Supply Chain Resilience: Tactical-Operational Quantitative Models

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Abstract

The complex structure of modern supply chains (SC) and their tendency towards globalization, have increased their exposure to unpredictable events. In order for companies to sustain their competitive advantage, establishing resilient SCs has become a concern over the years, and now with the current pandemic, a priority. Nonetheless, despite the increasing awareness on the importance of resilience enhancing actions, it still presents a growing body of literature scarce on quantitative tools to aid decision-makers, particularly, at the tactical-operational decision level. To understand the current state of the art on this subject, this work performs a systematic literature review (SLR). Focus is given on the SC activity that is addressed and which operations research methods are used. It is also highlighted how the analysed publications model risk and uncertainty, as well as which resilience metrics have been used, culminating in the identification of paths for further research. Towards reducing the identified gaps, a multi-objective mixed integer linear programming (MILP) model is developed in this present dissertation with a novel stochastic approach to deal with uncertain parameters. Further uncertainties are explored regarding the disruptions time frame and source of occurrence. Focus is also given in understanding the weight of timely responses. The model is then applied to a case study where insights on operational decisions taken under disruptive events are discussed and final conclusions are withdrawn.

Keywords: Supply chain resilience; tactical-operational; quantitative models; operations research methods; metrics; uncertainty.

1. Introduction

Recent past has experienced several unpredictable catastrophic events, from natural disasters to terrorist attacks and now the current pandemic. While supply chain risk management (SCRM) has been able to deal, in part, with predictable and well-known events that might disturb operations, to deal with these unpredictable events it is crucial to complement such measures with resilience management for companies to successfully respond [1]. Being able to respond and recover quickly to disruptions is a key factor for companies to survive by maintaining their competitive advantage [2].

Modern supply chains (SC) are becoming ever more exposed to these unpredictable events due to its increasing complexity and globalization [3], [4]. In fact, daily operations require the normal functioning of several interlinked entities that are geographically dispersed. Therefore, local disturbances in one node can cause severe consequences that can quickly ripple throughout the whole network. Due to this, and coupled with the current pandemic conditions, interest on supply chain resilience (SCR) is significantly increasing for companies worldwide, as they are forced to cope with a "new normal", as well for the academic community.

The present crisis sets apart from previous disruptions by its global reach and the severe impact to both supply and demand simultaneously. As pointed out recently by Sodhi & Tang, (2021), there is an urgency in further researching SCM for these "extreme" conditions. By witnessing current challenges the importance of SCR has become more visible, but also exposed new paths to be considered in future works, such as the study of the shift towards automation, governmental interventions and the struggle of small businesses with e-commerce competition [5].

In recent years, resilience in the context of supply chain management (SCM) has gained more attention by the academic community, thus developing significant work to establish a sound definition by consolidating knowledge of other areas where it has been more thoroughly researched [6]. Although no consensus has been achieved on a single SCR definition, in this present work, the following 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."*

Regarding the literature on SCR, much of what has been published revolves heavily on qualitative insights. Quantitative approaches on SCR remain scarce and directed to the strategic and tactical level, while being relatively unexplored on the operational decision level [7]. Reducing this gap is fundamental, given that these quantitative models are of most value, aiding decisions makers to evaluate and adopt strategies towards resiliency.

This work intends to contribute to the literature by further developing the knowledge on quantitative SCR models at the tactical-operational decision level. Towards that end, firstly, it is established a well-founded understanding of the subject from the importance of the industry's point of view, and on how the academic community has tackled it. To achieve the latter, a SLR was elaborated. The review additionally focused on the modelling approaches adopted to tackle uncertainty, risk, and which metrics have been used to quantify SCR. With this assessment, directions for future research are identified.

Secondly, a model is developed to further enlighten the tactical-operational decisions taken under disruptive events. Particularly, attention is given in addressing the importance of timely decisions, by incorporating in the model outsourcing options and alternative products. In this line, it is also explored the time frame of the disruptive events, which is taken as uncertain. The model is applied to a case study, where the results are thoroughly analysed and discussed, and future work to be developed in this field is outlined.

2. Industry view on SCR

Over the years, most companies have adopted a more reactive approach in face of disruptions, still allocating more importance into maximising efficiency rather than building up resilience [3], [8]. According to a Gartner survey on May 2020 [9], one of the first reports on the consequences of the COVID-19 pandemic, only 21% of the SC leaders that were inquired considered their SC, up-to-date, as being highly resilient.
The analysis of actions taken by leading companies demonstrated the importance of quickly sensing disturbances to their business, whether of clients' demand or overall environmental necessity, and their rapid responsiveness. Surges in demand for specific products were quickly identified and resources were reallocated accordingly, highlighting, now more than ever, the importance of agility and flexibility of their SCs. Currently, it is assessed that companies are adopting a long-term view on the actions taken to mitigate the impact of this crisis on SCs, aiming to acquire resilience for future disruptive events. On May 2020, a McKinsey's survey reported that 93% of the leading global companies that were inquired are planning to increase their resilience in the near future [10]. Amongst the planned actions, dual sourcing of raw materials is the most mentioned strategy by the respondents followed by increases in inventory of critical products and nearshoring and expanding supplier base. However, it is relevant to keep in mind that the importance of these strategies can vary by industry. For instance, for automotive companies, nearshoring is the most cited option to improve SCR, and only secondly would be dual sourcing of raw materials.
Overall, despite all the difficulties that are being faced, organisations can take current conditions as an opportunity to innovate and balance back more agile than before.

