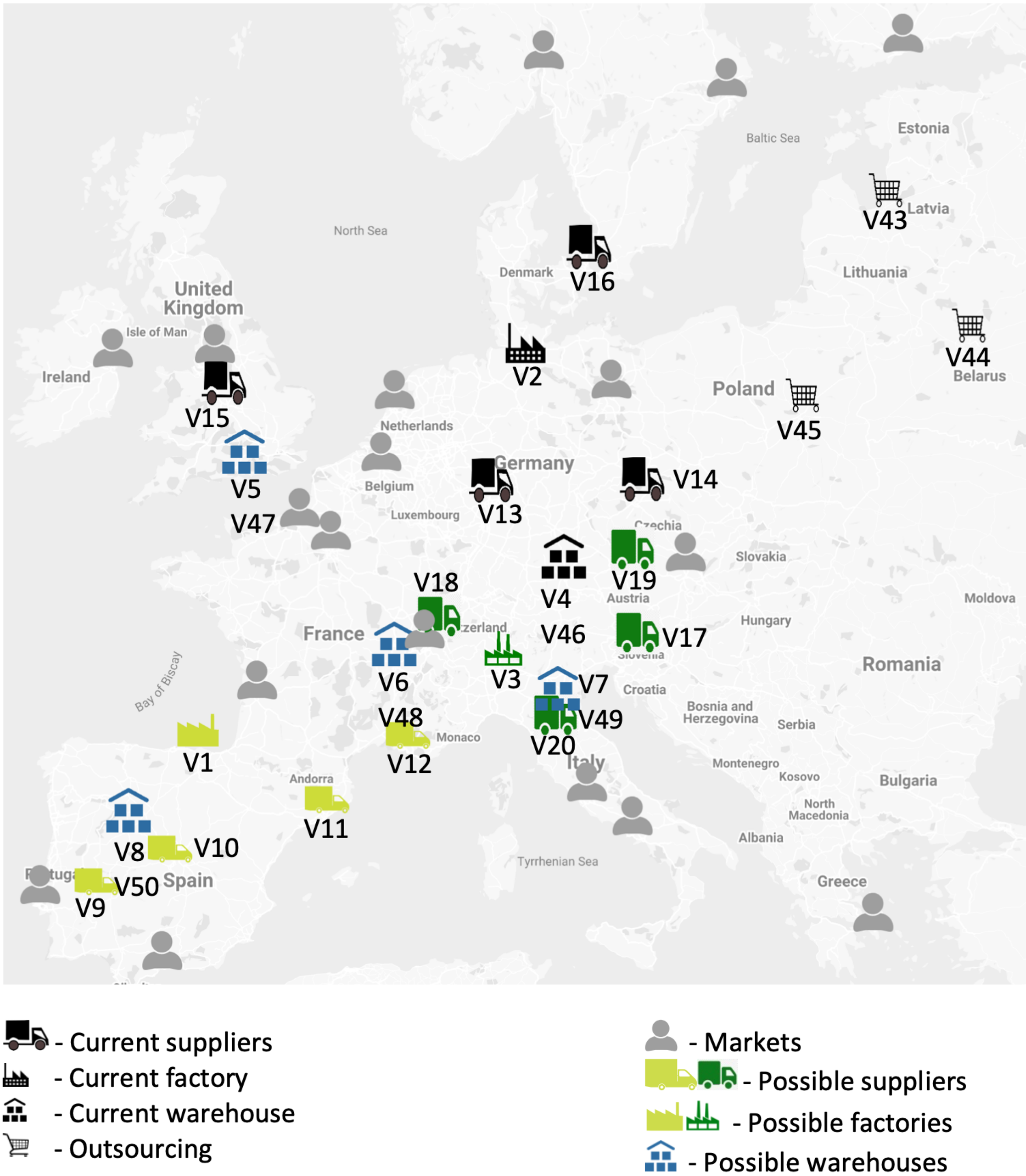


Figure 5.2: SC network configuration with current and prospective facilities

Table 5.1: Case Study costs table

Costs		
Inventory Costs		0.3€/ton 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 for each product p_x		$p_{29} = 250€$, $p_{30} = 270€$, $p_{31} = 240€$, $p_{32} = 290€$, $p_{33} = 255€$, $p_{34} = 265€$
Plants' investment cost		1€/ton
Warehouses' investment cost		0.5€/ton
Disassembling Centres' investment cost		0.1€/ton

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

- Capacity expansions lower than 400 000 ton/entity
- Flow between entities lower than 5000 ton
- Warehouse turnover ratio is equal to 20, and no initial inventories are considered
- 20% of products sent to markets each period are non-conforming
- A minimum of 10% of products to be collected at markets, 20% of the collected goods are sent to disposal
- Demand is assumed to be known for the 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 penalised by 5% in the subsequent periods of time

5.7.2 Possible SC network configurations

Five different cases, with different SC possible network configurations, under steady-state conditions (no disruption) and a set of disruptive scenarios are analysed. The comparison between the combination of the various cases and disruptive scenarios helps to identify how the SC network can be designed to achieve higher resilience. The explored cases are depicted in Figure 5.3, allowing for the generation of comparable results.

- Case A - a forward supply chain;
- Case B - forward and reverse flows between consecutive echelons;
- Case C - forward and reverse flows between consecutive echelons, but plants and markets can directly exchange products, thus bypassing the warehouses;
- Case D - forward and reverse flows between consecutive echelons, but with the possibility of transhipment at plants, disassembling centres and warehouses;
- Case E - A closed-loop supply chain where all flows previously described are possible.

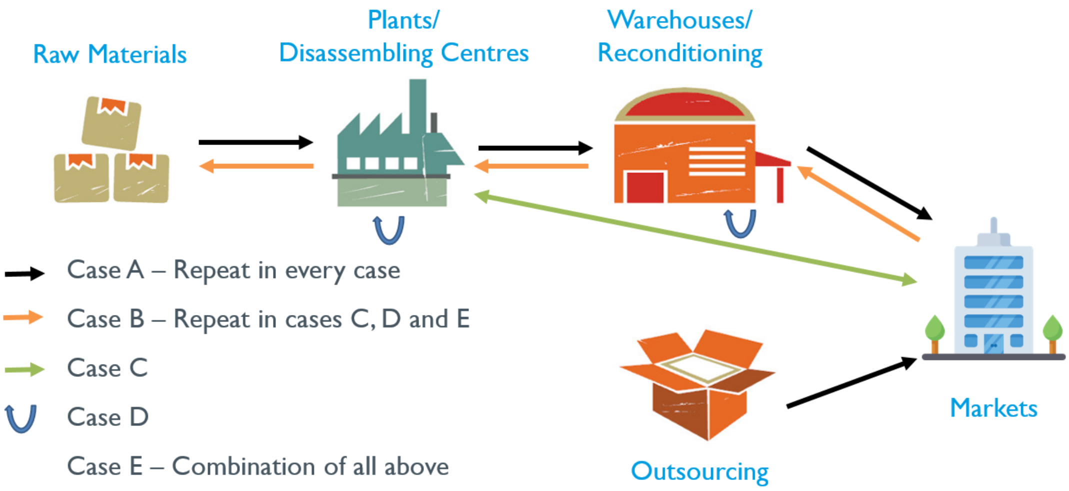


Figure 5.3: Conceptual description of the SC network, with all cases considered

5.7.2.A Disruptive events - Case study

The SC is to be evaluated under four operational conditions; one reference case with perfect operational conditions and three types of disruptions. From the discussion in Section 5.6 the representative set of disruptions is applied to the case study. One event for each type of disruption is created and is believed to be a good approach for the study of SCR. The disruptive events are defined below.

- Steady-state - No disruptions occur
- Disruption 1 (Production Facilities)- The plant located in Milan, which is the one with higher production, ceases production in time period 2;
- Disruption 2 (Supply)- The raw materials suppliers, with higher contributions, located in Birmingham, Badajoz, Marseille, Ljubljana and Lausanne cannot supply in time period 2;
- Disruption 3 (Transportation)- The plant in Milan, which is the one with higher production, cannot send any product to warehouses in Munich, Portsmouth and Bologna in time period 2.

5.7.3 Results

The case study was applied with the presented model optimising the contrasting metrics here discussed; maximising ENPV or the new resilience metric. The cases related with the maximisation of ENPV are described as "Case x" while those related with the new SCR metric are described as "Case Nx".

On the one hand, the supply chain performance behaviour is presented, Sub-section 5.7.3.A, focusing on SCM performance indicators, allowing for a broader comparison between the two models. Those indicators vary from SC network characteristics (SC complexity, a usual resilience indicator) to economic and operational SC characteristics. On the other, a more in-depth analysis of the ripple effect is performed in Sub-section 5.7.3.B. This explores a better understanding of how could the new metric improve SC responsiveness and resilience. Additionally, the visualisation of flows is presented, allowing for a comparison between different instances and recognise differences in fundamental decisions of SCM.

5.7.3.A Supply Chain Performance

Following the methodology described in Section 5.7, the results when maximising SC ENPV are presented in Table 5.2 and results from the maximisation of SCR performance, based on the newly proposed metric, are presented in Table 5.3. Comparing the results in both tables is clear that the new metric optimisation leads to a more resilient SC, with increased responsiveness, enabling to handle disruptive events better. In detail, each case is analysed below.

Table 5.2: Results maximising ENPV

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	1.45E+07	1.02E+06	1.00E+06	1048.564	374026	40300000	60.7%
Disruption 3	44	1.83E+07	7.80E+05	7.52E+05	1278.613	313617	48435000	75.7%
Case B	**Complexity**	**ENPV**	**FCI**	**Investment**	**Inventory**	**Purchases**	**Sales**	**ECSL**
Reference	89	1.91E+07	7.65E+05	7.20E+05	1449.680	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	302463	47672000	72.0%
Disruption 3	87	1.79E+07	7.89E+05	7.45E+05	1301.026	304995	48744000	77.0%
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%
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	42559300	65.5%
Disruption 2	89	1.77E+07	1.04E+06	9.95E+05	1227.958	302705	47651000	72.0%
Disruption 3	88	1.79E+07	7.88E+05	7.44E+05	1301.334	304861	48747000	77.0%
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	44065000	77,8%
Disruption 3	104	1,84E+07	9,31E+05	8,77E+05	885,033	454900	51674000	98,4%

Table 5.3: Results maximising Resilience Performance

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%	0.98
Disruption 1	49	1.47E+07	9.46E+05	9.15E+05	1458.818	1015990	50039000	85.6%	0.61
Disruption 2	47	8.30E+06	8.90E+06	8.87E+06	2229.688	1172260	50760000	89.2%	0.32
Disruption 3	47	1.64E+07	8.48E+05	8.18E+05	1560.005	871100	51675000	92.3%	0.76
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%	0.98
Disruption 1	94	1.39E+07	9.13E+05	8.67E+05	1554.218	950520	51169000	91.4%	0.64
Disruption 2	94	1.59E+07	1.09E+06	1.05E+06	1589.617	671200	51856000	93.6%	0.77
Disruption 3	93	1.69E+07	8.68E+05	8.23E+05	1642.735	530850	52543000	97.0%	0.85
Case NC	**Complexity**	**ENPV**	**FCI**	**Investment**	**Inventory**	**Purchases**	**Sales**	**ECSL**	**Obj. Function**
Reference	138	2.05E+07	8.73E+05	8.04E+05	913.444	383580	53045000	100.0%	1.00
Disruption 1	138	1.54E+07	1.11E+06	1.04E+06	969.317	820960	51504000	95.2%	0.70
Disruption 2	136	8.79E+06	5.46E+06	5.39E+06	1040.172	1001520	48453000	86.9%	0.3
Disruption 3	138	2.05E+07	8.73E+05	8.04E+05	913.426	383650	53045000	100.0%	1.00
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%	0.56
Disruption 2	97	9.30E+06	9.03E+06	8.98E+06	1582.006	693940	51227000	91.3%	0.40
Disruption 3	97	1.62E+07	9.25E+05	8.77E+05	1665.886	666800	52755000	98.4%	0.83
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%	1.00
Disruption 1	107	1.61E+07	1.02E+06	9.66E+05	945.353	642790	49620000	93.7%	0.72
Disruption 2	105	1.47E+07	1.13E+06	1.07E+06	1036.188	686157	48572080	91.3%	0.63
Disruption 3	108	1.90E+07	9.61E+05	9.06E+05	913.887	447640	53045000	100.0%	0.93

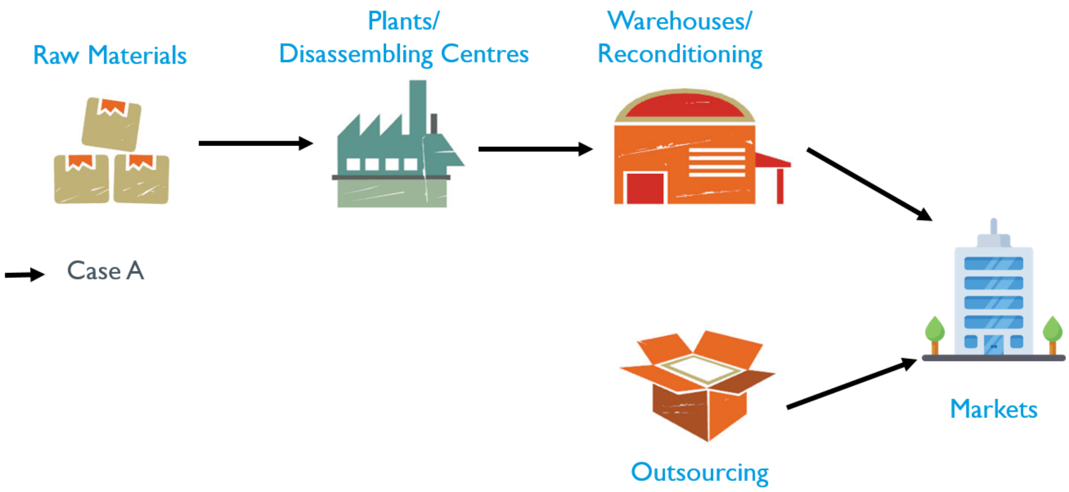


Figure 5.4: Schematic configuration of flows allowed in SC Network Configuration A

A – Supply Chain Network Configuration A Case A represents a simple SC structure (lower network complexity), allowing only forward flows, as depicted in Figure 5.4. For the maximisation of ENPV, and from Table 5.2 it can be seen that, under disruptions, the network loses some of its capacity to meet customer demand (ECSL) and consequently reduces its financial performance (ENPV).

On the other hand, when considering the new SCR metric, the results obtained are substantially different, Table 5.3. Generically, the results show a lower value in ENPV and a higher value for the expected customer service level (ECSL). Such behaviour translates the increased guarantee of customer satisfaction at the expense of lower profits.

In the eventuality of no disruption occurring, the OF value in Table 5.3, stays close to 1, revealing the similarity between the network configuration from the Reference case when maximising the ENPV (Table 5.2) and the new SC network configuration. The new metric provides a slightly smaller return in ENPV, 1.91 versus 1.96, however, the ECSL moves from 85,7% to 100%.

From Table 5.3, Case NA, it can be seen that between disruptions there are significant ENPV fluctuations. Disruption 2 returns the lowest ENPV amongst the different disturbances, also leading to a lower value of the presented resilience metric. In turn, Disruption 3 returns the higher value of ENPV and with the smallest percentual variation to the results from ENPV maximisation, 10%. Other disruptions also negatively affect the ENPV, with reductions of 11% and 53% for Disruptions 1 and 2, respectively.

With the proposed new OF, there is an innovative relevance being given to ECSL that does not exist when maximising ENPV. This new element brings a significant improvement in service quality, leading to an ECSL of above 85% for all disruptions. The latter value is better than that returned by the reference model, where the mean ECSL for Case A is 70.37%. Comparatively, there are deviations of 35%, 24% and 22% for Disruptions 1, 2 and 3 respectively. This effort to meet customer demand does not come from added complexity but mainly from an increased number of purchases of final products from outsourcing, which allows for an increase in sales and consequently in ECSL, visible in Figure 5.5 where the normalised average results from each model are presented.

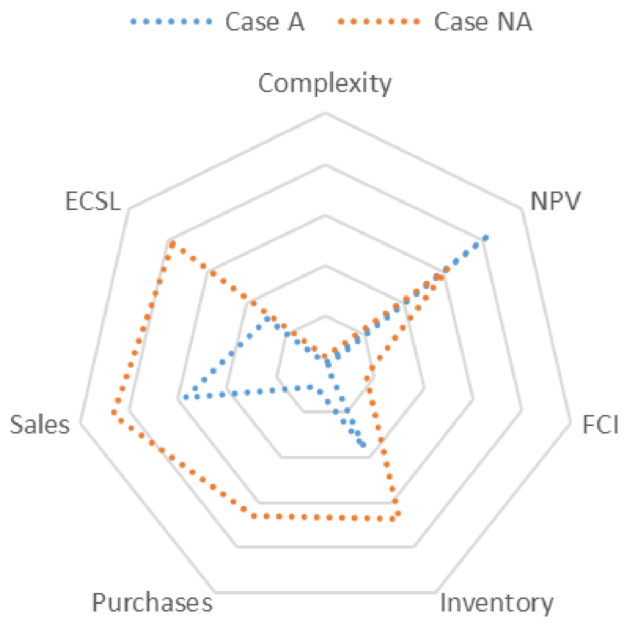


Figure 5.5: Average results of SC network configuration A for the two presented models

B – Supply Chain Network Configuration B Case B represents a SC structure where reverse flows are allowed between consecutive echelons adding complexity to the operation, Figure 5.6.

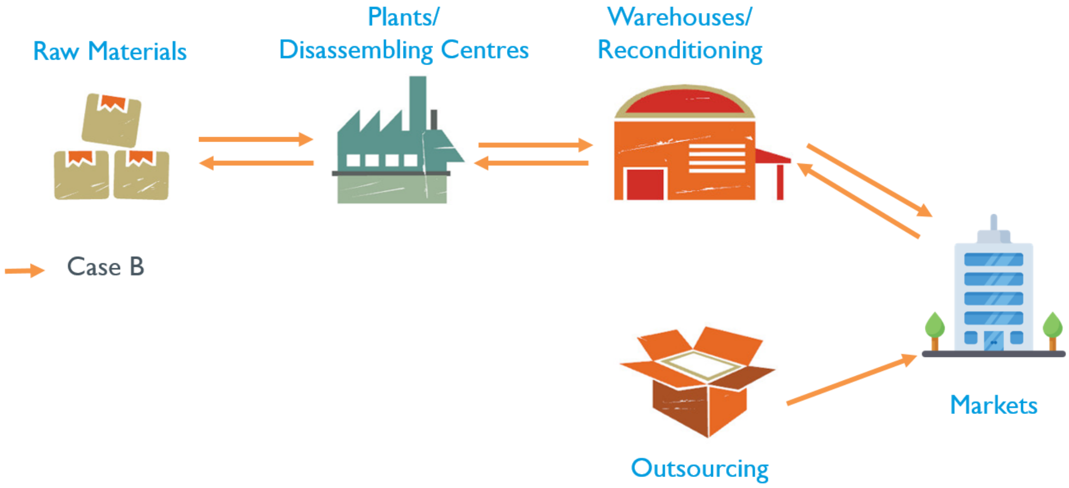


Figure 5.6: Schematic configuration of flows allowed in SC Network Configuration B

For this structure, when maximising ENPV, disruptions cause negative impacts on several performance metrics, particularly on the ECSL, with decreases higher than 10% when compared with the reference state operation.

When maximising the new resilience performance metric, ENPV values are expected to be lower than those from the reference configuration to all cases, due to the inclusion of customer demand satisfaction in the OF. Disruption 1 returns 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.

Nevertheless, 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 economically driven model by 43%, 30% and 26% for Disruptions 1, 2 and 3 respectively. Such findings represent a trade-off between increased costs and better ECSL when deploying an operation achieved by the presented model, Figure 5.7.

In Case NB, the values for the OF are always higher than those from Case NA, implying a smaller deviation from the ENPV and an improvement in ECSL, when compared to the reference case. This is justified by the higher flexibility, translated into the complexity metric, that characterises this SC configuration.

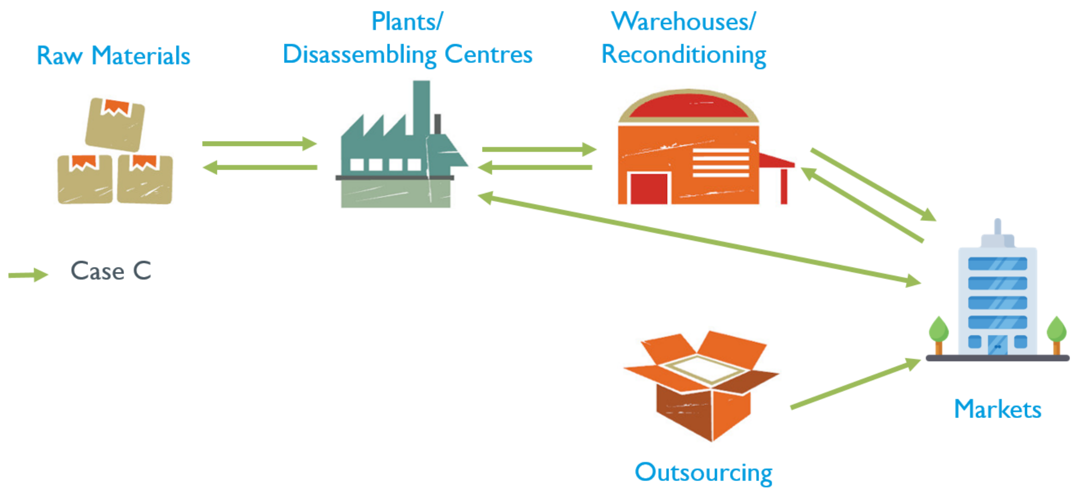


Figure 5.8: Schematic configuration of flows allowed in SC Network Configuration C

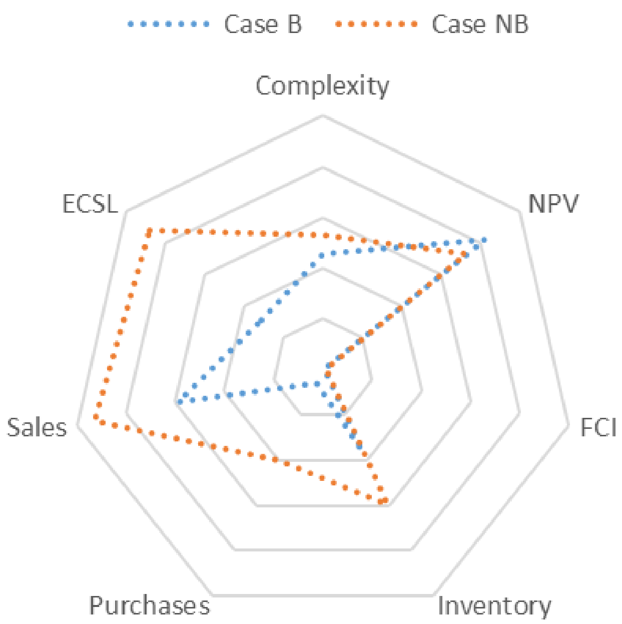


Figure 5.7: Average results of SC network configuration B for the two presented models

C – Supply Chain Network Configuration C Case C introduces a different kind of flexibility to the network as it allows the same flows as Case B and allows for plants and markets to exchange products without any warehouse intervention, Figure 5.8.

In this configuration, the results become somehow distinct to Cases A and B. For instance, the 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. However, this configuration still provides better results than SC configurations obtained in Cases A and B. The increased susceptibility to Disruption 2 in Case C, is related with the lower inventory, when compared with the alternative configurations (a characteristic visible in Figure 5.9), which in combination with the non-existence of transhipment between entities turn the consequences of failure in supply inevitable.

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

The new metric caused a higher impact on ENPV, with divergences of -1%, -28% and 2% for Disruptions 1, 2 and 3 respectively. This means that, while for Disruption 2 the ENPV decreased significantly, for Disruption 3 this new OF provided a network that guarantees a better economic return.

ECSL is benefited in the new SC network configuration as this provides 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 causes the most economic 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. The different outcomes for the two models are depicted in Figure 5.9.

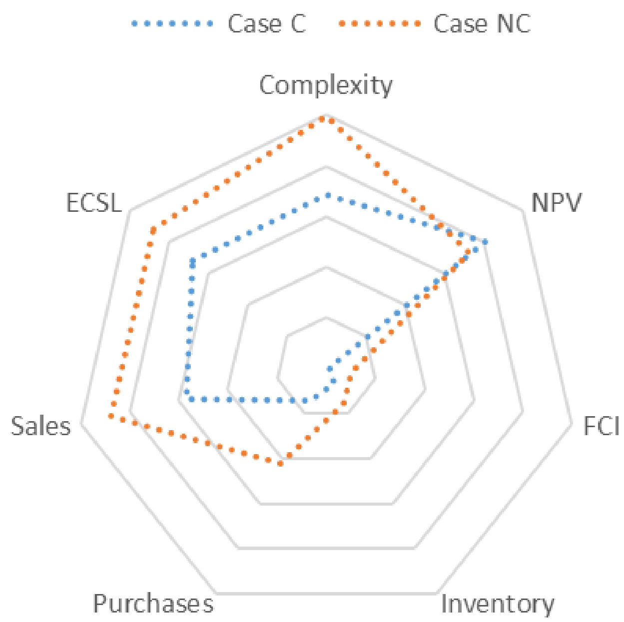


Figure 5.9: Average results of SC network configuration C for the two presented models

D – Supply Chain Network Configuration 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 5.10.

For the economic return driven model, the results are similar to Cases A and B, where Disruption 1 is again, the event that causes the most stress to the operation and its objectives. Such disruption causes a significant decrease in both ENPV and ECSL.

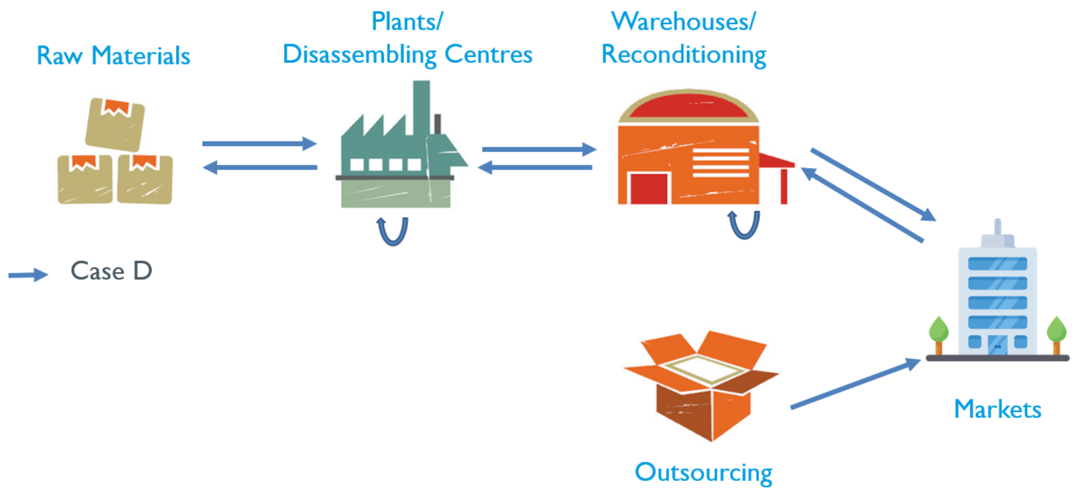


Figure 5.10: Schematic configuration of flows allowed in SC Network Configuration D

Results for Case ND, when no disruption occurs, show a small decrease in ENPV with an improvement in ECSL, the increase in service quality means to near-total demand fulfilment.

Concerning the maximisation of the SCR performance, 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 economic returns, however, with smaller proportions representing -14%, -47% and -9% for Disruptions 1, 2 and 3 respectively.

In line with other cases, due to the introduction of concerns regarding service quality in the OF, ECSL is higher in this model with customer demand being met nearly 90% of the times of all the disruptions represented, at the expense of increased flow complexity and outsourcing purchases, Figure 5.9. This represents an improvement from the reference case of 32%, 27% and 28% for Disruptions 1, 2 and 3 respectively.

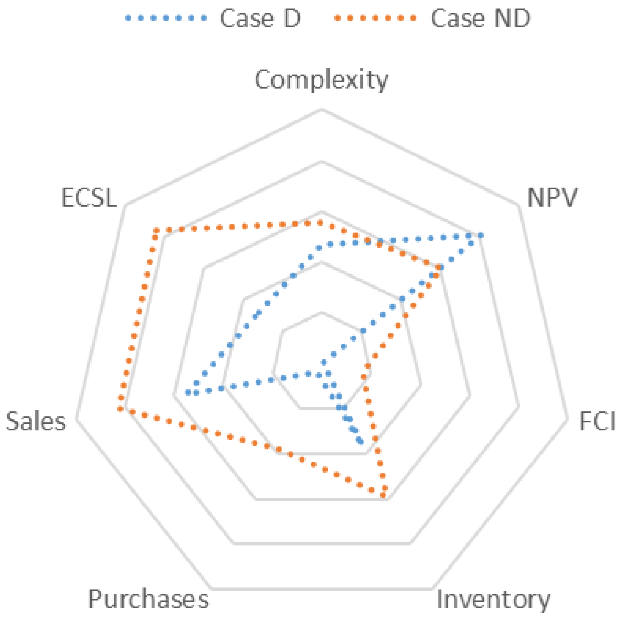


Figure 5.11: Average results of SC network configuration D for the two presented models

E – Supply Chain Network Configuration E The last case in our study represents a network that includes all 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 5.12.

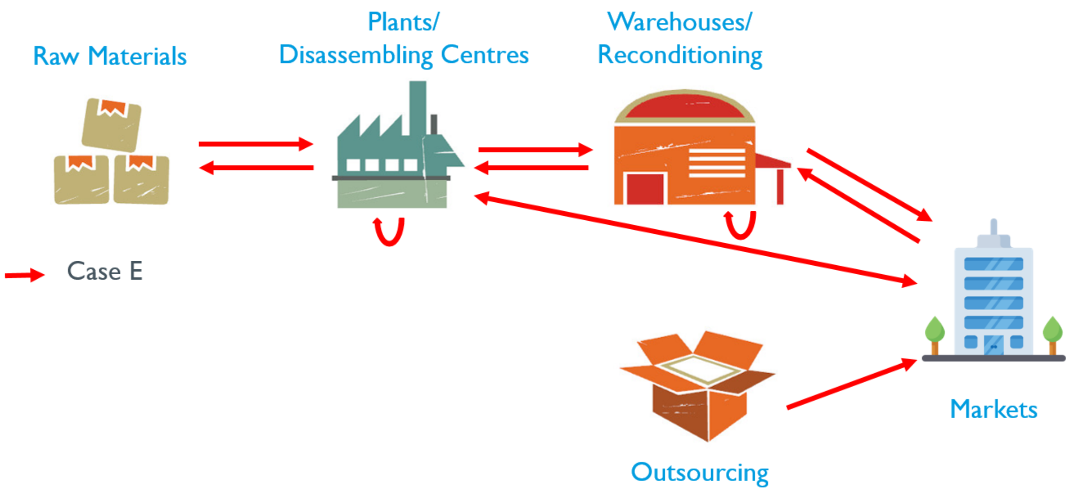


Figure 5.12: Schematic configuration of flows allowed in SC Network Configuration E

From the results, when maximising economic return, it is perceptible that Disruption 1 is the event that influences ENPV the most. Whereas Disruption 2 is the scenario that affects ECSL with an increased impact, with the SC lacking responsiveness and not being able to cope with the lack of supply of raw materials, due to the lower inventory, as shown in Case C (Section C –).

For this case, when no disruption is present, the value of the new resilience metric 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 the 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. Disruption 2 is the event that originates the lowest resilience metric, caused by the significantly lower ENPV, due to the reduction on inventory available. On the contrary, Disruption 3 is able to provide a solution that improves the result from the reference case, although only slightly.

Although the new SC network in case NE provides better ECSL, with all disruptive events reaching values above 92%, it is the case where the percentual variation between the new and reference model results is smaller, Figure 5.13, with 12%, 19% and 2% for Disruptions 1, 2 and 3 respectively. This is much due to the fact of the reference case already reaching better results in this disturbance than in other cases, leaving less space for percentual increases, even if with a good absolute outcome.

Figure 5.13: Average results of SC network configuration E for the two presented models

5.7.3.B Ripple Effect

A deeper analysis of the ripple effect is here performed, following the concerns described in the introduction, Section 7.2, regarding the cascading effect on SC caused by disruptions. In the case study considered, four different SC tiers are considered, and the disruptive scenarios were built to represent failures in the different levels, therefore providing the basis for an analysis on how a disruption in one layer can impact other entities of the SC.

For all the different SC network configurations in this case study, there are four distinct types of flows. Take Figure 5.14 as an illustrative example:

- Top left corner: Flows from factories (v1 to v3) to warehouses (v4 to v8)
- Middle left: Flows from raw materials suppliers (v9 to v20) to factories (v1 to v3)

- Top right corner: Flows from warehouses (v4 to v8) to markets (v21 to v38)
- Bottom left corner: Flows from outsourcing (v43 to v50) to warehouses (v4 to v8)

Outsourcing entities v46 to v50 are implemented in warehouses, v4 to v8, and represent an intermediate product that warehouses must buy to sell some products, for example, extra packaging. v43 to v45 represent the outsourcing entities of final products ready to be sold.

Using this representation for the flows between different entities in the SC is possible to compare the different disruptive scenarios and infer on the real impact of disruptions and the ripple effect it causes.

A – Supply Chain Network Configuration A When no disruption occurs, the flows obtained by deploying the new Resilience Metric are presented in Figure 5.14. Is visible a high dependency on factory v3 and outsourcing, represented by high colour intensity.

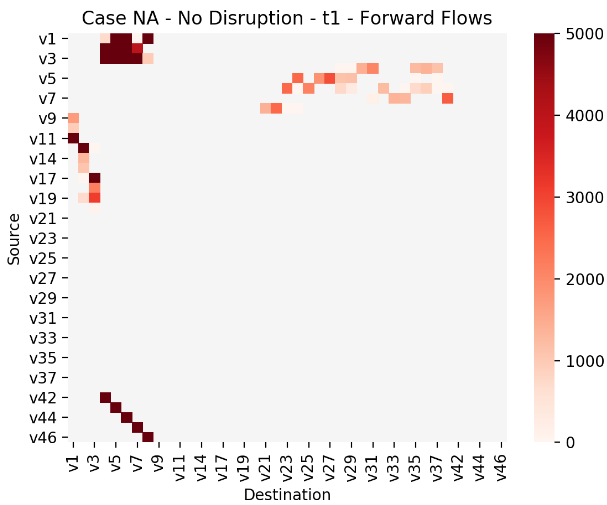


Figure 5.14: Forward flows (ton) in Case NA in period 1 when no disruption occurs.

In disruption 1, when one factory (v3) ceases activity in period 2, the effort to fulfil the demand is distributed throughout the remaining working factories, as it can be seen in Figure 5.15, top right corner where the line of v3 disappeared, and the other lines increased in colour intensity, meaning increased flows intensity. Disruption 3 causes a similar ripple effect when the transportation between a factory (v3) and some warehouses (v4, v6 and v7) cease. The result is a higher workload for the remaining factories, particularly in v1, which can fulfil the demand from the affected warehouses, seen by the increased colour intensity for v1 and v2 while most of the flows from v3 disappear in the top left corner in Figure 5.16. Consequently, the shifts in the pattern supply/demand lead to higher activity for the flows connecting the raw materials suppliers and the factory (Flow v9 to v1), as shown in Figure 5.16.

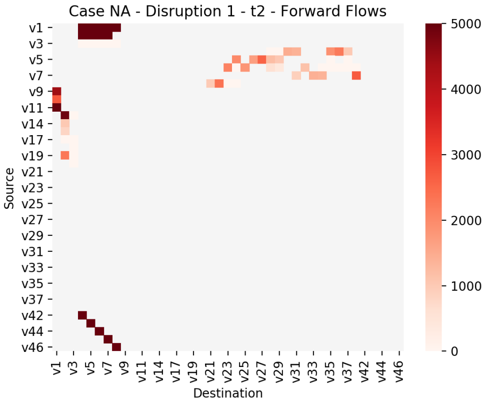


Figure 5.15: Forward flows (ton) in Case NA in period 2 for disruption 1.

