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A methodological framework for efficient and resilient supply network design

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Abstract: The growing competition and the destabilising effects of climate, disease and other external perils bring important challenges to companies worldwide. Supply chain (SC) networks become more and more complex with a growing exposure to a broad range of uncertainties, some of which may cause network disruptions. Neglecting these kinds of risks may lead to adverse consequences, such as negative financial effects, higher transportation costs, order delays, inventory shortages, and loss of market shares. Frequent disruption events that have been continuously increasing over recent years have clearly shown the key role of supply chain resilience. To hedge against SC disruptions, a well-designed and reliable supply network that performs efficiently in normal situations and resiliently during unstable conditions is a top priority. In this paper, starting from the discussion of the main design drivers for a resilient SC, a methodological framework is proposed to support both efficient and resilient supply network design. The procedure gets foundation from the recent literature, and it is directly derived from its application in a numerical example and an industrial case.

Keywords: supply chain, resilience, disruption, design framework

1. INTRODUCTION

In recent decades, supply chains (SCs) have greatly suffered from major disruptions (Ghadge et al. 2021, Rozhkov et al. 2022). The frequency of severe weather events, epidemics, and human-made disasters is increasing globally, and it is becoming ever more challenging to keep pace with the corresponding changes and impacts. The recent IPCC 6th Assessment Report identified that extreme events, such as droughts, fires, and floods, are increasingly compounding each other, likely as a consequence of human influence (IPCC, 2021). Japanese tsunami and earthquake in 2011 caused Toyota's parts suppliers failure to deliver parts at the expected volume and rate. This forced Toyota to halt production for several days (Fortune, 2016). Similarly, General Motors was forced to interrupt production due to a shortage of raw materials from their Japanese suppliers (BBC News, 2011). In March 2012, Ford's key supplier Evonik faced a devastating explosion in its plant in Marl, Germany, which also caused major interruptions in the downstream production facilities of Ford and other major automakers (Simchi-Levi et al., 2014). More recently, the COVID-19 outbreak and the subsequent global pandemic have immensely affected all areas of the economy and society at an unprecedented scale. In January 2020, operations from and to China were completely suspended by many global companies on a larger scale (CNBC, 2020). Furthermore, 94% of the Fortune 1000 companies have been affected by pandemic-driven disruptions (Fortune, 2020). Again, in March 2021, the container ship Ever Given was blocked for six days in the Suez Canal causing a traffic jam of over 370 ships (Forbes, 2021). Similarly, in 2021 the summer floods in Europe and China disrupted global shipping and broken railway links resulted in extreme delays in cargo movements (CNBC, 2021).

Disruption management is therefore drawing significant attention from both academia and industry (Jabbarzadeh et al., 2016; Snyder et al., 2016; Xu et al., 2020). First, the increase in occurrence of sensitive events brought disruptions to the forefront of public attention. Second, the trends in recent decades, involving the just-in-time philosophy and lean design, led to SCs that perform well under standard working conditions but are more vulnerable to major disruptions. Third, companies are less vertically integrated, and suppliers are distributed all around the world, in regions that may be politically or economically unstable (Ivanov et al. 2021b).

Therefore, companies all over the world have to learn how to operate in a highly unstable and unpredictable environment (Ivanov et al., 2021a), raising the need of completely novel design and decision-making tools for supply chain researchers and practitioners (Ivanov, 2021). In this direction, the present paper proposes a new methodological framework for supply network design (SND). The proposed approach is directly derived from its application in a numerical example and an industrial case, and contributes to the literature in the area of the procedures to support resilient SND with a practically derived framework.

The remainder of the paper is structured as follows. Section 2 presents an overview of the existing literature on the topic, especially focusing on the frameworks proposed in the context of resilient supply chain networks design. In section 3 the framework proposed by the authors is presented together with a new design paradigm, i.e., the efficient resilience circle. Finally, section 4 concludes the study and proposes insights for future research.