3. Literature Review

This section aims to construct a reliable assessment on the state of the art on SCR quantitative models with a focus on the tactical-operational decision level, through a SLR. The methodology adopted follows an adapted form of the one presented by Ribeiro & Barbosa-Povoa, (2018), consisting in six main steps: research questions; previous literature reviews; material collection; descriptive analysis; category selection; material evaluation.

<u>*Research questions (RQ):*</u>

1. What insight can be withdrawn on SCR from COVID-19 pandemic responses?
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 has uncertainty and risk been modelled in tactical and operational problems?
5. What sustainability metrics have been considered within SCR?
6. Which resilience quantitative metrics have been used?

<u>*Previous literature reviews*</u>

A search on the Web of Science was performed for the terms *"supply chain" and "resilience" and "review"* published in English from 2010 up to November 2020, categorized as either review or article in a peer-reviewed journal. As a selection criteria of these results, those that did not specifically address SCR were excluded, as well as those that were not considered as a literature review, resulting in a final set of 17 reviews.
From these results, it is notable a significant rise in literature reviews over time, being 2020 the year with most published works. Such reflects the increased awareness of the academic community on further developing the subject [11]–[13]. In fact, all authors have recognized that research on SCR has been steadily increasing over the past few years, identifying the early 2000's as a starting point, and highlighting 2003 as a particular turning point, given that more work was developed in the aftermath of highly disruptive events, such as the 9/11 attacks [7], [14].
The papers here reviewed have all recognized that a sound definition of SCR still lacks in the literature and that the root for such problem may rely on the inherent multidisciplinary nature of the term resilience. Additionally, the ambiguity revolving SCR elements and how they are interdepended, has lead them to be used interchangeably. This problem has also been referred to as a source that hiders the development of a single definition of SCR, given that no consensus has currently been achieved [15]. Hence, earlier reviews have focused on developing and clarifying conceptual terms such as SCR principles, elements and strategies, with the goal to propose well-founded definitions of SCR.
Overall, despite some papers presenting quantitative approaches, much of it is executed briefly and without much depth. Further development on this subject has been recognized as necessary, and of most importance given its' usefulness in aiding decision-makers to adopt adequate strategies and to assess their performance [7], [19].
Out of the 17 reviews, only three were found to execute an in-depth review on SCR quantitative models and/or metrics.
Through a content analysis of 39 papers Ribeiro & Barbosa-Povoa (2018) explored not only OR methods and metrics used in modelling SCR but also at what SCM decision level such has been researched.
Later on, Hosseini et al. (2019) explored the advances of analytical approaches on SCR by reviewing 168 papers, guided by the concept of three distinctive resilience capacities (absorptive, adaptive and restorative).
Most recently, the goal of the review of Han et al. (2020) is to connect SCR capabilities to performance metrics through a single conceptual framework. Towards that end, 153 papers were analysed of which only 36 discussed SCR performance metrics, and the remainder discussed SCR capabilities qualitatively.

<u>*Material collection*</u>

Articles were retrieved by the following set of keywords: *"supply chain" and "resilience"* with "*tactical"; "operational"; "quantitative"; "optimization"; "simulation"; "heuristics"; "metrics"; "routing"; "scheduling"*; "*statistics"* and "*COVID-19"*. The set was restricted to publications in peer-reviewed journals, written in English, and published between 2010 and December 2020. The final sample obtained comprises a total of 42 articles.

<u>*Descriptive analysis*</u>

The sample demonstrates an increase in the research developed on quantitative models over the years, with a slight decline observed in 2018, while 2020 stands out with an elevated number of publications. Regarding the country of the institution of the authors, USA is the predominant origin of the developed research followed by Germany, China, Canada, India, and Iran with similar values. Considering the source in which the articles are published in, 29 journals were identified, demonstrating a prevalence in the field of engineering and management. To be noted that the remaining 24 journals, presented a single record within the sample, which highlights the multidisciplinary nature of the subject.

Material evaluation

SCR insights from COVID-19 responses (RQ 1)

The works available on December 2020 that are here considered, demonstrated that the severity of this crisis on SCs mostly derives from the simultaneous impact on both supply and demand. Hobbs (2020) and Zhu, Chou, & Tsai (2020) address food and medical SC, respectively, where a Just-In-Time (JIT) philosophy is adopted and concluded that these were not able to fully withstand unpredictable spicks in demand, be it from panic buying of groceries or increased necessity for high volumes of personal protective equipment, which led to short-run stockouts. Marzantowicz et al. (2020) assessed that most SC operation managers of polish companies experienced disturbances to their operations due to imposed restrictions in order to comply with protective regulation, witnessed a reduction in orders quantity and also extended transportation times, stating that most managers had to delay deliveries due to the problem of filling and ensuring transportation.