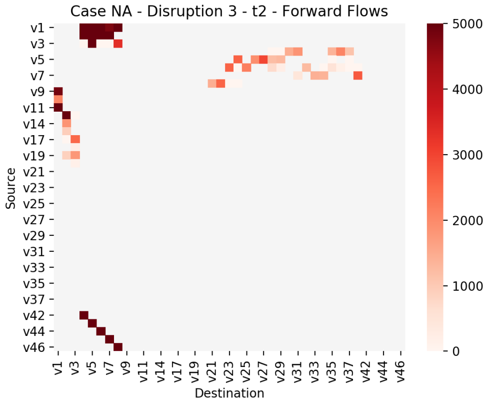


Figure 5.16: Forward flows (ton) in Case NA in period 2 for disruption 3.

The above mentioned adverse effects of the ripple effect are diminished using the new resilience metric. If the consequences of the disruptions are compared with the SC network coming from the conventional maximisation of ENPV, then the fluctuation along the SC are much higher, and the negative perception of disruptions for the clients is much higher. Comparing Figures 5.17 and 5.18 with Figures 5.15 and 5.16, the beforehand mentioned consequences are visible, with lower quantities reaching to the markets (top right corner), represented by the faded colour intensity in the flows referring to case A and with higher colour intensity in Case NA, a genuinely detrimental impact of the ripple effect, mitigated by the new resilience metric.

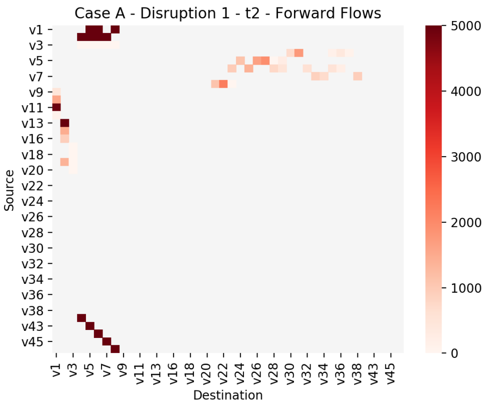


Figure 5.17: Forward flows (ton) in Case A in period 2 for disruption 1.

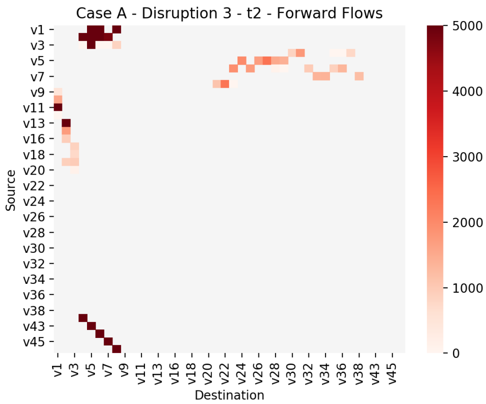


Figure 5.18: Forward flows (ton) in Case A in period 2 for disruption 3.

Upstream disruptions, as implemented in Disruption 2, cause the biggest impact, as seen in Subsection 5.7.3.A, and in terms of the ripple effect along the SC. Not having the suppliers available (v11, v13 and v17 to v19) leads to a reduction in the productive capacity of the SC, worsen by the nonexistence of reverse flows, leading to a reduction in the final flows from warehouses to markets. This inference is visible by comparing the Top Right Corner of Figures 5.15, 5.19 and 5.16 where the colour intensity is lower when considering Disruption 2.

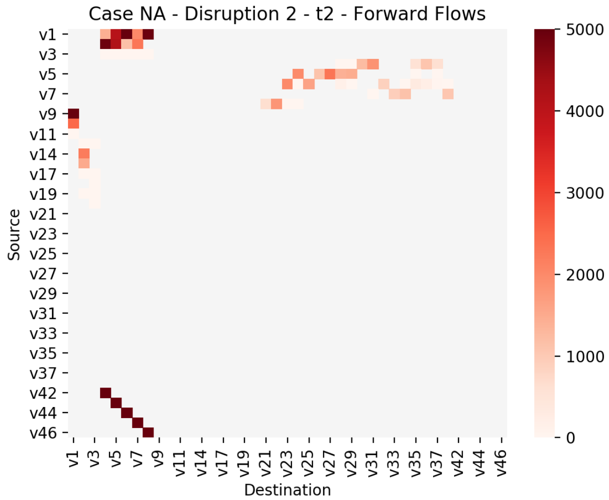


Figure 5.19: Forward flows (ton) in Case NA in period 2 for disruption 2.

B – Remaining Supply Chain Network Configurations As seen in Sub-section 5.7.3.A, so as to maximise NPV and the satisfaction of demand, the SC makes use of reverse flows, discarding the use of outsourcing, see the absence of flows in the bottom left corner of Figure 5.20. That is much related to the recovered material coming from reverse flows that are used for the production of products to deliver to markets, thus adding a substantial sustainable benefit.

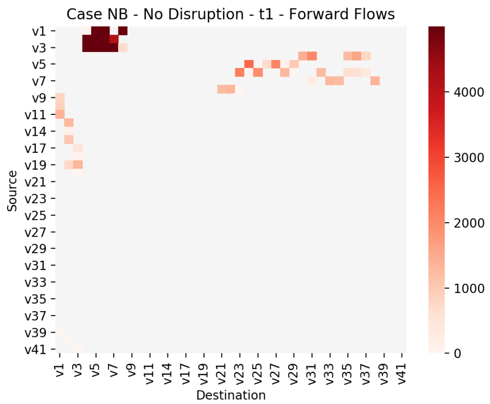


Figure 5.20: Forward flows (ton) in Case NB in period 1 when no disruption occurs.

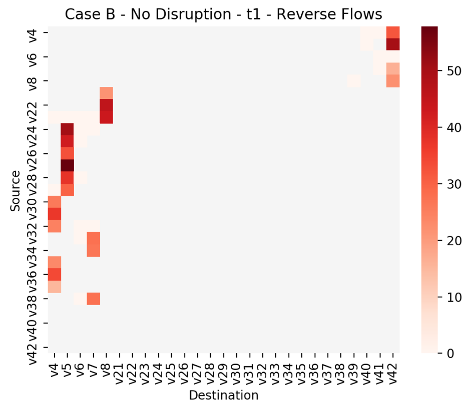


Figure 5.21: Reverse flows (ton) in Case B in period 1 when no disruption occurs.

From Figure 5.21 it is possible to see that there is a significant flow of products in the reverse flow, on the left, coming from the markets to the warehouses, a characteristic shared by the different SC network configurations allowing reverse flows. That flow is immediately followed by those in the top right corner representing the flows from the warehouses to the facilities which have reverse logistics activities, allowing to be introduced again in the forward SC.

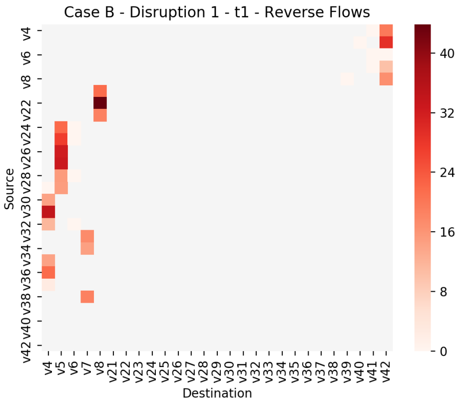


Figure 5.22: Reverse flows (ton) in Case B in period 1 when disruption 1 occurs.

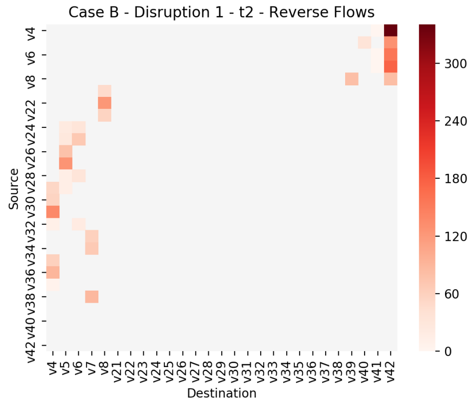


Figure 5.23: Reverse flows (ton) in Case B in period 2 when disruption 1 occurs.

The benefits of the newly introduced resilience metric are quite visible if ENPV maximisation (Figures 5.22 and 5.23) and the New metric (Figures 5.24 and 5.25) are compared when applied the simplest case of a closed-loop SC, in our case study represented by Case B. The reduction in the ripple effect is evident in this example, with a reduction in the variability between consequent time periods. While when maximising ENPV there is a reduction of flows when the description occurs, perceptible in the decrease in colour intensity between Figures 5.22 and 5.23. The cascading effect is almost imperceptible with the new SCR metric, there is practically no difference in colour intensity between Figures 5.24 and 5.25, thus contributing to a more resilient SC.

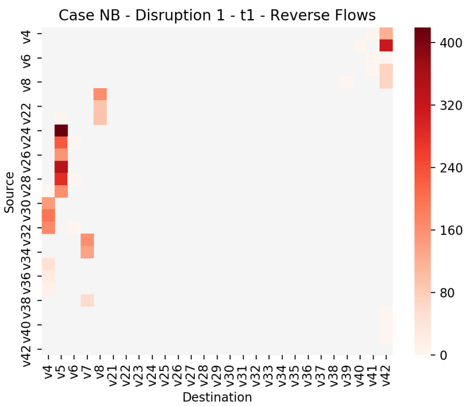


Figure 5.24: Reverse flows (ton) in Case NB in period 1 when disruption 1 occurs.

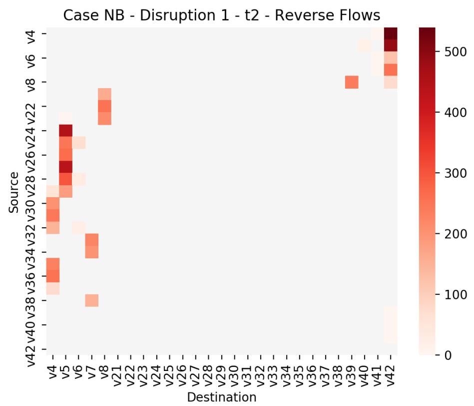


Figure 5.25: Reverse flows (ton) in Case NB in period 2 when disruption 1 occurs.

When facing a supply disruption, Disruption 2, our results show that the new resilience metric provides a SC better capable of reducing the negative impacts on the consumer, evident when comparing the top right corner of Figures 5.26 and 5.27.

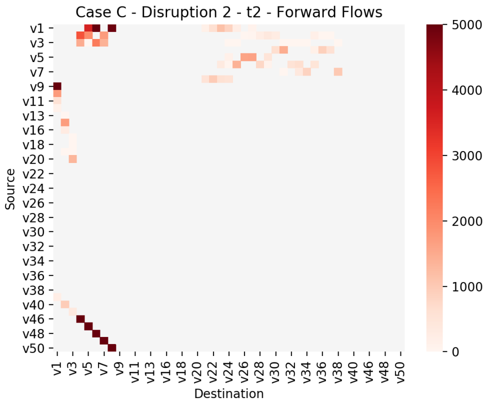


Figure 5.26: Forward flows (ton) in Case C in period 2 when disruption 2 occurs.

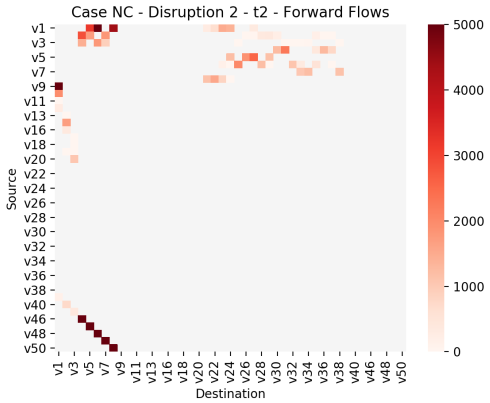


Figure 5.27: Forward flows (ton) in Case NC in period 2 when disruption 2 occurs.

It is relevant to note the different results from SC network configuration C and D, where the difference between the two cases is the possibility for plants and markets to connect directly for configuration C, and transhipment for configuration D. This added flexibility reduces the severity of the consequences, making use of such possibility to quickly address the disruption. On the other hand, in Case D (Figure 5.28) and Case ND (Figure 5.29) transhipment does not benefit the response, with an increased negative variation when meeting demand and an increased effort to factories and raw materials suppliers.

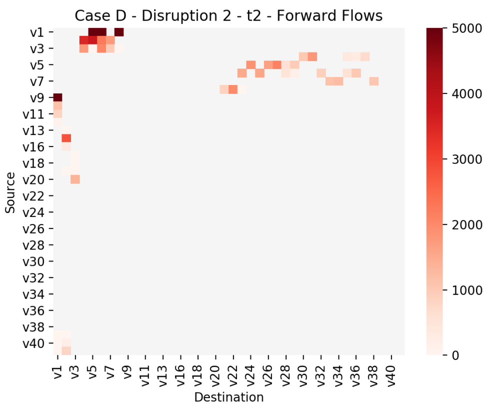


Figure 5.28: Forward flows (ton) in Case D in period 2 when disruption 2 occurs.

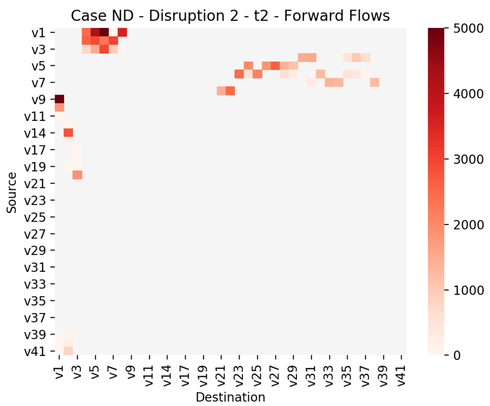


Figure 5.29: Forward flows (ton) in Case ND in period 2 when disruption 2 occurs.

The behaviour expressed for network configurations C and D goes well in line with the literature, as discussed in Section 7.2. and further explored in Sections 5.8 and 5.9.

5.8 Discussion

The new resilience metric, translated into the new OF defined in Equation 5.12, meets the challenge of generating a quantitative model that better encapsulates the strategic decisions to be made, regarding SC network resilience, in an uncertain environment. Within this approach, the responsiveness of the SC is considered and consequently improved.

Considering that, during the decision-making process, it should be pursued a trade-off between the gains in ECSL and losses in ENPV, a compromise solution between the increases in ECSL and losses in ENPV is targeted. The balance achieved in this balanced metric ensures a better fit between the model results and the challenges created by real scenarios of 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 maximising complexity) or low service quality (when the main goal is to maximise profit).

The results show that a balance between the different goals, achieved by applying the new metric, is beneficial to companies. The increase in flow redundancy created flexibility, resulting in a proactive strategy to mitigate the costs of disruptions, to keep the operation running while guaranteeing customer's satisfaction.

The case study analysis allows to conclude that it is possible to improve, normal and under disruption operations, with an acceptable amount of investment. The new SC network is responsible for an increase in the SC responsiveness and consequently in the quality of service provided to customers. Additionally, it guarantees an improved company image and consequently, higher success in the markets. That overall benefit is evident in Figures 5.5, 5.7, 5.9, 5.11 and 5.13 where it is possible to see that the SC from the new metric is much better than that obtained by the classical ENPV maximisation.

The increased responsiveness is aligned with the increased ability of the new SCR metric to reduce variability when disruptions occur as well as the ripple effect within the SC. The results presented in Sub-section 5.7.3.B show that shifting from the current and most commonly used metrics to the new metric results in a reduced cascading effect while maintaining a higher level of customer service.

This is summarised for all cases in Table 5.4, where the main improvement is seen in ECSL, through the increment in SC responsiveness in all conditions explored, with or without disruptive events.

Table 5.4: Percentage variation of ENPV and ECSL between the new resilience metric and the reference

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	-7%	14%	Case NC	-39%	21%	Case NC	11%	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	-11%	17%	Case NE	3%	2%

It is also evident that Disruption 2, a lack of supply, causes the most significant impact on ENPV, for all the Cases considered. This disruption is, however, compensated, based on the new proposed objective, by incrementing the purchase of final products from outsourcing to meet the gap caused by the disruptive event.

Disruption 3 is the event that causes the least amount of variation regarding ENPV, it is even possible, in two cases, to combine the increase of economic return with a better performance in service quality. Thus, the new metric provides a SC that can better cope with disruption than the

SC network from the NPV maximisation. A possible result because the SC network configuration is defined in the steady-state and our metric provides a more balanced network design in the context of SCR, in particular, better prepared for a transportation disruption.

Table 5.5: ENPV, Sales and Purchases results considering demand uncertainty for Case E

Scenario	ENPV - D1	Sales - D1	Purchases - D1	ENPV - D2	Sales - D2	Purchases - D2	ENPV - D3	Sales - D3	Purchases - D3
Deterministic + Optimistic + Optimistic	1,70E+07	5,24E+07	6,77E+05	1,53E+07	5,14E+07	7,27E+05	1,97E+07	5,63E+07	5,32E+05
Deterministic + Optimistic + Realistic	1,68E+07	5,18E+07	6,73E+05	1,52E+07	5,08E+07	7,22E+05	1,96E+07	5,57E+07	5,20E+05
Deterministic + Optimistic + Pessimistic	1,65E+07	5,10E+07	6,67E+05	1,50E+07	5,00E+07	7,19E+05	1,93E+07	5,49E+07	5,06E+05
Deterministic + Realistic + Optimistic	1,63E+07	5,03E+07	6,46E+05	1,49E+07	4,93E+07	6,85E+05	1,92E+07	5,37E+07	4,50E+05
Deterministic + Realistic + Realistic	1,62E+07	4,98E+07	6,43E+05	1,48E+07	4,87E+07	6,82E+05	1,91E+07	5,32E+07	4,42E+05
Deterministic + Realistic + Pessimistic	1,59E+07	4,90E+07	6,37E+05	1,45E+07	4,80E+07	6,78E+05	1,88E+07	5,24E+07	4,33E+05
Deterministic + Pessimistic + Optimistic	1,56E+07	4,78E+07	6,18E+05	1,41E+07	4,68E+07	6,63E+05	1,83E+07	5,08E+07	4,35E+05
Deterministic + Pessimistic + Realistic	1,54E+07	4,73E+07	6,15E+05	1,40E+07	4,62E+07	6,58E+05	1,82E+07	5,03E+07	3,85E+05
Deterministic + Pessimistic + Pessimistic	1,52E+07	4,66E+07	6,10E+05	1,37E+07	4,55E+07	6,53E+05	1,80E+07	4,96E+07	3,80E+05

Another critical point is the variation in demand, which was here considered through a scenario approach, see Section 5.4. This has a noticeable impact on SC performance and consequently, on results. It is the major cause of the decrease in sales, which ultimately causes a reduction in ENPV. The effect of such variation varies from disruption to disruption. For Disruptions 1 and 2, the relative impacts are similar, Table 5.5.

Disruption 3, a transportation disruption, has a lower variation in ENPV (9%). In line with what has been said previously, Disruptions 1 and 2 have a variation around 12% between the worst and best scenarios.

Additionally, from the mean value of the new Resilience Metric for the different runs, Table 5.6, it is possible to infer that the SC with the lower resilience value is also the simpler SC network, Case NA - Figure 5.4. Case ND closely follows, Figure 5.10, in the pursuit of improving SC responsiveness, reaches higher levels of ECSL with a more significant reduction of ENPV, which penalises the overall OF value. Case NB provides a network that leads to a substantial increase in ECSL, often with notable drops in economic return. Case NC allows direct flows between plants and markets, adding flexibility to the network by increasing flow complexity since the direct links to markets add redundancy, thus increasing ECSL. However, the increased flexibility is not able to cope with Disruption 2, an event that disrupts the supply side of the SC and where the SC cannot take advantage of the multitude of flows. To meet customer demand, the SC has to rely on outsourcing, reaching outstanding levels of service quality in an evident trade-off with the economic return. This shows that this management alternative should also be considered when planning SC. The case with fewer limitations, Case NE, although

Table 5.6: Mean Resilience Metric Values for Cases NA to NE

	Mean Resilience Metric Value
Case NA	0.665
Case NB	0.811
Case NC	0.749
Case ND	0.695
Case NE	0.705

providing a SC network similar to Case NC, does not return the SC with the higher resilient behaviour, since the increased investment leads to lower financial results when facing some types of disruptive events.

5.8.1 Comparison with other SCR Metrics

To the best of our knowledge, there are four publications that provide a single index metric for the resilience of a SC. It is relevant to compare how similar those are with the metric here presented and the pros and cons of each.

Hosseini & Ivanov (2019) provides a Bayesian approach to a resilience metric applied to the context of SC the ratio between recovery and loss presented by Henry & Emmanuel Ramirez-Marquez (2012). This metric is devoted to an operational level of SCM, where time has to be precisely described. This characteristic unable its use for strategic decisions, naturally with a multitude of periods. Due to its different objectives, any comparison between the results from the two metrics is rendered unpractical.

Azevedo et al. (2016) proposed an index obtained from four vectors (Lean, Agile, Resilient and Green) that ultimately provide a metric for resilience. However, this was done with the automotive industry in mind, and the adaptation to a generic SC is not trivial, in fact can hardly be done. The model is quantified in a SCale from 1 to 5 in terms of implementation of resilient practices or the perceived ability of the company for a particular behaviour. This approach is highly dependent on the collection of data from the SC and the company operation since it relies on the identification of practices and/or educated guesses on the SC capability, which, as mentioned before in this paper, can be an extremely difficult task in the context of SCR. As we aim to have a generic metric, the quantitative comparison with this metric renders difficult, as its focus is mainly operational.

Soni et al. (2014b)'s approach to measuring SCR relies on the identification of resilience enablers, recurring to a survey with practitioners and academics. The enablers found are in line with the literature (information, collaboration, agility, sustainability, risk and revenue sharing, trust, visibility, risk management culture, adaptive capability and structure) and, as in the previous work, fall under more operational objectives that entail qualitative interpretation of the SC operation.

D. Wang & Ip (2009)'s resilience metric is focused on the aircraft industry and is a far simpler approach to the problem. It takes into account the supply and demand needed for a continuous flow of aeroplanes. Nevertheless, this simplification reduces the depth of the analysis. The case study applied considers a two-tier SC, reducing the replicability of the metric dramatically to different case studies or industries, turning it impractical to compare with other SC.

In sum, the published metrics are often applied to operational problems, leaving untouched the strategic level of decision. In fact, it was impossible to use any of the published SCR metrics since those are restrictive in terms of the industry for which they were designed. Moreover, the metrics are operational or reliant on qualitative considerations that disable the possibilities of comparison between SC, when considering quantitative decision support approaches. Thus, there is a research gap identified which has been tackled in this paper. A new resilience metric is created from the combination of the two factors (economic and responsiveness). This resilience metric allows for a comparison between several possible cases and to infer on what are the more resilient cases. A positive correlation between what is the immediate interpretation of results with the value of the resilience metric was observed, where SC with poor results have a correspondent low level in the newly proposed metric.

5.9 Managerial Insights

There is a need to acknowledge that SCR capabilities are essential to prepare for unforeseen events. And in this context, the deployment of decision-making aiding tools is crucial for a well-designed resilient SC. Our results show that a specific, balanced metric is beneficial for companies to improve their resilient behaviour, improving its SC responsiveness while reducing the ripple effect.

Decision-makers should then use OR methods that aim for a balanced solution network, which will inform on a more resilient operation more capable of dealing with a multitude of events. Focusing on one type of events can be restrictive and leave out vulnerabilities in the SC. Thus, companies should invest in strategies aimed at mitigating diverse supply disruptions, being in this way prepared to reduce the harmful impacts in the long term.

In this set, increasing flow complexity is considered a good strategy to be adopted. However, it must be done in a trade-off with the related increasing costs. In our results, with the new proposed SCR metric, a balanced solution is obtained that improves the responsiveness, reducing the ripple effect while maintaining good operational results. Combining economic supply chain goals and customer service levels as objectives is then an enabler to a more resilient SC that should be pursued by the SC managers.

In conclusion, the only possible mindset to face disruptive scenarios is by proactively guarantee customer needs. The ultimate value for a SC is to provide goods to be sold and failing to do so, the main consequence of a SC disruption, can endanger the companies involved. The pursuit for a continuous selling activity is crucial, even if running the danger of lowering financial results in steady-state operations. The proposed metric helps to reach this goal.

5.10 Conclusions and Future Work

In this paper, a SCR quantitative model is presented, addressing the research gap of SCR metrics and the applicability of OR methods to the field of SC under resilience concerns.

We start by characterising a model to study SCR considering a set of resilience metrics, among which a new one is proposed. The latter is constructed to allow replicability and transferability between different applications, following the research gap identified.

The new model leads to SC that can better cope with the challenge of meeting customer demand while providing an easy way to measure and compare SCR.

It is imperative to relate the new findings to those already acknowledged in previous publications. While some general conclusions can be drawn, some results come from the particular nature of the combinations between the SC network, the case study, and the different disruptions.

The model developed considers some assumptions, such as the number of levels in the SC (four) and the uncertainty presence just on demand and disruptions. These aspects may be the focus of further research to incorporated more SC characteristics and contexts, leading to a more detailed model in terms of SC structure and uncertainty presence (supply; technologies, disruptions occurrence). Furthermore, the metric developed is dependent on the reference SC data. This may limit a generalised application of the proposed resilience quantification, and so further studies on different SC may be developed so as to acquire more knowledge on the application of the proposed resilience metric.

From the work developed, it can be stated that pro-active resilient strategies can have a positive impact on SC performance, by reducing the ripple effect, increasing its responsiveness, and service quality can be significantly improved. However, the understanding of SCR drivers is still an underdeveloped topic, with a perceived lack of how different drivers shape a SC operation under disruption. There is an evident need for further work on the impact that network complexity causes on SCR, especially to provide an insight into the relationship between increases in SC flow complexity and increased responsiveness and resilience.

The food SC is an interesting case study due to the perishability of products that create a particularity. A stop in sales leads not only to lost sales but also a direct cost in food spoiled, lost inventory. Therefore is could be a economic sector that would benefit from further study on SCR.

SCR is, in conclusion, a topic where there is space for improvement. Our work contributes to the development of SCR by presenting a novel resilience metric that can be applied to any SC and provide usable results that can be used to aid decision-making. There is still space for further testing the presented metric on the resilient behaviour, by applying it to different Case Studies and improving the knowledge on the resilience drivers to better understand the resilient performance of SC.

5.11 Annex

Sets

V,	set of entities/locations
P,	set of products
S,	set of nodes in the scenario tree
I,	set of available technologies
$I_{pro} \subseteq I,$	set of processing technologies
$I_{des} \subseteq I,$	set of disassembling technologies
$P_f \subseteq P,$	set of final products
$Prod_f \subseteq P,$	set of final products from reverse flows
$F_{v,w},$	set of pairs (v,w) such that a forward flow is allowed between v and w, v,w $\in$ V
$R_{v,w},$	set of pairs (v,w) such that a reverse flow is allowed between v and w, v,w $\in$ V
T,	set of time periods
$N_t \subseteq S$	set of scenarios of time period t $\in$ T
$pred_r \subseteq S$	set of scenarios that precede scenario r in the scenario tree, r $\in$ S
$predsec_r \subseteq S$	set of scenarios that precede in two time periods scenario r in the scenario tree, r $\in$ S
$V_{wh} \subseteq V,$	set of entities with warehousing

$V_{tr} \subseteq V,$	set of transforming entities
$V_{wr} \subseteq V,$	set of warehouses with reverse logistics technologies
$V_m \subseteq V,$	set of markets
$V_g \subseteq V,$	set of suppliers
$V_f \subseteq V,$	set of factories
$V_l \subseteq V,$	set of warehouses
$V_c \subseteq V,$	set of entities with technologies
$V_e \subseteq V,$	set of eliminating entities
$V_d \subseteq V,$	set of disassembling entities
$OUT_p \subseteq I$	set of technologies that produce product p $\in$ P
$OUTj_p \subseteq I$	set of technologies that produce product p $\in$ P from reverse logistics
$IN_p \subseteq I$	set of technologies that consume product p $\in$ P
$INJ_p \subseteq I$	set of technologies that produce product p $\in$ P from reverse logistics
$MP_i \subseteq P$	set of final products for each technology i $\in$ I
$MPJ_i \subseteq P$	set of final products for each technology i $\in$ I from reverse logistics
$PUR_v \subseteq P$	set of products that can be bought by entity v $\in$ V

Parameters

QPLupper	upper bound for the flow of materials between entities in time period 1
QPLower	lower bound for material flow between entities in time period 1
target	minimum percentage of demand satisfaction
tarec	minimum percentage of collection of non-compliant products
tar	minimum percentage of end-of-life product collection in markets
tarmax	maximum percentage of end-of-life product collection in markets
Percent	minimum percentage utilisation of each technology's installed capacity
FrNC	percentage of non-conforming collected products that are disposed
FrEOL	percentage of end-of-life products that are disposed of
return	percentage of non-conforming products on the markets
ir	interest rate
sv	residual value of investment
ti_t	tax rate in time period t $\in T$
FCImax	maximum value for total invested capital
NPVref	value for reference NPV
Pb_s	probability of occurrence of each node $s \in S$
tor_v	turnover rate for entity $v \in V$
Tp_p	service life of final products p $\in P_f$
is_v	initial investment associated with each entity with storage, v $\in V_{wh}$
in_v^s	initial capacity of each entity with storage, v $\in V_{wh}$
$CEarmmax_v$	maximum value for capacity expansion of entity v $\in V_{wh}$
$CEarmmin_v$	min value for capacity expansion of entity v $\in V_{wh}$
$Dvar_{s,t}$	demand variation for scenario $s \in S$ for periods $t \in T$ greater than 1
$DMKupper_{p,v}$	demand of product $p \in P$ on entity $v \in V$ in scenario 1 in time period 1
$Cinv_{v,t}$	inventory cost of entity $v \in V$ over time $t \in T$ in euros per year
$CPLinit_{i,v}$	initial technology capability $i \in I$ in entity $v \in V$
$in_{i,v}^p$	initial investment associated with each technology $i \in I$ in each entity $v \in V$
$Initinv_{p,v}$	initial inventory of product $p \in P$ on entity $v \in V$
$disp_{v,p,t}$	availability of raw material $p \in P$ at supplier $v \in V$ within time $t \in T$
$Coper_{i,v,t}$	operating cost of entity $v \in V$ and technology $i \in I$ per unit produced in euros per ton in time period $t \in T$
$Coperw_{i,v,t}$	operating cost of entity $v \in V$ and technology $i \in I$ per unit produced in euros per ton in time period $t \in T$
$SPrice_{p,v,t}$	price of final product sold at entity $v \in V$ over time $t \in T$ in euros per ton
$rm_{p,v,t}$	price of raw material $p \in P$ sold by entity $v \in V$ in time period $t \in T$ in euros per ton
$FIPL_{v,w}$	distance between entities $v, w \in V$

$prodmatp_{u,p}$	amount of raw materials $u \in P$ needed for each $p \in P$
$CEPLmax_{i,v}$	maximum limit for capacity expansion of each entity $v \in V$ and technology i $\in I$
$CEPLmin_{i,v}$	minimum limit for technology $i \in I$ capacity expansion in each entity $v \in V$
$NEXPL_{i,v}$	maximum number of capacity expansions allowed for each process $i \in I$ in each entity $v \in V$
$v^p_{i,v,t}$	variable investment associated with each technology $i \in I$ in each entity $v \in V$ in each time period $t \in T$ in euros
$v^s_{v,t}$	variable investment associated with each entity $v \in V$ with storage in time period $t \in T$ in euros
$Ctfarm_{v,w,t}$	unit cost of transporting a product from one entity $v \in V$ to another $w \in V$ in time period $t \in T$ in euros per ton.km
$lk_{v,w,t}$	contract cost of a carrier to make a journey from one entity $v \in V$ to another $w \in V$ in the period $t \in T$ in euros

Decision Variables

z	Objective variable
$PU_{v,w,p,s,t}$	Purchases of product $p \in P$ made by entity $v \in V$, from entity $w \in V$, in scenario $s \in S$ and in time period $t \in T$
$Win_{i,v,p,s,t}$	Flow of product $p \in P$ which is consumed by technology $i \in I$ in entity $v \in V$, in time period $t \in T$ and scenario $s \in S$
$Winw_{i,v,p,s,t}$	Product flow $p \in P$ which is consumed by technology $i \in I$ in entity $v \in V$, in time period $t \in T$ and scenario $s \in S$
$Wout_{i,v,p,s,t}$	Flow of the product $p \in P$ which is produced by technology $i \in I$ in entity $v \in V$, in time period $t \in T$ and scenario $s \in S$
$Woutw_{i,v,p,s,t}$	Flow of product $p \in P$ which is produced by technology $i \in I$ in entity $v \in V$, in time period $t \in T$ and scenario $s \in S$
$Q_{v,w,p,s,t}$	Product flow $p \in P$ sent from entity $v \in V$ to entity $w \in V$ in time period $t \in T$ and scenario $s \in S$
$QNC_{v,w,p,s,t}$	Product $p \in P$ reverse flow not as sent from entity $v \in V$ to entity $w \in V$ in time period $t \in T$ and scenario $s \in S$
$QEL_{v,w,p,s,t}$	End-of-life product $p \in P$ reverse flow sent from entity $v \in V$ to entity $w \in V$ in time period $t \in T$ and scenario $s \in S$
$SA_{v,p,s,t}$	Sales value of each product $p \in P$ on market $v \in V$ for time period $t \in T$ and scenario $s \in S$
$INV_{v,p,s,t}$	Inventory of product $p \in P$ kept in entity $v \in V$ in time period $t \in T$ and scenario $s \in S$
$IL_{v,s,t}$	Mean inventory level maintained at entity $v \in V$ in each time period $t \in T$ and scenario $s \in S$
$im_{i,v}$	Capacity of technology $i \in I$ in entity $v \in V$
$CE^p_{i,v,t}$	Technology $i \in I$ capacity expansion in entity $v \in V$ over time period $t \in T$
$Carm_{v,t}$	Storage capacity of entity $v \in V$ over time period $t \in T$
$CE^s_{v,t}$	Storage expansion of entity $v \in V$ over time period $t \in T$
NPV_s	Net present value in scenario $s \in S$
$CF_{s,t}$	Cash flow in time period $t \in T$ and scenario $s \in S$
$NE_{s,t}$	Profit after Tax in time period $t \in T$ and scenario $s \in S$
FDC_t	Fraction of total depreciable capital that has to be paid over time period $t \in T$
FCI	Fixed Capital Investment
DEP_t	Depreciation term in time period $t \in T$
$Y_{v,w,t}$	Binary variable equal to 1 if the forward link between entity $v \in V$ and entity $w \in V$ is established at time period $t \in T$ and 0 otherwise
$YNC_{v,w,t}$	Binary variable equal to 1 if the reverse link between entity $v \in V$ and entity $w \in V$ is established at time period $t \in T$ and 0 otherwise
$YEL_{v,w,t}$	Binary variable equal to 1 if the end-of-life reverse link between entity $v \in V$ and entity $w \in V$ is established at time period $t \in T$ and 0 otherwise

$D_{p,v,s,t}$	Demand for each product p $\in P, ineachentityv \in V, inthescenario$s $\in S$ and at time period t $\in T$
$Transp_t$	Cost of transportation in time period t $\in T$
$Product_t$	Cost of production in time period t $\in T$
$Purchases_t$	Cost in purchases in time period t $\in T$
$Inventory_t$	Cost with inventory in time period t $\in T$
$Sales_t$	Value of sales in time period t $\in T$
$ID_{p,v,s,t}$	Unsatisfied demand of product $p \in P$ in entity $v \in V$ for scenario $s \in S$ in time period t $\in T$
$CService_t$	Customer service in time period t $\in T$
$Invest_t$	Cost with investment in time period t $\in T$
$CFtot_t$	Total cash flow in time period $t \in T$
$Xnodes_{v,t}$	Binary variable equal to 1 if entity $v \in V$ opens in period $t \in T$ and 0 otherwise
NPVtotal	NPV considering all scenarios

Objective function

$$\text{z} = \sum_{s \in S} \left(\frac{\text{pb}_s \cdot \text{NPV}_s}{\text{NPVref}} \right) - \sum_{t \in T} \left(\frac{\text{CService}_t}{|T|} \right)$$