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2. LITERATURE OVERVIEW

2.1 Supply chain resilience

Disruption management is drawing significant attention from both academia and industry (Ivanov et al. 2017b; Aldrighetti et. al., 2021b; Bier et al., 2020). SC resilience represents the capability of a system to come back to its original state or even a more desirable condition after being disrupted (Ivanov and Ivanova 2008, Aven, 2017; Christopher and Peck, 2004). Resilience includes an integration of both proactive and reactive decisions, by utilising the synergetic effects between mitigation and contingency plans (Tomlin, 2006). According to Ivanov, Sokolov, and Dolgui (2014) and Ivanov et al. (2017c) the three main factors that characterise the resilience of a SC are redundancy, robustness, and flexibility.
SC robustness is defined as the ability to mitigate disturbances and continue the operation with minimal impact on performance (Ivanov and Dolgui, 2019). In general, robustness refers to the anticipation and management of risks, and aims to plan for redundancies (e.g. buffer capacities, backup suppliers, or risk mitigation inventory) to prevent risks or minimize the ensuing damage. Furthermore, redundant measures could ensure both robustness and flexibility (Llaguno et al., 2021). On the other hand, flexibility represents the capacity of adjusting or changing processes and structures according to the given context or situation. This often implies good coordination among all SC entities and, again, it can require the implementation of some redundancies (Llaguno et al., 2021).

2.2 Resilient supply chain design and related frameworks

In the last years, several researchers have focused on quantitative models to optimize design and planning decisions in SCs with consideration of resilience and disruption risk (Aldrighetti et al., 2021b; Bier et al., 2020; Bottani et al., 2019; Hosseini et al., 2019; Queiroz et al., 2020). Particular attention has been placed on how to proactively program mitigation strategies and preparedness plans. Studies mainly concluded that more investment in SC robustness and reserves such as backup suppliers and redundancy capacity increase the SCs' ability in performing well after disruption events (Ivanov and Dolgui, 2019). In compared to the mitigation plans, a few works considered reactive contingency plans to include recovery activities after disruption events (Fattahi et al., 2020). However, SC resilience is well established as a multi-dimensional measure (Giannoccaro and Iftikhar, 2022; Ponomarov and Holcomb, 2009). For example, Chowdhury and Quaddus (2017) defined primary dimensions of resilience as proactive capability, reactive capability, and SC design quality. Similarly, Hosseini et al. (2019) framed resilience as a mixture of absorptive capacity, adaptive capacity, and restorative capacity. Hence, most of the research works that focus on quantifying and reducing the impact of disruption do not address all dimensions of resilience (Ivanov et al., 2017a; Llaguno et al., 2021). Moreover, the concept of resilience is generally seen as opposite to efficiency, i.e. resilience increase lead to efficiency reduction, or vice versa. Besides, many papers studied SC resilience in general, or they just focused specifically on SC robustness, while very few examined combinations of efficiency and resilience.

