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Towards a model assessing supply chain resilience strategies

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Abstract

The ongoing pandemics has shown that the resilience of our global supply chains can be strengthened. Several mitigation strategies can be put in place in order to respond to major disruptions, but assessing their performance is still a challenge. This article proposes a review of possible disruptions and the main drivers to improve the SC resilience. This leads us to propose a list of risk mitigation strategies that could be adopted to prevent or react to disruptions, and a list of resilience indicators. Finally, a methodology is proposed to assess different mitigation strategies under comprehensive disruptions scenarios, regarding various resilience indicators.

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Keywords: Supply chain; Resilience; Mitigation strategy; Optimization

1. Introduction

Supply Chains (SC) around the world being increasingly interconnected, a disruption at any point can threaten the entire network. In a world facing a growing number of uncertainties and disruptions, this dependence makes the network more vulnerable. Covid-19 is one of the most recent examples: we have all seen how this unpredictable and uncontrollable pandemic has greatly weaken the supply chains of our global system.

March and Shapira describe risk in SC as “the variation in the distribution of possible SC outcomes, their likelihood, and their subjective values” [20]. This variation or disturbance then represents a radical and sudden change. The sources of risk can be environmental, organizational or economic, concerning e.g. cost, quality or market share, and cannot be defined with certainty [16]. In particular, Jüttner et al. explain that a risk can result from a more or less sudden incompatibility between market demand and the capacity of the SC. Thus, a risk is a probable event (disruption), the consequence of which, if it occurs, affects the demand and/or the capacity of the SC. Depending on the nature and severity of the disruption, the impact can range from a single factory to the entire SC. SC must put in place strategies to manage these risks to adapt to unforeseen and heavily impacting circumstances, and thus become more resilient. The growing importance of the notion of resilience in SC, especially in light of the current pandemics [29], calls for defining and measuring this new characteristic. What does the word “resilience” mean for SC? How do companies characterize the resilience of their distribution network? Is resilience a measurable performance?

This article addresses these questions through two main contributions: (1) a review of the literature on several dimensions: the possible disruptions, the main drivers to improve the SC resilience, the risk mitigation strategies that could be adopted to prevent or react to disruptions, and resilience indicators ; (2) a methodology to assess different mitigation strategies under comprehensive disruptions scenarios. We assume the SC is a mature one, with steady production under normal conditions, and thus do not include its ramp-up phase in this study.

Several state-of-the-art articles already exist regarding SC resilience [27, 6, 14, 13]. The most recent one by Golan et al. [11] focuses on the modeling and quantification of resilience, studying 141 papers to compare their approaches and models. Although SC resilience is an emerging subject in many research works (especially in the light of the Covid-19 crisis), they note that “systematic studies on how it is defined and modeled are still rare” [11].

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Four stages of defining the resilience of a SC defined by the National Research Council [23] are common to more than half of the texts collected :

Plan The company anticipates potential problems (disruptions) and sets up action plans for these scenarios. This can be done through the creation of documents (procedures, FMEA, insurance, etc.) or through measures in the field (safety stocks, distribution of production on different sites, etc.). The more the company secures its SC in this planning phase, the less the impact of the disruption on the system should be in the following stages (Absorb, Recover).

Absorb Over the period immediately following the disruption, the SC normally perceives its negative effects to its maximum. As with a mechanical shock in a car accident, a system will be expected to absorb the impact as much as possible in order to limit the damage. In the case of SC, observing the decrease in performance caused by the disruption might assess the absorption capacity.

Recover After the shock comes a phase where the objective is to return to normal conditions. The system is expected during this recovery phase to improve as quickly as possible and under the best conditions. As an example, Menoni and Schwarze [21] propose mitigation measures for this phase in the context of the Covid-19 pandemic.

Adapt Once the storm has passed, the company can learn from the ordeal it has gone through and evolve to become stronger. This transformation helps to increase resilience.

In short, to ensure their functions and successes, the actors of the SC must plan various means of absorption, recovery and adaptation following disruptions that can vary in sizes, impacts and probabilities of occurrence. Therefore, the National Research Council defines resilience as "the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events" [23].