Constraints

Constraint 1$_{v,p,s,t}$

$$\sum_{w \in V} \text{PU}_{v,w,p,s,t} + \sum_{i \in \text{OUT}_{i,p}} \text{Wout}_{i,v,p,s,t} + \sum_{w \in \text{F}_{w,v}} \text{Q}_{w,v,p,s,t} = \sum_{w \in \text{F}_{v,w}} \text{Q}_{v,w,p,s,t} + \sum_{i \in \text{IN}_{i,p}} \text{Win}_{i,v,p,s,t} \quad \forall v \in V, p \in P, t \in T, s \in$$

Constraint 2$_{s,t}$

$$\sum_{v \in V, w, p \in \text{PUR}_{p,v}} \text{PU}_{v,w,p,s,t} \leq 0 \qquad \forall t \in T, s \in \text{N}_t$$

Constraint 3$_{v,p,s,t}$

$$\sum_{w \in V} \text{PU}_{w,v,p,s,t} \leq \text{disp}_{v,p,t} \qquad \forall v \in V, p \in P, t \in T, s \in \text{N}_t$$

Constraint 4$_{i,v,u,s,t}$

$$\text{Win}_{i,v,u,s,t} = \sum_{p \in \text{MP}_{p,i}} (\text{Wout}_{i,v,p,s,t} \cdot \text{prodmatp}_{u,p}) \qquad \forall i \in I_{pro}, v \in V_{tr}, u \in P, t \in T, s \in \text{N}_t$$

Constraint 5$_{v,p,s,t}$

$$\sum_{r \in \text{pred}_{s,r}} \text{INV}_{v,p,r,t-1} + \sum_{w \in V_f} \text{Q}_{w,v,p,s,t} + \sum_{w \in V_l} \text{Q}_{w,v,p,s,t} + \sum_{w \in V} \text{PU}_{v,w,p,s,t} + \sum_{i \in \text{OUT}_{i,p}} \text{Wout}_{i,v,p,s,t} + \sum_{w \in \text{R}_{w,v}} \text{QNC}_{w,v,p,s,t} + \sum_{w \in \text{R}_{w,v}} \text{QEL}_{w,v,p,s,t} = \sum_{w \in V_{mw}} \text{Q}_{v,w,p,s,t} + \sum_{w \in V_l} \text{Q}_{v,w,p,s,t} + \text{INV}_{v,p,s,t} + \sum_{i \in \text{IN}_{i,p}} \text{Win}_{i,v,p,s,t} + \sum_{x \in V_e} \text{QNC}_{v,x,p,s,t} + \sum_{x \in V_e} \text{QEL}_{v,x,p,s,t} + \sum_{x \in V_d} \text{QEL}_{v,x,p,s,t} \qquad \forall v \in V_l, p \in P, t \in (T \wedge t > 1), s \in \text{N}_t$$

Constraint 6$_{v,p,s,t}$

$$\text{Initinv}_{p,v} + \sum_{w \in V_f} \text{Q}_{w,v,p,s,t} + \sum_{w \in V_l} \text{Q}_{w,v,p,s,t} + \sum_{w \in V} \text{PU}_{v,w,p,s,t} + \sum_{i \in \text{OUT}_{i,p}} \text{Wout}_{i,v,p,s,t} + \sum_{w \in V_{mw}} \text{QNC}_{w,v,p,s,t} + \sum_{w \in V_{mw}} \text{QEL}_{w,v,p,s,t} = \sum_{w \in V_{mw}} \text{Q}_{v,w,p,s,t} + \sum_{w \in V_l} \text{Q}_{v,w,p,s,t} + \text{INV}_{v,p,s,t} + \sum_{i \in \text{IN}_{i,p}} \text{Win}_{i,v,p,s,t} + \sum_{x \in V_e} \text{QNC}_{v,x,p,s,t} + \sum_{x \in V_e} \text{QEL}_{v,x,p,s,t} + \sum_{w \in V_d} \text{QEL}_{v,w,p,s,t} \qquad \forall v \in V_l, p \in P, t \in (T \wedge t = 1), s \in \text{N}_t$$

Constraint 7$_{v,p,s,t}$

$$\text{SA}_{v,p,s,t} = \sum_{w \in \text{F}_{w,v}} \text{Q}_{w,v,p,s,t} \qquad \forall v \in V_m, p \in P, t \in T, s \in \text{N}_t$$

Constraint 8$_{v,p,s,t}$

$$\text{SA}_{v,p,s,t} \geq \text{D}_{p,v,s,t} \cdot \text{target} \qquad \forall v \in V_m, p \in P, t \in T, s \in \text{N}_t$$

Constraint 9$_{v,p,s,t}$

$$\text{SA}_{v,p,s,t} \leq \text{D}_{p,v,s,t} \qquad \forall v \in V_m, p \in P, t \in T, s \in \text{N}_t$$

Constraint 10$_{i,v,s,t}$

$$\sum_{p \in \text{MP}_{p,i}} \text{Wout}_{i,v,p,s,t} \leq \text{im}_{i,v,t} \qquad \forall i \in \text{I}_{pro}, v \in V_{tr}, t \in T, s \in \text{N}_t)$$

Constraint 11$_{i,v,s,t}$

$$\text{Percent} \cdot \text{im}_{i,v,t} \leq \sum_{p \in \text{MP}_{p,i}} \text{Wout}_{i,v,p,s,t} \qquad \forall i \in \text{I}_{pro}, v \in V_{tr}, t \in T, s \in \text{N}_t)$$

Constraint 12$_{i,v,s,t}$

$$\text{im}_{i,v,t} \geq \sum_{p \in \text{IN}_{i,p}} \text{Win}_{i,v,p,s,t} \qquad \forall i \in \text{I}_{pro}, v \in V_{tr}, t \in T, s \in \text{N}_t)$$

Constraint 13$_{i,v,t}$

$$\text{im}_{i,v,t} = \text{im}_{i,v,t-1} + \text{CE}_{i,v,t} \qquad \forall i \in I, v \in V_c, t \in (T \wedge t > 1)$$

Constraint 14$_{i,v,t}$

$$\text{im}_{i,v,t} = \text{CPLinit}_{i,v} + \text{CE}_{i,v,t} \qquad \forall i \in I, v \in V_c, t \in (T \wedge t = 1)$$

Constraint 15$_{i,v,t}$

$$\text{CE}_{i,v,t} \leq \text{CEPLmax}_{i,v} \qquad \forall i \in I, v \in V_c, t \in T$$

Constraint 16$_{i,v,t}$

$$\text{CE}_{i,v,t} \geq \text{CEPLmin}_{i,v} \qquad \forall i \in I, v \in V_c, t \in T$$

Constraint 17$_{i,v}$

$$\sum_{t \in T} \text{CE}_{i,v,t} \leq \text{NEXPL}_{i,v} \qquad \forall i \in I, v \in V_c$$

Constraint 18$_{v,s,t}$

$$\sum_{p \in P} \text{INV}_{v,p,s,t} \leq \text{Carm}_{v,t} \qquad \forall v \in V, t \in T, s \ \in \ \text{N}_t$$

Constraint 19$_{v,s,t}$

$$2 \cdot \text{IL}_{v,s,t} \leq \text{Carm}_{v,t} \qquad \forall v \in V, t \in T, s \ \in \ \text{N}_t$$

Constraint 20$_{v,s,t}$

$$\text{IL}_{v,s,t} = \frac{\sum\limits_{w \in F_{v,w}, p \in P} \text{Q}_{v,w,p,s,t}}{\text{tor}_v} \qquad \forall v \in V, t \in T, s \ \in \ \text{N}_t$$

Constraint 21$_{v,t}$

$$\text{Carm}_{v,t} = \text{Carm}_{v,t-1} + \text{CE}^s{}_{v,t} \qquad \forall v \in V, t \ \in \ (t > 1)$$

Constraint 22$_{v,t}$

$$\text{Carm}_{v,t} = \text{in}^s{}_v + \text{CE}^s{}_{v,t} \qquad \forall v \in V, t \ \in \ (t = 1)$$

Constraint 23$_{v,t}$

$$\text{CE}^s{}_{v,t} \leq \text{CEarmmax}_v \qquad \forall v \in V_z, t \in T$$

Constraint 24$_{v,t}$

$$\text{CE}^s{}_{v,t} \geq \text{CEarmmin}_v \qquad \forall v \in V_z, t \in T$$

Constraint 25$_{v}$

$$\sum_{t \in T} \text{CE}^s{}_{v,t} \leq \text{NEXarm}_v \qquad \forall v \ \in \ \text{V}$$

Constraint 26$_{v,w,s,t}$

$$\sum_{p \in P} (\text{Q}_{v,w,p,s,t} + \text{PU}_{v,w,p,s,t}) \leq \text{QPLupper} \cdot \text{Y}_{v,w,t} \qquad \forall (v,w) \in \text{F}_{v,w}, t \in T, s \ \in \ \text{N}_t$$

Constraint 27$_{v,w,s,t}$

$$\sum_{p\in P}(\mathsf{Q}_{v,w,p,s,t} + \mathsf{PU}_{v,w,p,s,t}) \geq \mathsf{QPLower} \cdot \mathsf{Y}_{v,w,t} \qquad \forall (v,w) \in \mathsf{F}_{v,w}, t \in T, s \in \mathsf{N}_t$$

Constraint 28$_s$

$$\mathsf{NPV}_s = \sum_{t\in \mathsf{N}_t}\left(\frac{\mathsf{CF}_{s,t}}{(1+\mathsf{ir})^t}\right) \qquad \forall s \in S$$

Constraint 29$_{s,t}$

$$\mathsf{CF}_{s,t} = \mathsf{NE}_{s,t} - \mathsf{FDC}_t \qquad \forall t \in (T \wedge t \leq (|T|-1), s \in \mathsf{N}_t$$

Constraint 30$_{s,t}$

$$\mathsf{CF}_{s,t} = \mathsf{NE}_{s,t} - \mathsf{FDC}_t - \mathsf{sv}\cdot\mathsf{FCI} \qquad \forall t \in (T \wedge t = |T|, s \in \mathsf{N}_t$$

Constraint 31$_{s,t}$

$$\mathsf{NE}_{s,t} = (1-\mathsf{ti})\cdot\Big(\sum_{v\in V_m, p\in P}(\mathsf{SPrice}_{p,v,t}\cdot\mathsf{SA}_{v,p,s,t}) - \sum_{v\in V_m, w\in V, p\in P, (v,w)\in R}(\mathsf{QNC}_{v,w,p,s,t}\cdot\mathsf{SPrice}_{p,v,t}) - \sum_{v\in V, w\in V_g, p\in P}(\mathsf{rm}_{p,w,t}\cdot\mathsf{PU}_{v,w,p,s,t}) - \sum_{i\in I, v\in V_{tr}, p\in P}(\mathsf{Coper}_{i,v,t}\cdot\mathsf{Wout}_{i,v,p,s,t}) - \sum_{i\in I, v\in V_d, p\in P}(\mathsf{Coperw}_{i,v,t}\cdot \mathsf{Woutw}_{i,v,p,s,t}) - \sum_{v\in \mathsf{V}}(\mathsf{Cinv}_{v,t}\cdot\mathsf{IL}_{v,s,t}) - \sum_{v\in V, w\in V, p\in P}(\mathsf{Ctfarm}_{v,w,t}\cdot(\mathsf{Q}_{v,w,p,s,t}+\mathsf{QNC}_{v,w,p,s,t}+\mathsf{QEL}_{v,w,p,s,t}+\mathsf{PU}_{w,v,p,s,t})\cdot\mathsf{FIPL}_{v,w})\Big) + \mathsf{ti}\cdot\mathsf{DEP}_t \qquad \forall t\in T, s \in \mathsf{N}_t$$

Constraint 32$_t$

$$\mathsf{DEP}_t = \frac{(1-\mathsf{sv})\cdot\mathsf{FCI}}{|T|} \qquad \forall t \in T$$

Constraint 33

$$\mathsf{FCI} = \sum_{i\in I, v\in V_c, t\in T}(\mathsf{v}^p{}_{i,v,t}\cdot\mathsf{CE}_{i,v,t}) + \sum_{i\in I, v\in V}(\mathsf{im}_{i,v}\cdot\mathsf{in}_{i,v}) + \sum_{v\in\mathsf{V}}(\mathsf{in}^s{}_v\cdot\mathsf{is}_v) + \sum_{v,t\in\mathsf{V}}(\mathsf{v}^s{}_{v,t}\cdot\mathsf{CE}^s{}_{v,t}) + \sum_{v\in V, w\in V, t\in T}(\mathsf{lk}_{v,w,t}\cdot(\mathsf{Y}_{v,w,t}+\mathsf{YNC}_{v,w,t}+\mathsf{YEL}_{v,w,t}))$$

Constraint 34

$$\mathsf{FCI} \leq \mathsf{FCImax}$$

Constraint 35$_t$

$$\mathsf{FDC}_t = \frac{\mathsf{FCI}}{|t|} \qquad \forall t \in T$$

Constraint 36$_{v,p,s,t}$

$$\sum_{x \in \mathsf{R}} \mathsf{QEL}_{v,x,p,s,t} \geq \sum_{w,r \in (\mathsf{F}_{w,v} \wedge \mathsf{pred}_{s,r})} \mathsf{Q}_{w,v,p,r,t-\mathsf{Tp}_p} \cdot \mathsf{tar}[(\mathsf{Tp}_p \leq 1)] + \sum_{w,r \in (\mathsf{F}_{w,v} \wedge \mathsf{predsec}_{s,r})} \mathsf{Q}_{w,v,p,r,t-\mathsf{Tp}_p} \cdot \mathsf{tar}[(\mathsf{Tp}_p \geq 2)] \quad \forall v \in V_m, p \in Prod_f, t \in T, s \in \mathsf{N}_t$$

Constraint 37$_{v,p,s,t}$

$$\sum_{x \in \mathsf{R}} \mathsf{QEL}_{v,x,p,s,t} \leq \sum_{w,r \in (\mathsf{F}_{w,v} \wedge \mathsf{pred}_{s,r})} \mathsf{Q}_{w,v,p,r,t-\mathsf{Tp}_p} \cdot \mathsf{tarmax}[(\mathsf{Tp}_p \leq 1)] + \sum_{w,r \in (\mathsf{F}_{w,v} \wedge \mathsf{predsec}_{s,r})} \mathsf{Q}_{w,v,p,r,t-\mathsf{Tp}_p} \cdot \mathsf{tarmax}[(\mathsf{Tp}_p \geq 2)] \quad \forall v \in V_m, p \in Prod_f, t \in T, s \in \mathsf{N}_t$$

Constraint 38$_{v,p,s,t}$

$$\sum_{w \in V_e} \mathsf{QNC}_{v,w,p,s,t} = \mathsf{FrNC} \cdot \sum_{x \in V_{mx}} \mathsf{QNC}_{x,v,p,s,t} \quad \forall v \in V_l, p \in P, t \in T, s \in \mathsf{N}_t$$

Constraint 39$_{v,p,s,t}$

$$\sum_{w \in V_e} \mathsf{QEL}_{v,w,p,s,t} = \mathsf{FrEOL} \cdot \sum_{x \in V_{mx}} \mathsf{QEL}_{x,v,p,s,t} \quad \forall v \in V_{wr}, p \in \mathsf{P}_f, t \in T, s \in \mathsf{N}_t$$

Constraint 40$_{v,p,s,t}$

$$\sum_{w \in \mathsf{R}_{v,w}} \mathsf{QNC}_{v,w,p,s,t} \geq \sum_{w \in \mathsf{F}_{w,v}} \mathsf{Q}_{w,v,p,s,t} \cdot \mathsf{return} \cdot \mathsf{tarec} \quad \forall v \in V_m, p \in P, t \in T, s \in \mathsf{N}_t$$

Constraint 41$_{v,p,s,t}$

$$\sum_{w \in \mathsf{R}_{v,w}} \mathsf{QNC}_{v,w,p,s,t} \leq \sum_{w \in \mathsf{F}_{w,v}} \mathsf{Q}_{w,v,p,s,t} \cdot \mathsf{return} \quad \forall v \in V_m, p \in P, t \in T, s \in \mathsf{N}_t$$

Constraint 42$_{i,v,u,s,t}$

$$\mathsf{Winw}_{i,v,u,s,t} = \sum_{p \in \mathsf{MPJ}_{p,i}} (\mathsf{Woutw}_{i,v,p,s,t} \cdot \mathsf{prodmatp}_{u,p}) \quad \forall i \in \mathsf{I}_{des}, v \in V_d, u \in P_f, t \in T, s \in \mathsf{N}_t$$

Constraint 43$_{v,p,s,t}$

$$\sum_{i \in \mathsf{OUTj}_{i,p}} \mathsf{Woutw}_{i,v,p,s,t} + \sum_{w \in \mathsf{R}_{w,v}} \mathsf{QEL}_{w,v,p,s,t} = \sum_{w \in \mathsf{F}_{v,w}} \mathsf{Q}_{v,w,p,s,t} + \sum_{i \in \mathsf{INJ}_{i,p}} \mathsf{Winw}_{i,v,p,s,t} + \sum_{w \in V_e} \mathsf{QEL}_{v,w,p,s,t} \quad \forall v \in V_d, p \in P, t \in T, s \in \mathsf{N}_t$$

Constraint 44$_{i,v,s,t}$

$$\sum_{p \in \mathsf{MPJ}_{p,i}} \mathsf{Woutw}_{i,v,p,s,t} \leq \mathsf{im}_{i,v,t} \quad \forall i \in \mathsf{I}_{des}, v \in V_d, t \in T, s \in \mathsf{N}_t$$

Constraint 45$_{i,v,s,t}$

$$\text{Percent} \cdot \text{im}_{i,v,t} \leq \sum_{p \in \text{MPJ}_{p,i}} \text{Woutw}_{i,v,p,s,t} \qquad \forall i \in \text{I}_{des}, v \in V_d, t \in T, s \in \text{N}_t$$

Constraint 50$_{v,p,s,t}$

$$\sum_{w \in \text{R}_{w,v}} \text{QEL}_{w,v,p,s,t} - \sum_{w \in V_e} \text{QEL}_{v,w,p,s,t} = \sum_{i \in \text{INJ}_{i,p}} \text{Winw}_{i,v,p,s,t} \qquad \forall v \in V_d, p \in P, t \in T, s \in \text{N}_t$$

Constraint 51$_{v,w,s,t}$

$$\sum_{p \in P} \text{QNC}_{v,w,p,s,t} \leq \text{QPLupper} \cdot \text{YNC}_{v,w,t} \qquad \forall (v,w) \in \text{R}_{v,w}, t \in T, s \in \text{N}_t$$

Constraint 52$_{v,w,s,t}$

$$\sum_{p \in P} \text{QNC}_{v,w,p,s,t} \geq \text{QPLower} \cdot \text{YNC}_{v,w,t} \qquad \forall (v,w) \in \text{R}_{v,w}, t \in T, s \in \text{N}_t$$

Constraint 53$_{v,w,s,t}$

$$\sum_{p \in \text{prod}_f} \text{QEL}_{v,w,p,s,t} \leq \text{QPLupper} \cdot \text{YEL}_{v,w,t} \qquad \forall (v,w) \in \text{R}_{v,w}, t \in T, s \in \text{N}_t$$

Constraint 54$_{v,w,s,t}$

$$\sum_{p \in \text{prod}_f} \text{QEL}_{v,w,p,s,t} \geq \text{QPLower} \cdot \text{YEL}_{v,w,t} \qquad \forall (v,w) \in \text{R}_{v,w}, t \in T, s \in \text{N}_t$$

Constraint 55$_{v,p,s,t}$

$$\sum_{w \in V_{mw}} \text{QEL}_{w,v,p,s,t} - \sum_{w \in V_e} \text{QEL}_{v,w,p,s,t} = \sum_{w \in V_d} \text{QEL}_{v,w,p,s,t} \qquad \forall v \in V_l, p \in P, t \in T, s \in \text{N}_t$$

Constraint 56$_{i,v,s,t}$

$$\text{im}_{i,v,t} \geq \sum_{p \in \text{INJ}_{i,p}} \text{Winw}_{i,v,p,s,t} \qquad \forall i \in \text{I}_{des}, v \in V_d, t \in T, s \in \text{N}_t$$

Constraint 57$_{v,p,s,t}$

$$\text{D}_{p,v,s,t} = \sum_{r \in \text{pred}_{s,r}} \text{D}_{p,v,r,t-1} \cdot \text{Dvar}_{s,t}) \qquad \forall v \in V_m, p \in \text{P}_f, t \in (T \wedge t > 1), s \in \text{N}_t$$

Constraint 58$_{v,p,s,t}$

$$\text{D}_{p,v,s,t} = \text{DMKupper}_{p,v} \qquad \forall v \in V_m, p \in \text{P}_f, t \in (T \wedge t = 1), s \in \text{N}_t$$

Constraint 59$_t$

$$\text{Transp}_t = \sum_{s \in S, v \in V, w \in V, p \in P} (\text{pb}_s \cdot (\text{Ctfarm}_{v,w,t} \cdot (\text{Q}_{v,w,p,s,t} + \text{QNC}_{v,w,p,s,t} + \text{QEL}_{v,w,p,s,t} + \text{PU}_{w,v,p,s,t}) \cdot \text{FIPL}_{v,w})) + \sum_{v \in V, w \in V} (\text{Ik}_{v,w,t} \cdot (\text{Y}_{v,w,t} + \text{YNC}_{v,w,t} + \text{YEL}_{v,w,t})) \qquad \forall t \in T$$

Constraint 60$_t$

$$\text{Produc}_t = \sum_{s \in S, i \in I, v \in Trans_v, p \in P} (\text{pb}_s \cdot (\text{Coper}_{i,v,t} \cdot \text{Wout}_{i,v,p,s,t})) \qquad \forall t \in T$$

Constraint 61$_t$

$$\text{Purchases}_t = \sum_{s \in S, v \in V_{tr}, w \in V_g, p \in P} (\text{pb}_s \cdot (\text{rm}_{p,w,t} \cdot \text{PU}_{v,w,p,s,t})) \qquad \forall t \in T$$

Constraint 62$_t$

$$\text{Inventory}_t = \sum_{s \in S, v \in \text{V}} (\text{pb}_s \cdot (\text{Cinv}_{v,t} \cdot \text{IL}_{v,s,t})) \qquad \forall t \in T$$

Constraint 63$_t$

$$\text{Sales}_t = \sum_{s \in S, v \in V_v, p \in P} (\text{pb}_s \cdot (\text{SPrice}_{p,v,t} \cdot \text{SA}_{v,p,s,t})) \qquad \forall t \in T$$

Constraint 64$_{v,w,p,s,t}$

$$\text{PU}_{v,w,p,s,t} = \text{Q}_{w,v,p,s,t} \qquad \forall v \in V_f, w \in V_g, p \in P, t \in T, s \in \text{N}_t$$

Constraint 65$_{p,v,s,t}$

$$\text{ID}_{p,v,s,t} = \text{D}_{p,v,s,t} - \sum_{w \in \text{F}_{w,v}} \text{Q}_{w,v,p,s,t} \qquad \forall p \in P, v \in V_m, t \in T, s \in \text{N}_t$$

Constraint 66$_t$

$$ESC = \frac{\sum_{t \in T} \left(1 - \sum_s pb_s \left[\frac{\sum_{v \epsilon V_m} \sum_{p \in P} ID_{pvst}}{\sum_{v \epsilon V_m} \sum_{p \in P} D_{pvst}} \right] \right)}{|T|} \qquad \forall t \in T$$

Constraint 67$_t$

$$\text{Invest}_t = \sum_{i \in I, v \in V_c} (\text{v}^p{}_{i,v,t} \cdot \text{CE}_{i,v,t}) + \sum_{i \in I, v \in V} (\text{CPLinit}_{i,v} \cdot \text{in}_{i,v}) + \sum_{v \in \text{V}} (\text{in}^s{}_v \cdot \text{is}_v) + \sum_{v \in \text{V}} (\text{v}^s{}_{v,t} \cdot \text{CE}^s{}_{v,t})$$
$$\forall t \in T \ \wedge \ (t = 1)$$

Constraint 68$_t$

$$\text{Invest}_t = \sum_{i \in I, v \in V_c} (\text{v}^p{}_{i,v,t} \cdot \text{CE}_{i,v,t}) + \sum_{v \in \text{V}} (\text{v}^s{}_{v,t} \cdot \text{CE}^s{}_{v,t}) \qquad \forall t \in T \ \wedge \ (t > 1)$$

Constraint 69$_t$

$$\mathsf{CFtot}_t = \sum_{s \in \mathsf{N}_t} (\mathsf{pb}_s \cdot \mathsf{CF}_{s,t}) \qquad \forall t \in T$$

Constraint 72$_{v,t}$

$$\sum_{w \in \mathsf{F}_{v,w}} \mathsf{Y}_{v,w,t} + \sum_{w \in \mathsf{R}_{v,w}} (\mathsf{YNC}_{v,w,t} + \mathsf{YEL}_{v,w,t}) + \sum_{w \in \mathsf{F}_{w,v}} \mathsf{Y}_{w,v,t} + \sum_{w \in \mathsf{R}_{w,v}} (\mathsf{YNC}_{w,v,t} + \mathsf{YEL}_{w,v,t}) - 99999 \cdot \mathsf{Xnodes}_{v,t} \leq 0 \qquad \forall v \in V, t \in T$$

Constraint 73$_{v,t}$

$$\sum_{w \in \mathsf{F}_{v,w}} \mathsf{Y}_{v,w,t} + \sum_{w \in \mathsf{R}_{v,w}} (\mathsf{YNC}_{v,w,t} + \mathsf{YEL}_{v,w,t}) + \sum_{w \in \mathsf{F}_{w,v}} \mathsf{Y}_{w,v,t} + \sum_{w \in \mathsf{R}_{w,v}} (\mathsf{YNC}_{w,v,t} + \mathsf{YEL}_{w,v,t}) \geq \mathsf{Xnodes}_{v,t} \qquad \forall v \in V, t \in T$$

Constraint 74

$$\mathsf{NPVtotal} = \sum_{s \in S} (\mathsf{pb}_s \cdot \mathsf{NPV}_s)$$

$\mathsf{PU}_{v,w,p,s,t} \geq 0 \; \forall v, w, p, s, t$

$\mathsf{Wout}_{i,v,p,s,t} \geq 0 \; \forall i, v, p, s, t$

$\mathsf{Q}_{v,w,p,s,t} \geq 0 \; \forall v, w, p, s, t$

$\mathsf{Win}_{i,v,p,s,t} \geq 0 \; \forall i, v, p, s, t$

$\mathsf{INV}_{v,p,s,t} \geq 0 \; \forall v, p, s, t$

$\mathsf{QNC}_{v,w,p,s,t} \geq 0 \; \forall v, w, p, s, t$

$\mathsf{QEL}_{v,w,p,s,t} \geq 0 \; \forall v, w, p, s, t$

$\mathsf{SA}_{v,p,s,t} \geq 0 \; \forall v, p, s, t$

$\mathsf{D}_{p,v,s,t} \geq 0 \; \forall p, v, s, t$

$\mathsf{im}_{i,v,t} \geq 0 \; \forall i, v, t$

$\mathsf{Carm}_{v,t} \geq 0 \; \forall v, t$

$\mathsf{IL}_{v,s,t} \geq 0 \; \forall v, s, t$

$\mathsf{FDC}_t \geq 0 \; \forall t$

$\mathsf{FCI} \geq 0 \; \forall$

$\mathsf{Woutw}_{i,v,p,s,t} \geq 0 \; \forall i, v, p, s, t$

$\mathsf{DEP}_t \geq 0 \; \forall t$

$\mathsf{Winw}_{i,v,p,s,t} \geq 0 \; \forall i, v, p, s, t$

$\mathsf{Xnodes}_{v,t} \in \{0, 1\} \; \forall v, t$

6

Supply Chain Resilience: optimising decisions at the tactical and operational level

Contents

This chapter is under review, aiming at providing an in-depth look into SCR at the tactical and operational levels. This work was done in collaboration with Márcia Batista in her work to obtain an MSc.

Ribeiro, J. P., & Bátista, M., & Barbosa-Póvoa, A. P. F. (2023). Supply Chain Resilience: optimising decisions at the tactical and operational level, under review

6.1 Abstract

The complex structure of modern SC and their tendency towards globalisation have increased their exposure to unpredictable events. For companies to sustain their competitive advantage, establishing resilient SC has become a concern over the years, and now with the current disruptive events (eg. pandemic, Ukraine invasion), a priority. Nonetheless, despite the increasing awareness of the importance of resilience enhancing actions, it still exists scarce literature on quantitative tools to aid Decision-maker (DM), particularly at the tactical-operational decision level when facing disruptive events. Towards reducing this gap, a multi-objective MILP model is developed in this paper, with an original stochastic approach to deal with uncertain parameters such as demand, return rates, disruption occurrence and response time. The model is applied in a case study, where insights on tactical-operational decisions taken under disruptive events are discussed and managerial insights are drawn.

6.2 Introduction

Modern supply chains (SC) are vulnerable to unexpected events due to their growing complexity and globalisation (Christopher & Peck, 2004; Kamalahmadi & Parast, 2016). Daily operations depend on the normal functioning of numerous interconnected entities located in different regions (Cheng et al., 2021). Local disruptions in one node can quickly spread throughout the entire network and cause significant consequences. The recent global pandemic has significantly increased interest in supply chain resilience (SCR) among both the academic community and companies worldwide, as they struggle to adapt to a "new normal" amid unprecedented challenges.

This crisis differs from previous disruptions due to its global impact and simultaneous effects on both supply and demand. As noted by Sodhi & Tang (2021), there is an urgent need for more research on Supply Chain Management (SCM) in these extreme conditions. The current challenges have emphasised the importance of SCR.

Much of the existing literature on SCR consists of qualitative insights, while quantitative approaches to SCR are still scarce and largely focused on the strategic and tactical levels, rather than the operational decision level (Ribeiro & Barbosa-Povoa, 2018). Closing this gap is crucial, as quantitative models can be valuable tools for decision-makers to evaluate and adopt strategies for resilience.

SC objectives have been changing and are an example of how SC managers must simultaneously be aware of different challenges Pires Ribeiro & Barbosa-Póvoa (2019). Besides the challenges above, societal and environmental concerns lead to SC adaptations, namely the stimulus for the implementation of Closed-Loop SC (CLSC) allowing more sustainable operations (Guide Jr & Van Wassenhove, 2009; Mota, Gomes, Carvalho, & Barbosa-Póvoa, 2015; **?**). Studying how these types of SC can contribute to better SC is then of extreme relevance since its characteristics allow for the re-purposing of products, thus reducing the economic and environmental impact caused by producing new products from raw materials (Jauhari et al., 2020; Ribeiro & Barbosa-Póvoa, 2021). Many SC produce waste, either by products being non-conforming but also by reaching their end-of-life, leading to environmental and economical impacts. Thus, creating value through spoilage re-use and re-introduction into the SC can be a SCR enabler that is worth exploring (Cruz et al., 2019).

This paper aims to contribute to the literature by developing knowledge on quantitative SCR models at the tactical-operational decision level. To that end, a quantitative model is designed to further inform tactical-operational decisions under disruptive events. The model particularly emphasises the importance of timely decisions through the incorporation of outsourcing options and alternative products. The model also models disruptive events as uncertain and their time frame and source of occurrence as uncertain through a scenario tree approach that clusters time periods. The results of the model applied to a case study will provide insights and outline future work in this field.

This paper is structured as follows: the model formulation in Section 6.4. The latter explains the general goals of the model, including its Objective Functions (OF), as well as any extensions applied, such as a novel stochastic approach to model uncertain parameters and the modelling of disruptive events. Section 6.5 introduces the case study to which the model is applied, and the results for the deterministic and stochastic approaches are presented and analysed in Sections 6.6 and 6.7, respectively. Finally, the results are discussed in Section 6.8 along with the managerial insights in Section 6.9.

SCR is a relatively recent research field, presenting its initial developments in the early 2000s. The ever-expanding nature of modern SC and their tendency towards globalisation have increased the interest of both practice and academic communities, displaying a steady rise of dedicated work over the years (I. Ali & Gölgeci, 2019). Despite presenting a fast-growing body of literature, no single unifying SCR definition has currently been established. The multidisciplinary nature of the term resilience has influenced the hindering of a commonly accepted definition, whose elements are still recurrently used interchangeably (Hosseini & Ivanov, 2019). Noteworthy developments can be found, developing and clarifying conceptual terms such as SCR principles, elements and strategies, as a mean to propose well-founded definitions of SCR (Cardoso et al., 2015; Hohenstein et al., 2015; Kamalahmadi & Parast, 2016; Tukamuhabwa et al., 2015; J. Wang et al., 2016; Ribeiro & Barbosa-Povoa, 2018).

On this setting it has been recognised that conceptual work on SCR is now giving place to more quantitative approaches to measure resilience (Kochan & Nowicki, 2018; Ribeiro & Barbosa-Póvoa, 2022a). Indeed, it is well acknowledged the necessity to further develop tools that aid the implementation of resilience practices (Y. Han et al., 2020).Nonetheless, despite the efforts witnessed on quantitative developments, these mainly address the strategic decision level over the long-term planning horizon, some in combination with the tactical level, but scarcely considering the operational level (Khalili et al., 2017; Ribeiro & Barbosa-Povoa, 2018).

To guide this work, the definition proposed by Ribeiro & Barbosa-Povoa (2018) will be considered: “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”. From the framework proposed by the same authors, when tackling SCR, four constructs are pivotal to be addressed: adaptive framing, speed, performance level and focus event.

6.2.1 Overview

From above, it can be said that practitioners and academics alike have identified relevant research gaps that still require attention, and mitigate such void is the main purpose of this work.

Companies are often faced with alternative options, if alternative locations are considered in SC network design models, the same does not happen with alternative products. It is common for products that satisfy the same demand but with different characteristics. These products can have different production processes, different environmental impacts or originated from different locations. Yet, the option for alternative products has not been found, leaving their benefits unexplored in this subject. For the present work, this topic is explored by specifically, looking at the trade-off between offshore and nearshore for production, and regarding the alternative products, various configurations of the base product will be designed.

To deal with the uncertainty brought by the enormous scope of sources that disruptions may originate from, three types of representative disruptions will be tested in the present paper as this is seen as a sound approach to meet the challenge of disruption modelling (Azad et al., 2013; Elluru et al., 2019; Ribeiro & Barbosa-Póvoa, 2022a). Namely disruptions on supply, production and transportation activities are created. These type of disruptions are adapted from those identified by Rice & Caniato (2003). The details on how these disruptions are implemented are further detailed in Section 6.4.4.

In line with these approaches and the research gaps identified, three objective functions will be considered (further detailed in Section 6.4.1): **Maximise the total profit** - Is the most common objective function used where SCR is studied by analysing how specific KPI respond to different disruptive scenarios; **Maximise the resilience metric** proposed by Ribeiro & Barbosa-Póvoa (2022a) - a dimensionless SCR metric establishing a trade-off between economic return and meeting demand; **Minimising the total flow time** - As identified above the speed on which a SC can respond to a disruption can be a SCR enabler, thus a hypothesis is that by reducing the lead time along the SC it is possible to SC responsiveness, hence SCR.

Overall, this paper aims to contribute to the extant literature by delivering a holistic approach to SC activities at the planning and operational level that can be vulnerable to risk events. Furthermore, the effects of different length disruptions remain relatively unexplored and the impact of immediate or delayed responses. To bridge this gap, the model developed presents a generic form that allows being easily adapted to different use cases and facilitate the implementation of the concerns stated beforehand.

6.3 Problem definition

The objective of this study is to advance knowledge in the field of SCR using an optimisation decision tool and focusing on the tactical and operational level, as there is a gap in the current literature regarding this aspect of SCR. The study aims to compare different objective functions, exploring from a purely economic perspective to a more comprehensive, resilient perspective. How SC following such objectives behave under disruptive scenarios and how can academics and practitioners use OR tools to better prepare their organisations.

Uncertainty is a key factor that impacts SCR, and this study also aims to investigate how it can be modelled and incorporated into decision-making. Namely we consider uncertainty in demand, return rates, disruptions occurrence and the correspondent response time. In addition, the impact of total lead time, specifically whether onshoring or offshoring supply, will be assessed in terms of its impact on SCR. The impact of disruption duration and the delay in acknowledging the occurrence of disruptions will also be analysed.