Apart from quantitative models, some authors have also proposed design procedures and methods that can be useful for achieving the proper level of resilience. In some cases, these have been structured in frameworks. Among others, Burgos and Ivanov (2021) started from a case study to develop a post-disruption framework to increase SC resilience in the food retail industry. Llaguno et al. (2021) derived a conceptual framework for resilient SCs highlighting and classifying the possible risks as well as the possible benefits of digital technologies. Similarly, the framework of Shishodia et al. (2021) defined which are the main drivers (e.g. profit and loss, uncertainties and risks, services/performance loss) that can lead practitioners to develop a resilient SC. According to the authors, this can be done by implementing absorptive capacities, adaptive capacities and restorative capacities. On the other hand, Agrawal and Jain (2021) focused on a framework summarizing all the SC resilience strategies to mitigate supply chain disruption. Mishra et al. (2021) started from situation-actor-process (SAP) and learning-action-performance (LAP) frameworks and obtained a general framework considering the supply side requirements together with the logistics side and demand side ones. The study was based on empirical investigations in agri-food SC, mainly focusing on disruptions due to the COVID-19 pandemic. Ivanov (2021) formalized the AURA (Active Usage of Resilience Assets) framework, referring to five areas, i.e. plan, source, make, deliver and return.
As it can be seen from the reported literature, the topic of SC resilience is still evolving rapidly. Although some studies tried to theorize its main aspects in frameworks, most of them have been solely derived from the literature (e.g. Llaguno et al., 2021, Agrawal and Jain, 2021). However, it would be interesting to have more frameworks which are based not only on the literature but also on case studies and industrial practices, as the ones proposed by Burgos and Ivanov (2021) and Mishra et al. (2021). The framework proposed in the next section aims to cover this main need, trying to overcome the limitations of the previous frameworks. In particular, this is not only based on literature and authors' perceptions, but refers also to practical cases. Moreover, it wants to keep an adequate level of generality, not explicitly focusing on a single industry (i.e., food retail and agri-food) and a specific kind of disruption (i.e., COVID-19 pandemic), like the ones of Burgos and Ivanov (2021), Mishra et al. (2021), Ardolino et al. (2022) and Paul et al. (2022).

3. EFFICIENT RESILIENCE SUPPLY NETWORK DESIGN

3.1 Methodological framework

The complexity of the modern era SCs makes them vulnerable to all kinds of disruption. Moreover, the network structure of SCs becomes disadvantageous during a disruption, as the effects of the disruption can propagate through ripple effect (Dolgui et al., 2018). Even though the resilience principles yield, in general, expensive systems that "could help SCs only in rare cases", they can be essential for maintaining the viability of SC networks. Therefore, it would be important to identify the relations between disruption duration and magnitude and the efficiency of preparedness and adaptation strategies. In this way, SC managers would be able to decide on investment in redundancy allocation and efficient use of this redundancy at recovery stages and in adaptation or preparedness strategies.

Analyzing disruption risk and its implications on systems could be considered a complex process. In this section, a framework to guide the efficient resilience creation of a SC is presented, to help practitioners with a common path to follow when considering threats due to severe and high-impact events. The framework, composed of three main steps and depicted in Figure 1, has been derived following the phases proposed both in a numerical example and in a real-life case study application that can be found in Aldrighetti et al. (2019) and Aldrighetti et al. (2021a).

