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Resilience metrics in the assessment of complex supply-chains performance operating under demand uncertainty☆

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ABSTRACT

The design and planning of resilient supply chains is a major challenge due to the increasing complexity of these systems that operate in a global market and therefore are more exposed to disruptions. In the present work a design and planning model that integrates demand uncertainty is applied to five supply chain structures that are submitted to different types of disruptions. Disruptions are modelled in a probabilistic manner, resulting in the incorporation of two sources of uncertainty. Eleven indicators are considered to assess the supply chains' resilience, which comprise network design, centralization and operational indicators. The goal is to provide managers what are expected operational impacts (measured by the operational indicators) by assessing the behavior of network and centralization indicators and their known resilience behaviors from the literature. A case study of a European supply chain is used to illustrate the methodology and a discussion on the results obtained is presented in order to conclude which main characteristics a manager should consider when designing and planning resilient supply chains.

1. Introduction

Nowadays supply chains (SCs) are becoming more complex and simultaneously more vulnerable to disruptions. This is due to many causes as supply chains operate more and more over a global market, under constant market changes caused by technological innovations and costumers needs that increase demand volatility. Furthermore, cases of potential disruptions caused by unexpected natural causes or man-made disasters such as earthquakes, fires, equipment breakdowns, labour strikes, economic crisis or terrorist attacks are becoming more frequently reported, with descriptions of their highly damaging effects on SCs [32]. All these events have a low probability of occurrence but when happening may cause a significant business impact [27]. In this way, SCs must adopt new strategies to improve their ability to respond rapidly and cost effectively to unpredictable changes [6]. In order to do that, decision makers have to incorporate the concept of SC resilience when designing and planning these systems [8]. The need of accounting for resilience, under the threat of foreseeable disruptions, has been recognized by academics and an increasing number of papers have been published in this area, however there is still a lack of quantitative decision support models to deal with such events [34,12,20].

The present paper aims to contribute to this field by identifying main SC characteristics that a decision maker should account for in order to design and plan a resilient network. To this end, the behavior of three operational indicators – expected net present value, expected customer service level and investment level – will be assessed against literature based resilience indicators—network and centralization indicators. A Mixed Integer Linear Programming (MILP) formulation is developed, based on a previous work of the authors [5] that considers demand uncertainty, the modelling of all indicators and a generic SC structure. This SC contemplates five echelons, namely raw materials suppliers, plants, warehouses, final products suppliers and markets, thus allowing the modeling of the main supply chains operations, i.e. production, assembly, storage, distribution, collection, sorting, remanufacturing and disposal. Reverse supply chain activities are considered simultaneously with forward supply chain activities resulting into the modeling of closed-loop supply chains, structures that have been the focus of an increasing interest by both companies as well as academics [5,13]. The proposed model is applied to five types of networks with different levels of flexibility in terms of transportation links, ranging from a simple forward SC to a more complex closed-loop supply chain (CLSC). These networks are subjected to disruptions that affect different echelons and the analysis is conducted considering that each disruption has given probability

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of occurrence, which originates the modelling of two sources of uncertainty—demand and disruption.

The paper is structured as follows: in Section 2, relevant literature on the design and planning of CLSCs is reviewed where the focus is placed on the study of resilience. In Section 3, the main problem characteristics are detailed. The mathematical formulation is characterized in Section 4. The case study is presented in Section 5 and in Section 6 the results obtained are discussed. Finally, in Section 7 the conclusions are presented and some directions for future developments identified.

2. Literature review

At the present time, supply chains need to adjust to a number of new market and business trends, such as globalization, outsourcing, centralization, lean processes, etc., as well as to an increasing dependence on information technologies, that while giving them competitive advantages, make them also more vulnerable to several risks [23]. According to Tang [35] there are two types of risks facing a supply chain: operational risks and disruption risks. The former are related to inherent uncertainties, e.g. in demand, supply, delivery lead times, prices, availability of raw materials, quantity and quality of returned products, with demand uncertainty being the most common [22]. Thus the need to explore the stochastic nature of SCs is a very important challenge, namely its quantitative management [15]. With regard to disruption risks, such as earthquakes, fires, equipment breakdowns, labour strikes and terrorist attacks, they might have a low probability of happening, but when occurring may cause a significant business impact [27].