It is also examined the behaviour of a forward supply chain structure versus a closed-loop supply chain in terms of resilience, as closed-loop SC are often seen as a way of leveraging the SCR potential of SC as they could foster flexibility, redundancy, visibility and efficiency all acknowledged SCR enablers (Ribeiro & Barbosa-Povoa, 2018).

As stated before, closed-loop supply chains have the ability to adapt to changing conditions by reusing and re-purposing materials. This makes them more flexible than forward supply chains that are focused on a one-way flow of materials and information. This ability comes useful when dealing with product spoilage, as CLSC have the capability of generating value from what would otherwise be waste. Due to a reduced dependency on a single source of raw materials or components Closed-loop supply chains have higher redundancy in their design. With multiple sources of materials (raw and reused), they are able to continue operating even if one source is impacted by a disruption. Thus, closed-loop supply chains reduce the amount of waste generated, enabling them to be more sustainable while being also less vulnerable to disruptions that may result from resource scarcity (**?**).

In sum, the problem in study analysis forward and closed-loop supply chains and can be explained as:

Given

- A set of products to be produced and its demand
- A set of alternative products
- A set of locations to be defined as suppliers, factories, retailers, markets and disposal facilities
- A set of outsourcing suppliers
- Product characteristics such as: Involved costs, sell prices, production time and bill of materials

Determine:

- The supply chain network to be deployed
- The flows between entities
- The characteristics of production and the technologies involved for each location, considering the existence of alternative products
- The production quantities for each product
- The capacity of storage and production at each location considering possible expansions

So as to:

- Maximise the resilience metric
- Minimise the flow time
- Maximise the profit

6.4 Model Formulation

The presented model considers a four-echelon closed-loop supply chain (CLSC) composed of suppliers, factories, retailers, and markets. Figure 6.1 illustrates this structure along with the allowed flows among the entities. The model structure includes trivial production, distribution and capacity planning, upon which considerable additions were made.

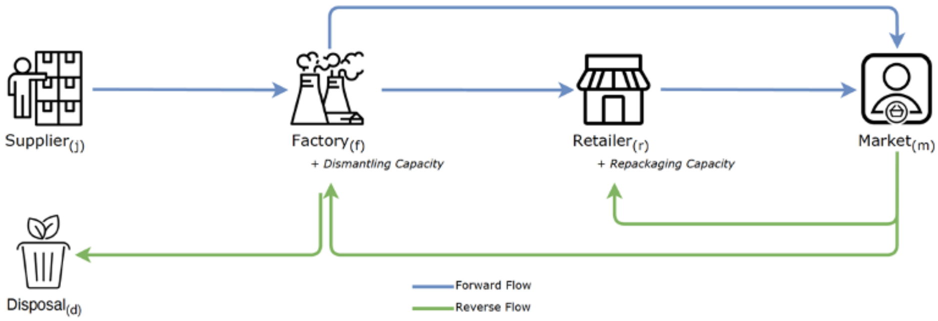


Figure 6.1: Supply Chain structure

Being this a planning-operational model, relative to production, the decision variables are related with which product should be produced, given that demand can be satisfied by original and alternative products; where they should be produced, considering the restricted set of products that the factories are capable of manufacturing; and whether it is necessary to extend the original production capacity. The expansion can occur either by increasing the capacity of owned factories (activation of redundant capacity) or through outsourcing. Additionally, the products are also restricted to markets in which they can be sold.

Following a similar approach as the one in the work of Cardoso et al. (2015), the reverse flow can occur for non-conforming products as well as for end-of-life products, where they are returned to the retailer to be repacked or to the factory to be disassembled, respectively, and reintegrate the forward flow.

6.4.1 Objective Functions

The following sub-sections present the three objective functions considered. The first intends to balance the economic performance of the SC with the delivered service level, whose benefit is further explained in section 6.4.1.A. Secondly, the flow time objective function's goal is to optimise the SC's responsiveness by guaranteeing the minimum lead time possible, which has been shown in the literature to boost SCR, presented in section 6.4.1.B. Lastly, a typical profit maximisation is considered to reinforce the importance of maintaining attractive economic returns and sustaining financial viability, described in section 6.4.1.C. These three objective functions allow for the comparison of resilience strategies and are used throughout this paper.

6.4.1.A Objective function 1: Resilience metric

The first objective function involves economic goals and customer satisfaction to guarantee SC resilience as presented in equation 6.1, and is derived from Ribeiro & Barbosa-Póvoa (2022a) that proved its higher performance to create resilient supply chains at the strategic-tactical levels. A reference value ($profitREF$) is used in the first term, representing the optimal profit level within normal operating conditions. Hence, the first term favours profit levels that approximate the reference value. This term is then balanced out with a measure of service level in the second term. The latter will deteriorate the overall function with increased lost sales ($LS_{p,m,t}$), thus considering the concern to meet customers' demand ($dem_{p,m,t}$). Since both terms are interacting in negative feedback, customers' satisfaction is not disregarded in pursuit of economic returns. Equation 6.2 determines the profit value.

$$Max\ Z_1 = \frac{profit}{profitREF} - \frac{\sum_{(p,m)\in PM}\sum_{t\in T} LS_{p,m,t}}{\sum_{(p,m)\in PM}\sum_{t\in T} dem_{p,m,t}} \tag{6.1}$$

$$profit = sales - (TMC + TTC + TIC + TDC + TEC) \tag{6.2}$$

Total sales are obtained by the amount of products sold ($SA_{p,m,t}$) at price ($sellprice_p$), in equation 6.3.

$$sales = \sum_{p\in P}\sum_{(p,m)\in PM}\sum_{t\in T} sellprice_p \times SA_{p,m,t} \tag{6.3}$$

Total manufacturing cost - TMC: Equation 6.4 measures the costs incurred during production. It includes the costs of raw materials ($mc_{i,j}$) that are supplied for production ($FSF_{i,j,f,t}$), the fixed cost of opting to operate facility f to produce product p ($fpc_{p,f}$) as well as the variable cost ($vpc_{p,f}$) per unit produced at each factory ($PRO_{p,f,t}$). Also, it is accounted the possibility of raw materials or product to be spoiled ($SPOi_{i,f,t}$, $SPOp_{p,f,t}$), incurring in a unitary cost ($scost_i$, $scost_p$).

$$\begin{aligned} TMC = &\sum_{i\in I}\sum_{j\in J}\sum_{f\in F}\sum_{t\in T} mc_{i,j} \times FSF_{i,j,f,t} + \sum_{p\in PF}\sum_{f\in F}\sum_{t\in T} vpc_{p,f} \times PRO_{p,f,t} \\ &+ \sum_{p\in PF}\sum_{f\in F} fpc_{p,f} \times E_{p,f} + \sum_{i\in I}\sum_{f\in F}\sum_{t\in T} scost_i \times SPOi_{i,f,t} + \sum_{p\in PF}\sum_{f\in F}\sum_{t\in T} scost_p \times SPOp_{p,f,t} \end{aligned} \tag{6.4}$$

Total transportation cost - TTC: Calculated by equation 6.5, where the unitary transportation cost of product p between two entities ($vtcs_{i,j,f}$, $vtcr_{p,f,r}$, $vtcd_{p,f,m}$, $vtcm_{p,r,m}$, $vtcdd_{p,d,f}$) is multiplied by the quantity of its flow in all time periods. Here it is assumed that the cost between two entities is equal whether it is a forward or reverse flow ($RMF_{p,m,f,t}$, $RMR_{p,m,r,t}$), as is the case between markets and factories or retailers. The remaining terms add fixed costs ($ftcs_{j,f}$, $ftcr_{f,r}$, $ftcd_{f,m}$, $ftcm_{r,m}$) when a transportation link is established throughout the planning horizon ($Xs_{j,f}$, $Xr_{f,r}$, $Xd_{f,m}$, $Xm_{r,m}$).

$$TTC = \sum_{i \in I} \sum_{j \in J} \sum_{f \in F} \sum_{t \in T} vtcs_{i,j,f} \times FSF_{i,j,f,t} + \sum_{p \in PF} \sum_{f \in F} \sum_{r \in R} \sum_{t \in T} vtcr_{p,f,r} \times FFR_{p,f,r,t}$$
$$+ \sum_{p \in PF} \sum_{f \in F} \sum_{m \in PM} \sum_{t \in T} vtcd_{p,f,m} \times (FFM_{p,f,m,t} + RMF_{p,m,f,t})$$
$$+ \sum_{p \in P} \sum_{r \in R} \sum_{m \in PM} \sum_{t \in T} vtcm_{p,r,m} \times (FRM_{p,r,m,t} + RMR_{p,m,r,t})$$
$$+ \sum_{p \in PF} \sum_{f \in F} \sum_{d} \sum_{t \in T} vtcdd_{p,d,f} \times RFD_{p,f,d,t} + \sum_{j \in J} \sum_{f \in F} ftcs_{j,f} \times Xs_{j,f} +$$
$$\sum_{f \in F} \sum_{r \in R} ftcr_{f,r} \times Xr_{f,r} + \sum_{f \in F} \sum_{m \in M} ftcd_{f,m} \times Xd_{f,m} + \sum_{r \in R} \sum_{m \in M} ftcm_{r,m} \times Xm_{r,m} \quad (6.5)$$

Total inventory cost - TIC: Equation 6.6 calculates the inventory cost by multiplying the unitary holding cost ($invcfi_{i,f}$, $invcfp_{p,f}$, $invcr_{p,r}$) by the amount of inventory that is held in each time period ($INVfi_{i,f,t}$, $INVfp_{p,f,t}$, $INVr_{p,r,t}$). The first term is for the inventory of raw materials and the second term for final products, both held at the factories, while the last term serves for the final products held at the retailers.

$$TIC = \sum_{i \in I} \sum_{f \in F} \sum_{t \in T} invcfi_{i,f} \times INVfi_{i,f,t} + \sum_{p \in PF} \sum_{f \in F} \sum_{t \in T} invcfp_{p,f} \times INVfp_{p,f,t}$$
$$+ \sum_{p \in P} \sum_{r \in R} \sum_{t \in T} invcr_{p,r} \times INVr_{p,r,t} \quad (6.6)$$

Total duties cost - TDC: Equation 6.7 assumes that the cost occurs when final products leave the factories, either directly to the market ($FFM_{p,f,m,t}$) or to a retailer ($FFR_{p,f,r,t}$) where a duty cost may be applied ($dcm_{p,f,m}$ and $dcr_{p,f,r}$, respectively). The referred duty costs depended on the products' characteristics and the duty rate applied between the two locations ($drm_{p,f,m}$, $drr_{p,f,r}$), and are therefore calculated beforehand by equation 6.8 and 6.9.

$$TDC = \sum_{p \in PF} \sum_{f \in F} \sum_{m \in PM} \sum_{t \in T} dcm_{p,f,m} \times FFM_{p,f,m,t} + \sum_{p \in PF} \sum_{f \in F} \sum_{r \in R} \sum_{t \in T} dcr_{p,f,r} \times FFR_{p,f,r,t} \quad (6.7)$$

$$dcm_{p,f,m} = drm_{p,f,m} \times (beta_p \times vpc_{p,f} + gama_p \times vtcd_{p,f,m}) \quad (6.8)$$
$$dcr_{p,f,r} = drr_{p,f,r} \times (beta_p \times vpc_{p,f} + gama_p \times vtcr_{p,f,r}) \quad (6.9)$$

Total expansion cost - TEC: If recurring to a production capacity expansion, the total cost is calculated by equation 6.10 depending on the expanded amount ($CAPInc_{f,t}$), applying a unitary variable cost ($vcec_f$) additional to the head cost ($fcec_f$) for selecting such option (XE_f).

$$TEC = \sum_{f \in F} fcec_f \times XE_f + \sum_{f \in F} \sum_{t \in T} vcec_f \times CAPInc_{f,t} \quad (6.10)$$

6.4.1.B Objective function 2: Flow time

Flow time is intended to represent the total time a product takes from production to the final consumer. Thus, it is possible to study the impact of faster and more responsive SC and its relationship with resilience.

Thus, equation 6.11 represents the summation of times for production ($pt_{p,f}$) and transportation. Due to the multi-product characteristic of our model, there must be deployed an effort to avoid the bias introduced by the size/value of products. Although different strategies can be used, a relationship between the product's volume and twenty-foot equivalent unit (TEU) is considered. This is, the volume of each product divided by the volume of a TEU, making the contribution of each product to the total flow time as greater as greater is its total volume. This relationship can be adapted to match the decision marker's preferences. This objective function translate the relationship that measures the transportation time between two entities ($tts_{j,f}$, $ttr_{f,r}$, $ttd_{f,m}$, $ttm_{r,m}$) with importance proportional to the amount sent ($FSF_{i,j,f,t}$, $FFR_{p,f,r,t}$, $FFM_{p,f,m,t}$, $FRM_{p,r,m,t}$), adjusted according to the products' volume within a container ($lunit_p$). $lunit_p$ is obtained by equation 6.12, based on the TEU, according to each product's volume (vol_p). Additionally, it is also included the necessary production time of the item ($pt_{p,f}$).

$$\begin{aligned} Min\ Z_2 = & \sum_{i \in I} \sum_{j \in J} \sum_{f \in F} \sum_{t \in T} (tts_{j,f} \times liunit_i \times FSF_{i,j,f,t}) + \sum_{p \in PF} \sum_{f \in F} \sum_{t \in T} pt_{p,f} \times PRO_{p,f,t} \\ & + \sum_{p \in PF} \sum_{f \in F} \sum_{r \in R} \sum_{t \in T} (ttr_{f,r} \times lunit_p \times FFR_{p,f,r,t}) + \sum_{p \in PF} \sum_{f \in F} \sum_{m \in PM} \sum_{t \in T} (ttd_{f,m} \times lunit_p \times FFM_{p,f,m,t}) \\ & + \sum_{p \in P} \sum_{r \in R} \sum_{m \in PM} \sum_{t \in T} (ttm_{r,m} \times lunit_p \times FRM_{p,r,m,t}) \end{aligned} \tag{6.11}$$

$$lunit_p = \frac{vol_p}{TEU} \tag{6.12}$$

6.4.1.C Objective function 3: Profit

Lastly, the third objective function is a straightforward profit maximisation, where total costs are subtracted to the revenue, obtained by the sold products ($SA_{p,pp,m,t}$), as seen in equation 6.2.

6.4.2 Constraints

The model includes the constraints presented in the following subsections, divided by categories. Those categories are production (section 6.4.2.A), reverse-flow (section 6.4.2.B), demand (section 6.4.2.C).

6.4.2.A Production Constraints

This section presents the equations which define and constrain production at the factories. Equation 6.13 defines the upper and lower limit ($pmin_{p,f}$ and $pmax_{p,f}$) for initiating production of product p at factory f in each time period ($PRO_{p,f,t}$). The binary variable $W_{p,f,t}$ imposes these limits if the product is assigned to be produced at the designated factory and time period, otherwise it takes the value of 0.

To obtain final products it is necessary the consumption of raw materials ($CON_{i,f,t}$) in a given quantity according to each product's requirements ($ireq_{p,i}$), which is accounted for in equation 6.14. Equation 6.15 guarantees that total production does not surpass the production capacity of the factory ($CAP_{f,tt}$). For this limit, the production initiated at instant t is considered as well as any ongoing operations. Such is necessary given that the production time ($pt_{p,f}$) varies by product and factory. The first term accounts for products with immediate production ($pt_{p,f} = 0$), while for higher production duration it is measured by variable $ONG_{p,f,t,tt}$, as defined by equation 6.16, which takes the value of the initiated production ($PRO_{p,f,t}$) at time t until the end of production at $t + pt_{p,f}$.

$$pmin_{p,f} \times W_{p,f,t} \leq PRO_{p,f,t} \leq pmax_{p,f} \times W_{p,f,t} \qquad \forall (p,f) \in PF, t \tag{6.13}$$

$$\sum_{p \in PF} (PRO_{p,f,t} \times ireq_{p,i}) = CON_{i,f,t} \qquad \forall i, f, t \tag{6.14}$$

$$\sum_{(p,t):\, pt_{p,f}=0} PRO_{p,f,tt} + \sum_{t} \sum_{p \in PF} ONG_{p,f,t,tt} \leq CAP_{f,tt} \qquad \forall f, tt \tag{6.15}$$

$$ONG_{p,f,t,tt} = PRO_{p,f,t} \qquad \forall (p,f) \in PF, t \leq tt < t + pt_{p,f} \tag{6.16}$$

As aforementioned, if needed, equation 6.17 allows the factories' production capacity to be increased in $CAPInc_{f,t-stime_f}$ units, where $stime_f$ stands for the necessary set up time for the capacity to become available. This increase is added to the capacity at the previous instant ($CAP_{f,t-1}$), with the exception for the first instant where the initial production capacity ($icap_f$) is considered (equation 6.18). However, this increase can be executed in different manners; either by activating redundant capacity present at the owned factories, or through outsourcing. The former option is represented by equation 6.19, here the increase allowed is proportional to the original capacity of the factory, having a minimum and maximum percentage ($pcemin_f$ and $pcemax_f$), while for the latter option, since these do not belong to the original SC, do not have an initial capacity, still, appropriate bounds are established by equation 6.20.

$$CAP_{f,t} = CAP_{f,t-1} + CAPInc_{f,t-stime_f} \qquad \forall f, t > 1 \tag{6.17}$$

$$CAP_{f,t} = icap_f + CAPInc_{f,t-stime_f} \qquad \forall f, t = 1 \tag{6.18}$$

$$pcemin \times icap_f \times XE_f \leq \sum_{t} CAPInc_{f,t} \leq pcemax \times icap_f \times XE_f \quad \forall f \in F_{own} \tag{6.19}$$

$$ocemin \times XE_f \leq \sum_{t} CAPInc_{f,t} \leq ocemax \times XE_f \qquad \forall f \in F_{out} \tag{6.20}$$

6.4.2.B Reverse Flow constraints

Regarding the reverse flows, these can occur for two kinds of products: non-conforming and end-of-life products. The first are regular returns from the market to the retailer due to minor defects ($RMR_{p,m,r,t-ttm}$), defined by equation 6.21, which can occur up to a fraction ($nconf$) of the total sales ($SA_{p,pp,m,t}$) and higher than a minimum collection percentage ($mincol$). These products are then repacked and reintegrated in the forward flow The second type takes into account the life span of the product itself (ltp), after which they are returned to the factories ($RMF_{p,m,f,t}$). Similarly, as the previous case, these returns are bounded by the total sales of the product and a minimum percentage of collection through equation 6.22. The items are disassembled, and its individual parts integrate the factories source of raw materials to be repurposed in the production of new products. Nonetheless, once at the factories, a fraction of products are considered as unsalvageable (dis) and are disposed of, which is considered in equation 6.23 that defines the amount sent to disposal ($RFD_{p,f,d,t}$).

$$mincol \times nconf \times \sum_{p \in P \wedge m \in M} SA_{p,m,t} \leq \sum_{r} RMR_{p,m,r,t} \leq nconf \times \sum_{p \in P \wedge m \in M} SA_{p,m,t} \quad \forall (p,m) \in PM, t \tag{6.21}$$

$$mincol \times \sum_{p \in P \wedge m \in M} SA_{p,m,t-lt_p} \leq \sum_{f \in PF \wedge F_{own}} RMF_{p,m,f,t} \leq \sum_{p \in P \wedge m \in M} SA_{p,m,t-lt_p} \quad \forall (p,m) \in PM, t \tag{6.22}$$

$$\sum_{d} RFD_{p,f,d,t} = dis \times \sum_{m \in PM} RMF_{p,m,f,t-ttd_{f,m}} \qquad \forall (p,f) \in PF \bigwedge F_{own}, t \tag{6.23}$$

6.4.2.C Demand Constraints

The following equations address demand satisfaction. Equation 6.24 allows the demand for product p ($dem_{p,m,t}$) to be met by the sale of that product or an alternative one pp ($SA_{pp,m,t}$) which are defined in set ALT. Equation 6.25 establishes these sales to occur from products arriving directly from the factories or from retailers ($FFM_{p,f,m,t-ttd}$ and $FRM_{p,r,m,t-ttm}$, respectively). Lastly, any demand not satisfied, by either the original or the alternative product, at the specified time period is considered as lost ($LS_{p,m,t}$) by equation 6.26. However, to ensure a target service level, the lost sales need to be lower than an acceptable amount of the total demand (ds) that needs to be satisfied (equation 6.27).

$$\sum_{pp \in ALT \wedge m \in M} SA_{pp,m,t} + \sum_{p \in P \wedge m \in M} SA_{p,m,t} \leq dem_{p,m,t} \qquad \forall (p,m),(pp,m) \in \ PM, t \tag{6.24}$$

$$\sum_{p \in P \wedge m \in M} SA_{p,m,t} = \sum_{f \in PF} FFM_{p,f,m,t-ttd_{f,m}} + \sum_{r} FRM_{p,r,m,t-ttm_{r,m}} \qquad \forall\ (p,m) \in \ PM, t \tag{6.25}$$

$$dem_{p,m,t} - \sum_{pp \in ALT \wedge m \in M} SA_{pp,m,t} - \sum_{p \in P \wedge m \in M} SA_{p,m,t} = LS_{p,m,t} \qquad \forall\ (p,m) \in \ PM, t \tag{6.26}$$

$$\sum_{p} \sum_{m \in PM} \sum_{t} LS_{p,m,t} \leq \ ds \times \sum_{p} \sum_{m \in PM} \sum_{t} dem_{p,m,t} \tag{6.27}$$

6.4.3 Uncertainty modelling

With the goal to adapt the deterministic model to a stochastic model where demand and product return rates are considered uncertain, a stochastic multi-stage approach is adopted. The associated scenario tree is composed of nodes and arcs at each stage.

Since we are dealing with a tactical-operational model, time is usually depicted on a smaller scale (eg. one day or less). Thus, considering each time period of the planning horizon as a stage for the scenario tree would result in a large model with many variables and constraints that would endanger its use in a tactical and operational context.

To deal with this complexity an approach is used, where the model's size is reduced by having a different time description in the decisions and the scenario tree. This approach is intended to mimic real-life scenarios where actions that change the steady-state might not occur daily. Thus, a different time description is possible in the scenario tree, where time periods are clustered in stages. This means that subsequent time periods where no alterations are expected are clustered within the same time description. This approach allows the construction of a scenario tree with fewer ramifications and, consequently, a reduced number of scenarios to reflect more realistically when new information should be considered, thus being more adaptable for cases with different characteristics. Figure 6.2 illustrates a scenario tree following the described approach.

Due to the clustering of time periods into stages, when recalling previous instant variables' values, these may or may not belong to a different stage and, consequently, to a different scenario. This applies to every decision that spans other time periods, such as product production or transportation. The methodology used in most scenario tree applications, where a set of scenarios belong to each time period, is unfeasible in our preposition, forcing a new approach to dealing with precedences. For

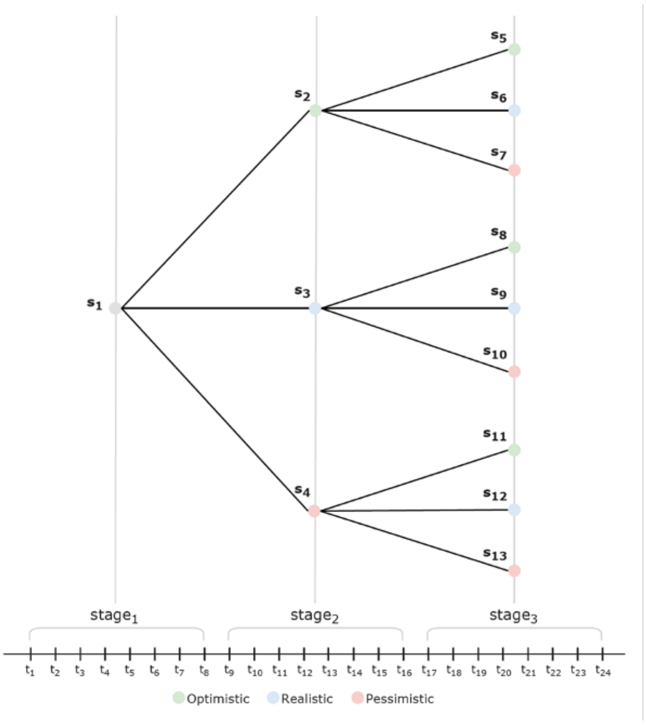


Figure 6.2: Scenario tree for uncertain parameters

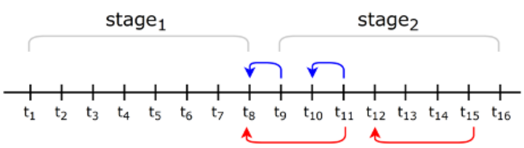


Figure 6.3: Scenario node precedence illustration Blue for distance=1t; Red for distance=3t

example, by observing the blue arrows in Figure 6.3, at t11, returning to the previous instant would still belong to the same scenario in stage 2. But, at t9, the predecessor would belong to stage 1.

On the other hand, this is also influenced by the temporal distance from the present node. For example, observing the red arrows from Figure 6.3, which require values three time periods away, for this case, t11 would already call a predecessor belonging to stage 1. Hence, the set that links scenarios to their predecessors needs to consider the current time period and the temporal distance to the predecessor.

To deal with these, the variable $ONG_{p,f,t,tt}$, representing the ongoing production at a given time tt, forces the creation of a new set relating scenarios and time periods. Specifically, variable $ONG_{p,f,t,tt}$, requires two indexes of time periods to measure any ongoing production at time tt having started at time t. Consequently, this variable in the stochastic model also requires two scenario indexes to link to each time index ($ONG_{p,f,s,ss,t,tt}$). Hence, set fwS has the function of providing the succeeding scenario ss that should be linked to time tt for non-null production times.

To fulfill these objectives new sets need to be defined and are presented bellow in Table 6.2.

The objective functions were updated accounting with the probability of the scenarios (pbs), resulting in equation 6.28 for the resilience metric, equation 6.29 for the flow time, and equation 6.30 for the profit. The deterministic equations presented before are also updated to include the scenario index.

Table 6.1: Main indices, sets, subsets and variables for the mathematical model

Sets	Indices	Description
DT	dt	Allowable distances between time periods
S	s, ss	Scenario tree nodes (scenarios)
ST	(s,t)	Time periods t belonging to a scenario s
$preS$	(ss,s,dt,t)	Scenario ss predecessor of scenario s at a distance dt from period t
fwS	(ss,s,dt,t)	Scenario ss sucessor of scenario s at a distance dt from period t

$$Max\ Z_1 = \frac{profit}{profitREF} - \frac{\sum_{(p,m)\in PM}\sum_{t\in ST}\sum_{s\in S} pb_s \times LS_{p,m,s,t}}{\sum_{(p,m)\in PM}\sum_{t\in ST}\sum_{s\in S} pb_s \times demand_{p,m,s,t}} \tag{6.28}$$

$$Min\ Z_2 = \sum_{s} pb_s \times (\sum_{i\in I}\sum_{j\in J}\sum_{f\in F}\sum_{t\in ST}(tts_{j,f} \times liunit_i \times FSF_{i,j,f,s,t}) + \sum_{p\in PF}\sum_{f\in F}\sum_{t\in ST} pt_{p,f} \times PRO_{p,f,s,t} + \sum_{p\in PF}\sum_{f\in F}\sum_{r\in R}\sum_{t\in ST}(ttr_{f,r} \times lunit_p \times FFR_{p,f,r,s,t}) + \sum_{p\in PF}\sum_{f\in F}\sum_{m\in PM}\sum_{t\in ST}(ttd_{f,m} \times lunit_p \times FFM_{p,f,m,s,t}) + \sum_{p\in P}\sum_{r\in R}\sum_{m\in PM}\sum_{t\in ST}(ttm_{r,m} \times lunit_p \times FRM_{p,r,m,s,t})) \tag{6.29}$$

$$Max\ Z_3 = \sum_{s\in S} pb_s \times (sales_s - (TMC_s + TTC_s + TIC_s + TDC_s)) - \sum_{p\in PF}\sum_{f\in F} fpc_{p,f} \times E_{p,f} + \sum_{f\in F} fcec_f \times XE_f + \sum_{f\in F}\sum_{t\in T} vcec_f \times CAPInc_{f,t} + \sum_{j\in J}\sum_{f\in F} ftcs_{j,f} \times Xs_{j,f} + \sum_{f\in F}\sum_{r\in R} ftcr_{f,r} \times Xr_{f,r} + \sum_{f\in F}\sum_{m\in M} ftcd_{f,m} \times Xd_{f,m} + \sum_{r\in R}\sum_{m\in M} ftcm_{r,m} \times Xm_{r,m} \tag{6.30}$$

Following the same reasoning as above, constraints 6.13 to 6.16 and 6.21 to 6.27 are adapted to include the scenario. Restrictions 6.17 to 6.20 remain unchanged since the expansion of capacity does not change by scenario but only for time period.

6.4.4 Disruption modelling

Disruption modelling is a challenging task and is seen as one of the most distinctive characteristics of SCR. In this work, the modelling of disruption will follow a binary approach, whether it is assumed that it occurs or not. However, the means by which it originates will be considered uncertain. This approach follows a commonly used practice in SCR modelling and is even more satisfactory in this context of tactical and operational level of decision (Ribeiro & Barbosa-Póvoa, 2022a). For each disruption type, possible scenarios are constructed, that are different events of the same kind that can disturb the SC activity. Under a resilience setting, the probabilities in the scenario tree do not intend to reflect the likelihood of occurrence of a particular event following the principles that separate SC risk and resilience. These scenarios are associated with a weight that reflects the likelihood of its incidence, or the relevance given by the decision maker, compared to those within the same disruption type. This assertion can be made without any suggestion on the likelihood of the event itself.

To implement this approach an additional index was added to the variables (ds) in the model to register the disruptive scenario at hand.

Table 6.2: Outsourcing options design

Outsourcing Factory	Location	Time to markets	Production Cost
f5	Offshore	Further away than f6	x 2,00
f6	Offshore	Slower to markets	x 2,30
f7	Nearshore	Faster to all markets	x 4,30
f8	Nearshore	Faster to most markets	x 4,00

6.5 Case Study

In order to show the model applicability a case study on an European CLSC is studied. This is illustrated in Figure 7.9, where 3 different families products (p1-p3) to serve 6 markets dispersed in the European region. In this SC there are 3 suppliers, 4 factories (f1-f4), and 2 retailers.

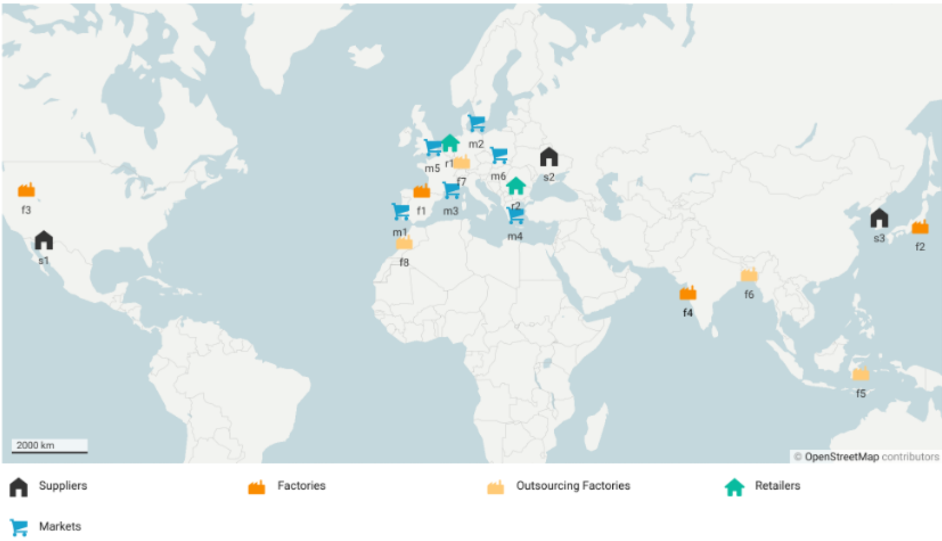


Figure 6.4: Case Study's SC configuration

The production capacity expansion can be achieved by increasing the production capacity of the owned factories or by resorting to outsourcing. The former strategy assumes that the factories possess idle redundant capacity that can be activated when necessary. In this case, it is considered that these factories can increase up to 25% their current capacity. For the outsourcing, four options were designed to understand the trade-off between offshore and near-shoring decisions. These options are summarised in table 6.2, noting that the production costs are presented relative to the difference of the average values verified at owned factories. In addition, it is assumed that the products at outsourcing factories have no production time, simulating the condition that the product is already in stock and ready to be purchased.

The outsourcing facilities are considered to be capable of producing any product, which deviates from the owned factories, which may only be qualified to manufacture some products. Table 6.3 presents this relation, along with the initial capacity of each facility.

The products stated in table 6.3 beyond $p_1 - p_3$ represent the alternative products for product p_1. These items are supposed to be sold at a lower price, forfeiting 5% of the profit margin, but offering appealing features which ease their production process to compensate the loss they provide in rev-

Table 6.3: Owned factories characteristics

Factory	Products	Initial Capacity (units)
f1	All	700
f2	$p_1, p_{11}, p_{12}, p_{13}$	300
f3	p_2, p_{13}	150
f2	p_3, p_{13}	150

enue as follows: p_{11} -Lower production time; p_{12} - Fewer raw material requirements; p_{13} - Possible to produce at more factories

This SC experiences weekly demands in the horizon of 24 time periods (figure 6.5). However, these values will be taken as uncertain for the stochastic model, further detailed in Section 6.7.

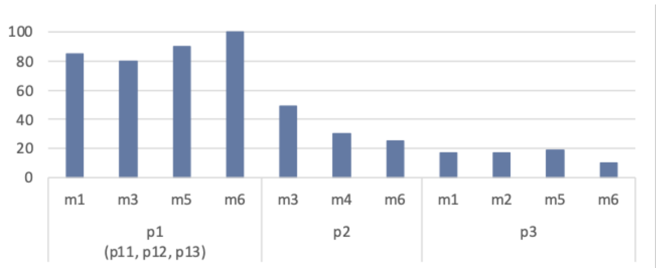


Figure 6.5: Deterministic demand volume

Regarding the reverse flows, it is set that 20% of the products sold are non-conforming, and that 20% of the end-of-life products are too damaged to be re-purposed after their 10 week life-span. Both types of reverse flow need to meet a minimum of 10% of product collection. The uncertainty of these values will also be considered in the stochastic model.

6.5.1 Discussion Outline

The remaining sections of this work will now focus on analysing the results obtained by applying the model presented in the case study. The analyses are divided for the deterministic model and, subsequently, compared with the stochastic model, where demand and product return rates will be considered uncertain parameters. A multistage approach is followed to study the impact of different prioritisation in the objective functions and how this preference influences the corrective measures taken to maintain operations. Consequently, it will demonstrate which indicator leaves the SC more resilient to the disruptions that will be tested. Two points of the pareto front will be used for this end as representative of these preferences, being characterised as follows: **Point A:** The point that values most the resilience metric; **Point B:** The point that values most the flow time.

Nonetheless, the response to a crisis can take different forms, being possible to alternate the DM's priority in regards to which is the most relevant indicator to optimise promptly. An analysis of response strategies will be conducted to clarify the effects of exchanging the OF's preference when faced with a disruption.

Table 6.4: Payoff table of the deterministic model

	Res Metric (RM)	Flow Time (FT)	Profit (PF)
max RM - FT - PF	1,000	050 733,88	396 305,37
min FT - PF - RM	0,146	007 986,60	097 665,91
max PF - RM - FT	1,000	051 124,26	396 403,47
max RM - PF - FT	1,000	396 364,04	051 119,00
max PF - FT - RM	1,000	396 403,47	051 124,26
min FT - RM - PF	0,146	097 654,45	007 986,60

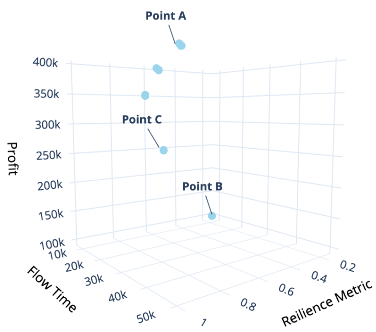


Figure 6.6: Three-dimensional representation of the deterministic model multi-objective solution

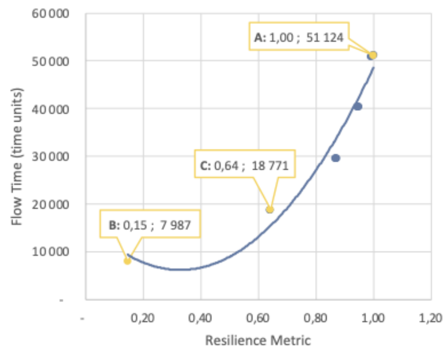


Figure 6.7: Two-dimensional representation of the deterministic model multi-objective solution

6.6 Deterministic model results

The following sub-sections present the results of the deterministic model for the outlined analyses. These results are obtained using GAMS software running the CPLEX solver with a gap of 0%.