Although this multicriteria view of resilience has developed in recent years, many authors continue to address only certain aspects. New approaches reflect a better understanding of resilience as a complex property of interconnected systems.

This paper starts with a review of possible disruptions in our constantly changing world. Then we discuss about the main drivers to improve the SC resilience. This leads us to propose a list of risk mitigation strategies that could be adopted to prevent or react to disruptions, and a list of resilience indicators. We conclude proposing a methodology to assess different mitigation strategies under comprehensive disruptions scenarios, regarding resilience indicators.

2. Review of possible disruptions

Disruptions on the SC can happen on each of its components, commonly identified as Plan/Source/Make/Deliver/Return in the SCOR model [2]. Table 1 lists those disruption as well as their possible impact, for each stage. Disruptions on the "plan" process can have many origins (as observed e.g. in the food SC during the Covid-19 pandemics: panic buying behaviors regarding key items, or change in consumption patterns away from the food service sector to meals prepared and consumed at home [13]) but ultimately result in a sudden and significant change in customer demand. Disruptions in the "source" and "make" processes respectively change the available supplier and production capacity. Finally, disruptions on transport ("deliver" and "return" processes) can have very different origins (pandemic, natural disaster, gasoline shortage), impacts (cut road, price increase, change of mode of transport) and areas of action (ports, railways, land routes).

3. Drivers to improve supply chain resilience

Many works in the literature concur to identify the key characteristics and drivers of SC resilience. In this section, we review those drivers, i.e. key components of SC resilience that will afterwards be combined into mitigation strategies.

3.1. *Planning*

Representation of the central decision-making SC processes, i.e. planning, command and control of the SC, is necessary to model and then assess the resilience of a SC. Managers must exploit several technologies and tools to help manage risk as effectively as possible: risk mapping and visualization tools reflecting all aspects of the chain, modeling and simulation technologies and global information management systems. Approaches have evolved drastically in recent years, from their lack of consideration in assessing resilience (because it was assumed that decisions taken were not supposed to evolve [8]) to the application of Artificial Intelligence and Machine Learning techniques more recently [3]. Other approaches include optimization (optimizing multiple objectives for designing supply networks among proposals for multimodal multi-route transportation solutions [1]) or "if-then" reaction strategies [17, 25]. Rajesh [25] examines agent-based decision control through four SC managerial processes: supplier relations management, customer relations management, internal SC management, and managing external environments. This is however not a centralized decision-making process.

3.2. *Transportation*

The representation of transport networks is essential because transport, be it by sea, land or air, makes the vitality of the SC. Transport is a significant improvement lever for companies and several avenues have been proposed in the literature. Resilience can be first taken into account when making investment choices relating to transport, as suggested by Ganin et al. [9] regarding the urban areas of large American cities.

To avoid a disruption in their supply (or delivery) chain as a result of a disruptive event (e.g. pandemic, natural disaster, gasoline shortage, cut roads. . .), companies will look for alternative solutions to move goods by an alternate route. Itinerary

Table 1. Possible SC disruptions and their impact

	Event / disruption	Impact on the SC
Plan	Shortage/price change of a basic commodity (eg: toilet paper, food products during lock down)	Increase in demand from all customers
	New regulation that prohibits a product ; brand scandal Sudden change in consumption patterns	Reduction in customer demand
Source	Explosion, strike, supplier bankruptcy Global lockdown A supplier obtains a monopoly / is the only reachable one	Reduction in the production capacity of a supplier Reduction in the production capacity of all suppliers Increase in quantities purchased from one supplier, and set to 0 at others
Make	Explosion, strike, epidemic in a factory Global lockdown	Sudden and significant reduction in the production capacity of a factory Reduction in the production capacity of the factories
Deliver/Return	Embargo of a country, strike/explosion at a port A mode of transport becomes unusable (planes can no longer fly, trucks can no longer drive)	Impossibility of using the usual route Impossibility of using a type of transport

changes are common practice in the logistics sector to deal with hazards, but they are part of a crisis decision taken after the disruption occurred. To use it as a driver for improving resilience in a model, it would be necessary to determine the alternative routes in advance, in order to assess their interest: "redundancy within transportation networks in the event of a natural disaster could enable a SC to use nonstandard and more expensive routing options to ensure continuity" [14].