Some works recognized that actions are being taken to reduce single-sourcing dependence and increase the pursuit of local and nearshoring options [21]. In fact, it has been observed that shorter SCs were less impacted by having closer proximity to regional suppliers, opposed to longer ones that were more affected due to transport modes restrictions [22].

One measure that has been vastly referred to for future improvements on SCR are technological investments towards digitizing end-to-end operations [19]–[21]. Cooperation between SC entities has also been identified as crucial, recognizing the importance in strengthening relationships in order to attenuate the negative impacts of the disruption, along with changes to inventory management policies, allowing levels to be increased [18], [19].

SCR quantitative models on the tactical and operational level (RQ 2&3)

Models that tackle SCR problems and support decisions at the tactical-operational level, can be classified into four general categories:

Distribution problems: regard coordination of product flows, through optimization of supply lead time and routing assignments;

Inventory problems: present solutions for inventory management decisions;

Production problems: planning and scheduling considerations for production;

SC problems: models that tackle the implementation of recovery policies and timely allocation of resources in more than one SC activity.

Of the collected papers, it was found that production problem are the least addressed in the quantitative SCR literature, and distribution, inventory and SC integrated activities in the recovery process problems are equally prevalent. Regards to the OR method employed, optimization and simulation are the clear preferred methods adopted across problems, with residual occurrences that use meta-heuristics, heuristics and decision analysis methods.

Risk & uncertainty in tactical-operational models (RQ 4)

Regarding how risks have been modelled, in the vast majority, simple approaches are adopted. For instance, some works that address the occurrence of severe disruptions, model such events in a pre-specified time frame, specifying the instance for the event to take place and [23]–[25] or which node of the network to be disrupted with a given time length [26]–[28].

Another approach is the setting of different risk profiles that may arise [29]–[32]. Schmitt & Singh, (2012) base the risk profiles on interviews on operational personnel and literature, Das & Lashkari, (2017) recur to historical data.

Nevertheless, a few works can be found to actively develop formulations to account for risk in their models. Ivanov et al., (2018) develop a perturbation function to assess its impact, and Thomas & Mahanty, (2019) use unit step impulse for customer demand disturbances.

Relative to uncertainty, a few papers have been identified to integrate such condition into their model. Fuzzy approaches have been identified to model uncertain parameters in stochastic models [37], [38].

SCR metrics

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.

The nature of the most prevalent indicators in the literature derive from the resilience triangle principles (readiness, response and recovery) [2], [39]–[41].

Other works consider that SCR measures should reflect key performance indexes (KPIs) of the system such as end-customers' satisfaction [42] or revolve more on economic interests [43].

Relative to sustainability metrics, only one paper has been identified to consider resilience and sustainability factors concurrently [44].

Discussion and future research directions

SCR presents a fast-growing body of literature that is expected to continue to grow, with current conditions inciting a possible stream of case studies to be explored. Regarding extant decision-supporting tools, these present a variety of applications, while some challenges still need to be addressed.

The models developed thus far, dealing with tactical-operational decisions, present a clear preference for optimization and simulation techniques. Only few works can be found to use heuristics and decision analysis methods. Consequently, the benefits that these two OR methods may provide remain relatively unexplored and future efforts should be made in exploring both.

It was found that the inclusion of risk events is mostly modelled deterministically. Uncertainty, considering as well other parameters of the model, has also been scarcely addressed. In order to reflect more accurately the dynamics and randomness of real-world events, future research should consider the adoption of stochastic approaches.

Nevertheless, resilience performance metrics need to be carefully selected to guarantee that they truthfully reflect the objectives of the developed model. Thus, despite existing in the literature some indicators that are more vastly cited, these are still majorly context-driven.

4. Model Formulation

The model here developed considers a four-echelon CLSC, composed by suppliers, factories, retailers, and markets. Figure 1 illustrates this structure along with the allowed flows among the entities. For the formulation of this model, the production, distribution and capacity planning model developed by Liu & Papageorgiou (2013) was used as a basis, upon which considerable alterations were made.

Being this a planning-operational model, relative to production, the model determines which product should be produced, given that demand can be satisfied by 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.

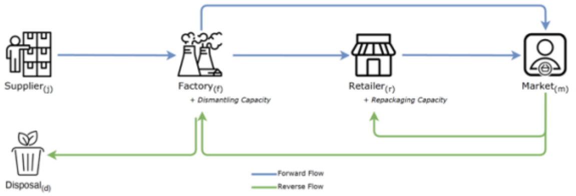

Figure 1: Supply chain structure

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. It is also taken into account that some end of life products are too damaged to be repurposed and are therefore disposed of.

This is a multi-objective model with three objective functions (OF) presented below.