6.6.1 Reference case analysis

Foremost, the model is run for normal operating conditions where no disruption occurs, and no uncertainty is included.

The solution set is plotted in figure 6.6, following the priority defined by Z_1, Z_2 and then Z_3. To ease its interpretation, a two-dimensional representation is given in figure 6.7, where the pareto front's extreme points and an in-between point are signalled. Point A represents the solution that delivers the maximum resilience metric and profit value, contrasting to point B for the lowest flow time possible. Observing figure 6.7, improvements on the resilience metric become harder to obtain as the metric reaches higher values, as the possibilities of improvement become smaller requiring higher flow times.

From the payoff table (table 6.4), it can be concluded that maximising the resilience metric or the profit initially will result in similar solutions. However, comparing this solution to the one that favours the flow time, the differences are significant, as shown in figure 6.7.

Table 6.5 presents the values of performance indicators of the selected solutions to comprehend their difference further. Multiple conditions aggravate the disparity between point A and point B. Firstly, the flow time objective function does not include any concern regarding the service level, limiting the solution to fulfil the minimum acceptable amount of demand that is pre-established, in this case, of 90%.

Table 6.5: Deterministic model performance indicators of selected solutions

Point	SL	Revenue	Costs				
			TMC	TTC	TDC	TIC	TEC
A	1,00	632 683	175 121	54 260	4 323	326	2 250
B	0,90	561 713	428 093	10 466	7 034	335	18 118

SL: Service Level; TMC: Manufacturing Cost; TTC: Transportation Cost; TDC: Duties Cost; TIC: Inventory Cost; TEC: Capacity Expansion Cost

Overall, the distinction of the three SC configurations that the points represent is mainly driven by production-related decisions. For example, maximising the resilience metric first (point A) concentrates production internally, even increasing the capacity of f2 while minimising the flow time (point B) only operates with outsourcing production facilities (near-shoring) leaving the owned factories idle, since it ignores production times at outsourcers.

Some general recommendations can be provided depending on a final DM's preference. For example, point B negatively stands out in the economic return by exhibiting a far lower profit value than the other solutions. Such low income may not be appealing even if the flow time is a high priority leaving it as a unfeasible option for most practical applications. Point A may lead to a high time consumed from supply to delivery to the final consumer. That results enable the SC to have a high service level and a high economic return, even during steady state scenarios, no disruption is implemented.

6.6.2 Disruptions analysis

As mentioned, a two-stage approach is followed to analyse the impact of disruptive events on SC's configuration from different OF. The three points previously presented in Section 6.6.1 are used as first-stage decisions. This is done so as to prevent the model to anticipate the occurrence of the disruptive event, and thus more realistically react to it. Foremost, the variables' values obtained by the selected point in analysis are fixed for all instants previous to the disruption, as illustrated in figure 6.8. For the second stage optimisation, the epsilon constraint method is applied

The disruptions are separated into three types according to the SC activity they affect and are run independently. Each disruption type includes different disruptive scenarios, as explained in section 6.4.4. The three types here considered are adapted from a commonly used approach first presented by Rice & Caniato (2003). The disruptions are as follows:

- Supply: For a supply type disruption, the scenarios cover each supply node present in the SC. Three scenarios will be considered taking each of the three suppliers of this case study to become incapable of providing raw materials. The probabilities of these scenarios are 30%, 40% and 30% to disturb $s1$, $s2$ and $s3$, respectively.

- Production: The production disruption will prohibit factories from initiating any new production. Similarly to the supply disruption, unless stated otherwise, this type will consider four scenarios to cover the four production entities of this case study with equal probabilities of occurrence.

- Transportation: Disruptions at the four most important connections between factories and markets will be considered, with equal probabilities. However, the links to be disrupted also vary

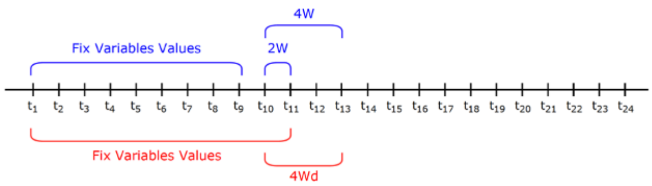


Figure 6.8: Disruption modelling. Blue: Immediate Response; Red: Delayed Response

according to the analysis being performed. Given the distinctive behaviour between the different solutions, the transportation links considered as the most critical depend on such results. Therefore, for each selected Pareto point, the four links directed to the final markets with the highest flow at t10 and t11 are selected to become unavailable.

Additional uncertainty will be explored regarding the length of the disruption as well as the time necessary to acknowledge the existence of a disruption taking place. Firstly, the disruptions will be modelled to take place at t10 for the duration of two and four weeks. This allows for the understanding of how each disruption type and the consequent corrective measures impact the SC. It is also possible to infer if such conclusions remain unaltered for longer disruptions by comparing both cases with varying event lengths. However, as past experiences have shown, identifying and responding to disturbances in the SC may not occur immediately, and that should also be considered when modelling. In the case study, this will be represented by comparing two cases, immediate response to the disruption (blue lines in Figure 6.8) or with a delay of two weeks (red lines in Figure 6.8).

6.6.2.A Point A - Maximising SCR metric

Table 6.6 presents the results obtained taking point A as the decisions taken prior to any disruption, separated by the varying disruptions' length (Two and four weeks). As expected, the scenarios with a four-week disruption with delayed sensing present the most damaging results to the resilience metric and profit. The source of lower profits can be traced, with a significant impact, to the selection of outsourcing to sustain operations continuity and to other cost increases resulting from spoilages and decreases of revenue.

Table 6.6: Deterministic model results considering disruptive events, fixing decisions of point A

Case	Res Metric	Flow Time	Profit	SL	Revenue	TMC	TTC	TDC	TIC	TEC
Ref	1,000	51 124	396 403	1,000	632 683	175 121	54 260	4 323	326	2 250
2 Weeks Disruption										
Supply	0,993	50 052	393 485	1,000	630 791	175 928	53 588	4 351	370	3 068
Prod	0,986	50 236	390 670	1,000	630 807	177 993	54 280	4 236	379	3 249
Transp	0,994	50 329	394 617	0,999	630 129	174 765	54 069	4 045	383	2 250
4 Weeks Disruption										
Supply	0,988	49 710	391 678	1,000	631 414	177 379	53 353	4 717	404	3 883
Prod	0,981	49 798	389 044	1,000	631 407	179 639	53 599	4 709	473	3 942
Transp	0,994	50 392	394 533	0,999	630 060	174 724	54 114	4 055	384	2 250
4 Weeks Disruption with Delay										
Supply	0,983	49 438	389 643	1,000	631 609	178 876	52 714	4 893	336	5 148
Prod	0,951	48 301	377 706	0,998	627 541	185 546	53 108	4 765	409	6 008
Transp	0,973	50 065	389 571	0,990	625 687	174 516	53 498	4 200	596	3 305

SL: Service Level; TMC: Manufacturing Cost; TTC: Transportation Cost; TDC: Duties Cost; TIC: Inventory Cost; TEC: Capacity Expansion Cost

Figure 6.9 exhibits the capacity expansions experienced in the cases here considered. The delayed response presents the most elevated need for production capacity expansions and the only situation where a nearshoring option is recurred to, particularly for production and transportation type disruptions. Such demonstrates the necessity to resort to the only available option, a rapid, more expensive solution since the disruption is ongoing.

Furthermore, Figure 6.9 allows visualising which capacity expansion strategy is more appropriate to tackle each case studied. It is visible that the transportation disruptions do not resort to offshore facilities. Such can be justified given that the links disrupted connection to the final markets. Therefore, opting for solutions more distant than the current operation may not be appealing if the delivery of products were to take longer than the disruptions' length.

The other two types of disruptions (production and supply) recur to outsourcing for all the cases. Supply disruptions favour most the expansion of f5, and also f6 for the delayed response case, being the only disruption type to disregard the need for nearshoring. On the other hand, production disruptions favour f6, which demonstrates the need for faster solutions.

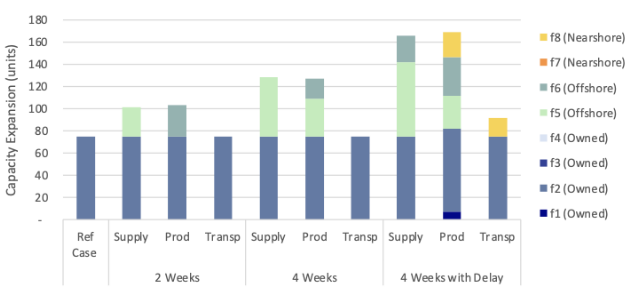


Figure 6.9: Capacity expansions of the deterministic model under disruptions, fixing point A

Regarding the type of disruption, it can be viewed that a production-related disruption causes the highest impact on the resilience metric for all scenarios. This type of disruption is also the only one to incur in additional costs due to raw material spoilage, as presented in table 6.7. Such is due to the fact that shipments of raw material are already in course at the time of the disruption expecting to be immediately used for production. Once they arrive at a production facility that is incapable of initiating production, all materials that exceed the factory's storage capacity are considered spoiled and disposed of. For a two and four weeks long disruption, a total of 345,25 units of raw materials are spoiled, increasing to 991 units for the case with a delay in sensing the disruption. This allows concluding that the length of the disruption should not influence the amount of spoilage, however only if the disruption is immediately acknowledged.

From the studied cases, all transportation disruptions incurred in a slight drop in sales. The production disruption with a delayed response also verified a minor decline in sales volume, meeting the demand in its entirety for the remaining instances (figure 6.10). Within the transportation disruptions, it is visible that the four-week disruption with delay presents the highest sales decline, and its return to regular sales values also takes longer. This is highly relevant since the same disruption but with immediate acknowledgement can recover after two weeks and stabilise sales even though the disruption remains ongoing. Furthermore, the lost sales of this kind of disruption are immediately sensed by the end consumer, whereas for a production type, such is experienced further along.

Table 6.7: Amount of product sold and spoilages occurred for the deterministic model under disruptions, fixing point A

Case	Products Sold (units)						Spoilage (units)	
	p1	p2	p3	p11	p12	p13	SPOi	SPOp
Ref	5 778,13	1 768,00	1 071,00	256,87	-	-	-	-
2 Weeks Disruption								
Supply	5 525,76	1 768,00	1 071,00	509,24	-	-	-	-
Prod	5 531,70	1 768,00	1 070,70	503,30	-	-	345,25	-
Transp	5 530,79	1 764,15	1 071,00	497,21	-	-	-	-
4 Weeks Disruption								
Supply	5 608,88	1 768,00	1 071,00	426,12	-	-	-	-
Prod	5 616,07	1 768,00	1 070,34	418,93	-	-	345,25	-
Transp	5 529,04	1 763,38	1 071,00	498,96	-	-	-	-
4 Weeks Disruption with Delay								
Supply	5 634,86	1 768,00	1 071,00	400,14	-	-	-	-
Prod	5 239,28	1 754,32	1 070,27	795,03	-	-	991,00	-
Transp	5 542,96	1 763,38	1 070,10	411,79	-	-	-	-

p11: Alternative product 1 (lower production time); p12 – Alternative product 2 (fewer raw material requirements); p13: alternative product 3 (possible to produce at more factories); SPOi: Spoilage of raw materials; SPOp: spoilage of final products

Table 6.8: Deterministic model results considering disruptive events, fixing decisions of point B

Case	Res Metric	Flow Time	Profit	SL	Revenue	TMC	TTC	TDC	TIC	TEC
Ref	0,146	7 987	97 666	0,90	561 713	428 093	10 466	7 034	335	18 118
2 Weeks Disruption										
Supply	0,146	7 987	97 666	0,90	561 706	428 087	10 466	7 034	335	18 118
Prod	0,132	7 987	91 834	0,90	561 846	432 616	10 328	6 917	387	19 765
Transp	0,142	7 987	95 899	0,90	562 529	430 305	10 430	6 975	348	18 572
4 Weeks Disruption										
Supply	0,146	7 987	97 666	0,90	561 706	428 087	10 466	7 034	335	18 118
Prod	0,114	7 987	84 825	0,90	561 707	434 414	10 332	6 620	381	25 135
Transp	0,136	7 987	93 520	0,90	561 757	431 152	10 394	6 898	359	19 436
4 Weeks Disruption with Delay										
Supply	0,146	7 987	97 666	0,90	561 706	428 087	10 466	7 034	335	18 118
Prod	0,098	7 987	78 467	0,90	564 668	439 802	10 277	6 615	405	29 101
Transp	0,134	7 987	92 917	0,90	561 872	432 300	10 354	6 983	378	18 940

SL: Service Level; TMC: Manufacturing Cost; TTC: Transportation Cost; TDC: Duties Cost; TIC: Inventory Cost; TEC: Capacity Expansion Cost

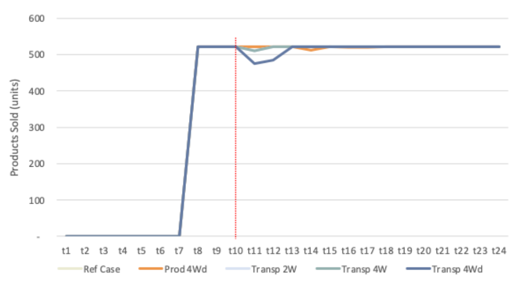


Figure 6.10: Sales level over time of the deterministic model under disruptions fixing point A

6.6.2.B Point B - Minimising flow time

For the case in which the first stage decisions are fixed to achieve point B, the overall results are presented in Table 6.8. The minimum flow time value from the reference case remains unchanged for all the tested cases, as the SC meets the service level of 90% since it is the minimum percentage of the total demand that needs to be satisfied, however, at the cost of the achieved profit level. Hence, the decrease of the resilience metric stems from the profit's further deviation from the reference value.

For this configuration, the supply related disruptions have no influence on the solutions since all products are sourced from external entities, as explained previously, whose raw material supply was assumed to be near-unlimited to mimic the condition of purchasing final products.

The production disruption was considered to occur at factory f7 and f8, and the transportation type

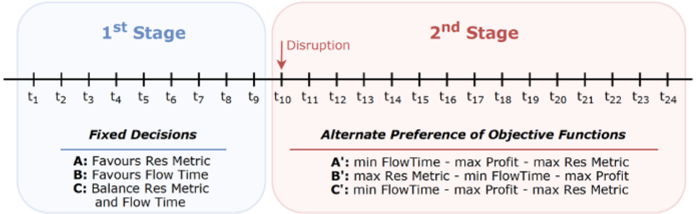


Figure 6.12: Response strategy analysis schema

Table 6.9: Results of the deterministic model changing OF priority at the 2nd stage

	Point A'			Point B'		
Solution	**Res Metric**	**Flow Time**	**Profit**	**Res Metric**	**Flow Time**	**Profit**
Ref	1,000	51 124	396 403	0,146	7 987	97 666
2 Weeks Disruption						
Supply	0,288	27 971	153 676	0,597	27 754	240 907
Prod	0,288	27 971	153 823	0,588	27 785	240 576
Transp	0,288	27 971	153 587	0,597	28 349	241 957
4 Weeks Disruption						
Supply	0,287	27 971	153 304	0,591	26 320	238 484
Prod	0,288	27 971	153 788	0,577	28 976	239 557
Transp	0,287	27 971	153 304	0,596	28 183	241 703
4 Weeks Disruption with Delay						
Supply	0,255	28 862	140 805	0,540	22 955	218 095
Prod	0,273	31 350	147 656	0,505	23 962	211 473
Transp	0,321	32 572	166 896	0,528	23 869	217 660

disrupted links f8-m5; f8-m1; f8-m3; f7-m4.

Similarly to point A, the production disruptions incurred in higher costs than the transportation disruptions. Figure 6.11 demonstrates the capacity expansions experienced, noting that f7 is mostly increased to deal with the production disruptions, further increasing with the length of the disturbance and with the delayed sensing case. Overall, the production decisions across disruptive scenarios vary only between the two factories already in use (f7 and f8), thus continuing to deliver a reduced resilience metric value.

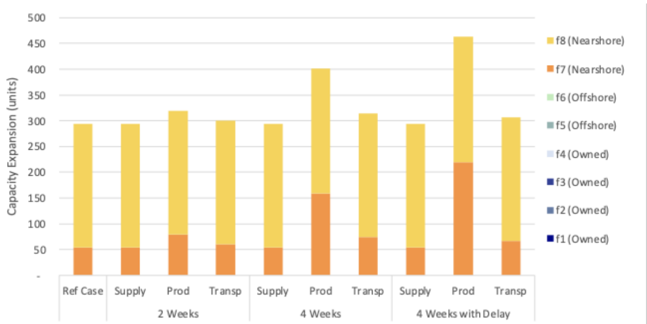


Figure 6.11: Capacity expansions of the deterministic model under disruptions, fixing point B

6.6.3 Response strategy analysis

This section studies the effects of adjusting the indicators' preference in the presence of a disruptive event, meaning that the DM may consider appropriate to tackle the situation by alternating the OF priority as opposed to the priority employed during steady-state, as depicted in figure 6.12. Table 6.9 provides a summarised view of the results.

For point A', the flow time decreases notably, independent of the disruption type and length (Table 6.9). When the priority of the flow time is only considered after the disturbance, delayed responses will ultimately increase costs and a subsequent reduction in profits.

Regarding the shift between privileging the flow time to the resilience metric, point B', the best performing solutions will deliver a resilience metric close to 0.60, being the two weeks supply disruption the case to provide the best result. Again, the production at owned factories justifies the increase of the resilience and profit metric instead of relying on outsourcing, pursuing low flow times.

Figure 6.13 presents the capacity expansions incurred for this analysis of point B'. Relative to outsourcing selection, similar increases are observed for preferring offshore alternatives (both f5 and f6). In contrast, the production disruption with a delayed response remains the sole solution that requires further increases through nearshoring. Furthermore, since the first stage production, minimizing flow time, was concentrated at outsourcing factories, a low inventory level is held; thus, no spoilage of raw materials occurs.

Point A' validates the feasibility of enhancing flow time during disruptions regardless of its length. However, compared with purely minimizing flow time (Point B), point A' achieves this result with minor degradations to the resilience metric. This seems to indicate that following a SC network based on the resilience metric is a good strategy, even if the objectives are to be changed afterwards.

On the other hand, point B' is also capable of increasing notably the new preferred indicator (resilience metric), nonetheless displaying far lower performing results for the delayed cases compared with the original case of Point A.

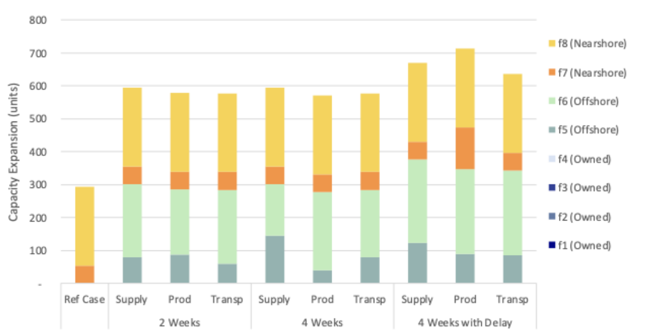


Figure 6.13: Capacity expansions of the deterministic model response strategy, point B'

6.7 Stochastic Model

The following sub-sections present the results of the stochastic model, presented in Section 6.4.3. The results are obtained using GAMS software running the CPLEX solver, however, given the higher complexity, a gap of 1% is set.

For this section, the customer demand and the products' return rate will be modelled as uncertain parameters following the approach described in section 6.4.3. The planning horizon is 24 weeks (6 months). Information regarding the uncertain parameters is updated every two months with an optimistic, realistic and pessimistic variation, which means that each stage is composed of eight time periods. The uncertainty is applied at the first time period of each stage, remaining constant for the succeeding periods. This results in a three stages scenario tree with nine leaf nodes. Table 6.10

Table 6.10: Characterisation of the scenarios considered in the stochastic model

Node	Associated time periods	Probability (%)	Demand variation (%)	Return rate variation (%)
s1	t1, t2, t3, t4, t5, t6, t7, t8	100	0	0
s2	t9, t10, t11, t12, t13, t14, t15, t16	25	10	10
s3	t9, t10, t11, t12, t13, t14, t15, t16	50	5	5
s4	t9, t10, t11, t12, t13, t14, t15, t16	25	-10	0
s5	t17, t18, t19, t20, t21, t22, t23, t24	6,25	10	10
s6	t17, t18, t19, t20, t21, t22, t23, t24	12,50	5	5
s7	t17, t18, t19, t20, t21, t22, t23, t24	6,25	-10	0
s8	t17, t18, t19, t20, t21, t22, t23, t24	12,5	10	10
s9	t17, t18, t19, t20, t21, t22, t23, t24	25	5	5
s10	t17, t18, t19, t20, t21, t22, t23, t24	12,50	-10	0
s11	t17, t18, t19, t20, t21, t22, t23, t24	6,25	10	10
s12	t17, t18, t19, t20, t21, t22, t23, t24	12,50	5	5
s13	t17, t18, t19, t20, t21, t22, t23, t24	6,25	-10	0

Table 6.11: Payoff table of the stochastic model for priority 1

	Res Metric	Flow Time	Profit
max Res Metric	0,984	48 673,84	414 607,81
min Flow Time	0,200	8 270,83	124 640,27
max Profit	0,979	46 872,99	412 693,28

summarizes the aggregation of time periods for each scenario, the corresponding probability and the variation that is applied to the uncertain parameters.

6.7.1 Reference case analysis

Table 6.11 presents the payoff table following the priority: Resilience Metric; Flow time; Profit. Once again, optimising the resilience metric or the profit firstly will result in similar solutions. Please note that the 1% gap allows the resilience metric to return higher profit value than maximising profit.

Due to similarity between the objective functions Z_1 and Z_3, this model was run bi-objectively (Z_1 - Point A; Z_2 - Point B) instead of the three OF, obtaining the Pareto front in figure 6.14.

Table 6.12 showcases the selected solutions' performance indicators. Point A nearly meets the profit reference value, falling short on the maximum value of the resilience metric due to the service level of 98,6%. For the same reasoning as argued beforehand, point B only meets 90% of the total demand and experiences elevated manufacturing cost by heavily resorting to outsourcing alternatives, expanding f7 by 76,91 units and f8 by 252,79 units.

Comparing the results from the stochastic model to the ones obtained for the deterministic model, it can be observed that the present model returns a higher level of profit from the former 396 305 and 97 666 for points A and B respectively. This is due to the variations assumed for the uncertain

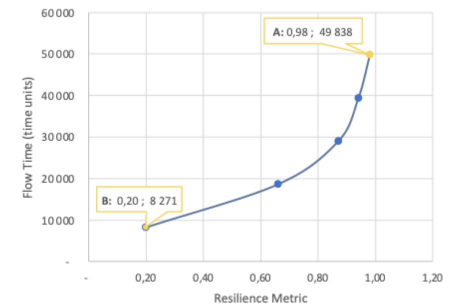


Figure 6.14: Pareto front of the stochastic model with the resilience metric and flow time as objective functions

Table 6.12: Stochastic model performance indicators of selected solutions

Point	Res Metric	Flow Time	Profit	SL	Revenue	Costs				
						TMC	TTC	TDC	TIC	TEC
A	0,984	48 674	414 620	0,986	643 841	171 061	53 452	3 895	639	174
B	0,200	8 271	124 653	0,900	584 403	421 932	11 952	7 154	245	18 466

SL: Service Level; TMC: Manufacturing Cost; TTC: Transportation Cost; TDC: Duties Cost; TIC: Inventory Cost; TEC: Capacity Expansion Cost

Table 6.13: Stochastic model results considering disruptive events, fixing decisions of point A

Case	Res Metric	Flow Time	Profit	SL	Revenue	TMC	TTC	TDC	TIC	TEC
Ref	0,984	48 674	414 620	0,986	643 841	171 061	53 452	3 895	639	174
2 Weeks Disruption										
Supply	0,976	47 834	411 562	0,986	643 771	173 369	52 744	4 164	697	1 235
Prod	0,973	48 612	410 120	0,986	643 807	174 119	53 773	4 020	698	1 077
Transp	0,980	48 656	413 580	0,984	642 639	170 882	53 438	3 900	665	174
4 Weeks Disruption										
Supply	0,972	47 604	409 867	0,985	644 667	174 438	52 995	4 451	698	2 218
Prod	0,966	47 331	407 389	0,986	644 038	176 661	52 549	4 427	780	2 231
Transp	0,979	48 696	413 345	0,984	642 635	170 904	53 509	3 893	662	321
4 Weeks Disruption with Delay										
Supply	0,962	45 824	405 671	0,985	642 888	177 154	50 597	4 896	654	3 916
Prod	0,862	39 991	365 641	0,982	637 678	207 727	45 922	6 600	1 021	10 768
Transp	0,959	48 468	408 561	0,975	637 791	170 370	53 074	3 941	932	913

SL: Service Level; TMC: Manufacturing Cost; TTC: Transportation Cost; TDC: Duties Cost; TIC: Inventory Cost; TEC: Capacity Expansion Cost

parameters (table 6.10). Furthermore, the scenarios that account for a rise in the products' return rate make use of the closed-loop SC and are able to reduce manufacturing costs from the previous value of 175 121 and 428 093 also for point A and point B, respectively.

6.7.2 Disruption analysis

A two-stage approach is followed to analyze the impact of disruptive events on SC's configuration that value the objective functions differently. The two previously studied points, in Section 6.7.1, will be used as first-stage decisions. Subsequently, for the second stage decisions, the model is solved bi-objectively, in order of the preferred indicator of the point. The disruptions implemented follow the same reasoning presented in section 6.6.2.

6.7.2.A Point A

This point primarily values an appealing outcome of the resilience metric. The results obtained in table 6.13 show that a four-week long disruption at production facilities with a delayed response hiders the most the achievement of such goal. In fact, disruptions tested with the delayed response return significant degradation of the resilience metric as opposed to the results where immediate responses are implemented. The case with the most significant decrease of the service level is for a transportation type disruption with a delayed reaction.

The cost indicator with the highest increase for supply and production disruptions is the total manufacturing cost, a consequence of the production capacity expansion. In Figure 6.15 is visible the preference for offshore alternatives to deal with the disruption (f5 and f6) since they offer lower costs. Nonetheless, nearshore options are selected for more extreme conditions, as for the lowest-performing solution (f7 and f8). Like the deterministic model results, such occurs for the production and transportation cases.

It is worth noting that the capacity expansion strategy behaves differently for transportation disruptions. These cases scarcely expand their production capacity, accepting the loss of sales and

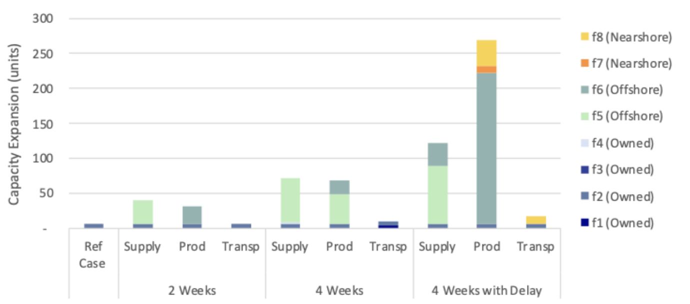


Figure 6.15: Capacity expansions of the stochastic model under disruptions, fixing point A

Table 6.14: Amount of product sold and spoilages occurred for the stochastic model under disruptions, fixing point A

Case	Products Sold (units)						Spoilage (units)	
	p1	p2	p3	p11	p12	p13	SPOi	SPOp
Ref	5 647,90	1 804,52	1 093,17	511,04	-	-	-	-
2 Weeks Disruption								
Supply	5 632,78	1 804,60	1 093,17	526,79	-	-	-	-
Prod	5 642,78	1 804,60	1 093,10	516,23	-	-	281,45	-
Transp	5 595,91	1 803,34	1 091,62	553,30	-	-	-	-
4 Weeks Disruption								
Supply	5 772,58	1 802,50	1 093,16	386,99	-	-	-	-
Prod	5 668,61	1 804,60	1 093,15	490,96	-	-	282,18	-
Transp	5 603,47	1 802,51	1 091,61	545,74	-	-	-	-
4 Weeks Disruption with Delay								
Supply	5 529,67	1 803,58	1 093,10	629,39	-	-	-	-
Prod	5 116,78	1 797,33	1 093,10	1 014,62	-	-	1 244,56	-
Transp	5 637,50	1 801,38	1 089,95	430,64	-	-	-	-

p11: Alternative product 1 (lower production time); p12 – Alternative product 2 (fewer raw material requirements); p13: alternative product 3 (possible to produce at more factories); SPOi: Spoilage of raw materials; SPOp: spoilage of final products

increasing the sale of alternative products with lower production time, visible in the reduction of revenues relative to the other cases.

Regarding the spoilage of items, such solely occurs for raw materials in case of a production disruption (Table 6.14). For a two-week-long disruption 281,45 units are spoiled, for an increased duration of four weeks, the value is 282,18 units, and, lastly, for the delayed response, such increases substantially to a total of 1 244,56 units. Immediate responses, despite still being vulnerable to the possibility of spoilage of raw materials, by acknowledging the occurrence of the event fastest disposals can be avoided regardless of the disturbance's length. On the other hand, lagging in the necessary adjustments will continuously aggravate the excess of raw materials arriving to production facilities that cannot be used.

Table 6.14 further presents the total amount of products sold per case. Compared to the deterministic model, where the reference case sold 256,87 units of option 1 of the alternative products, the value increases to 511,04 units for this model. This value increases in order to deal with a disruptive event.

Nonetheless, similar to the results obtained by the deterministic model, it is visible how a delayed response presents to be far more impactful to the SC as opposed to immediate responses. Moreover, these latter responses can maintain an acceptable level of operation and recover faster to a steady-state of operation.

Table 6.15: Stochastic model results considering disruptive events, fixing decisions of point B

Case	Res Metric	Flow Time	Profit	SL	Revenue	TMC	TTC	TDC	TIC	TEC
Ref	0,200	8 271	124 653	0,90	584 403	421 932	11 952	7 154	245	18 466
2 Weeks Disruption										
Supply	0,199	8 271	124 275	0,90	584 096	421 961	11 910	7 211	272	18 466
Prod	0,183	8 271	117 535	0,90	584 972	428 087	11 602	6 977	265	20 506
Transp	0,194	8 271	122 223	0,90	584 619	424 410	11 766	7 121	349	18 750
4 Weeks Disruption										
Supply	0,199	8 271	124 144	0,90	583 445	421 448	11 876	7 219	292	18 466
Prod	0,183	8 271	117 454	0,90	583 790	425 009	11 818	6 905	270	22 335
Transp	0,186	8 271	118 824	0,90	583 512	424 830	11 789	6 951	279	20 839
4 Weeks Disruption with Delay										
Supply	0,199	8 271	124 023	0,90	584 314	422 425	11 853	7 181	324	18 508
Prod	0,172	8271	113 043	0,90	584 974	427 465	11 749	6 706	266	25 504
Transp	0,183	8 271	117 711	0,90	585 959	429 503	11 683	7 033	252	19 776

SL: Service Level; TMC: Manufacturing Cost; TTC: Transportation Cost; TDC: Duties Cost; TIC: Inventory Cost; TEC: Capacity Expansion Cost

6.7.2.B Point B

Table 6.15 presents the results of a SC that prioritizes the minimization of the flow time. It can be seen that the minimum flow time achieved for the reference case is sustained for all types of disruptions. Nonetheless, meeting this value requires the degradation of the profit obtained throughout the planning horizon and the resilience metric.

The production disruption was defined to occur at factory f7 and f8, and the transportation type disrupted links f8-m5; f8-m1; f8-m3; f7-m6. The scenarios within both types of disruptions were considered to be equally probable.

Similar to point A, the disruption to economically strain the results the most is the production one with a delayed response. On the other hand, all the supply type disruptions present negligible deviations from the reference case.

Across the cases tested, a production disruption required higher costs than a transportation-related one to maintain a low level of flow time. Once again, such can be linked to capacity expansion decisions needed to keep with the required service level.

In sum, this section supports the conclusions stated previously for the deterministic model. The implementation of a stochastic model adds robustness to the outcomes of this work. Both deterministic and stochastic models maintain coherence between them on the broader recommended strategies.

6.8 Discussion

Additionally and to better visualise the effect of the different disruption lengths, figure 6.16 demonstrates the decline of the resilience metric incurred between a two-week and a four-week-long disruption (blue bars) and between four weeks and four weeks with delayed response disruptions (yellow bars). Figure 6.17 serves the same purpose for the results of the stochastic model.

Both deterministic and stochastic models indicated that delayed responses can lead to avoidable spoilage of raw materials by increasing its responsiveness. The decrease in sales, leading to spoilage, is far greater when there is a delay in response, as can be seen in Figure 6.10. A higher responsiveness can be effective on mitigating the consequences of disruptions. While spoilage of raw materials is highly probable during production-related disruptions, its volume appears to be relatively insensitive to the disruption's length as can be seen when comparing Tables 6.7 and 6.14. However,

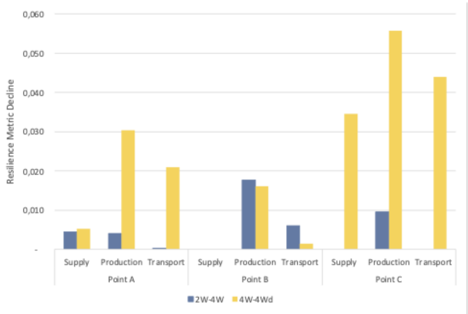


Figure 6.16: Decline of the resilience metric of the deterministic model results

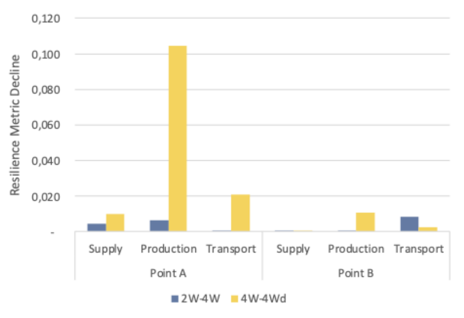


Figure 6.17: Decline of the resilience metric of the stochastic model results

the response time can have severe consequences, especially in industries dealing with perishable products, emphasising the importance of considering SCR.

The analysis revealed that delayed response had a more significant effect on the resilience metric than the length of the disruption, underscoring the significance of transparency and communication in SC networks. However, balancing the three objective functions did not guarantee a consistently high level of the resilience metric. Recurring to an all responsiveness approach, by minimising the flow time, point B, is less susceptible to disruptive events, comparing Table 6.6 and Table 6.8. The reduced variability in results is however a non-suitable solution as it comes with the erosion of profit and decreased service level. Conversely, adopting a resilience metric similar to the one used in this study, could enable SC networks to better address SCR at the tactical and operational level by providing a balanced solution between increased responsiveness, maintaining high levels of service level with an acceptable reduction in profits. These results were already expected from the interpretation of Figures 6.6 and 6.7 where the added concern of flow time lead to an erosion of the resilience metric and thus with expected lower results under disruptive scenarios.

Finally, closed-loop supply chains are better explored in situations where the resilience metric is maximised, allowing for greater advantage to be taken when disruptions occur. Point A shows an increase in reverse flows to the factory, helping to mitigate the effects of the disruption. The CLSC at point A, maximising the resilience metric, achieves high responsiveness as evidenced by the high levels of service maintained even in the face of disruptions. The use of CLSC is then a promising enabler for enhancing the resilience of supply chains, as it allows for the recovery of products and materials that might otherwise be lost during disruptions.

6.9 Managerial Insights

From the work developed a set of managerial insights are identified:

- **Rapid solutions play a critical role in dealing with SC disruptions. Outsourcing during disruptions is a useful strategy, provided that outsourcers are reliable.** That becomes evident from our results if the results from the non-disruptive scenarios are compared with the disruptive one. If no disruption is considered, no outsourcing is even used. However, when disruptions come at play outsourcing is used as a way to enable SC Resilience.