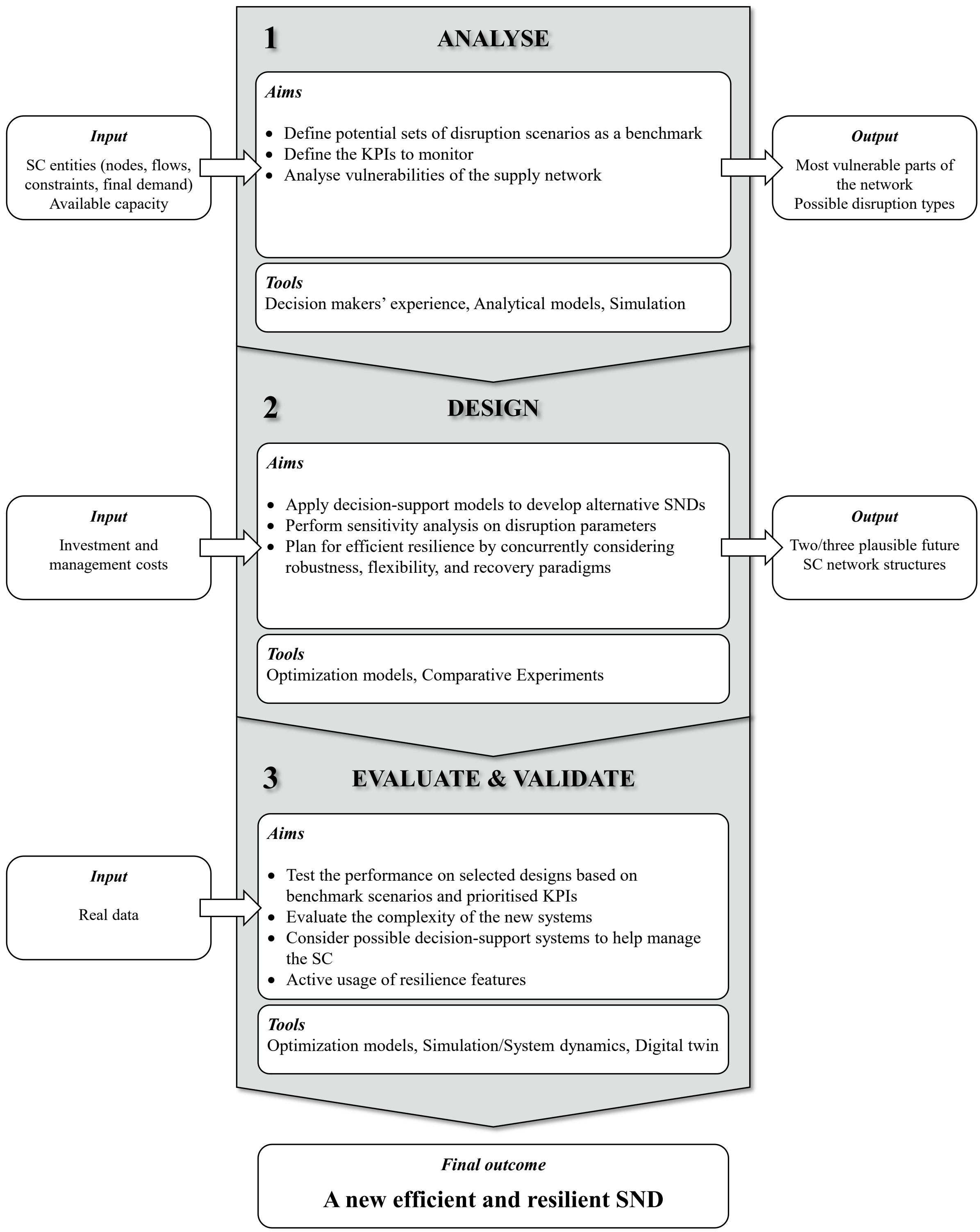

Figure 1. Efficient resilience SND framework.

In the first step, called "Analyse", a first analysis and evaluation of the current state and performance of the SC is recommended. The input information are related to the characteristics of the SC entities (i.e., nodes, flows, contraints, final demand) and of the available capacity. Companies should start by developing a set of disruption scenarios (in terms of affected SC echelons, impact on capacity, and duration of the interruption) to test the SC. Moreover, in this phase, the identification of the most important key performance indicators is crucial to properly measure and monitor the SC performance. As an example, the service level, the total cost, and/or the lead time may be interesting metrics to study (Han et al., 2020). Subsequently, the "as is" network should be assessed to test preparedness against disruption risk. These experiments aim to identify the most vulnerable parts of the supply network, together with the possible disruption types, to prioritise the following analyses.

The second step, called "Design", focuses on developing alternative configurations to better address the disruption risk. Further to the results of the previous phase, information about investment and management costs can be useful as inputs. In this phase, decision-support models and specific analytical methods supported by linear programming approach or heuristics and meta-heuristics could be essential to help SC managers identifying the most efficient proposal, also through proper sensitivity analyses among disruption parameters (Aldrighetti et al., 2021a). Based on the previously defined priorities and identified vulnerabilities, two or three plausible future SC configurations should be derived in this phase for further investigation.

Finally, the third step, called "Evaluate and validate", should focus on evaluating the selected plausible future designs in greater detail. Here, SC managers should assess the complexity of these new SC configurations, also taking into account real data. Decision-support systems could be planned as supporting the day-to-day operation in complex SCs, such as digital-twins to simulate sourcing and distribution policies based on the actual SC state. Furthermore, in the case of flexible or redundant capacity, new opportunities are available in terms of smart employment of these assets, such as for product development or active allocation of redundancies in a rotation system to decrease average usage and increase reliability, e.g., using the cloud supply chain framework (Ivanov et al. 2022).