Additionally, clients' expectations are becoming stricter, demanding the right quantity of products, at the right time and in the right place. A major challenge is then to balance the cost of acquiring the necessary operational capabilities to deal with disruptions, against acceptable levels of resilience. Different types of disruptions, namely transport vehicles breaking down, labour strikes or even extreme weather conditions affect the normal daily operations. Despite all supply chains being susceptible to these unforeseen events, the same disruption can cause different impacts on different supply chains depending on their resilience level.

Supply chain resilience can be defined as the ability of a supply chain to return to its original state or move to a new one, more desirable state after being disturbed [7], or in other words, as the 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 [24]. This concept is sometimes mistaken for other two: responsiveness and robustness. Nevertheless, they have different meanings. Responsiveness can be defined as the ability of a supply chain to respond rapidly to changes in demand in terms of volume and mix of products [16] and robustness is the ability of a supply chain to remain effective for all plausible futures [22]. In this work, the focus is on resilience.

As recognized by Bode et al. [3], despite their importance, resilience strategies to mitigate disruption effects in supply chains have been rarely anticipated and incorporated into the design models. Some authors proposed strategies to design resilient supply chains exploring different alternatives: information sharing among partners [2], multiple sourcing and safety stock [17], postponement and flexible transportation [35], investment in flexibility and redundancy [26]. However, none of the authors have simulated or implemented these strategies and monitored their performance under disruptions. Also most of the literature that studies disruptions focuses on single facilities, even though disruptions may have effects through the entire supply chain [30].

Despite the increasing interest on the subject, supply chain resilience is a new and still largely unexplored area of research and very few studies have attempted to measure it on the supply chain performance [34]. Indeed most of the papers provide qualitative insights to the problem with few quantitative measures being proposed.

To the best of our knowledge, some of the first authors proposing a resilience measure were Datta et al. [10], who presented an agent-based computational framework for analysing a production and distribution system subject to demand variability in order to improve resilience. In their paper resilience is defined, conceivably in a strict sense, as the ability of the system to meet each costumer's demand. Later, Vugrin et al. [38] developed a framework that includes a quantitative approach to measure resilience in terms of costs involved in recovering from a disruption. The framework also includes a qualitative approach that examines the supply chain characteristics that affect resilience in order to provide directions for potential improvements, which was applied to two different scenarios of a petrochemical supply chain affected by a hurricane. Kima et al. [19] presented some metrics derived from social network analysis that can help decision makers to understand the network complexity, if a supply chain is highly dependent on one node and also if it has high density, and how these factors can affect the reliability of supply chains. The concept of reliability can be defined as the capacity of the supply chain to fulfil commitments [37]. According to Adenso-Diaz et al. [1] an increase in supply chain resilience implies higher reliability. To evaluate the systems reliability, the authors applied thirteen metrics to supply chains and concluded that node complexity (total number of nodes), density (overall connectedness of a network, estimated as the ratio between the number of actual ties and the number of potential ties) and node criticality (number of critical nodes) affect negatively the supply chain reliability, while flow complexity (total number of flows) affects it positively.

Klibi and Martel [21] developed a stochastic programming model for the location–allocation problem under uncertainty of customers' demand and network disruptions for a two-echelon supply chain with a single product. They also proposed and compared three alternative design approaches in an attempt to incorporate resilience–seeking formulations. The first approach considered that there should be a backup depot for each client in case the assigned depot cannot ship the orders. The second allows multiple sourcing, while the third implies the specification of a maximum distance between depot and client. The different approaches were compared in terms of expected revenues and robustness, measured as the variability of the returns obtained under different scenarios. Carvalho et al. [6] used simulation to compare the supply chain response to a disruption using two design strategies: one based on flexibility and another on redundancy. The first strategy is related to ensuring more flexibility in terms of transportation links and the second implies having additional stock that may be used if a disturbance occurs. Both strategies reduced the negative effects of the disruption, but while the strategy based on flexibility had a higher impact on the total cost, the one on stock redundancy had it on the lead time ratio. The lead time ratio and the total cost were therefore the chosen performance measures in this study, where the focus was on responsiveness and not resilience, since it used lead time to measure the response time of the supply chain after a disruption.

On the other hand, Schmitt and Singh [31] implemented a simulation model to analyse inventory placement and back-up methodologies in a multi-echelon supply chain, in order to minimize the impact of disruptions and improve the resilience of the system. Here, the performance metric used was the customer fill rate, which seems an adequate measure of resilience, since it allows assessing the extent a SC maintains its normal operation after being disrupted, in terms of customers' satisfaction. Ishfaq [18] analysed the supply chain resilience only against transportation disruptions,