- **Near-shoring options, despite being costly, were found to be necessary to handle the most challenging conditions in the SC**. Although high-cost solutions, near-shoring alternatives are selected as rapid solutions in times of SC disruptions. **To address this, it would be of value to establish nearby backup facilities with pre-arranged agreements**, thus avoiding the high prices of short-notice requirements and ensuring that such an option is effectively available when needed.
- **Maximising the resilience metric through a CLSC can lead to significant improvements in supply chain performance under disruptive events**, particularly in terms of responsiveness. **Under disruptive scenarios the SC takes advantage of the reverse flows and becomes a true SCR enabler**. However, it is important to note that the benefits of CLSC depend on the specific context and characteristics of the supply chain.
- **Delay in response to the disruptions has mostly avoidable negative consequences.** To improve SC resilience, network visibility and communication between entities need to be enhanced. **Digital adaptations to SC, such as end-to-end digitalization of operations, can help in quickly acknowledging and communicating disruptions, making the SC more responsive and thus, more resilient.** Swift actions are essential for dealing with SC disruptions, even in long lasting disruptions as can be seen in our results by comparing the different duration on the disruptive events.
- **Alternative products that ease the production process can enhance SC resilience.** This work found that products that impose reduced production time were preferred following a disruption, despite providing a lower profit margin. Companies should, therefore, consider such products while conceiving and manufacturing them.

Acknowledgments

The authors acknowledge the support provided by FCT - Foundation for Science and Technology, I.P., under the project UIDB/00097/2020 and SFRH/BD/148499/2019

7

A step towards Green Resilient Supply Chain under Uncertainty

Contents

This chapter is under review, aiming at combining the work done previously and sustainability concerns. For that two novel approaches are presented. A robust optimisation model is presented to account for uncertainty in the price of CO2, combined with a novel approach to account for disruptions uncertainty.

Ribeiro, J. P., & Santos, D., & Barbosa-Póvoa, A. P. F. (2023). A step towards Green Resilient Supply Chain under Uncertainty, under review

7.1 Abstract

A resilient supply chain (SC), capable of responding or quickly recovering from unexpected disruptions, is a key competitive advantage. Resilient capability combined with environmental concerns are becoming a fulcrum part of any SC operation, even more justified by the recent world events that combine SC disruptions with a steep increase in CO_2 allowances prices. The two objectives are often in conflict since, to accommodate a reduction in CO_2 emissions, the resilient capabilities of a supply chain might be compromised. The present work develops an optimisation model for the design and planning of SC that combines green and resilient objectives, accounting for three sources of uncertainty: Demand, CO_2 emissions prices and disruptions. The model is applied to a real base case study, drawing valuable conclusions and managerial insights. It was concluded that SC Design and Planning accounting for uncertainty leads to more resilient SC, with companies able to take advantage of greener investments when CO_2 prices rise. Also, Closed-Loop Supply Chains (CLSC), although more expensive and complex to run, lead to lower overall emissions and appear more resilient, thus suggesting that CLSC should be incentivised to achieve greener and more resilient SC.

7.2 Introduction

Supply chains (SC) play a crucial role in the performance and competitiveness of modern enterprises. A well-planned supply chain capable of responding to or quickly recovering from unexpected disruptions can significantly impact the outcomes for different competitors. In this context, SC resilience is a concern that decision-makers cannot overlook and should be seen as an opportunity for companies to gain a competitive advantage. Companies should aim to achieve the most significant benefit from their supply chains in both steady-state conditions and under disruptive scenarios (Wieland & Durach, 2021).

Modelling a resilient and environmentally friendly SC is not straightforward. Our approach in this work to meet the desired objective of a green-resilient SC is to consider the cost of CO_2 influencing the SC's Net Present Value (NPV). This line of thought presents itself as a novel approach, and it gains even more relevance if we consider the increase in the price of this commodity. In fact, at the end of June 2019, the price was around 27€, whereas in 2018 it was 15€ and in 2017 it was 5€, i.e. an increase of more than 430% in just two years (AG, 2019). The spike during the COVID-19 pandemic, which made the price rise to 94€, eclipsed these variations resulting in a price surge of 19 times in just five years. Price volatility is not expected to reduce as the world faces a combination of societal pressure to reduce emissions and geo-political challenges brought to light by the Russia-Ukraine conflict, which disrupted not only the global SC but also the energy sources of much of Europe. Until the beginning of August 2022, the price of CO_2 in the EUETS fluctuated between 80€ and 90€. This is more than undeniable evidence of the importance that must be given to this topic. Companies must be prepared to face this significant cost uncertainty (McKinsey & Company, 2020). One benefit of considering this cost is that it is a metric that can be easily measured, understood and felt by the decision-makers, thus adding to the relevance of considering the price of CO_2.

The concept of SC resilience (SCR) is not consensual and is a topic of debate among academics, and it is closely related to other concepts in supply chain management, such as risk (S. Y. Ponomarov & Holcomb, 2009; Pettit, Croxton, & Fiksel, 2013; Heckmann et al., 2015b; König & Spinler, 2016) and vulnerability (Jüttner & Maklan, 2011; Gligor et al., 2019). While these concepts may have a negative connotation, resilience is viewed positively and as a desirable characteristic for a supply chain to possess (Elleuch et al., 2016). Despite the lack of consensus on a definition of SC resilience, the terms used in the literature have stabilised. This study will use the definition proposed by Ribeiro & Barbosa-Povoa (2018), which states that "a resilient supply chain should be able to prepare, respond and recover from disturbances and afterwards maintain a positive steady-state operation at an acceptable cost and time."

Implementing resilient strategies can increase competitiveness, as has been demonstrated in several cases (Mensah & Merkuryev, 2014; Barroso et al., 2015). However, the path to resilience is not easy, and it does not mean that a supply chain must be able to withstand all the disruptive scenarios it may face. While increasing strength or reducing vulnerabilities can improve resilience, having excessive capabilities may negatively impact a company's profitability (Pettit et al., 2019). Unfortunately, resilience is often only appreciated after a disruption has occurred (Sheffi, 2005). This situation can be improved by increasing awareness of the topic and better managing its consequences (Zsidisin & Wagner, 2010; Pettit, Fiksel, & Croxton, 2013; Pettit et al., 2019).

There is a pressing need for action towards sustainable SC prioritising resilience. This has become a concern for society as a whole, from consumers to companies and industry regulators (Mota, Gomes, Carvalho, & Barbosa-Povoa, 2015; Centobelli et al., 2020). Implementing a resilient, low-carbon, and high-growth supply chain is not easy, and states can play a significant role by prioritising climate change in economic recovery efforts, as seen in the efforts taken following the COVID-19 pandemic (McKinsey & Company, 2020), and is clearly set as a target in the new European green deal strategy (European Comission, 2019) .

However, few works address both supply chain resilience and sustainability simultaneously. Sustainability models tend to be simplistic when it comes to an understanding of the dynamics of resilience (Fiksel, 2006). For example, Giannakis & Papadopoulos (2016) studied the impact of environmental disruptions but did not consider the effects of supply chain disruptions on a sustainable supply chain. Only a few examples of publications combine supply chain resilience and environmental impact, such as Fahimnia & Jabbarzadeh (2016b); Ivanov (2018a); Barbosa-Póvoa et al. (2018); Mehrjerdi & Shafiee (2021). However, a proper process of designing and planning a supply chain can help companies overcome vulnerabilities and achieve a balance between resilience and sustainability (Min et al., 2019). Aldrighetti et al. (2021) studied the impact of supply chain network design on supply chain disruptions, emphasizing the trade-off between added sustainability and increased resilience. These results demonstrate the value of proactive and preventive strategies in integrating supply chain resilience and environmental sustainability. While resilience often involves redundancy or flexibility, these strategies typically come at the cost of increased resource use and reduced efficiency under steady-state conditions. However, given the importance of supply chain resilience, a more in-depth study of the trade-off between sustainability and resilience is necessary (Rajesh, 2019; Mohammed, 2020; Nowakowski et al., 2020; Barbosa-Povoa & Pinto, 2020).

This paper presents itself as a step towards developing green, resilient supply chains under CO_2 price uncertainty. It offers a tool to assist in developing knowledge in the Supply Chain Resilience area. This is based on a Mixed Integer Linear Programming (MILP) model with approaches of interest to the current context and to prepare for the future. For this purpose, the model is created to be flexible, allowing its application to be adapted to a wide range of SC configurations, whether forward or closed-loop. It considers several sources of uncertainty (demand and CO_2 price), allowing for exploring their consequences and presenting managerial insights that help decision-makers face these challenges. From an environmental policy point of view, the monetisation of environmental impact is implemented by using the cost of emissions attributed by the European Union's Emissions Trading Scheme (EUETS) to existing activities in SC, even if outside the formal scope of the system. This option was taken as resorting to the prices of CO_2 for monetisation is a feasible approach to represent the environmental concerns of modern societies. Its implementation forces companies to make more sustainable decisions and invest in environmentally friendly technologies and products. Companies must also decide whether they want to invest in new products, aiming to reduce environmental impacts while bearing the associated investment costs. The model also addresses this issue, where the possibility of investing in new products with varying costs and lower environmental impacts is considered. Additionally, waste treatment is also studied, allowing the analysis of Forward versus Closed-Loop SC (CLSC). In the latter, waste valorisation is considered, and its impact on adding resilience to the SC is analysed.

Integrating all these aspects in a decision-supporting tool demonstrates the importance of considering them together to guarantee the design and planning of resilient supply chains that simultaneously account for environmental goals.

With this in mind, this paper makes significant contributions in three key areas. Firstly, it presents a robust optimization approach to address the uncertainty surrounding CO_2 prices. By developing a framework that accounts for CO_2 price uncertainty, this paper offers a valuable tool for analysis in the field outside the industries directly affected by carbon pricing. Secondly, the paper introduces a novel approach to modelling disruptions uncertainty. By providing a detailed methodology for capturing and quantifying disruptions, this paper is able to support the design and planning of green and resilient SC. Lastly, this work provides valuable insights and managerial implications for both academics and practitioners.

This paper is structured as follows. Section 7.2 presents the challenges and options when modelling a green and resilient SC and how to account for uncertainty, and is divided into two subsections. Subsection 7.2.1 addresses the challenges associated with managing CO_2 emissions, while subsection 7.2.2 focuses on the modelling of uncertainty in SCR. Section 7.3 characterises the SC problem, identifying its goals and scope. The mathematical formulation for the base model is presented in section 7.4. The modelling of uncertainty on the price of CO_2 is presented in section 7.4.3, where the robust optimisation approach is explored. The uncertainty related to disruptive events is presented in section 7.4.4. Section 7.5 offers the case study characteristics. The results from applying the model to the case study, and corresponding discussion, are presented in section 7.6. The main managerial insights drawn from this work, as well as suggestions for future work, are presented in section 7.7.

7.2.1 CO_2 emissions as a cost

Two options exist for converting carbon dioxide (CO_2) emissions into a cost. One option is implementing a carbon tax, which places a value on emissions. The other option is to establish a carbon emissions trading scheme in which allowances for emissions are distributed and traded. The European Union has implemented such a scheme, the EUETS, which aims to provide a cost for CO_2 emissions. Since 2005, the price of CO_2 has been determined by the market and has exhibited significant variability in its early years and more recent steady growth (Boubaker et al., 2018). The effectiveness of an emissions trading scheme has been evaluated using game theory models to determine optimal pricing strategies for sustainable outcomes (Dazhi et al., 2022).

Predicting the prices of CO_2 allowances can be crucial in designing and planning a sustainable SC network. The particular dynamics of CO_2 pricing have been the focus of numerous publications, particularly in the field of economics (see Benz & Trück (2009); Boubaker et al. (2018); Chesney & Taschini (2012); Daskalakis et al. (2009); Conrad et al. (2012)). CO_2 prices have been found to be more responsive to weather and political risks than financial information (Boubaker et al., 2018), which can result in sudden price fluctuations, often associated with the study of SC resilience.

Treating CO_2 emissions as a commodity that can be freely traded has advantages and disadvantages. Sijm et al. (2005) conducted a study on the electricity market in the Netherlands and expressed scepticism about the overall benefits of such a measure. The main concern was financial, and the potential environmental benefits were less considered. However, a follow-up study (Sijm et al., 2006) emphasised the need for strategies to address this challenge. While a carbon tax may provide more certain prices, an emissions trading scheme can be an effective solution for SC performance in terms of costs, emissions, and service level (Zakeri et al., 2015; Q. Wang et al., 2016). Imposing a direct price on CO_2 emissions can also incentivize using renewable energy sources and decrease SC emissions (Lin & Chen, 2018). In SC management (SCM), there is a clear relationship between different SC players in the buying and selling of CO_2 allowances. In a free market, each player will try to optimize its outcome, presenting an opportunity to use game theory approaches to understand how CO_2 prices fluctuate (Du et al., 2015). Additionally, by directly considering CO_2 emissions as costs, the environmental impact can be accounted for without double counting, as in a bi-objective optimization model that minimizes costs and emissions (Yavari & Zaker, 2020).

As companies seek to optimize profits while being environmentally sustainable, it is required to identify their position on the trade-off between resilience and green strategies. Naeeni & Sabbaghi (2022) examined this trade-off, specifically regarding harmful emissions, through a design and planning model, highlighting the importance of strategic decision-making in creating resilient and sustainable SC. SC often involve the linked efforts of various entities that do not share the same physical space, making transportation necessary. As such, CO_2 emissions from transport are a significant factor in achieving a carbon-free SC. Harris et al. (2011) studied the impact of transportation CO_2 emissions and the influence of SC structure on environmental behaviour, concluding that economic and environmental concerns should be explicitly addressed in the design and planning of SC. Optimizing flows within the SC can lead to reductions in CO_2 emissions (Nakamichi et al., 2016).

The increased costs of CO_2 brought about by the EUETS significantly impact the prices of final products. Rootzén & Johnsson (2016) studied the effect of CO_2 costs on the final cost of a product. In 2016, the price of CO_2 was almost 17 times lower than in 2022, and the impact on the cost of a car to the final consumer was less than 1%. It can be assumed that the impact is higher now.

CO_2 prices will become increasingly important in the cost matrix for companies, and a study on their impact on the design and planning of a SC, particularly on its resilient behaviour, would benefit academics and practitioners. Such a study would provide results that are easier to interpret and, therefore, can be trusted by decision-makers and used confidently in managerial decisions. To the best of our knowledge, no work has been done to specifically explore the relationship between CO_2 prices and resilience under uncertainty in closed-loop multi-product SC and how SC will have to adapt to these demanding conditions. Ramudhin et al. (2010) present a model on the impact of the carbon market on SC network design, but it only considers a forward SC and does not take uncertainty or resilient concerns into account.

7.2.2 Dealing with uncertainty towards a resilient supply chain

According to S. Li et al. (2021), supply disruptions are among the most severe disturbances to a SC, as they can be as the lack of flexibility and redundancy within the SC can lead to unavoidable consequences. While safety stock or alternative sources may suffice for shorter disruptions, they become impractical due to mounting costs and reduced effectiveness for more prolonged disruptions. This highlights the need for more in-depth research into the design and planning of SC to address long-term disruptions.

In addition, a survey of practitioners (Brusset & Teller, 2017) found that risk perception is a crucial factor for managers in developing resilient strategies within their SC, a challenge that academics working on this topic must address. This can be achieved through trust and identification with the model, which can be fostered through multi-period modelling, an approach not often used in published works on quantitative methods to SC uncertainty (Govindan et al., 2017).

Several methods can be used to model uncertainty, depending on the source of uncertainty, the level of decision-making involved, the objective of the model, and any implementation characteristics (e.g., decision-makers objectives, deployment limitations) (Ribeiro & Barbosa-Povoa, 2018). Peidro et al. (2009) identify four modelling approaches: analytical models, artificial intelligence models, simulation models, and hybrid approaches. Within the analytical category, some models use robust optimization or stochastic programming. Stochastic programming is the most commonly used approach for dealing with demand uncertainty in SC modelling (Baptista et al., 2019).

Govindan et al. (2017) categorizes uncertainty modelling according to the knowledge of the source of uncertainty, dividing it into three groups: when the probability distributions are known to the decision-maker, when there is no knowledge of the distribution, and when there is ambiguity and vagueness (a fuzzy environment). Stochastic programming can be used when the probability distribution can be assumed (Cardoso et al., 2013). On the other hand, when no distribution is known, robust optimization is suitable for uncertainty modelling, as it prepares the SC for the worst-case scenario (Baghalian et al., 2013).

As discussed in Section 7.2, SC resilience is a derivative of SC risk management (SCRM), with one key difference being the definition of probabilities for disruptive events. SC resilience deals with events with very low probabilities of occurrence, and using classical risk management techniques can lead to bias in SC preparedness for disruptive events and potentially jeopardize operations. Quantitative approaches to SC disruptions often involve “what if” scenarios and additional analysis to assess SC resilience (Ribeiro & Barbosa-Povoa, 2018; Katsaliaki et al., 2021), but this approach has limitations as it treats the disruption as a known scenario, ignoring uncertainty in parameters and the probability of the disruptive event occurring.

Several works have been developed in the context of SC resilience that model uncertainty. Fattahi & Govindan (2020) use a scenario tree to address demand uncertainty and implement SC resilience principles by modelling disruptions using Bernoulli random variables. Snoeck et al. (2019) present a stochastic model that deals with the unpredictability of disruptive events, defining a set of scenarios and using probability distributions to model the occurrence of the events. However, both approaches have limitations, as they do not fully address the inherent uncertainty in disruptive events.

Cardoso et al. (2015) explore a closed-loop supply chain and address possible forms of measuring resilience within these systems. However, the authors do not tackle environmental aspects explicitly. On the other hand, Mota et al. (2018) study the design of sustainable supply chains and incorporate the three pillars of sustainability but resilience concerns are left out. By combining sustainability and resilience, Jabbarzadeh et al. (2018) present a stochastic bi-objective model that minimizes total cost and maximizes sustainability (through the definition of a sustainability score for suppliers) in a forward SC under a set of disruptive scenarios. Later, and addressing uncertainty in demand, Jabbarzadeh et al. (2019) present a robust optimization model with environmental concerns focused on the effectiveness of postponement strategies under demand variability. Their bi-objective model aims to reduce costs as well as minimize harmful emissions. Hahn & Kuhn (2012) study risk management in SC, using robust optimization to represent demand uncertainty and preparing the SC for the worst-case scenario, a key focus of SC resilience. Although the scope of their work is different, it adds to the validity of using robust optimization in SCM modelling. Jabbarzadeh et al. (2016) present a model in which robust optimization is used to deal with uncertainty in demand and disruptions in the supply of facilities. Due to the added complexity, a Lagrangian relaxation is used to reduce computational time, even in a simple case study. The authors then study the impact of investing in fortification capabilities to reduce the probability of disruption.

7.3 Problem characterisation

The problem involves strategic decisions spanning multiple periods related to SC network design, including choices such as facility openings and technology investments. Tactically, planning decisions are made for each time period and scenario, incorporating various uncertainties like CO_2 emissions and demand variations. These decisions encompass product quantities, corresponding technologies and internal distribution, connecting strategic and tactical decisions through optimal flows in various scenarios.

A comprehensive SC with five echelons is considered, as illustrated in Figure 7.1. These echelons include Raw Material Suppliers, Plants, Warehouses, Clients (Markets), and Outsourcing Entities. Forward and reverse flows link these echelons, and inter-echelon transshipments are possible. Reprocessing may occur within existing facilities. This scenario defines a multi-product, multi-period, multi-echelon SC design and planning challenge.

The SC comprises products produced by different technologies, each with its bill of materials. These products constitute flows satisfying market demand. Alternative products, with superior environmental performance but higher investment costs, can substitute for others. This relationship allows assessing the balance between investment costs and environmental benefits.

Furthermore, reverse flows are considered aligned with circular economy principles. Damaged or obsolete products can be reprocessed, adding value and mitigating costs and CO_2 emissions. Reuse involves investing in new technologies for factories or warehouses, balancing costs and reducing material dependence. Unsold products not suited for the CLSC face disposal costs. This holistic approach addresses the challenge of incorporating circular economy principles in a sustainable SC.

Sustainability concerns extend to quantifying CO_2 emissions from different sources. Emissions stem from product production, transportation, and facility installation. Products' emissions are based on their Life Cycle Assessment (LCA). Transportation emissions account for the efficiency difference between forward and reverse flows. Facility installation emissions gauge construction's environmental impact.

Recognizing the realities of SCM, uncertainty plays a significant role. Demand uncertainty, a commonly studied source, is central to this analysis. Additionally, environmental uncertainty arises from CO_2 costs linked to emissions, monetized through emissions market rates like the European Union Emissions Trading Scheme. This approach facilitates decision-making by aligning emissions with monetary costs, supporting trust in results.

Overall, this study addresses uncertainty in various parameters, including disruptions categorized as production or supply disruptions. The strategic and tactical approach accounts for uncertainties in SC configuration, infrastructure, and facilities. As the world faces environmental and societal challenges, this research underscores the importance of green resilient SC in a changing landscape.

Given:

- An existing SC network
- Possible new entities to include in the SC
- The products to be produced and their bill of materials
- Alternative green products and their bill of materials
- The technologies associated with the production of each product
- The technologies associated with the recovery of products
- Possible new production technologies
- The minimum satisfaction of demand
- Warehousing capabilities
- A cost structure (facilities, technologies, purchases, transports, CO_2)
- The environmental impact of each product, facility and transportation mode
- Demand levels
- Representative disruptive events
- A multi-period time frame

Determine:

- The SC network design
- Logistic flows
- Production and storage levels
- Investments in technology upgrades and new entities
- Alternative products strategy

So as to:

- Maximise the Expected Net Present Value
- Reduce the environmental impact
- Provide insights on how to build a more resilient SC

The problem in study can be summarised and depicted as in Figure 7.1, which presents the generic SC, its echelons, flows, and its sources of uncertainty (in red). The three sources of uncertainty are those related to the cost of CO_2, the market demand, and the possible disruptions in supply and production. In the next section, we present the mathematical model developed that stems from this problem characterisation.

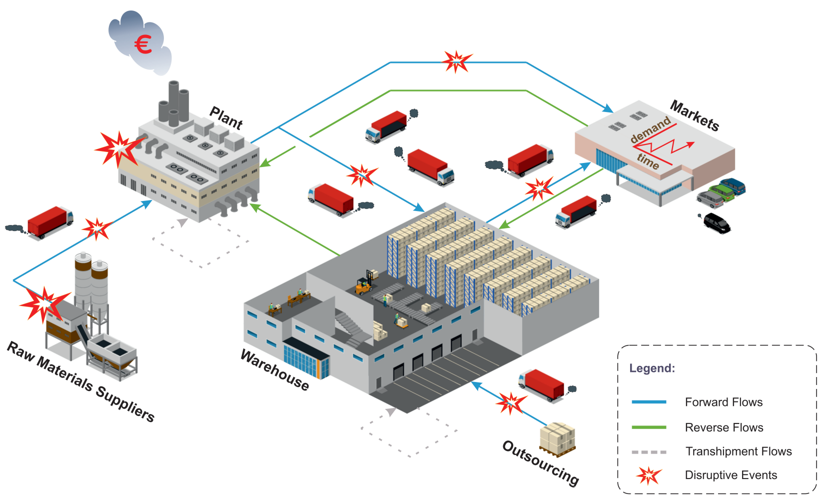


Figure 7.1: Graphical Abstract

7.4 Model description

The problem described in the previous section is modelled using Mixed Integer Linear Programming (MILP). The formulation for the SC structure is based on the work of Ribeiro & Barbosa-Póvoa

(2022b) and is extended in several ways to suit the characteristics of the current problem. In particular, the new model presented here allows for decision-making regarding waste management and whether to include it in a valorisation flow within a CLSC or send it for disposal. It also enables the analysis of the consequences of investing in alternative products with reduced emissions and new added costs. Additionally, the model simultaneously accounts for two sources of uncertainty: demand and CO_2 price. As such, the proposed model is a generic one that can be applied to many SC realities and can be used to study variations, such as only considering forward flows, products without alternatives, or fewer or no sources of uncertainty.

Due to the length of the complete model, the main body of the paper only presents the constraints necessary for understanding the scope and objectives of the model. Please see Annex 1 for the full model, which includes a list of sets, parameters, and decision variables.

This section is organised as follows. We discuss conceptually modelling uncertainty in Section 7.4.1. Then, in Section 7.4.2, we present the base model only considering uncertainty in demand, leaving uncertainty in CO_2 prices for Section 7.4.3. In Section 7.4.4 the approach to disruptions modelling is presented. Finally, Section 7.4.5 summarises the different models used to obtain comparable results.

7.4.1 Uncertainty Approach

One of the main advantages of the model proposed in this work is that it addresses different sources of uncertainty. For this purpose, we adopt a hybrid robust-stochastic optimisation methodology.

Following the approach of Ribeiro & Barbosa-Póvoa (2022b), demand uncertainty is modelled through multi-stage stochastic programming. Specifically, different demand scenarios are considered in each time period, allowing a scenario tree to be constructed. Demand foresight is often applied to this method because it is easily interpretable by decision-makers, who can define optimistic, realistic, and pessimistic scenarios, providing a reasonable basis for decision-making. Given that the set of possible outcomes is considered known, and each scenario can be associated with a probability, a set of nodes to which a certain probability and a specific outcome are associated are created. The outcomes and probabilities of the nodes visited on the path between the root node and the corresponding node in the final time period are used to construct the final scenarios.

In addition to the uncertainty in demand, a robust optimisation approach is applied to the price of CO_2, which aims to increase SC resilience by preparing the SC for a range of challenging operating conditions. As seen in recent years, the price of CO_2 emissions has increased dramatically and unexpectedly. Thus, it is essential to study the impact of this trend in a worst-case scenario. This concern can be addressed using robust optimisation (Bertsimas & Sim, 2003). Therefore, the CO_2 price in each period is considered uncertain and defined to contribute to the worst case possible. Its implementation is described in Section 7.4.3.

Finally, to create a network considering the hypothesis of the occurrence of disruptions, a new scenario tree is built on a set of disruptive events of reference for that SC. Two types of disruptions are considered, supply and production, combining the work of Rice & Caniato (2003) and Pires Ribeiro & Barbosa-Póvoa (2019). The relevant disruptions are categorised, and production and supply come as the most consequential type of disruptions to SC. The modeling of these disruptions is presented in section 7.4.4. The criticality concept presented by Cardoso et al. (2015) is brought to this paper to identify the most critical locations in the SC. The associated locations are identified for each type of disruption, and their criticality is normalised. In this way, it is possible to build a scenario tree for each of the disruptions from that set of normalized weights calculated from their criticality. The probabilities associated with this scenario tree are not those related to the occurrence of the events, as this could go against the SCR principles, but instead intend to mimic the relevance of each location to the SC (see section 7.4.4). Using this approach, the model aims to establish the strategic decisions that return a better result for the expected value of the disruptions. Thus, the model may have to make a trade-off between resilient enabler strategies for each of the disruptions that may occur. Therefore, the result of the resilient network will be the one that prepares for the highest expected value of the objective function, implicitly performing the cost-benefit trade-off of applying different strategies.

The complete model is then the simultaneous combination of these sources of uncertainty. The robust optimisation is combined with the scenario tree built by joining the scenario trees of demand uncertainty and uncertainty about disruptive events. The final scenario tree is created by multiplying the probabilities of the nodes of each period of the scenario tree for each uncertainty, thus creating a new combined scenario tree.

7.4.2 Base model

This section presents the base model, considering only uncertainty in demand. The objective function and the equations related to the SC's economic performance are presented in Section 7.4.2.A. The novel introduction of waste treatment is presented in Section 7.4.2.B. In Section 7.4.2.C, the different environmental impacts related to transportation, facilities, and production are modelled. Finally, in Section 7.4.2.D, the uncertainty in demand is presented alongside the possibility of considering alternative products, since the former depends on the latter. This last section also defines the expected customer service level.

7.4.2.A Objective function

The objective function considered in this model is the maximisation of the ENPV, presented in expression (7.1), which is given by the sum of the Net Present Value (NPV) for each scenario multiplied by its probability of occurrence.

$$Maximise \sum_{s \in S} \pi_s \, \mathsf{NPV}_s \tag{7.1}$$

The NPV is calculated for each scenario and period as depicted in equations (7.2), considering the cash flows and an interest rate. In turn, the cash flows are given by equations (7.3) and result from the difference between the net earnings and the fraction of the depreciated capital, to which we subtract the costs associated with the environmental emissions (production, transportation, and facilities), which will be defined later in Section 7.4.3.

$$NPV_s = \sum_{t \in T} \frac{CF_{s,t}}{(1+\rho)^t} \qquad \forall s \in N_t \tag{7.2}$$

$$CF_{s,t} = NE_{s,t} - FDC_t - \frac{C^{\text{prod}} + C^{\text{transp}} + C^{\text{fac}}}{NT} \qquad t = 1, ..., NT-1, \quad \forall s \in N_t \tag{7.3}$$

The net earnings are defined in equations (7.4), and result from the difference between the income, i.e. sales revenue, and the costs (not including CO_2 emissions), namely the refunds from non-conforming products, product purchasing costs, operational costs, inventory costs, and transportation costs. The expression also accounts for the depreciation of invested capital, considering taxes.

$$NE_{s,t} = (1-\lambda) \Bigg[\sum_{v \epsilon V_m} \sum_{p \in P} S_{v,p,s,t} - \sum_{v \epsilon V_m} \sum_{w:(v,w) \epsilon R} \sum_{p \in P} RQNC_{v,w,p,s,t} - \sum_{v \epsilon V_g} \sum_{p \in P} Pu_{p,v,s,t} \\ - \sum_{i \in I} \sum_{v \in V} \sum_{p \in P} Op_{i,v,p,s,t} - \sum_{v \epsilon V_z} IC_{v,s,t} - TC_{s,t} \Bigg] + \lambda DP_t \qquad \forall t \in T, s \in N_t \tag{7.4}$$

Transportation costs comprise different components expressed in equations (7.5). These costs consider the distances in kilometres travelled between entities and the unitary cost per kilometre of transporting a ton of product. These are multiplied by the flows in the network, namely when transporting products, waste, non-conforming products, end-of-life products, and outsourced products.

$$\text{TC}_{s,t} = \sum_{v \in V, w \in V, p \in P} (c^{\text{transp}}_{v,w,t} \cdot (\text{Q}_{v,w,p,s,t} + \text{QWA}_{v,w,p,s,t} + \text{QNC}_{v,w,p,s,t} + \text{QEL}_{v,w,p,s,t} + \text{PU}_{w,v,p,s,t}) \\ \cdot \text{FIPL}_{v,w})) \qquad \forall t \in T, s \in \text{N}_t \tag{7.5}$$

As for the fraction of the depreciated capital (FDC), equations (7.6) define it as the value of the fixed capital of investment (FCI), presented below in equations (7.7), divided by the amount of time periods in the model.

$$\text{FDC}_t = \frac{\text{FCI}}{NT} \qquad \forall t \in T \tag{7.6}$$

Finally, the FCI accounts for the cost of technology capacity and its eventual expansion, the cost of warehousing, the initial costs and the costs arising from expansions, and the fixed costs of establishing a link between two entities in the SC (i.e., contract costs).

$$\text{FCI} = \sum_{i \in I, v \in V, t \in T} (\text{alfaPL}_{i,v,t} \cdot \text{CEPL}_{i,v,t}) + \sum_{i \in I, v \in V} (\text{CPLinit}_{i,v} \cdot \text{Invinit}_{i,v}) + \\ \sum_{v \in \text{Arm}_v} (\text{Centityinit}_v \cdot \text{Initialinv}_v) + \sum_{v \in \text{Arm}_v, t \in T} (\text{alfaWH}_{v,t} \cdot \text{CEarm}_{v,t}) + \\ \sum_{v,w \in V, t \in T} (c^{\text{link}}_{v,w,t} \cdot (\text{YPL}_{v,w,t,s} + \text{YWA}_{v,w,t} + \text{YNC}_{v,w,t} + \text{YEL}_{v,w,t})) \tag{7.7}$$

7.4.2.B Waste

As in any SC, waste that should not go unaddressed is inevitably created. It is essential to quantify and monetise the waste produced, done in constraints (7.8)–(7.10). Two sources of waste are considered, one associated with end-of-life products and the other with products not ready to be sold when they arrive on the market. Part of these products will enter the circular economy process (QEL and QNC); the rest will be waste sent for disposal (QWA).

As this is a strategic-tactical model, accounting for end-of-life products is done through a factor of the quantities that reach the end of their life without being sold. It is expected that a portion of the products that reach each market will not be sold during their useful period of use (TP_p). Equations (7.8) define the quantities of products that reach their shelf-life without being sold, either because they are sent for disposal ($\mathsf{QWA}^{\mathsf{QEL}}$) or because they enter the reuse process (QEL). The sum of these two components is equivalent to the percentage of products that spoil from the direct flow sent to the market.

It is important to note that the quantity of products wasted due to not being sold during their shelf life is determined by the waste factor (τ^p), which is associated with the shelf life of each product. This allows for defining the expected waste for each product based on any historical data or other method chosen. For example, the waste factor can be determined by a function of the shelf life for each product, as products with shorter shelf lives tend to generate more spoilage.

$$\sum_{x \in R_{v,w}} (\mathsf{QWA}^{\mathsf{QEL}}_{v,p,s,t} + \mathsf{QEL}_{v,x,p,s,t}) = \sum_{w,r \in (\mathsf{F}_{w,v} \wedge \mathsf{pred}_{s,r})} \mathsf{Q}_{w,v,p,r,t-\mathsf{Tp}_p} \cdot \tau^p \qquad \forall v \in V_m, p \in P_f, t \in T, s \in \mathsf{N}_t \quad (7.8)$$

Non-conforming products are considered in constraints (7.9) and (7.10). In constraint (7.9), the SC is forced to send a minimum quantity of products to be used in the CLSC (ν). The quantities of non-conforming products are determined from a percentage (μ) of the products that reach that market. Equation (7.10) determines the amount of products that do not enter the reuse process, establishing that the sum of the flows that lead products for reprocessing ($\mathsf{QNC}_{v,w,p,s,t}$) and the flow for disposal ($\mathsf{QWA}^{\mathsf{QNC}}_{v,p,s,t}$) is equal to the amount of non-conforming products in this market.

$$\sum_{w \in \mathsf{R}_{v,w}} \mathsf{QNC}_{v,w,p,s,t} \geq \sum_{w \in \mathsf{F}_{w,v}} \mathsf{Q}_{w,v,p,s,t} \cdot \mu \cdot \nu \qquad \forall v \in V_m, p \in P, t \in T, s \in \mathsf{N}_t \quad (7.9)$$

$$\sum_{w \in \mathsf{R}_{v,w}} (\mathsf{QWA}^{\mathsf{QNC}}_{v,p,s,t} + \mathsf{QNC}_{v,w,p,s,t}) = \sum_{w \in \mathsf{F}_{w,v}} \mathsf{Q}_{w,v,p,s,t} \cdot \mu \qquad \forall v \in V_m, p \in P, t \in T, s \in \mathsf{N}_t \quad (7.10)$$

Finally, equations (7.11) ensure that the quantity of products that have been identified as not relevant to enter the CLSC, will be considered as a waste flow between the markets and the elimination facilities (V_e).

$$\mathsf{QWA}_{v,w,p,s,t} = \mathsf{QWA}^{\mathsf{QNC}}_{v,p,s,t} + \mathsf{QWA}^{\mathsf{QEL}}_{v,p,s,t} \qquad \forall v \in V_l, w \in V_e, p \in P, t \in T, s \in \mathsf{N}_t \quad (7.11)$$

7.4.2.C Environmental impact

A novel aspect of the model presented in this work is that it considers the environmental impact through CO_2 emissions. This environmental impact is accounted for in three categories: transportation, production and facilities.