Objective function 1: Resilience Metric

The first OF involves both economic goals and customer satisfaction to guarantee SC resilience (equation 1) [46]. In the first term a reference value (profitREF) is used, which represents the optimal profit level within normal operating conditions. Hence, the first term favours profit levels that approximate to the reference value. This term is then balanced out with a measure of service level. The second term will deteriorate the overall function with increased lost sales ($LS_{p,m,t}$), thus taking into account the concern to meet customers' demand. Since both terms are valued equally, customers' satisfaction are not disregarded in pursuit of economic returns.

$$Max\ Z_1 = \frac{profit}{profitREF} - \frac{\sum_p \sum_{m \in PM} \sum_t LS_{p,m,t}}{\sum_p \sum_{m \in PM} \sum_t dem_{p,m,t}} \quad (1)$$

Objective function 1: Flow time

The second objective has the function to minimize the total flow time, optimizing the SC's responsiveness. The goal of this metric is to increase the SC's capability to react rapidly to customers demand. Such is of most importance to the modern fast-changing markets, and in particular to this case since response time is a critical component of SCR.

Thus, equation 2 measures the transportation time between two entities ($tts_{j,f}$, $ttr_{f,r}$, $ttd_{f,m}$, $ttm_{r,m}$) with an importance proportional to 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 ($lunit_p$). Additionally, it is also included the necessary production time of the item ($pt_{p,f}$).

$$\begin{aligned} Min\ Z_2 = & \sum_i \sum_j \sum_f \sum_t (tts_{j,f} \times liunit_i \times FSF_{i,j,f,t}) \\ & + \sum_{p \in PF} \sum_f \sum_t pt_{p,f} \times PRO_{p,f,t} \\ & + \sum_{p \in PF} \sum_f \sum_r \sum_t (ttr_{f,r} \times lunit_p \times FFR_{p,f,r,t}) \\ & + \sum_{p \in PF} \sum_f \sum_{m \in PM} \sum_t (ttd_{f,m} \times lunit_p \times FFM_{p,f,m,t}) \\ & + \sum_p \sum_r \sum_{m \in PM} \sum_t (ttm_{r,m} \times lunit_p \times FRM_{p,r,m,t}) \end{aligned} \quad (2)$$

Objective function 2: Profit

Lastly, the third objective function is a straightforward profit maximisation, where total costs are subtracted to the revenue, as seen in equation 3. The costs are measured by auxiliary variables measuring manufacturing (TMC), transport (TTC), inventory (TIC), duties (TDC) and expansion costs (TEC).

$$profit = sales - (TMC + TTC + TIC + TDC + TEC) \quad (3)$$

Uncertainty modelling

To adapt the deterministic model to a stochastic model where demand and product return rates are uncertain parameters, a scenario tree approach is adopted.

Since we are dealing with a tactical-operational model, considering each time period of the planning horizon as a stage would result in an excessive amount of scenarios. To overcome these limitations, and to the best of the authors' knowledge, a novel approach is developed. In this case, a different time description is presented solely when new information becomes available, being that subsequent time periods where no alterations are expected are clustered within the same time description. This novel approach, allows the construction of a scenario tree with fewer ramifications and, consequently, with reduced number of scenarios to reflect more realistically when new information should be taken into consideration, thus being more adaptable for cases with different characteristics.

Disruption modelling

Regarding the disruption modelling here it is certain that a disruption will take place, however, the means by which it occurs will be considered as uncertain. For a disruption type, possible scenarios are constructed which can disturb the SC activity at hand. These scenarios are then associated to a probability which reflects the likelihood of its incidence compared to those within the same disruption type. Under resilience setting here the probabilities do not intend to reflect the likelihood of occurrence of a particular event, under the unpredictability, that separates risk management with scenario case. Hence, within each disruption type, the sum of the probabilities of the possible scenarios is equal to 1.

Solution approach

Given the objective functions presented previously, a suitable multi-objective optimization method is deemed necessary to appropriately solve the model. For this end, the augmented ε-constraint method with lexicographic optimization (AUGMECON2) developed by Mavrotas & Florios, (2013) will be used.

5. Case study

The case study here presented consists of a CLSC, that produces 3 different products (p_1-p_3) to serve 6 markets dispersed in the European region. In this SC there are 3 suppliers, 4 factories (f_1-f_4), and 2 retailers.

The production capacity expansion can be achieved by increasing the capacity of the owned factories or by resorting to outsourcing. For the former strategy it is assumed that the factories possess idle redundant capacity that can be activated when necessary up to 25% of their current capacity. For the outsourcing factories four options were designed to understand the trade-off between offshore and nearshoring decisions. These options are summarized in table 1. 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.

Table 1: Outsourcing options design

Factory	Location	Time to markets	Prod Cost
f_5	Offshore	Further away than f_6	x 2,0
f_6	Offshore	Slower to markets	x 2,3
f_7	Nearshore	Faster to all markets	x 4,3
f_8	Nearshore	Faster to most markets	x 4,0

The study of the benefits of alternative products (AP) is conducted by allowing p_1, the product with the highest demand, to have three additional options to satisfy its demand. 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 as follows:

AP1: Lower production time;

AP2: Fewer raw material requirements;

AP3: Possible to produce at more factories.

Discussion outline

The analyses here executed are divided for the deterministic model and, subsequently, compared with the stochastic model, where demand and product return rates will be considered as uncertain parameters. Adopting a multistage approach, it will be studied different prioritization of the OFs prior to the occurrence of a disruption and how this preference influences the corrective measures taken to sustain operations for both models. Three type of points of the pareto front will be used for this end as representative of the value attributed to the OFs, being characterised as follows:

Point A: values most the resilience metric.