Another driver lies in providing for alternative methods of transporting goods [27]. Multimodal transport provides several means of transport available for the same route (truck, plane, helicopter, bicycle, etc.), thus makes it more likely that at least one mode can use a route. Several carriers can also be contracted at the same time, in order to be able to temporarily transfer the load from one carrier facing difficulties to another. For example, a transport company that is slowed down because of a strike could call on a partner company to take over part of its activity.

3.3. SC structure

Different parameters of SC structure can improve its resilience. To minimize the impact of a disruption on the performance of a Supply Chain, one driver could be to design the network of the SC including a diversification at all stages. A SC with multiple suppliers, multiple manufacturers, warehouses, located in different geographical regions, will be likely to adapt more easily is case of a disruption impacting one node of its network. The segmentation of the SC, by separating products with different risk characteristics (not produced in the same plant, material not sourced from the same suppliers), and regionalizing supply chains also helps to limit the impact of disruptions [5]. For example, the United States, European Union and India have regionalized their healthcare industry supply chains in response to the Covid-19 pandemics, by restricting exports to ensure local supply.

4. Possible mitigation strategies

To deal with risks and their possible consequences, supply chains implement risk mitigation strategies, defined as "the identification and management of risks for the SC, through a coordinated approach amongst SC members, to reduce SC vulnerability as a whole" [16]. The strategies, combining different resilience drivers, are therefore multiple and depend on the nature of the risk. Their common role is to allow the SC to return to its initial state (before the disruption) in the fastest and cheapest way possible.

Table 2 lists the different strategies found through four literature review articles literature. These strategies are detailed in the next sections, organized in preventive and reactive categories as defined by Thun et al. [28].

Table 2. Possible mitigation strategies from the literature

	[27]	[13]	[6]	[14]
Strategic stock	x	x	x	x
Flexible supply base / Multiple sourcing	x	x	x	x
Facility / Supplier dispersion		x	x	x
Flexible transportation (multimodal, multi-carrier)	x			x
Postponement	x		x	
Back-up supplier			x	x
Rerouting				x
Make and buy	x	x		
Revenue management (dynamic pricing, promotion)	x			
Substitution				x
Assortment planning	x			

4.1. Preventive risk mitigation strategies

Strategic stock or safety stock is one of the first drivers used to manage risk in a SC. To keep holding costs reasonable, firms can pool extra inventory in strategic locations close to factories and distributors.

Multiple sourcing strategy working with different suppliers shares the risk and allows a better service rate than with a single supplier [14]. However, it reduces potential economies of scale made by massifying orders.

Facility or supplier dispersion reduces the impact of a risk limited to a single geographical area ; for example, if a hurricane hits the United States, the company can rely on its plant in Japan.

Flexible transportation with either multi-modal or multi-carrier transportation, as mentioned in subsection 3.2.

Postponement shifts the point of product differentiation through standardization or modularity [27], reducing demand uncertainty by massifying production as much as possible and delaying product customization.

4.2. Reactive risk mitigation strategies

Back-up supplier to supplement or temporarily replace the main supplier [12].

Rerouting in case the main route is inaccessible (e.g. traffic jams, roadworks or crowded port unable to process containers [14]).

Make and buy since companies that can produce part of their product and outsource the rest have a more flexible SC.

Revenue management via dynamic pricing and promotion, i.e. changing the selling price of a product, is an effective way to influence its demand [27].

Substitution of a usual raw material by a similar one, until the situation returns to normal.

Assortment planning the location of products on the shelves of a store can influence customer choices and thus impact customer demand [4].

4.3. Challenges in implementing mitigation strategies

According to Tang [27], three major challenges can be noted in the implementation of this type of solutions. First, although these solutions safeguard the SC from major disruptions, their return on investment is difficult to assess since they may never happen. A trade-off must be made between spending money to prepare for a disruption that will never happen and spending money to deal with a disruption that has not been anticipated. Secondly, risk mitigation strategies can go against the overall corporate strategy. For example, the company's strategy may be to massify its orders by working with only one supplier, whereas to be more resilient, the company must have more than one. Finally, to be effective, the strategy must be adapted to the risk ; but a strategy can be useless for one type of risk, or even counterproductive for another. For example, a multiple sourcing strategy might not suffice when a global pandemic breaks out. Companies therefore need to combine different strategies in order to cover a wide range of different risks and situations.