The emissions resulting from transportation activities are represented by the result of Equation (7.12), taking into account the quantity of products transported in the SC, the distance between the origin and destination, and the emissions associated with each type of flow (forward ϵ^{fwd} and reverse ϵ^{rev}). This means that the equivalent emissions associated with transport emissions per each unit of product transported depend on the distance and type of flow, as represented by the parameters used to determine transportation emissions. Forward flows are often more optimized and can more easily take advantage of higher transportation density, often resulting in full truckloads and lower emissions per unit transported. On the other hand, logistics optimization of reverse flows can be challenging due to the diversity of product formats, leading to lower levels of transportation density and difficulty in arranging full truckloads, resulting in higher transportation emissions per product compared to forward flows.

$$E_t^{\text{transp}} = \sum_{s \in N_t, v \in V, w \in V, p \in P} \pi_s \cdot Q_{v,w,p,s,t} \cdot FIPL_{v,w} \cdot \epsilon^{\text{fwd}} + \sum_{s \in N_t, v \in V, w \in V_e, p \in P} \pi_s \cdot \text{QNC}_{v,w,p,s,t} \cdot FIPL_{v,w} \cdot \epsilon^{\text{rev}} + \sum_{s \in N_t, v \in V, w \in V_e, p \in P} \pi_s \cdot QEL_{v,w,p,s,t} \cdot FIPL_{v,w} \cdot \epsilon^{\text{rev}}, \forall t \in T \quad (7.12)$$

Production emissions are given by Equation (7.13), where the CO_2 emissions associated with final products are multiplied by the quantities produced for both forward and reverse flow technologies. Here, the emissions are associated with the final products, but this can be adapted to include the whole set of products in the SC, depending on the product's LCA. The decision to include the emissions from final products is based on the fact that there is often more available information on the final products of a SC and less detailed information upstream. As the final product's LCA includes the environmental impact upstream, this decision ensures that the environmental assessment for the SC is feasible and realistic. It is also important to note that reverse technologies, which introduce reconditioned products to the SC, also have an environmental impact, even if smaller than producing new products from raw materials.

$$E_t^{\text{prod}} = \sum_{p \epsilon p_f} (\sum_{i \in I, v \in V, s \in N_t} (\pi_s \cdot W_{i,v,p,s,t}^{\text{out}} \cdot \epsilon_p^{\text{prod}}) + (\sum_{i \in I, v \in V, s \in N_t} (\pi_s \cdot W_{i,v,p,s,t}^{\text{out-r}} \cdot \epsilon_p^{\text{prod}} \cdot \epsilon^{\text{reproc}})), \forall t \in T \quad (7.13)$$

The emissions of installing facilities are presented in equations (7.14), where a facility contributes with emissions proportionally to its area. Note that the emissions from installing facilities are considered on the period when the facility is opened the first time. To model this fact, auxiliary variables $Vnodes_{v,t}$ that define the first period when a facility is opened were created, which is modelled by constraints (7.15)–(7.17). If the facility is opened in $t = 1$, then constraints (7.17) ensure that $Vnodes_{v,1} = 1$. Otherwise, for $t \geq 2$, constraints (7.16) guarantee that a facility cannot be opened for the first time in t if it had been opened in the previous time period $t - 1$. Finally, constraints (7.15) make sure that if a facility was opened at any point, then $Vnodes_{v,t} = 1$ for some time period.

$$E_t^{\text{fac}} = \sum_{v \in V} Vnodes_{v,t} \cdot A_v \cdot \epsilon^{\text{fac}}, \forall t \in T \quad (7.14)$$

$$\sum_{t \in T} Xnodes_{v,t} \leq NT \sum_{t \in T} Vnodes_{v,t} \quad \forall v \in V \quad (7.15)$$

$$Xnodes_{v,t-1} + Vnodes_{v,t} \leq 1 \qquad t = 2, ..., NT, \quad \forall v \in V \quad (7.16)$$

$$Xnodes_{v,t} - Vnodes_{v,t} = 0 \qquad t = 1, \quad \forall v \in V \quad (7.17)$$

The aggregation of all emissions is presented in equation (7.18), accounting for emissions in transportation, production and facilities.

$$E^{total} = \sum_{t \in T} E_t^{\text{transp}} + E_t^{\text{prod}} + E_t^{\text{fac}} \quad (7.18)$$

The cost associated with the disposal process is then the cost of establishing a contract with a specialised service to ensure proper procedures are followed. The cost of the service is present in equation (7.19) and has two components, one a variable cost associated with the quantities transported by such company and another a fixed cost of establishing a contract when a link between two facilities is established.

$$C^{waste} = \sum_{S \in N_t, v \in V, w \in V_e} \pi_s \cdot c^{\text{transp}}_{v,w,t} \cdot QWA_{v,w,p,s,t} + \sum_{v \in V, w \in V_e} c^{\text{link}}_{v,w,t} \cdot YWA_{v,w,t} \tag{7.19}$$

With the environmental impacts described above, it is possible to define its associated cost as presented in equation (7.20).

$$EnvTotal = C^{waste} + C^{\text{transp}} + C^{\text{fac}} + C^{\text{prod}} \tag{7.20}$$

The constraints presented in this section consider that the cost of CO_2 emissions is deterministic. In our full model, however, we consider the cost of CO_2 to be uncertain and resort to robust optimisation. We discuss this is more detail in Section 7.4.3.

7.4.2.D Uncertainty in demand and alternative products

Demand is ultimately what drives any SC. However well it is predicted, it is still uncertain. To account for this uncertainty, a multi-stage stochastic programming approach is used, which relies on defining a scenario tree with the different outcomes and corresponding probabilities (Cardoso et al., 2015; Jabbarzadeh et al., 2017).

The Expected Customer Service Level (ECSL), defined in equation (7.21), is a KPI on the capability of the SC to meet such demand. The ECSL is the percentage of demand met, calculated as the relationship between unsatisfied and total demand. This metric must consider the results for each scenario, thus the need to include the probability of each node of the scenario tree in the expression.

$$ECSL = \frac{\sum_{t \in T} \left(1 - \sum_{s \in S} \pi_s \left[\frac{\sum_{v \epsilon V_m} \sum_{p \in P} ID_{pvst}}{\sum_{v \epsilon V_m} \sum_{p \in P} D_{pvst}}\right]\right)}{NT} \tag{7.21}$$

To calculate unsatisfied demand, we use equations (7.22), which represent the difference between the product demand in each market and the quantity of product delivered to those markets.

$$ID_{pvst} = D_{pvst} - \sum_{w \epsilon F_{w,v}} Q_{wvpst} \qquad \forall p \epsilon P_f, v \epsilon V_m, \forall t, s \in N_t \tag{7.22}$$

In this model, demand uncertainty is established through a scenario tree, which allows for variations in demand from one time period to the next. For each time period, the probabilities of each variation must sum to 1. The variations and probabilities for each scenario should be defined specifically for each SC under study.

In our model, we consider the possibility of satisfying demand through the use of alternative products. The inclusion of alternative products allows for a more comprehensive model that can consider the challenge of deciding which new technologies to invest in, in terms of newer products or technologies. Below, we present constraints to model this possibility. In general, new alternative products involve a cost of investment for new technologies and development, but may also bring added value in their characteristics or environmental impact. Therefore, our model allows for the trade-off to be studied between these new investments and maintaining the use of original products.

Products without alternatives

For products without alternatives, the demand in period $t = 1$, representing the present time, is known and considered deterministic. Equation (7.23) accounts for the demand when $t = 1$, equal to the deterministic value of demand of product p in market v.

$$\mathsf{D}_{p,v,s,t} = \mathsf{DMKupper}_{p,v} \qquad \forall v \in V_m, p \in \mathsf{P}_{fnoalt}, t = 1, s \in \mathsf{N}_t \quad (7.23)$$

Thus, it is only needed to account for uncertainty for $t > 1$. In equation (7.24), the demand for the period t is given by the demand of said product and facility from a predecessor scenario in the previous time period multiplied by the assumed variation for that scenario ($\mathsf{Dvar}_{r,t}$). The definition of a predecessor scenario comes as a necessity to identify the scenario that successively leads to a new scenario when time advances. With this relationship between scenarios from the scenario tree, it is then possible to accurately represent the relationship between scenarios when periods change.

$$\mathsf{D}_{p,v,s,t} = \sum_{r \in \mathsf{pred}_{s,r}} \mathsf{D}_{p,v,r,t-1} \cdot \mathsf{Dvar}_{r,t} \qquad \forall v \in V_m, p \in \mathsf{P}_{fnoalt}, t \in T : t > 1, s \in \mathsf{N}_t \quad (7.24)$$

The amount of client demand not met in markets for products without alternatives is given by equation (7.25), corresponding to the demand of product subtracted from the flows of product that reach the considered market.

$$\mathsf{ID}_{p,v,s,t} = \mathsf{D}_{p,v,s,t} - \sum_{w \in \mathsf{F}_{w,v}} \mathsf{Q}_{w,v,p,s,t} \qquad \forall p \in \mathsf{P}_{fnoalt}, v \in V_m, t \in T, s \in \mathsf{N}_t \quad (7.25)$$

Equation (7.26) established the feasible range for the unmet demand where it has to be lower than the fraction of demand, defined by the $target$ value that must be fulfilled.

$$\mathsf{ID}_{p,v,s,t} \leq \mathsf{D}_{p,v,s,t} \cdot (1 - \mathsf{target}) \qquad \forall p \in \mathsf{P}_{fnoalt}, v \in V_m, t \in T, s \in \mathsf{N}_t \quad (7.26)$$

Products with alternatives

For the products with alternatives, there are a different set of equations that deal with satisfying demand (equations (7.27) to (7.30)).

The demand for the original product in the first period is deterministic and is determined by the difference between the known value of demand and the actual demand for the alternative product pp, and that relationship is presented in equation (7.27).

$$\mathsf{D}_{p,v,s,t} = \mathsf{DMKupper}_{p,v} - \mathsf{D}_{pp,v,s,t} \qquad \forall v \in V_m, p \in \mathsf{P}_{falt}, t = 1, s \in \mathsf{N}_t, (p,pp) \in P_{p,pp} \quad (7.27)$$

For periods $t > 1$ it is required to take into account the demand for both alternative products p and pp, since uncertainty is already taken into account, which is presented in equation (7.28). The combined demand of the original product and its alternative product is equal to the initially known demand multiplied by the variation expected in the scenario tree.

$$\mathsf{D}_{p,v,s,t} + \mathsf{D}_{pp,v,s,t} = \mathsf{DMKupper}_{p,v} \cdot \mathsf{Dvar}_{s,t} \qquad \forall v \in V_m, p \in \mathsf{P}_{falt}, t \in T : t > 1, s \in \mathsf{N}_t, (p,pp) \in P_{p,pp} \quad (7.28)$$

The unsatisfied customer demand for products with alternatives is modelled with equations (7.29) and (7.30). The demand not met for the original product is given by the difference between the aggregated demand of original and alternative products and the flows arriving at each market.

The range of admissible values for unmet demand is similarly defined, in equation (7.30), as being lower than the aggregated demand of original and alternative products multiplied by the fraction of demand, defined by the $target$ objective.

$$\mathsf{ID}_{p,v,s,t} = (\mathsf{D}_{p,v,s,t} + \mathsf{D}_{pp,v,s,t}) - \sum_{w \in \mathsf{F}_{w,v}} \mathsf{Q}_{w,v,p,s,t} - \sum_{w \in \mathsf{F}_{w,v}} \mathsf{Q}_{w,v,pp,s,t} \qquad \forall p \in \mathsf{P}_{falt}, v \in V_m, t \in T, s \in \mathsf{N}_t \tag{7.29}$$

$$\mathsf{ID}_{p,v,s,t} \leq (\mathsf{D}_{p,v,s,t} + \mathsf{D}_{pp,v,s,t}) \cdot (1 - \text{target}) \qquad \forall p \in \mathsf{P}_{falt}, v \in V_m, t \in T, s \in \mathsf{N}_t \tag{7.30}$$

7.4.3 Uncertainty on the price of CO_2

As mentioned in Section 7.2, CO_2 prices have increased in recent years. Unlike other sources of uncertainty, this is expected to continue, which may see rises and falls. For this reason, it is important to ensure that the SC can withstand the impact of continued price growth. Although the cost of CO_2 emissions per time period, namely c_t^{em}, can reflect this growth by having consecutively higher values, it is still highly uncertain if the expected growth could not be even higher than predicted. Robust optimisation is one of the adequate forms of modelling uncertainty as in the case of CO_2 prices (Bertsimas & Sim, 2004).

More precisely, we follow the cardinality-constrained robust optimisation approach of Bertsimas & Sim (2004) in which we assume that the cost c_t^{em} is uncertain in an interval $[\overline{c_t^{\text{em}}} - \delta_t, \overline{c_t^{\text{em}}} + \delta_t]$, for any $t \in T$. In this approach, $\overline{c_t^{\text{em}}}$ is called the nominal value, that is, the deterministic value used if uncertainty did not exist, and δ_t is the maximum allowed deviation permitted from the nominal value. Since it is implausible that all parameters are at their worst-case simultaneously, Bertsimas & Sim (2004) propose the introduction of a budget of uncertainty Γ, which controls how many of the uncertain parameters can deviate from their nominal value. Mathematically, we can thus define the uncertainty set U as:

$$U = \left\{ c_t^{\text{em}} \in [\overline{c_t^{\text{em}}} - \delta_t, \overline{c_t^{\text{em}}} + \delta_t], \ \forall t \in T : \sum_{t \in T} \frac{\left| c_t^{\text{em}} - \overline{c_t^{\text{em}}} \right|}{\delta_t} \leq \Gamma \right\} \tag{7.31}$$

In our model, the cost of CO_2 affects three equations: transportation emission costs, production emission costs, and facility installation emissions costs. These are then used in the objective function, namely in the cash-flow equations (7.3), as explained in Section 7.4.2.A. We show how to model each of the three referred emission costs in the remainder of this section.

7.4.3.A Uncertainty in CO_2 costs in transportation

As explained in Section 7.4.2.C, we quantify the CO_2 emissions arising from transportation E_t^{transp} in equations (7.12). Thus, the emission costs of transportation C^{transp} are given by equation (7.32) below.

$$C^{\text{transp}} = \sum_{t \in T} c_t^{\text{em}} \, E_t^{\text{transp}} \tag{7.32}$$

However, to apply the cardinality-constrained approach, there is the need to change this equality into an inequality as follows.

$$C^{\text{transp}} \geq \sum_{t \in T} c_t^{\text{em}} \, E_t^{\text{transp}} \tag{7.33}$$

Observe that by doing so the optimal value is unchanged. In fact, since the objective function (7.1) is the maximisation of the ENPV, the emission costs of transportation will never be higher than required, i.e., they will be at their minimum possible value. In other words, equality (7.32) is equivalent to inequality (7.33) under the objective function considered.

Inequality (7.33) is the deterministic representation of the calculation of transportation costs related to CO_2 emissions. Now, by introducing uncertainty to c_t^{em}, we have expression (7.34).

$$\sum_{t \in T} c_t^{\text{em}} \, E_t^{\text{transp}} \leq C^{\text{transp}} \qquad \forall c_t^{\text{em}} \in U \tag{7.34}$$

If expression (7.34) must hold for every $c_t^{\text{em}} \in U$, then it must hold for the worst-case, i.e., expression (7.34) is equivalent to inequality (7.35).

$$\max_{c_t^{\text{em}} \in U} \sum_{t \in T} c_t^{\text{em}} \, E_t^{\text{transp}} \leq C^{\text{transp}} \tag{7.35}$$

All that remains is to linearise inequality (7.35) by solving the maximisation problem on the left-hand side. Following the cardinality-constrained approach of Bertsimas & Sim (2004), for fixed E_t^{transp} this is equivalent to solving the following problem:

$$\sum_{t \in T} \overline{c_t^{\text{em}}} \, E_t^{\text{transp}} + \text{Maximise } \sum_{t \in T} (\delta_t \, y_t) \, E_t^{\text{transp}} \tag{7.36}$$

$$\text{subject to: } \sum_{t \in T} |y_t| \leq \Gamma \tag{7.37}$$

$$|y_t| \leq 1 \qquad \forall t \in T \tag{7.38}$$

$$\tag{7.39}$$

Since both $E_t^{\text{transp}} \geq 0$ and $\delta_t \geq 0$ for any $t \in T$, then the optimal solution of the above problem will only have positive deviations y_t. Thus, we can equivalently write:

$$\sum_{t \in T} \overline{c_t^{\text{em}}} \, E_t^{\text{transp}} + \text{Maximise } \sum_{t \in T} (\delta_t \, y_t) \, E_t^{\text{transp}} \tag{7.40}$$

$$\text{subject to: } \sum_{t \in T} y_t \leq \Gamma \tag{7.41}$$

$$y_t \leq 1 \qquad \forall t \in T \tag{7.42}$$

$$y_t \geq 0 \qquad \forall t \in T \tag{7.43}$$

This problem is a linear programming problem; thus, it is possible to write its dual. Consider ω^1 as the dual variable associated with the budget of uncertainty constraint (7.41) and ω_t^2 as the dual variables associated with the upper bound of the deviations (7.42). Then, the dual problem is as follows.

$$\sum_{t \in T} \overline{c_t^{\text{em}}} \, E_t^{\text{transp}} + \text{Minimise } \Gamma \, \omega^1 + \sum_{t \in T} \omega_t^2 \tag{7.44}$$

$$\text{subject to: } \omega^1 + \omega_t^2 \geq \delta_t \, E_t^{\text{transp}} \qquad \forall t \in T \tag{7.45}$$

$$\omega^1 \geq 0 \tag{7.46}$$

$$\omega_t^2 \geq 0 \qquad \forall t \in T \tag{7.47}$$

By using strong duality, we can replace the maximisation (primal) problem in inequality (7.35) by its minimisation dual problem and obtain:

$$\sum_{t \in T} \overline{c_t^{\text{em}}} \, E_t^{\text{transp}} + \min\{\Gamma \, \omega^1 + \sum_{t \in T} \omega_t^2 : \text{(7.45)–(7.47)}\} \leq C^{\text{transp}} \tag{7.48}$$

Finally, to ensure that inequality (7.48) holds for the minimum, it is clearly sufficient to ensure that it holds for any dual solution. Thus, it is possible to replace (7.48) by the following system of inequalities:

$$\sum_{t \in T} \overline{c_t^{\text{em}}}\, E_t^{\text{transp}} + \Gamma\, \omega^1 + \sum_{t \in T} \omega_t^2 \leq C^{\text{transp}} \tag{7.49}$$

$$\omega^1 + \omega_t^2 \geq \delta_t\, E_t^{\text{transp}} \qquad \forall t \in T \tag{7.50}$$

$$\omega^1 \geq 0 \tag{7.51}$$

$$\omega_t^2 \geq 0 \qquad \forall t \in T \tag{7.52}$$

In other words, the system of inequalities (7.49)–(7.52) is the robust counterpart of the deterministic inequality (7.33) following the cardinality-constrained approach and, therefore, is what we use to model uncertainty in CO_2 costs in the particular case of transportation emissions.

7.4.3.B Uncertainty in CO_2 costs in facility installation

The quantification of CO_2 emissions concerning the installation of facilities E_t^{fac} is given in equations (7.14). Therefore, the cost of these emissions C^{fac} can be determined as:

$$C^{\text{fac}} = \sum_{t \in T} c_t^{\text{em}}\, E_t^{\text{fac}} \tag{7.53}$$

By following the same approach as in Section 7.4.3.A, we can replace equation (7.53) by its robust counterpart (7.54)–(7.57):

$$\sum_{t \in T} \overline{c_t^{\text{em}}}\, E_t^{\text{fac}} + \Gamma\, \omega^3 + \sum_{t \in T} \omega_t^4 \leq C^{\text{fac}} \tag{7.54}$$

$$\omega^3 + \omega_t^4 \geq \delta_t\, E_t^{\text{fac}} \qquad \forall t \in T \tag{7.55}$$

$$\omega^3 \geq 0 \tag{7.56}$$

$$\omega_t^4 \geq 0 \qquad \forall t \in T \tag{7.57}$$

Note that Γ and δ_t, for $t \in T$, are the same as the ones used in the system of inequalities (7.49)–(7.52), since the cost of CO_2 per ton is the same for transportation and for facility installation. However, new dual variables ω^3 and ω_t^4 must be introduced since the worst-case for the former and the latter could be different.

7.4.3.C Uncertainty in CO_2 costs in production

Finally, we repeat the same process as in the two previous subsections for the costs of emissions related to production, which are given in equation (7.58).

$$C^{\text{prod}} = \sum_{t \in T} c_t^{\text{em}}\, E_t^{\text{prod}} \tag{7.58}$$

In this case, the robust counterpart (7.59)–(7.62) is thus written as:

$$\sum_{t \in T} \overline{c_t^{\text{em}}}\, E_t^{\text{prod}} + \Gamma\, \omega^5 + \sum_{t \in T} \omega_t^6 \leq C^{\text{prod}} \tag{7.59}$$

$$\omega^5 + \omega_t^6 \geq \delta_t\, E_t^{\text{prod}} \qquad \forall t \in T \tag{7.60}$$

$$\omega^5 \geq 0 \tag{7.61}$$

$$\omega_t^6 \geq 0 \qquad \forall t \in T \tag{7.62}$$

7.4.4 Uncertainty in disruptions occurrence

The consideration of disruptive events and the particularity of their definition in the context of SCR is fundamental for an efficient study of the resilience of a supply chain (Rice & Caniato, 2003). Due to the implicit characteristic of this context that defines these events as having very low probability and high consequence, it is not adequate to model these events through their probability of occurrence (Ribeiro & Barbosa-Póvoa, 2022b). Instead, we propose modelling disruptive events using a weight given by the relative relevance of a disrupted node, grouped by type of disruption. Thus, in order to insert the context of uncertainty determined by these events, a scenario tree is developed following the methodology described below.

Following the presented literature, two types of disruptions seen as the most relevant to SCR are considered (Pires Ribeiro & Barbosa-Póvoa, 2019): **Supply** and **Production**. For each of the disruptions, there are a set of possible SC nodes where that disruption might be possible. Supply disruptions can occur in suppliers, and production disruptions are related to factories reducing their capacity. For studying each type of disruption individually, it is necessary to choose which locations are being disrupted.

To fulfil that objective, we propose considering the criticality of each node, a KPI based on the work of Cardoso et al. (2015) which is determined based on the inbound and outbound flows of a node, which are compared to a predetermined target set by the manager. If the sum of these flows exceeds the specified target, the node is identified as critical. In our approach, as a way to isolate any bias, criticality refers to the measure of importance or significance of different components or entities within a SC. This approach allows the researchers to assess the importance of each node within the SC.

The importance of disrupted nodes in the scenario tree is determined by their relative criticality, which is calculated based on the weight assigned to each node. For each type of disruption, the relevant nodes are identified and the criticality from the steady state is obtained. The criticality for each node is then normalized and becomes the weight of the scenario in the scenario tree when that disruption occurs. Following this methodology means that the model will not consider nodes which are not used (i.e., which have a criticality of zero) and will take into higher consideration those that have a higher criticality to the SC.

A generic example is presented in Figure 7.2, where for a given disruption type there are three possible disrupted locations with the corresponding values of criticality: v1=3, v2=6, v3=0. From those values, the weight of each node is then obtained as described above. The applied methodology for

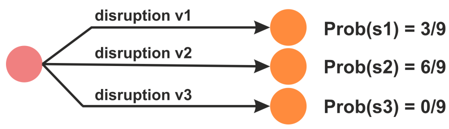


Figure 7.2: Generic disruptions's weight through its criticality

further study involves several steps. The initial step involves obtaining the solution of the base model, where the network is fixed, and criticality is determined as described earlier, considering the specific disruptions under investigation.

Then, to assess the preparedness of the SC across different operational states, a two-step approach is followed. In the first step, the criticality values obtained from the base model are utilized to assign weights to each type of disruption. This allows for a comprehensive evaluation of the unprepared SC's response to various disruptions.

In the second step, a new network design and planning solution is generated while the diferent types of disruptions are considered with the probability obtained from the previous step. This enables the exploration of alternative configurations and potential improvements of the network towards resilience. In this case, where uncertainty in disruptions is considered, the model must be adapted. The required changes are described below for each type of disruption imposed.

Supply disruption To include the disruptive scenarios regarding supply disruptions, that is, when there is no, or less, raw material available from raw material suppliers, two new parameters are created. The original availability parameter ($\text{Disp}_{v,s,p,t}$), which indicates the amount of raw material available at the suppliers, is then defined by the difference between the two new parameters, as shown in equation (7.63). $\text{Dispi}_{v,p,t}$ represents the raw material supply when no disruption occurs. On the other hand, $\text{Disruptdisp}_{v,s,p,t}$ represents the level of disruption to occur for product p in facility v during scenario s in period t, which can correspond to a full disruption or when the availability is only reduced by $p\% < 100\%$.

$$\text{Disp}_{v,s,p,t} = \text{Dispi}_{v,p,t} - \text{Disruptdisp}_{v,s,p,t} \tag{7.63}$$

Production disruption Imposing a disruption to production can be done by imposing that no flow can leave the set of disrupted facilities v during scenario s and period t. The simplest way to enforce this condition is to set variables $\text{Q}_{v,w,p,t,s}$ to zero since these are responsible for the flow out of facility v to location w of products p during period t in scenario s. By fixing the variable as $\text{Q}_{v,w,p,t,s} = 0$, all outputs involving the identified disruption will also be forced to be zero, leading to a reduction in the available quantities , thus mimicking the inability of factories to ship products to other locations.

7.4.5 Summary

The model presented in this work is a generic model that is able to be used to study different approaches to SC design and planning. Specifically, we can use it to: compare a forward SC paradigm to a CLSC paradigm; evaluate the introduction of alternative products; and compare the solutions obtained given different sources of uncertainty.

We denote as CO_2-RO (CO_2 robust optimisation) the full model, that is, the model comprised of the objective function and the formulation considering uncertainty in demand and also in the price of CO_2. We denote as BM (base model) the model considering only uncertainty in demand. This model is obtained from the full model CO_2-RO by replacing the robust counterpart constraints (7.49)–(7.52), (7.54)–(7.57) and (7.59)–(7.62) with the deterministic versions (7.32), (7.53) and (7.58), respectively.

Finally, to compare a forward SC to a CLSC, we use the three models above but set $R_{v,w} = \emptyset$ in the former case, meaning that no reverse flows exist. We then identify the two cases with the keywords *Forward* and *Closed-loop*. To evaluate the use of alternative products or not, we simply introduce these products to set P_{falt}, leading to either a model with no alternatives (*No-Alt*) or a model with alternatives products (*Alt*). The different model applications' nomenclature and characteristics are given in Table 7.7.

7.5 Case study

The developed model is applied to a representative case study of a European SC with five echelons (raw materials, factories, warehouses, markets and outsourcing). Both forward and reverse flows are allowed between markets, warehouses and plants. The reverse flows exist because there is the option of reconditioning or refurbishing products to include circular economy concerns in the SC. This type of SC represents one of the most sought objectives for companies due to the pressures of including sustainability concerns by creating value in products that otherwise would be wasted. For the purpose of analysis, a forward SC, with no reverse flows but all other flows available, will be compared with a CLSC.

The scope of this model entails strategic decisions. Consequently, a significantly large decision time horizon is considered. More specifically, three periods of five years are analysed, resulting in a 15-year time span. As described in Section 7.3, there is an existing operational SC that the company wishes to expand to reach new markets. The current SC and the possibilities in terms of the SC network are presented in Figure 7.9.

The existing SC only has a factory in Hamburg to satisfy the 17 markets - represented by 17 cities in Europe it intends to sell to. The final products can be manufactured at the factory in Hamburg, purchasing the raw materials from suppliers in Frankfurt, Prague, Birmingham and Copenhagen. Production is ensured by 12 technologies that can be supported by six technologies for reprocessing products from reverse flows. Products can be purchased from external entities (outsourcers) located in Riga, Minsk and Warsaw as an alternative to production. The initial SC has a central warehouse in Munich where technologies are also available for final conditioning or re-purposing products from reverse flows. Intermediate products can either be outsourced or manufactured at factories with the appropriate technologies.

Expanding the current network to better cover the markets is possible. More precisely, two new factories can be installed with their associated raw material suppliers: a factory in Bilbao, with suppliers in Badajoz, Toledo, Barcelona and Marseille, and a factory in Milan, with suppliers located in Ljubljana, Lausanne, Linz and Florence.

The reprocessing of products from the reverse flows can be handled in locations contiguous to the factories. To deal with the increase in demand to be satisfied, there is the possibility of opening new warehouses in Portsmouth, Lyon, Bologna and Salamanca. Additionally, the disposal of products is made by a contract with a company that ensures proper disposal. As no more information regarding this process was available, it is defined as a virtual location (V42).

Regarding the products entering the reverse SC, their quantity is known, as defined in Section 7.4.2.B, from historical values that allow us to assess the quantities of products that reach their end of life or that remain in a damaged state that makes their sale impossible. Thus, of the products with a shelf-life of 1 period, it is known that 20% end up not being sold ($\tau^1 = 0.2$) and that, for products with a shelf-life of 2 periods, 15% are wasted ($\tau^2 = 0.15$). Regarding non-conforming products, it is known that 20% of the products that reach the markets end up being non-conforming ($\mu = 0.2$) and of these, the SC must necessarily include 50% in the CLSC ($\nu = 0.5$).

Demand uncertainty is built, acknowledging each scenario's probabilities and variations entailed in each scenario. Taking the demand for the first period as deterministic, in periods 2 and 3, there are three demand uncertainty scenarios: optimistic, realistic and pessimistic. In the second period, the optimistic scenario leads to a 10% increase in demand and has a probability of 0.25, the realistic scenario entails a 3% demand increase with a probability of 0.5, and the pessimistic scenario leads to a decrease in demand of 2% with a probability of 0.25. In the third period, there are again three scenarios, where the optimistic has a probability of 0.25 leading to an increase in demand of 5%, the realistic has a probability of 0.5 with a demand increase of 2%, and the pessimistic scenario in the last period has a probability of 0.25 and leads to a decrease in demand of 2%. The scenario tree based on these data has 13 nodes.

One of the SC's main concerns is understanding the influence of the CO_2 cost on its network. Until not long ago, the perspective on the evolution of CO_2 prices was reasonably coherent for the short term. The prices were expected to stabilise at 35 to 40 €/ton until 2023 (Watson, 2018). However, reality showed otherwise, and prices have spiked, as described in Section 7.2.1, leading to the need to prepare for the worst scenario.

In this case study, the original price of CO_2 per Kg.eq of emissions is 0.0271€, corresponding to 27.1€per ton. This value was established as representative of the relatively stable period between the beginning of 2019 and the end of 2020. As of the beginning of 2022, the prices soared to around 100€per ton. This value will be the nominal value when the robust optimisation is used.

Given this unpredictability in the evolution of CO_2 prices, and establishing the worst case, δ_t, which is the maximum allowed deviation permitted from the nominal value as explained in Section 7.4.3, is defined as $\delta_{t1} = 0.06$, $\delta_{t2} = 0.12$, $\delta_{t3} = 0.18$.

In this case study, there are 11 final products to which CO_2 emissions for their production are associated. Due to the structure of this case study, where each final product has its own defined path of production, the CO_2 emissions were associated with the final products following a LCA analysis using the SimaPro software. The associated emissions are described in Table 7.8.

Regarding the three most sold products, there is the possibility of investing in new technologies that can produce alternative products that meet the same demand but have different characteristics, namely less environmental impact. P12 is an alternative to P2, P13 can substitute for P7, and P14 is an alternative to P11. These alternative products cannot be bought from outsourcing sources nor be used as raw materials for other products. Their characteristics are described as a fraction of the original product. More precisely, these alternative products are 10% less pollutant, with a variable investment of the manufacturing technologies, which is 5% higher, and are sold at the same price.

Regarding transportation emission factors, the CO_2 emissions (kg.eq) from truck transportation in forward flows (per kg.km) is $\epsilon^{\text{fwd}} = 0.000434$, whereas, in reverse flows, it is $\epsilon^{\text{rev}} = 0.0018$.

Section 7.4 defines the environmental impact of facility installation. Only the facilities owned or managed by the SC will be considered. Those facilities are the plants, warehouses and reprocessing facilities, and the areas of such installations are presented in Table 7.9. The emission factor of construction ϵ^{fac} is $297kg.eq/m^2$.

7.6 Results Discussion and insights

In this section, the results obtained in the different applications of the model (see Table 7.7) are discussed. For all of them, the ENPV is maximised as given in equation (7.1). The SCR metric proposed by Ribeiro & Barbosa-Póvoa (2022b) is also considered.

Firstly, in section 7.6.1, the study on the impact of variation of CO_2 prices is presented. The results of the model with the most commonly addressed level of uncertainty, demand, are compared with the results when the model is applied with uncertainty in demand and in CO_2 emissions prices.

Section 7.6.2 presents an in-depth examination of the impact of disruptive events on the supply chain. Specifically, it explores the effects of demand uncertainty, disruption occurrence, and uncertainty on the price of CO_2. By incorporating these factors, the study sheds light on the resilience of the supply chain and provides valuable insights into its performance under uncertain conditions.

The impact of allowing alternative products with better environmental characteristics is presented in all cases.

7.6.1 The impact of CO_2 price variations

We start by evaluating the impact of CO_2 price variations on Forward and Closed-loop SC while maximising the ENPV or the SCR metric, as presented in Ribeiro & Barbosa-Póvoa (2022b). The results are compared with all the eight different applications of the model presented in Table 7.7 focusing in three aspects: the economic return, the service level, and the SC network.

CO_2 prices uncertainty impact

The ENPV results for all eight model applications, normalised relative to the ENPV obtained in the base case, Forward BM No-Alt, are shown in Figure 7.3. Similarly, Figure 7.4 shows the results regarding the service level. In both figures, the blue line represents the results obtained with the ENPV maximisation objective, and the orange line represents the results obtained with the SCR metric maximisation objective.

For a forward SC, there is a reduction in ENPV between around 3% and 4% when the SCR metric is maximised. On the other hand, when a closed-loop SC is implemented, the economic return is similar regardless of the objective function being used. This is justified since a closed-loop SC brings opportunities to reduce emissions and costs while keeping the service level high. Thus, it does not suffer a substantial decrease in economic return, whereas a forward SC must sacrifice economic return to meet demand. Based on these results, we can state that:

Under CO_2 price uncertainty, CLSC show similar economic returns regardless of the objective function, while forward supply chains experience a reduction in ENPV when maximising the SCR metric.

These results align with what is presented in Ribeiro & Barbosa-Póvoa (2022b), in that maximising the resilience metric leads to a higher responsiveness SC, but with a slight reduction in the economic return when no disruptions occur. Therefore, we can state that:

Regarding the use of alternative products, it seems clear that having them always implies a better ENPV, an effect that is not so noticeable in closed-loop due to the possibilities of redundancy allowed by reverse flows; therefore, the real advantage is obtained when CO_2 uncertainty is considered in a forward SC, where having alternative products is better, with higher improvements when the ENPV is being maximized. These considerations are discussed in further detail in the following sections.

CLSC effectively absorb the CO_2 price variations without a reduction in profit, while alternative products contribute to better ENPV in forward supply chains.

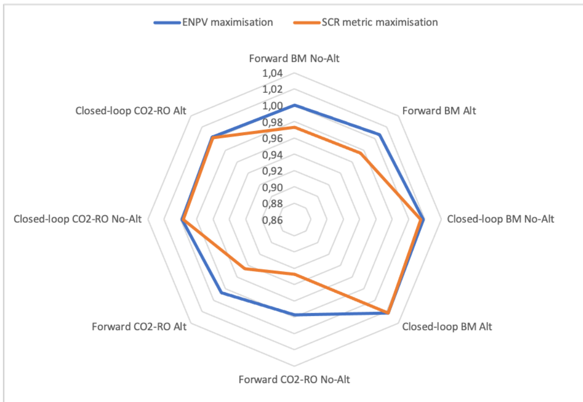


Figure 7.3: Normalised results of ENPV

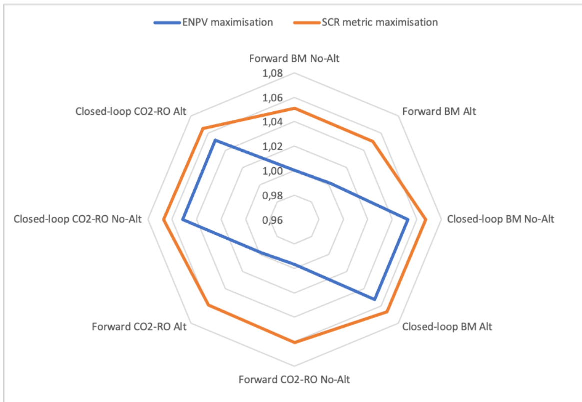


Figure 7.4: Normalised results of service level

Conversely, from Figure 7.4, it can be seen that the maximisation of the SCR metric leads to a higher service level than the ENPV maximisation. When the resilience metric is maximised, demand is almost completely satisfied, with service levels ranging from 98% to 100%, which does not happen with the ENPV goal where the forward SC has a service level of 94%. At the same time, the closed-loop SC manages to provide a service level of 99%. Closed-loop supply chains positively impact demand satisfaction since they still offer a higher service level, even when the ENPV is maximised instead of the SCR metric. Thus:

- Maximising the SCR metric results in higher service levels compared to maximising ENPV.
- Closed-loop supply chains consistently provide a higher service level than forward supply chains, even when maximising ENPV.