Point B: values most the flow time.

Point C: An in-between solution, which balances more equally the three OFs.

Point D: values most the profit.

6. Deterministic model results

The results are obtained using GAMS software running the CPLEX solver with a gap of 0%. The number of grid-points for the multi-objective resolution was set to 5.

Reference case

Foremost, the model is run for normal operating conditions where no disruption takes place as well as no uncertainty is included. Being this a multi-objective problem, a priority of the objective functions needs to be accounted for, which ultimately should reflect the interest of the decision-maker (DM). In this case priority 1 (Resilience metric; Flow time; Profit) will be used returning the payoff table of table 2, and a simplified two-dimensional pareto front of figure 2.

Point D will be excluded from the succeeding analyses due to its similar behaviour to point A, thus the conclusions would be redundant. Observing figure 2, point C provides the best resilience metric improvement for similar a degradation of the flow time function compared to the other solutions. This point is also of interest to analyse since it maintains a low flow time value but fully meets customers' demand, as well as balances outsourcing needs between nearshore and offshore solutions.

Table 2: Payoff table of the deterministic model for priority 1

	ResMetric	FlowTime	Profit
max RM	1,000	50 734	396 305
min FT	0,146	7 987	97 666
max PF	1,000	51 124	396 403

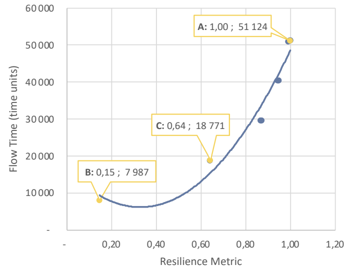

Figure 2: Two-dimensional representation of the deterministic model multi-objective solution

Table 3 presents the values of performance indicators of the selected solutions to further comprehend their difference. Multiple conditions aggravate the disparity between point A and point B. Firstly, the flow time OF 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%. This accounts directly for 0,10 difference in the resilience metric, being the remaining ≈0,75 decrease due to the deviation of the profit from its reference value. The amount of lost sales directly impacts the revenues, but does not singly justify the profit decrease. The selection of outsourcing options weight significantly in clarifying this difference.

Table 3: Deterministic model performance indicators of selected solutions

Point	SL	TMC	TEC	Capacity expansion (units)			
				f_5	f_6	f_7	f_8
A	1,0	175121	2250	-	-	-	-
B	0,9	428093	18118	-	-	54	239
C	1,0	324923	14473	-	204	-	119

SL: Service Level; TMC: Manufacturing Cost; TEC: Capacity Expansion Cost

Overall, the distinction of the three SC configurations that the points represent is mostly driven from production related decisions. Point A concentrates production internally, even increasing the capacity of f_2 by 75 units while point B only operates with outsourcing production facilities leaving the owned factories idle. Point C only scarcely selects f_1 for production, receiving most products from outsourcing options.

Some general recommendations can be provided depending on a final DM's preference. Foremost, it is important to have a clear understanding of financing targets that may be required to achieve. Point B stands out in this regard by exhibiting a far lower profit value as compared to the other solutions. Such low income may not be appealing to achieve even if the flow time is a high priority. To overcome such concern, it would be recommended to study the implementation of an additional restriction that would guarantee the delivery of a profit level more in line with the DM's goals.

Similarly, point A may lead the SC to operate under a total flow time which could not be of interest. The elevated time consumed from supply to the delivery to the final consumer may hinder the business to react swiftly to demand spikes or other sudden events.

Lastly, point C delivers a solution that mitigates these former two concerns. Nevertheless, such as point B, these solutions present a high reliance on third parties for production necessities. The loss of control provoked by the selection of outsourcing should be taken into consideration, developing an assessment on the resilience of said entities.

Deterministic model disruption analysis

The disruptions to be modelled are separated into three types according to the SC activity they affect, and are run independently, namely to supply, production and transport activities.

Uncertainty will also be explored regarding the length of the disruption as well as the time necessary to sense the disruption took place. Firstly, the disruptions will be modelled to take place at t_{10} for the duration of two and four weeks. This allows to understand the impact of each disruption type on the SC and the necessary corrective measures taken, and if such conclusions remain unaltered for longer disruptions. However, as past experiences have shown, identifying disturbances in the SC may not occur immediately. It will be considered a case in which a four week long disruption takes place, but only after two weeks such event is recognized and dealt with.

- **Point A**

Table 4 presents the results obtained taking point A as the decisions taken prior to any disruption, separated by the varying disruptions' length. As to be expected, the scenarios with a four weeks long 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 in order to sustain operations continuity, but also to other cost increases resulted from spoilages and decreases of revenue.

Table 4: 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

Regarding the type of disruption, it can be viewed that for all scenarios a production related disruption causes the highest impact to the resilience metric. This type of disruption is also the only one to incur in additional costs due to raw material spoilage. 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 uncapable to initiate production, all materials that exceed the storage capacity of the factory are considered as 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.

Figure 3 exhibits the capacity expansions experienced in the cases here considered. Indeed, the delayed sensing cases present the most elevated need for production capacity expansions, as well as the only situation where a nearshoring option is recurred to, in particular for production and transportation type disruptions. Such demonstrates the necessity of rapid solutions when a disruption has already been ongoing.