5. Resilience indicators

Measuring resilience with a dedicated indicator is a rather difficult task, that has been tackled from various entry points in the literature.

One entry point are the various internal and external obstacles that prevent a SC from having resilient capacities : Rajesh [25] proposes to measure barriers to resilience, but such a qualitative approach makes it hard to reach a quantitative metric.

Another approach, highlighted by Golan et al. [11] in their literature review, is to measure "resilience proxies", i.e. metrics that do not quantify supply chain resilience directly, but are quantitatively leveraged to compare the effects of certain resilience techniques or tools on the networks (e.g. preservation of market shares, backlog, product depreciation, expected disruption cost or total direct losses, delivery delay...). Many authors combine multiple proxies into an aggregated resilience metric, either by expressing all proxies through costs and using the total cost as an aggregated metric, or through multi-objective methods (e.g. AHP [18]).

Some researchers offer a graphical approach to the question. The company's performance over time is modeled in a graph, and the analysis of the characteristics function provides information about the resilience of the system (see Figure 1).

Munoz and Dunbar [22] use a simple model for their graphical approach, plotting time on the x-axis and performance, captured by the service rate (percentage of orders fulfilled), on the y-axis. The evolution of performance ("recovery curve") is observed from the time of the disturbance until the service rate exceeds 95%, considered as the return to normal. Several indicators are taken from this graph, each allowing to assess a specific dimension of resilience. The authors recommend combining these different indicators in a weighted sum to obtain an overall resilience score. Li et al. [19] critic such approaches based on the recovery curve to assess resilience, and propose an improved calculation method, which uses the so-called "maximum allowable recovery time". This new parameter puts supply chains on an equal footing by setting a time limit for recovery, defined by the user and depending on the type of SC. Besides the service rate, a second metric is introduced: the average distance traveled by products (cost of transport).

Another proxy that is widely used is the total cost of resilience (taking into account both the cost of preventive measures, and the cost incurred by the disruption if it happens). Indeed, improving supply chain resilience can contradict the traditional focus on improving a company's financial performance. Although both approaches deal with risks, recurrent risks (such as SC demand fluctuations) require companies to focus on efficiency, while disruptive risks require companies to build resilience despite additional cost [5].

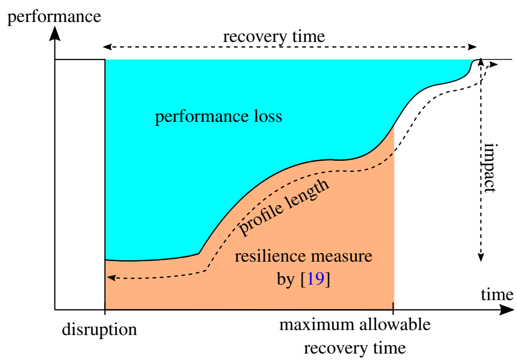

Fig. 1. Various resilience measures based on the recovery curve

Table 3. Overview of case study research works assessing SC resilience (* = several)

	Rezapour et al. [26]	Zhao and You [31]	Yavari and Zaker [30]	Fattahi et al. [7]	Ghavamifar et al. [10]
Supplier	*	*	0	0	0
Manufacturer	1	*	*	*	1
Warehouse	0	0	*	*	*
Retailer	*	*	*	0	*
Market / Customer	*	*	*	*	*
Customer return	No	No	Yes (constant rate)	No	No
Factories capacity	Constant	Constant	Constant	Stochastic	Constant
Demand	Variable /retail price	Constant	Constant	Stochastic	Stochastic
Multi-product	No	Yes	Yes	Yes	Yes
Perishable product	No	No	Yes	No	No
Multi-period	No	Yes	Yes	Yes	No
Competing for market share	Yes	No	No	No	No
Risk mitigation strategies	Extra production capacity at supplier, multiple sourcing, Extra inventory at the retailers	Extra capacity for manufacturers	Two network integration	Some facilities are fortified against disruption	No
Case study	Automotive industry	Several	Dairy industry	Glass industry	Automotive services