The final outcome of the whole procedure is a new efficient and resilient supply network design.

3.2 The efficient resilience circle

During the design phase, recovery, robustness and flexibility principles need to be considered concurrently to achieve efficient solutions against disruption risk. This concept can be summarised in the efficient resilience circle depicted in Figure 2.

Recovery principles aim to adapt the system and its operation plan based on availability, to successively restore the lost capacity as soon as possible. Robustness principles, in general, aim to build redundancies (i.e., new sites) and increase the network capacity to hedge against shortages. Finally, flexibility principles aim to reduce disruption effects and consequences due to the preparedness of more adaptable assets that can be adjusted based on new needs and urgent requests in the disrupted periods. It is important to highlight that these three principles (i.e., recovery, robustness, flexibility) have been observed to be usually effective for different environmental conditions (Aldrighetti et al., 2021a). For example, recovery actions are essential to cover short-term disruption; however, their effectiveness reduces when in case of long-term interruptions. Redundancies are then important to cover medium-scale disruption as the excess of capacity can sustain business operability; however, even the newly established sites or installed capacity are subject to possible disruptions. Furthermore, planning redundancies for high-scale interruption could lead to an extremely redundant network with high investment costs and low utilisation in nominal periods. Flexibility systems are then able to maintain the long-term business stability of a SC with high-scale disruptions due to the ability to adapt to the "new" situation and reduce the disruption impacts.

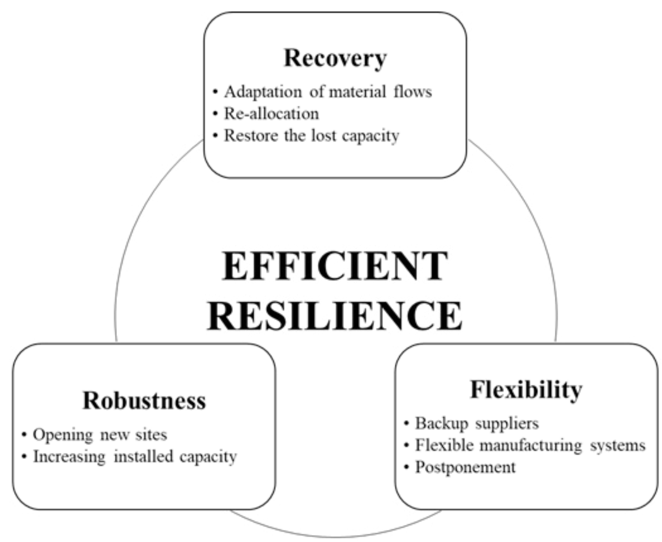

Figure 2. The efficient resilience circle.

4. CONCLUSIONS

The complexity of current SCs and the always increasing frequency of possible disruptions ask for studying SC resilience from various perspectives. Practitioners need improved knowledge to analyze the elements that define and significantly influence the resilience of supply chains towards disruptions in different industrial and environmental settings. In this paper, a three steps efficient resilience supply network design framework has been presented. This highlighted which are the possible phases to help companies in delivering decisions about SND with disruption risk. In this way, the development of a more efficient, robust, and resilient SC is fostered, increasing the competitive advantage and ensuring long-term business stability.

The proposed framework and the subsequent efficient resilience circle represented only a first attempt for structuring a topic which is manifold as well as continuously evolving. Moreover, these are considered to be representative for industrial SCs in the field of industrial machinery and/or components industry, which are the sectors of the real-life case study application here used as basis (Aldrighetti et al., 2021a).

Future research could focus on extending the analysis to other case studies, including other industrial sectors such as food and perishable products, pharmaceutical, big size, and luxury goods to derive insights from different SC configurations and allow a more powerful generalization of the results. Moreover, it would be interesting to develop specific KPIs and metrics that can support analysts and practitioners during the SND.

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