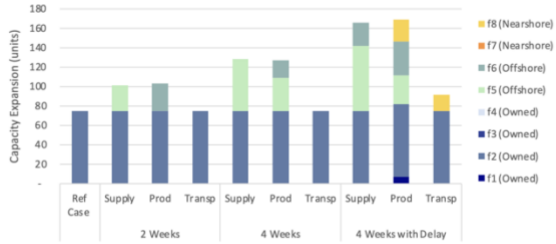

Figure 3: Capacity expansions of the deterministic model under disruptions, fixing point A

The disruptions tested, in general, also provoked a decrease in revenues even in cases with full met demand. This is justified by the decision to increase the delivery of alternative products with a lower production time across all disruptions.

Figure 4 plots the sales over time for the cases where demand was not fully met. From the studied cases, all transportation disruptions incurred in a slight drop in sales.

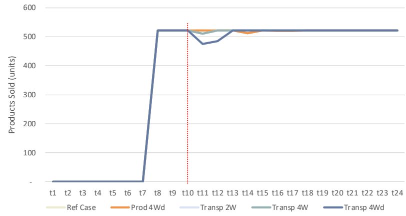

Figure 4: Sales level over time of the deterministic model under disruptions fixing point A

Within this type it is visible that not only does the four weeks disruption with delay present the highest sales decline, its' return to regular sales values takes longer than for the case of a disruption with the same duration but that is immediately sensed. This latter case can recover after two weeks and stabilize sales even though the disruption remains ongoing.

- **Point B**

For the case in which the first stage decisions are fixed to achieve point B, the overall results are presented in table 5. The minimum flow time value from the reference case remains unchanged for all the tested cases. Likewise, the service level also steadies at 90% since it is the minimum percentage of the total demand that needs to be satisfied, however at a cost of the profit level that is achieved.

Table 5: 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

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

Similarly to point A, the production disruptions incurred in higher costs than the transportation disruptions. Overall, the production decisions across cases shifts only between the two nearshoring factories that were already in use (f_7 and f_8), thus continuing to deliver a reduced resilience metric value.

- **Point C**

Taking now the trade-off point as the first stage decision, the results of table 6 are obtained. Due to the higher computational effort these results were, exceptionally, attained running with a 1% gap.

Table 6: Deterministic model results considering disruptive events, fixing decisions of point C

Case	Res Metric	Flow Time	Profit	SL	Revenue	TMC	TTC	TDC	TIC	TEC
Ref	0,642	18 771	254 643	1,000	628 612	324 923	21 116	13 194	263	14 473
2 Weeks Disruption										
Supply	0,776	29 368	307 547	1,000	630 984	264 294	32 393	10 868	287	15 595
Prod	0,763	31 374	306 923	0,989	624 961	258 290	34 585	9 829	242	15 092
Transp	0,778	31 837	311 407	0,993	627 620	256 556	34 985	9 930	268	14 473
4 Weeks Disruption										
Supply	0,777	30 342	307 939	1,000	631 690	263 486	33 485	10 933	252	15 595
Prod	0,753	30 531	303 174	0,988	624 320	260 515	33 680	10 299	243	16 409
Transp	0,778	31 796	311 476	0,993	627 409	256 402	34 894	9 903	262	14 473
4 Weeks Disruption with Delay										
Supply	0,742	27 214	294 224	1,000	631 672	277 431	30 011	11 862	249	17 895
Prod	0,698	27 376	283 434	0,983	620 418	274 918	30 322	10 890	235	20 619
Transp	0,735	28 587	295 188	0,990	625 289	271 365	31 472	10 949	223	16 092

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

It is visible in figure 5 that that production at owned factories for the disruptive cases increased from the reference case as a mean to reduce costs, also reducing production of the nearshore alternative across all cases. Nonetheless, it can also be observed that outsourcing production is higher for the cases of delayed responses, meaning that owned factories lacked the capacity of rapid responses when needed.

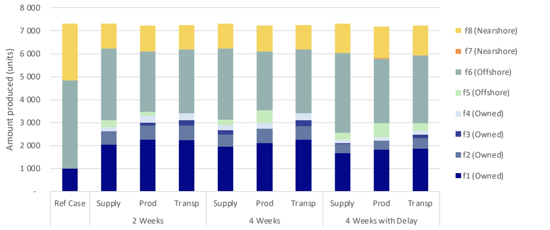

Figure 5: Amount produced by each factory for the deterministic model under disruptions, fixing point C

Once again the production type disruptions proved to degrade the resilience metric the most (table 6), however, for this configuration no spoilage of raw materials was verified. Regarding the length of the disruptions low declines are verified by increasing the disruptions' length from two to four weeks, being far more impactful the delay in responsive actions.

Concerning the service level, only the supply disruption was capable to maintain the full satisfaction of customers' demand. Figure 6 presents the sales level over time for the transportation disruption cases. The drop in sales for a 2 week disruption is barely noticeable. It is also visible that delaying the responsive actions will also increase the time it takes to resume regular sales levels.