6. Methodology for SC mitigation scenarios assessment

We have seen that many risks of different natures can disrupt supply chains and deteriorate their global performance. Several strategies can be applied to minimize the impact of such disruptions and improve SC resilience. This resilience can be measured thanks to a set of metrics. The challenge is to choose the best risk mitigation strategy to implement, in order to protect the SC and make it more resilient. Optimization methods could be useful to assess the resilience of a SC under various disruption scenarios. In this section, we propose a methodology, composed of five steps (Figure 2), that can be followed to help companies get prepared to face disruptive situations.

The first step is to create an optimization model of a generic SC network, configurable in order to match with the reality of a large number of companies. Table 3 gives an overview of research works having proposed to assess the resilience of a supply chain, especially based on case studies. We propose to build a model able to handle several suppliers, manufacturers, warehouses and retailers, but to pass up with customer return. At a first stage, we suggest to consider only one non perishable product, with a deterministic demand, but to include several transportation modes. We propose to use Integer Linear Programming to determine the best values for variables (production, inventory, delivery) over a given time horizon, that optimize the objective (minimize the cost), and satisfy all constraints (demand fulfillment, capacity limitation at each supply chain level, flow conservation at each node).

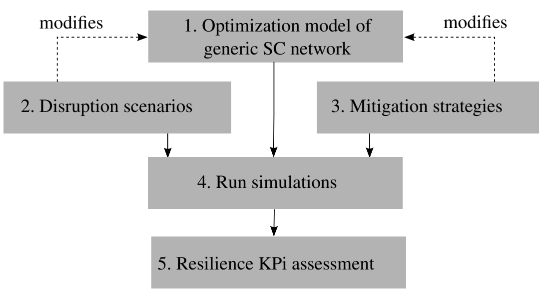

Fig. 2. 5-step methodology for SC mitigation scenarios assessment

The second step is to develop various disruption scenarios and translate them as modification in the parameters of the SC model created at the previous step, as in Table 1. For example closing a border, as in the case of the pandemic, will result in the cutting of a road between a supplier and a production plant.

The third step is to select mitigation strategies to reduce the disruptions impact on global performances. A strategy could also be modeled as modification in the optimization model. For example, strategy "implementing extra production capacity" will result in changing the capacity data of a manufacturer.

The fourth step is to run simulations combining disruption scenarios and selected mitigation strategies.

The fifth step is to define resilience indicators useful to compare the results of the simulations and help the decision maker choose the mitigation strategy leading to the best SC resilience. We propose indicators reflecting the ability of the SC to recover from the disruption :

- Recovery time;
- SC performance, given by the service rate for all customers over all periods;
- Total costs (transport, storage and delay in the delivery);
- Inventory levels of raw materials and finished products in all level.

These indicators should be measured after each simulation. We propose to rank the indicators using the AHP method [24]. This will lead to establish weights associated to each indicator, the weighted sum of the indicators being an aggregate metric to assess the SC resilience in all simulations.

At each step, we rely on the previous literature review as input to define the SC model, the disruption scenarios, the mitigation strategies and the resilience indicators.

7. Conclusion and perspectives

This article tackles the question of SC resilience through a review of the literature on several dimensions: possible disruptions, main drivers to improve the SC resilience, risk mitigation strategies that could be adopted to prevent or react to disruptions, and resilience indicators. Building on these reviews, we propose a methodology to assess different mitigation strategies under comprehensive disruptions scenarios, regarding various resilience indicators.

Several avenues are open for future research. First, the proposed methodology needs to be implemented and tested on several case studies in order to validate it. The obtained model might support trade-off decisions between SC resilience and financial performances, including the cost of implementing mitigation strategies. Lastly, extraordinary disruptions might need to be considered on the scale of viability, calling for specific indicators that go beyond the resilience aspects, including e.g. agility and survivability [15].

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