Figure 7.4 also highlights that the existence of alternative products does not necessarily lead to higher demand satisfaction, as all forward supply chains have similar results, having alternative products or not.

> The presence of alternative products does not necessarily lead to higher demand satisfaction in forward supply chains.

Closed-loop SC as an environmental trade-off

Implementing CLSC enables the reuse of products that would otherwise be discarded, reducing emissions and costs associated with production and disposal. Those products re-enter the SC as added value, reducing dependency on suppliers and allowing for greener production, which in combination allow for better service levels. However, the creation of new facilities and processes and increased transport emissions from reverse flows may increase emissions, particularly since reverse flows are characterized by their low efficiency. As analysed in the previous subsection, a CLSC showed benefits compared to a forward SC concerning ENPV when CO_2 prices and service levels are involved. We now extend the discussion of the potential benefits and drawbacks of implementing closed-loop supply chains by analysing the results of Figures 7.5 and 7.6, which show the kg CO_2-eq emissions associated with transportation and production, respectively, relative to the base model (Forward BM No-Alt). These are complemented by Tables 7.1 and 7.2, which present absolute values of the total kg CO_2-eq emissions and the respective costs in €, respectively, for the ENPV maximization objective and the SCR metric maximization objective.

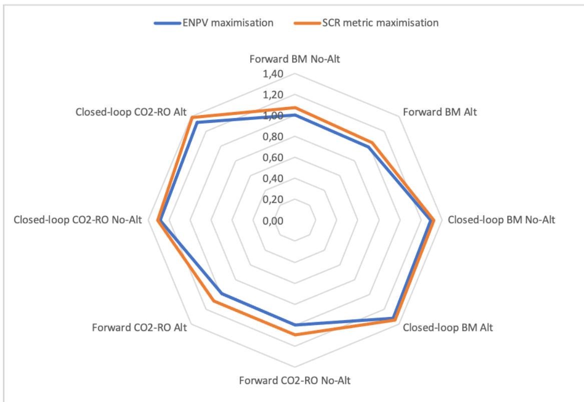


Figure 7.5: Normalised results of kg CO_2-eq associated with transportation

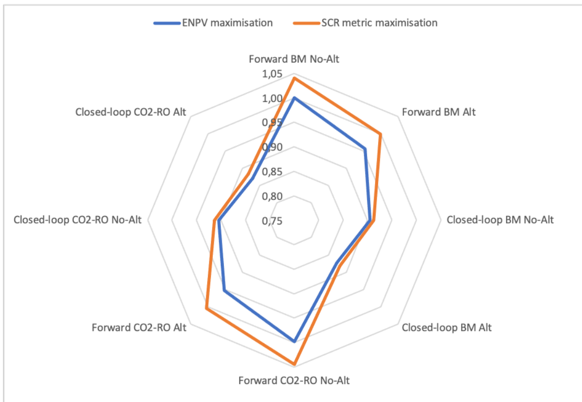


Figure 7.6: Normalised results of kg CO_2-eq associated with production

When considering the global environmental impacts and comparing both types of SC, it can be seen that a CLSC has lower impacts (see Tables 7.1 and 7.2). However, it should be noted that each type of emission changes differently as it responds to the changes in the SC operation. More precisely, there is an increase in emissions associated with transportation (see Figure 7.5) as a result of the need to collect and transport goods from markets to reprocessing facilities, leading to added distance travelled. A similar reasoning occurs in the emissions associated with facility installation, as the new facilities that would be the place for the circular economy activities to be performed must be implemented and their emissions considered. Production emissions show considerable improvements when CLSC are considered (see Figure 7.6). The emissions are reduced, taking advantage of the repurposed products that can be included in the SC as new products, but with a fraction of the emissions.

Looking in more detail at transportation activities, Figure 7.5 shows that uncertainty in the price of CO_2 and the availability of alternative products has little impact on their corresponding emissions when performing the comparison within the same type of SC. However, a CLSC leads to a 30% increase in transportation emissions, regardless of the price of CO_2 emissions.

Another difference is between the two objective functions in the case of a forward SC. Using the SCR metric as the objective function leads to an increase in emissions. In the base models (BM), this difference is around 6%, while in the robust optimization models (CO_2-RO), the difference increases to 9%. This is due to the greater focus on fulfilling demand, which leads to more transport activities. In the case of a CLSC, however, the two objective functions have similar transport impacts since both use inverse flows to achieve service quality or financial gain benefits. Thus:

Transportation emissions increase in CLSC due to the collection and transport of goods to reprocessing facilities.

Analysing now the environmental impact caused by production in the different model applications through Figure 7.6, it is possible to verify an apparent environmental gain in implementing CLSC instead of forward SC. Emissions are reduced by around 10% compared to the forward SC, whether with or without uncertain CO_2 prices and with or without alternative products. This benefit follows from the aforementioned trade-off, that is, the possibility in CLSC of re-using products to produce new products to be introduced in the SC, thus avoiding the total emissions of a new product. Predictably, the SC obtained through the optimization of the resilience metric implies a greater environmental impact on production (the orange line in Figure 7.6 is always higher than the blue line) since, by penalizing unsatisfied demand, the SC will always produce, even if for this purpose increased costs have to be incurred with emissions. Thus:

- CLSC show a reduction in production emissions compared to FSC, benefiting from the reuse of products.
- The environmental impact of production in CLSC is higher when the resilience metric is maximized, as the SC prioritizes production even with increased emissions.

The total emissions in kg CO_2-eq, for each type of SC, for each goal and whether alternative products exist, is not very sensitive to price variations, as can be seen in Tables 7.1 and 7.2 when comparing the BM variant of the model with the corresponding CO_2-RO variant. A more detailed analysis of the results shows that the SC is able to maintain approximately the same emission values by varying, mainly, its options in terms of production. Although a decrease in ENPV occurs as expected, this decrease is not as substantial as the increase in environmental costs. For example, from Table 7.1, and comparing the cases "Forward BM No-Alt" and "Forward CO_2-RO No-Alt", it is possible to verify that there is an increase in environmental cost in the robust solution of 1.4E6€ which leads to a reduction of only 0.4E6€ in the ENPV. Similarly, in Table 7.2, and comparing the same cases but resulting from the optimization of the resilience metric, there is an increase in environmental costs of 1.59E6€ with a reduction of 0.08E6€ in the ENPV. Similar conclusions can be drawn in the other scenarios. In other words, in any of the scenarios, accounting for an added cost in the CO_2 price when designing and planning a SC can allow companies to adapt and mitigate its effect. In short:

> Total emissions are not highly sensitive to price variations, and the SC maintains similar emission values by adjusting production options.

Forward SC face more significant challenges in reducing emissions, compared to CLSC. From the results of Tables 7.1 and 7.2, we can see that the scenarios involving a CLSC return around 5% fewer emissions than the Forward BM No-Alt. The availability of alternative low-emission products also plays a role in reducing emissions. These benefits are greater in forward SC than in CLSC since the latter, without alternative products, already makes use of the production of products with lower emissions. Our results show that a forward SC with alternative products can reduce emissions by 5%. It is thus possible to conclude that:

> CLSC face fewer challenges in reducing emissions compared to FSC, and the presence of alternative low-emission products further contributes to emission reduction.

Finally, expenditure on products sent to disposal is invariant to the objective function and depends only on the type of SC. In forward SC, there is no option for product reuse, so all unsold products must be disposed of. In closed-loop supply chains, however, these products can be integrated into the supply chain, reducing disposal costs by about 26%. However, these costs are significantly lower in magnitude, so their overall impact is reduced compared to the rest, so the advantage of CLSC lies in the use of less polluting products through reuse. Thus:

> Disposal costs are significantly lower in CLSC due to the integration of unsold products into the supply chain.

Table 7.1: Environmental results for models BM and CO_2-Ro while maximising ENPV

	ENPV Maximisation			
	Forward BM No-Alt	**Forward BM Alt**	**Closed-loop BM No-Alt**	**Closed-loop BM Alt**
Total emissions (kg CO_2-eq)	1.36E+7	1.30E+7	1.29E+7	1.26E+7
Total disposal (€)	5.22E+4	5.12E+4	3.86E+4	3.84E+4
Total environmental cost (€)	0.44E+6	0.42E+6	0.42E+6	0.41E+6
Total ENPV (€)	1.73E+7	1.74E+7	1.76E+7	1.77E+7
	Forward CO_2-RO No-Alt	**Forward CO_2-RO Alt**	**Closed-loop CO_2-RO No-Alt**	**Closed-loop CO_2-RO Alt**
Total emissions (kg CO_2-eq)	1.36E+7	1.30E+7	1.29E+7	1.26E+7
Total disposal (€)	5.21E+4	5.12E+4	3.86E+4	3.83E+4
Total environmental cost (€)	1.84E+6	1.77E+6	1.79E+6	1.76E+6
Total ENPV (€)	1.69E+7	1.71E+7	1.72E+7	1.73E+7

Table 7.2: Environmental results for models BM and CO_2-Ro while maximising the SC resilience metric

	SC resilience metric Maximisation			
	Forward BM No-Alt	**Forward BM Alt**	**Closed-loop BM No-Alt**	**Closed-loop BM Alt**
Total emissions (kg CO_2-eq)	1.42E+7	1.37E+7	1.31E+7	1.28E+7
Total disposal (€)	5.30E+4	5.22E+4	3.73E+4	3.84E+4
Total environmental cost (€)	0.46E+6	0.45E+6	0.43E+6	0.42E+6
Total ENPV (€)	1.68E+7	1.68E+7	1.75E+7	1.77E+7
	Forward CO_2-RO No-Alt	**Forward CO_2-RO Alt**	**Closed-loop CO_2-RO No-Alt**	**Closed-loop CO_2-RO Alt**
Total emissions (kg CO_2-eq)	1.43E+7	1.38E+7	1.30E+7	1.39E+7
Total disposal (€)	5.34E+4	5.23E+4	3.86E+4	3.83E+4
Total environmental cost (€)	2.05E+6	2.16E+6	1.81E+6	1.81E+6
Total ENPV (€)	1.60E+7	1.63E+7	1.72E+7	1.73E+7

SC network design variations

In this subsection, we analyse in more detail the particular variations in the SC network configurations stemming from different model applications. To exemplify, we show in Figures 7.7 and 7.8, respectively, the variations in the transportation flows between the "Forward BM No-Alt" and the "Forward CO_2-RO No-Alt" and the variations in production flows between the "Forward CO_2-RO No-Alt" and the "Closed-loop CO_2-RO Alt". The red lines represent negative variations, i.e., links that have lost influence in the network, while the green lines represent positive variations. Only the differences are presented, so flows that do not change are not represented. These variations can be analysed to understand how the network responds to the uncertainty in the price of CO_2 and changes in the complexity of the SC (forward SC compared to CLSC), respectively.

Looking first at the results in Figure 7.7, we note that the uncertainty in the price of CO_2 leads to slight alterations in the existing network. In particular, when uncertainty is introduced in the amount charged for emissions, suppliers (v9 to v20) located closer to the factories (v1 to v3) are favoured, leading to a reduction in transport emissions, even if the product becomes slightly more expensive from the new suppliers. This scenario may be of interest to the study of re-shoring. Thus:

> Uncertainty in the price of CO_2 leads to slight alterations in the SC network and transportation flows, favouring suppliers closer to factories and reducing transport emissions.

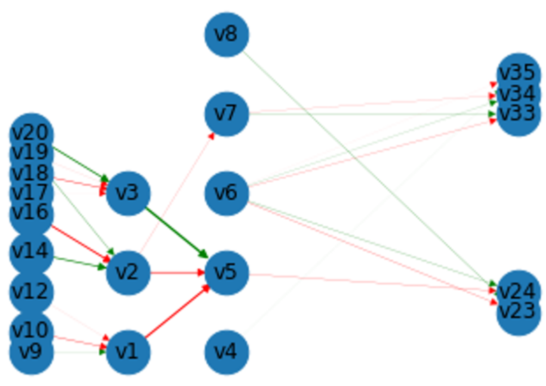


Figure 7.7: Normalised results of kg CO_2-eq associated with transportation between Forward and CLSC

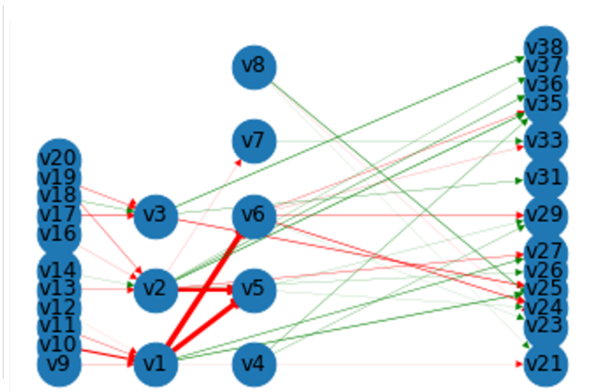


Figure 7.8: Normalised results of kg CO_2-eq associated with production between Forward and CLSC

As for the comparison between forward SC and CLSC, the particularities of the latter result in the elimination of a significant number of products leaving factories (v1 to v3) and their raw material suppliers (v9 to v20). This is made possible by the introduction of new products through a circular economy. The reduction in product production and transport between factories (v1 to v3) and warehouses (v4 to v8), seen in red in Figure 7.8, leads to the release of production capacity for direct connections between factories (v1 to v3) and markets (v21 to v38). This frees up space for the structures involved in the reverse network and facilitates the satisfaction of demand. It can thus be concluded that:

> The reduction in product production and transport between factories and warehouses in CLSC frees up production capacity for direct connections between factories and markets, improving demand satisfaction.

7.6.2 Supply Chains under disruption

We now study the SC's resilience while considering the entire model, that is, including not only uncertainty in demand but also in the price of CO_2, and in disruption occurrence, as described in Sections 7.3 and 7.4.4. As shown above, the CLSC with alternative products results in a more resilient SC, and thus this will be the focus of our study. The same reasoning is applied to justify using only the resilience metric in this context, as this has shown an overall more resilient capable SC when compared to the ENPV maximisation.

A comparison is made between the results obtained when considering the SC designed for disruptions and the SC designed by disregarding the existence of disruptions, that is, under normal operating conditions.

7.6.2.A SC designed for normal operating conditions

The supply chain from the *Closed-Loop* CO_2*-RO Alt* model is studied against disruptions as described in Section 7.4.4. The criticality for each of the nodes involved in production and supply are presented in Table 7.3. The criticality is then normalized, and the weight given to each disruption is calculated and merged with the remaining uncertainty sources. For the production disruption in a non-preparedness approach the overall scenario tree is as presented in Figure 7.10. The scenario tree for the remaining disruptions is constructed using a similar approach.

Table 7.3: Criticality values for the SC designed for normal operating condtions

Criticality														
Normal Operating Conditions														
Production			**Supply**											
v1	v2	v3	v9	v10	v11	v12	v13	v14	v15	v16	v17	v18	v19	v20
15	18	16	1	1	1	1	1	1	0	1	1	1	2	1

Based on the results presented in Table 7.4, our methodology reveals that the supply disruption has a minimal impact on the supply chain. This favourable outcome can be attributed to several key mitigating factors. Firstly, the presence of reverse flows effectively replenishes the supply chain, ensuring an uninterrupted flow of raw materials. Additionally, the inclusion of multiple supply locations, each with similar criticality levels, significantly reduces the overall impact of the disruption. In this particular case study, only one supplier (v15) remains unused in the original supply chain configuration. The collective effect of these factors grants the supply chain the necessary flexibility to source the required materials from alternative suppliers unaffected by the disruption. As a result, the supply chain exhibits comparable performance to normal operating conditions.

> Multiple supply locations with similar criticality levels reduce the overall impact of a supply disruption.

Table 7.4: Results from the SC network designed for normal operating conditions (non-resilient)

	Closed-Loop SC from **Non Resilient - Robust**		
	No Disruption	Supply	Production
Service Level	1	1	1
SCR Metric	1	0,99	0,97
ENPV	1,73E+07	1,72E+07	1,68E+07
Transport CO_2 Kg	2186152	2187028	2249318
Production CO_2 Kg	1,05E+07	1,05E+07	1,05E+07
Facilities CO_2 Kg	1284525	1284525	1284525
Cost CO_2	1,77E+06	1,77E+06	1,71E+06

Accounting for disruptions leads to a depreciation of results compared with the previous sections, where fewer sources of uncertainty were accounted for. Once again, circular economy principles combined with the objective function maximising the SCR metric lead to a high service level, with all the scenarios with service level close to 100%. The reduction in ENPV during disruptions justifies the variation in the objective function value. Production disruption causes a reduction of about 3% in economic return. This reduction in ENPV causes the metric to correspondingly decrease from 1 to 0,97 in the case of production disruption.

From an environmental perspective, the results demonstrate an interesting variation during disruptions. In production disruptions, there is an increase in transportation emissions of close to 3%, with the remaining emissions remaining fairly close to normal operating conditions. However, the choices made regarding when to operate the production and investments lead to an overall reduction in cost of CO_2 emissions.

> - Production disruptions cause a reduction in economic return (ENPV), leading to a corresponding decrease in the SCR metric value.
> - To mitigate the production disruption, the SC relies on not so efficient logistics leading to an increase in transportation emissions.

7.6.2.B SC designed for Supply and Production disruptions

To analyse the impact of disruptions, we implemented the disruptions as described in Section 7.4.4. This allowed to simulate the effects of different disruptive scenarios on the SC's performance. The disruptions were applied to the new scenario tree, taking into account the criticality levels determined during the SC's normal operation, from section 7.6.2.A. Importantly, no constraints were imposed on decision-making during this process.

Once the new SC structures prepared for disruptions and the criticality levels resulting from these disruptions were established, strategic decisions were fixed based on this information. The application of disruptions to the SC and the subsequent evaluation of its response under different conditions provided a comprehensive understanding of the SC's preparedness to enhance its resilience in the face of future disruptions.

The criticality for the supply and production nodes, for supply and production disruptions, are presented in Table 7.5.

Table 7.5: Criticality values of the SC networks designed for supply and production disruptions

Criticality														
Supply Disruption														
Production			Supply											
v1	v2	v3	v9	v10	v11	v12	v13	v14	v15	v16	v17	v18	v19	v20
15	18	16	1	1	1	1	1	1	0	1	1	1	2	1
Production Disruption														
Production			Supply											
v1	v2	v3	v9	v10	v11	v12	v13	v14	v15	v16	v17	v18	v19	v20
22	26	28	1	1	1	1	2	1	0	1	1	1	2	1

Supply Disruptions

The criticality of the supply locations remains similar in all cases, even from the normal operating conditions. This further contributes to the reasoning that the SC in its original form is capable of coping against supply disruptions and that the small criticality assumed by these locations lead to supply disruptions not being critical to this SC and therefore not worth exploring.

> Disruptions on locations with low criticality lead to non-critical disruptions.

Production Disruptions

The comparison of criticality between normal operating conditions and production disruptions highlights an increase in criticality at the production sites. This finding suggests that the SC design specifically tailored for production disruptions, by emphasizing the significance of factories, can effectively mitigate the potential consequences of such disruptions.

Table 7.6 presents the results for the SC considering production disruptions. In the event of production disruptions, implementing a supply chain configuration prepared for such occurrences yields a slight improvement in the resilience metric, accompanied by a small increase in ENPV, when compared with the results shown in Table 7.4. This small improvement can be attributed to the characteristics of the metric used and the adoption of a CLSC approach that generated an already high service level. Being prepared for disruptions enables the supply chain to maintain a high level of responsiveness while achieving greater efficiency and cost reduction associated with emissions when compared with a non-preparedness approach.

> SC preparedness can lead to a slight improvement in resilience against critical disruptions.

Table 7.6: Results from the SC network designed for a production disruption

Closed-Loop SC from **Production Resilient - Robust**		
	No Disruption	Production
Service Level	1	1
SCR Metric	1	0,98
ENPV	1,72E+07	1,68E+07
Transport CO_2 Kg	2179503	2227683
Production CO_2 Kg	1,05E+07	1,05E+07
Facilities CO_2 Kg	1284525	1284525
Cost CO_2	1,76E+06	1,70E+06

Upon comparing the obtained SC networks in the two discussed cases (from operating in normal conditions and production disruptions), it is evident that the presence of disruptions introduces increased flexibility primarily at the nodes directly affected by the disruptions. This is reflected by the higher criticality of those nodes, as presented in Table 7.5. However, this enhanced flexibility is not limited to the affected nodes alone but extends throughout the supply chain, including downstream of the factories. Examining the existing flows, specifically the decision to establish connections with open locations, reveals a significant increase of 69 new connections. While these additional links contribute to higher investment requirements in terms of contract costs, they also lead to a reduction in transportation emissions as the network becomes more adaptable and capitalizes on potentially closer locations. This trade-off between increased costs and improved resilience underscores the rationale behind the observed decrease in ENPV for the resilient network compared to the network designed for a scenario of normal operating conditions.

- Disruptions preparedness introduce increased flexibility primarily at the nodes directly affected, as reflected by higher criticality, extending throughout the supply chain, including downstream of factories.
- SC preparedness contributes to higher investment requirements but also to more efficient operations.

7.7 Conclusions, managerial insights and future work

This work aims to provide valuable information for academics and practitioners regarding lessons on environmentally sustainable resilient SC under uncertainty, using CO_2 monetisation through environmental credit systems such as the European Union Emissions Trading System (EUETS). The study presented in this article goes beyond the consideration of environmental impact alone. It encompasses the analysis of uncertainty in demand, variations in emission prices, as well as the occurrence of disruptions.

The impact of incorporating new alternative products is also studied. Although these products may entail additional costs, they exhibit improved environmental performance. This analysis highlights the importance of taking sustainability into account when making strategic decisions regarding product selection and diversification in supply chains.

Furthermore, the preparedness of supply chains in the face of disruptive events is studied. Specifically, a new methodology is proposed to consider and study disruptive events under a SC Resilience scope, focusing on mitigating the unknown-unknown characteristics of these types of events.

Monetizing the cost of CO_2 emissions and increasing it has limited benefits. If an SC cannot invest and adopt technologies to reduce emissions, there is a point beyond which the SC can no longer optimize its operation further. It will define its optimal operational functioning and consider the cost of CO_2 as a consequence of that operation.

When there is an opportunity to invest in more sustainable products, SC take advantage of this by enabling them to be responsible for lower environmental impacts. Thus, fostering investment in alternative, greener products is the main benefit of EUETS, and companies should be prepared for it by investing in R&D towards sustainability.

Implementing CLSC is often associated with additional costs. Our results also show that monetizing CO_2 allows for the recognition of the added benefits of CLSC. SC that reuse products have greater responsiveness, resulting in an easier adaptation to satisfy demand under diverse conditions of uncertainty. The existence of reverse flows enables the reduction of waste associated with the operation by integrating reprocessed products that, in turn, can produce new products without the impacts associated with a new product from virgin raw material. Additionally, CLSC results in more resilient SC as reverse flows add extra flexibility. It is possible to say that implementing CLSC can make a SC more sustainable and resilient.

Using alternative goals to profit can lead to more balanced solutions. In this case, the resilient goal (modelled through a resilience metric) generated SC with acceptable results and naturally adopting resilience enablers, such as flexibility and redundancy, which are seen as a way to contribute to greater responsiveness.

The mathematical model results may depend on the specific SC applied, which can vary from product to product and from network to network. So, a more in-depth analysis is needed on the type of SC and the impact of different SC structures and product characteristics. Thus, apart from the results obtained, there is a solid need to reinforce research and development activities in the business sector to address future challenges. This presents an opportunity for a symbiotic relationship between academia and the business world to jointly develop methods and solutions for a more sustainable and resilient future.

Acknowledgements

The authors acknowledge the support provided by FCT - Foundation for Science and Technology, I.P., under the project UIDB/00097/2020 and SFRH/BD/148499/2019

7.8 Supplementary Materials

Table 7.7: Different model applications

Name	SC paradigm	Alternative products	Uncertain Demand	Uncertain CO_2 price
Forward BM No-Alt	Forward	No	Yes	No
Forward BM Alt	Forward	Yes	Yes	No
Closed-loop BM No-Alt	Closed-loop	No	Yes	No
Closed-loop BM Alt	Closed-loop	Yes	Yes	No
Forward CO_2-RO No-Alt	Forward	No	Yes	Yes
Forward CO_2-RO Alt	Forward	Yes	Yes	Yes
Closed-loop CO_2-RO No-Alt	Closed-loop	No	Yes	Yes
Closed-loop CO_2-RO Alt	Closed-loop	Yes	Yes	Yes

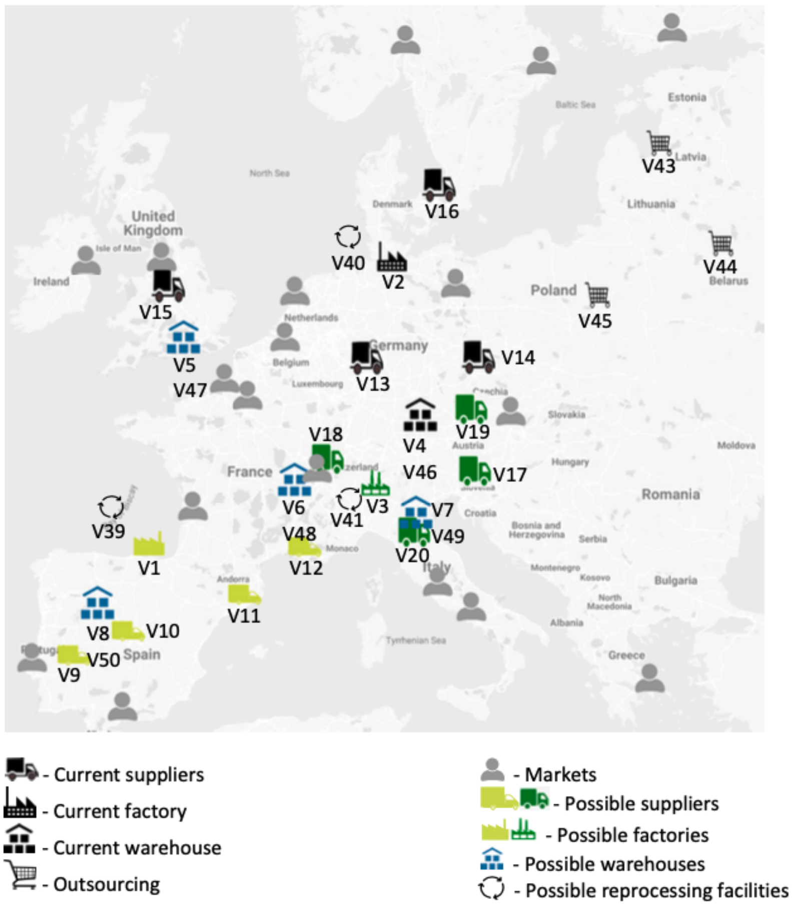


Figure 7.9: SC overall configuration and possibilities

Table 7.8: CO_2 emissions associated with each final product

Product	Emissions/unit (Kg)	Product	Emissions/unit (Kg)
P1	93.01	P7	66.40
P2	94.86	P8	66.06
P3	88.08	P9	66.29
P4	82.86	P10	73.47
P5	91.84	P11	74.87
P6	60.46		

Table 7.9: Areas of facilities

Facility	Emissions/unit (Kg)	Facility	Emissions/unit (Kg)
V1	350	V7	400
V2	400	V8	350
V3	450	V39	400
V4	400	V40	400
V5	375	V41	400
V6	400		

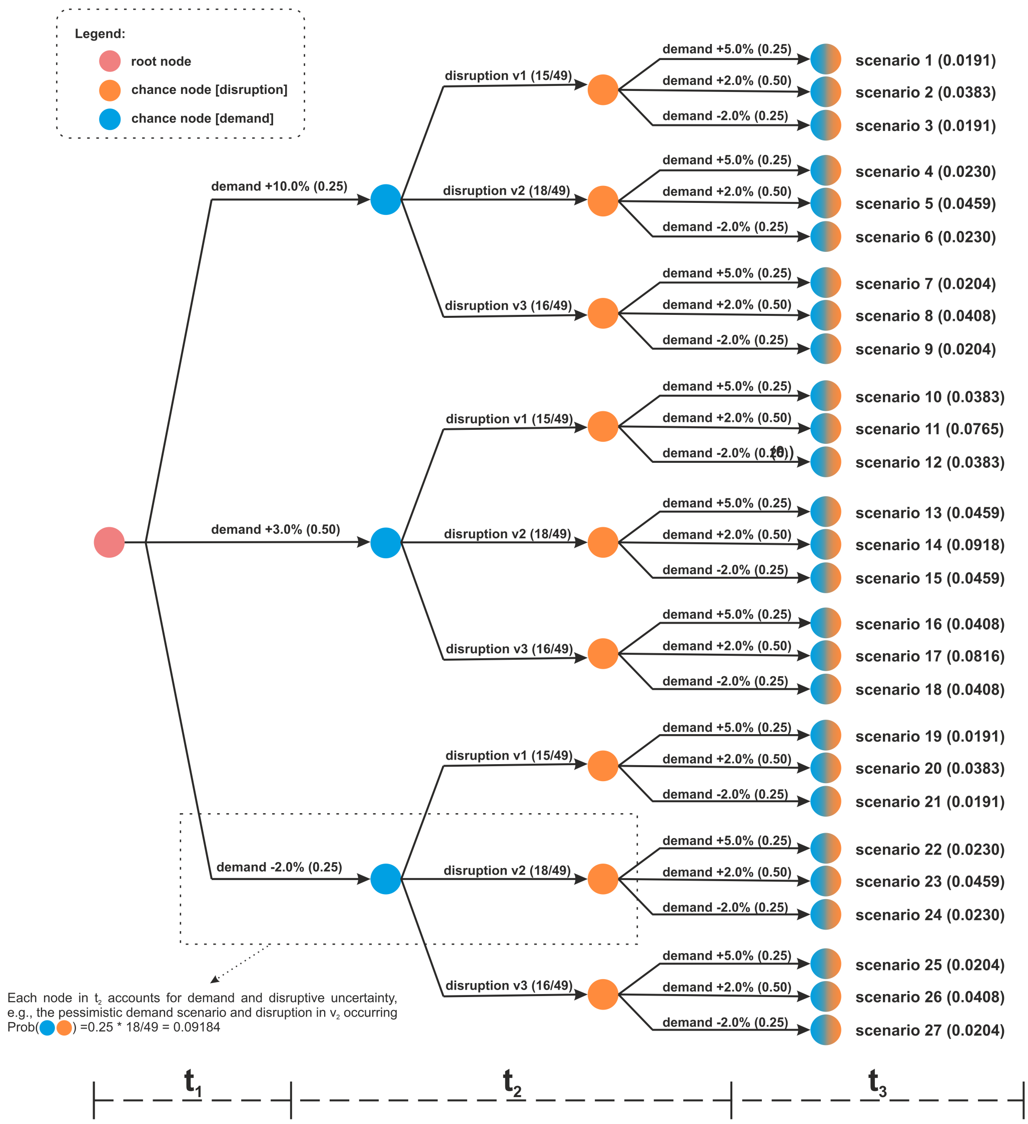


Figure 7.10: Overall scenario tree considering production disruptions in a SC with low preparedness for disruptions

8

Conclusions and Future Research

Contents

In recent years, there has been a significant evolution in society's concern over the resilience of SC. Recognizing the critical role of SC in ensuring the continuous flow of goods and services, recent world events have increasingly emphasized the need to build resilient supply chains capable of withstanding and recovering from disruptions. *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..*

Academics have been actively engaged in studying and addressing the challenges of SCR. They have explored various dimensions of resilience, including the identification of critical factors, the development of quantitative models, and the analysis of strategies and practices to enhance SCR. This research has contributed to the development of practical tools and frameworks for SCR management, providing valuable insights and contributing to the understanding of SCR. The research conducted encompasses a wide range of topics, making it relevant and useful to both academics and practitioners. It explores the multifaceted nature of SCR by considering different levels of decision-making, incorporating quantitative approaches, and proposing economic, sustainable, and resilient-driven models.

In conclusion, this thesis has endeavoured to address the pressing need for the understanding of how resilient SC can be explored. By investigating the various dimensions of SCR and presenting a diverse range of research outcomes, it seeks to contribute to both academic knowledge and practical applications. The insights gained from this study can inform decision-making processes, guide the development of strategies, and ultimately enhance the resilience of supply chains in the face of future disruptions. The main contributions are presented in section 8.1. This work also sets the stage for future research endeavours, encouraging further exploration and innovation in the field of SCR. This thesis's main limitations and directions for future research are presented in section 8.2.

8.1 Main Contributions

Besides the contributions of each of the different elements that constitute this thesis, it is also possible to identify the following main contributions:

1. Adequate definition and understanding of SCR within the context of Supply Chain Management.
2. Development of a comprehensive framework for the analysis and evaluation of SCR, providing a structured approach for assessing and enabling the enhancement of SCR.
3. Clarification of the distinction between SCR and risk management, highlighting the unique characteristics and objectives of SCR as a distinct field of study.
4. Compilation of a list of quantitative models and indicators that serve as a foundation for future research and practical applications in the field of SCR.
5. Recognition that there is no one-size-fits-all strategy for SCR, emphasizing the importance of tailoring resilience approaches to specific supply chain contexts. For instance, demonstrating that redundancy and flexibility have limitations in their effectiveness.

6. Empirical evidence supporting the notion that upstream disruptions have a more significant impact on SC compared to downstream disruptions.

7. Development of an easy-to-use SCR metric, designed to be readily understood and implemented by stakeholders. This metric has shown to facilitate the adoption of SCR enablers, leading to increased resilience and reduced ripple effects of disruptions.

8. Introduction of a tactical and operational quantitative model, addressing specific concerns such as time-related aspects, to aid decision-making processes in managing SCR.

9. Proposal of a robust optimization model for addressing uncertainty in CO2 prices, incorporating sustainability considerations and offering insights into managing environmental uncertainty in SC.

10. Highlighting the compatibility and importance of considering resilience and sustainability in an integrated manner, promoting the adoption of a holistic approach to supply chain management.

These contributions collectively enhance the understanding, assessment, and practical implementation of SCR, advancing the field of Supply Chain Management and providing valuable insights for both academia and industry.

8.2 Limitations and Future research

The decision support tools developed in this research have demonstrated their effectiveness in assisting decision-makers. However, like any scientific endeavour, this thesis also has its limitations, which pave the way for future research and improvement in the field of SCR.

Contrasting Points of View in a Rapidly Developing Field: This thesis was conducted during a period of rapid development in the field of SCR. Consequently, there may exist contrasting perspectives and approaches among different authors. Future research should focus on reconciling these viewpoints, establishing common frameworks, and integrating diverse theories to enhance the overall understanding of SCR.

Generalizability of the Models: The models presented in this thesis were applied to a specific case study, enabling comparability among different papers within this doctoral work. However, to assess the broader applicability and effectiveness of the proposed models, it is essential to test their outcomes in various industry contexts. Preliminary work has been initiated to explore this avenue, and initial results appear promising.

Deeper Understanding of Disruption Occurrence: Managing and modelling disruptions, particularly low-probability and high-impact events, remains a significant challenge in SCR. While this thesis proposes a methodology to address such events, further studies are necessary to delve deeper into the understanding of disruption occurrence and enhance the overall preparedness of SC to mitigate their adverse effects.

Exploring Degenerated Solutions and Optimization Models: Due to the complexity and uncertainties associated with larger-scale case studies, it is possible that degenerated solutions exist within the acceptable gap in the optimization models employed. Consequently, future research should focus on studying the characteristics of these solutions and their potential impact on supply chain outcomes.

Addressing these limitations and pursuing future research endeavours will contribute to the ongoing advancement of SCR management and modelling, further solidifying its position as a vital area of study within the field of supply chain management.

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