To sum up, the three analysed points despite their diverging behaviours still present some communalities in terms of the results. In short, the following conclusions can be withdrawn:

- A production type disruption with delayed responses affects most negatively the resilience metric;
- Transport related disruptions are more likely to produce lost sales;
- Delayed responses also delay the returning to a steady-state of operation even compared to a disruption with the same length.

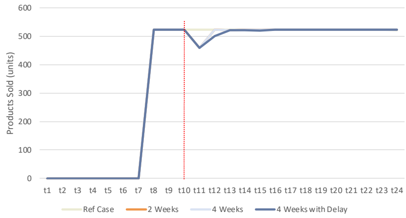

Figure 6: Sales level of the deterministic model, fixing point C under a transportation disruption

7. Stochastic model results

The results are obtained using GAMS software running the CPLEX solver with a gap of 1%.

For this model the customer demand and the products' return rate will be modelled as uncertain parameters following the approach described previously. In this case study, for the planning horizon of 24 weeks, information regarding the uncertain parameters is updated every two months with a optimistic, realistic and pessimistic variation. The variation is applied at the first time period of each stage, remaining constant for the succeeding periods. The probabilities of the arcs leading to an optimistic or pessimistic node are of 25%, and of 50% for the realistic case. Likewise, the variation of the demand values depends on the type of node of the tree, whether it is a optimistic, realistic or pessimistic scenario a variation of +10%, +5% and -10% is applied, respectively, while for the product return rates the variations are of +10%, +5% and 0%.

__Reference case analysis__

Table 7 presents the payoff table considering the same priority as for the deterministic model. Once again optimizing the resilience metric or the profit firstly will result in approximate solutions.

Table 7: Payoff table of the stochastic model for priority 1

	ResMetric	Flow Time	Profit
max RM	0,984	48 674	414 608
min FT	0,200	8 271	124 640
max PF	0,979	46 873	412 693

Due to the higher complexity, this model was run bi-objectively obtaining the pareto front in figure 7 for the optimization of the resilience metric and flow time. No in-between solution was analysed (point C) due to the higher computational effort it required.

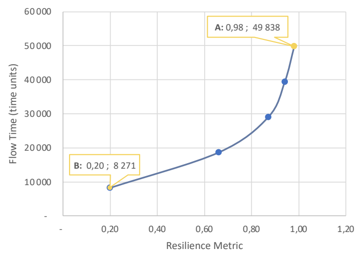

Figure 7: Pareto front of the stochastic model with the resilience metric and flow time as OF

Comparing these values to the ones obtained for the deterministic model, it can be viewed that the present model returns a higher level of profit from the former 396 305 and 97 666 for point A and B, respectively. This is due to the variations assumed for the uncertain parameters. Both optimistic and realistic branches of the scenario tree account for a rise in demand values, thus jointly enforcing the achievement of higher sales volume, consequently, increasing total revenues. The scenarios that account for a rise in the products' return rate also contribute to reduce manufacturing costs from the previous value of 175 121 and 428 093 for point A and point B, respectively.

Regarding the flow time, the stochastic model achieves a higher value from the previous value of 7 986,60 due to the need of delivering and collecting a more elevated volume of products.

Stochastic model disruption analysis

The two previously analysed points 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 for the deterministic model.

- **Point A**

This point values primarily an appealing outcome of the resilience metric, and through the results obtained in table 8 it can be concluded 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 notable degradations of the resilience metric as opposed to the results where immediate responses are implemented. The case with a largest decrease of the service level is for a transportation type disruption with a delayed response.

Table 8: 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

The cost indicator with the highest increase for supply and production disruptions is the total manufacturing cost, consequence of the production capacity expansion, as its' indicator also increases. Once again there is a preference for offshore alternatives to deal with the disruption (f_5 and f_6), since they offer lower costs. Nonetheless, for more extreme conditions, as it is the case for lowest performing solution, nearshore options are selected (f_7 and f_8). Like the deterministic model results, such occurs for the production and transportation cases.

Regarding the spoilage of items, these results corroborate that lagging in the necessary adjustments to shipments will continuously aggravate the excess of raw materials arriving to production facilities that are unable to be used.

- **Point B**

Table 9 presents the results of a SC configuration 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 type of disruptions. Nonetheless, meeting this value requires the degradation of the profit obtained throughout the planning horizon as well as the resilience metric.

Similar to point A, the disruption to economically strain the results the most is of the production type with a delayed response. On the other hand, all the supply type disruptions present negligible deviations from the reference case due to the same reasoning stated previously for the deterministic model results.

In sum, this section supports the conclusions stated previously for the deterministic model. The implementation of uncertain parameters lead to different numerical outcomes, however, maintaining coherent the major decisions taken.

Table 9: 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

8. Discussion

Overall, the cases here studied shed light on the critical role that time plays in SCM when faced with disruptive events.

To better visualise effect of the different length of a disruption, figure 8 demonstrates the decline of the resilience metric incurred between a two weeks and a four weeks long disruption (blue bars), as well between four weeks and four weeks with a delayed response disruptions (yellow bars). Figure 9 serves the same purpose for the results of the stochastic model.

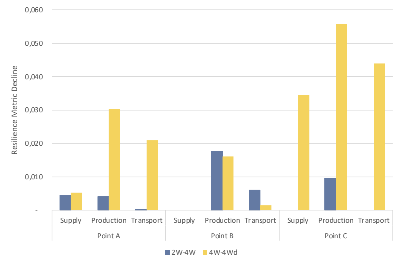

Figure 8: Decline of the res metric of the deterministic model results

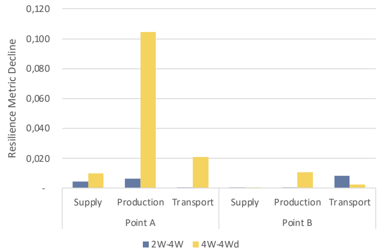

Figure 9: Decline of the res metric of the stochastic model results

It is immediately visible that lagging in sensing the presence of a crisis and adopting corrective measures presents in general more deteriorating effects than increases to the disruptions' length. Relative to the deterministic model, the solutions by fixing point C as first stage decision resulted in the highest decline of the resilience metric when considering these delayed responses. Thus, balancing the three objective functions did not leave the SC prepared to maintain an elevated level of the resilience metric.

The differences between the deterministic and stochastic model did not display highly contrasting decisions and conclusions. However, a deviation between both models is verified regarding the value of the objective functions. Given the assumed variations of the uncertain parameters, the results of the stochastic model returned better outcomes.
Both models demonstrated that despite spoilage of raw materials being probable to occur when dealing with a production related disruption, their volume is somewhat insensitive to the length of the disruption. If the event is sensed immediately, unnecessary orders are shipped and, consequently, the amount that gets disposed of stabilizes. With delayed responses excesses will continuously be shipped, and depending on the industry such can become even more damageable if we were to consider, for instance, perishable products.
Throughout the analyses, the option to activate redundant capacity at owned factories was not resorted to as a measure to tackle SC disturbances, relying most commonly on outsourcing facilities. The outsourcing solutions in this example where designed to provide rapid deliveries of the required product by not accounting for any production time, varying mostly on cost and market distance. Therefore, the expansion of the production capacity of owned factories did not prove to be an appealing means to mitigate consequences since any owned facilities would still require regular production times. Additionally, within the outsourcing options it was noted that nearshoring options, despite its elevated costs, were deemed necessary to deal with the most straining conditions to the SC.
In the same line, the selection of alternative products was concentrated to option 1 of the designed solutions which allowed a lower production time. The options that provided flexibility for the products to be produced in a wider range of facilities or to require a reduced amount of raw materials were not selected.
Managerial insights
Ultimately, supported by discussion of the results of this work, SCs face a dire need in improving network visibility and enhance communication between entities. While long lasting disruptions can cause severe damages to the normal operating conditions of a company, lagging in responsive actions not only accentuates such consequences but also may impact their competitive advantage in the long term, as they struggles to return to a steady-state.
The consequences of disruptive events have proven, in general, to be identical between SC configurations that value the OFs differently. Nonetheless, the decisions taken to diminish such impacts differ from one another. This highlights the importance of OR models that are capable to incorporate a multitude of options to deal with disruptions, providing DMs with a range of solutions suited to their specific capabilities.

9. Conclusion and future work

The work here developed addressed the need to further extend the extant literature on quantitative approaches in the emerging field of SCR, focusing on the tactical-operational level. Towards that end, a production, distribution and capacity planning model is tailored to retrieve insights on the weight of timely responses in the aftermath of disruptive events, and which decisions are key to sustain operations. A SLR is performed a priori to ground the scope of the subject.
SCR has been gaining gradual developments over time, becoming now with the pandemic a very current subject and a concern for most companies. The relevance of SCR is sustained by the SLR, however noting the need to enrich the literature on tactical-operational models that incorporate a high level of uncertainties, for a more accurate representation of disturbances.
In order to meet this need, the model developed accounts for three sources of uncertainties, namely, in selected parameters, the time frame of a disruption, and its source. A novel approach was developed to address the first source of uncertainty by adopting a scenario tree approach to cluster time periods into stages.
This work performs a parallel analysis of the results obtained through a deterministic and stochastic model, which required a noteworthy increase in computational effort between both models. The stochastic approach may present even less appealing computation times were it applied to a more complex case study, being therefore of interest to consider alternative solution approaches for future applications.
Furthermore, it is well acknowledged that responsiveness and cost-efficiency are conflicting measures, thus the present study addressing three objective functions; profit and flow time as well as a resilience metric. It was shown that to achieve the optimal flow time significant financial resources would be required which may not be appealing to a DM, as well as limiting the service level to achieve the minimum target. Future efforts should be made to better integrate these concerns in a measure of flow time.
The results proved that delayed responses have in most cases a higher impact on performance indicators than lengthier disruptions. Also, the designed options that delivered time efficient solutions prevailed in the decisions taken to overcome impactful disruptions. Nonetheless, it would be of interest to apply a broader selection of these options to cases with different characteristics to corroborate these conclusions. This would also contribute to the limitation of this work being based on an generic case study, whose data is based on a large amount of assumptions, further adding to the results' uncertainty.

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