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Supply chain resilience and structure: An evaluation framework

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Abstract

Unexpected supply chain disruptions are situations that could impact in high magnitude the supply chain performance. In this paper, an evaluation framework is proposed for quantifying supply chain resilience and network topology. A supply chain resilience index is hereby derived using 'system impact cost' and 'recovery effort cost' from the results of the company performance. The resilience index helps managers to consider the trade-off between resilience and cost. The supply chain network topology is evaluated with indices of density, scale and centralization. While previous researchers considered network design characteristics, the physical location of the supply chain entities has been omitted. In this work, two of the proposed network characteristics indices consider the location zones of the supply chain entities. The network analysis unveils configurations with risk concentrations. The proposed supply chain framework seeks to evaluate and compare different scenarios and strategies for use in designing and analysing supply chains. Additionally, a rating system is used to give guidance to the decision maker and to choose the best strategy depending on established objectives. A case study is used to show the applicability of the framework.

Keywords: supply chain network; framework; topology; resilience; uncertainty

1. Introduction

Supply chain (SC) disruptions are unexpected events that may interrupt in high magnitude the SC operations and cascade through several levels of the SC. The effects of such events can range from halting operations for a number

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of days to those where operations are suspended indefinitely. These situations underline the necessity to consider disruption effects at the strategic decisions level. Hence, an assessment of how resilient the SC is can be carried out. Based on this result, top management has to make cost-benefit decisions.

Models for SC disruptions have been developed in the last decades. The available methods divide the approaches to deal with and evaluate the problem. On the one hand, some researchers are focusing just on the SC performance as a measure of resilience. On the other, analysis of the SC structure is carried out. Hence, the objective of this paper is to present a framework to analyse the resilience and topology of the SC jointly.

2. Supply chain resilience

In SC, resilience was defined in [1] as the adaptive capability of the SC to be prepared for unexpected events, to respond and to recover to its original state. Some approaches to quantify the resilience in the SC are available in the literature. Barroso et al.[2] presented a quantification of the SC resilience using each company delivery performance impact. Individual indices for companies were used as a proxy to assess the individual companies' resilience. Vugrin et al. [3] proposed the resilience costs. They defined the resilience costs as a function of the sum of the system impact (SI) plus the total recovery effort (TRE) multiplied by a weighting factor, α, to assign relative significance.

Uncertainties in SC will always exist. Hence, we have to learn to handle this kind of situations. But we need to balance the desired performance and the cost to achieve this resilient SC within specified limits. The available approaches for measuring resilience in SC are evaluating resilience and/or its enablers. But some of these approaches are not considering the economic system impact and/or the economic recovery effort.

3. Supply chain topology

Supply chains are graphically represented as networks, where nodes represent an entity in the SC. Links represent the flow of material, information or money. The SC structure or topology is what portrays or configures a network. In the paper presented in [4], empirical research to analyse the severity of disruptions was presented. As a result, they derived three SC characteristics (density, complexity and node criticality) and mitigation capabilities of recovery. Later, based on these design characteristics the work presented in [5] provided a descriptive framework that includes the resilience concept and SC design. They added the dimension of time with the resilience triangle in order to get a measure of SC resilience. Despite the fact that the framework is just descriptive, it provides insights into the necessity of impact minimization. But they left aside the resources needed to get the impact minimization.

4. The supply chain resilience framework

The literature available to quantify SC resilience considers some strategies and enablers to represent the resilient behaviour, and/or just the impact of the SC. However, most of them are not done in conjunction with the network topology analysis. In contrast, the proposed framework is intended to evaluate the economic system impact and recovery effort, and the network characteristics. The result is intended to facilitate comparison between network configurations and strategies costs. The implementation of this framework can guide managers to choose the best network configuration and mitigation strategy according to their needs and available resources.

The proposed framework is described in Fig. 1. This framework uses the resilience index and the topology to assess SCs. These two factors are considered for the following reasons: the resilience index helps managers to consider and quantify the trade-off between proposed strategies and their associated cost. Additionally, analysing the network topology can unveil configurations that can be more severely impacted by a disruption.

In the first phase, a SC simulation model is developed as a base model. This model will be run and provide the performance of each company in different scenarios. Then, identification of potential disruptions and possible mitigation strategies and configurations is carried out. Disruptions that have the most significant impact on the SC should be the scenarios that must be analysed. The framework includes two evaluation dimensions. The first dimension evaluates the supply chain resilience index (SCRI). It measures throughout the system impact and recovery effort how the SC operations are affected and the cost of each strategy. The second dimension comprises the supply chain topology (SCT): density, scale and centralization are evaluated. Density was chosen due to a denser SC would be more likely severe to a disruption than a less dense SC [4]. Scale based on the numerousness of components (nodes and flows) is considered because bigger SCs could be more prone to disruptions. Centralization is considered because more centralized SCs will spread the disruption quicker.

The framework evaluates four metrics for each scenario. Hence, managers have comparable quantifications of the SC performance and configuration in each scenario. Then a rating system to evaluate the best alternative is developed. Consequently, informed decisions for the best alternative according to the company's requirements can be made.

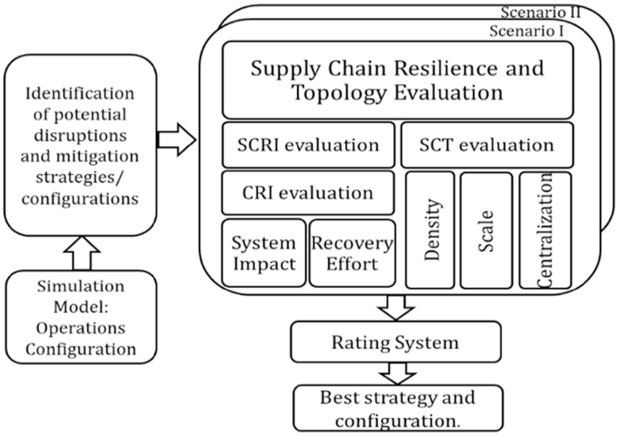

Fig. 1. The supply chain resilience framework.

4.1. Supply chain resilience index

Most of the time the design of a SC is determined by an economic factor. For that, in order to evaluate the SC performance, this framework is based on the recovery-dependent resilience cost (RDR) presented in [3]. RDR is the system resilience cost to a disruption under a particular recovery strategy (RE) as shown in Eq. (1). In other words, RDR of each recovery strategy is the proportion of the impact cost and the recovery cost, compared with the target cost. Where t_0 and t_f are the lower and upper limit of time where the resilience cost is evaluated. The subtraction in the numerator represents the system impact (SI), where TSP is the target system performance and SP is the system performance during the evaluation interval. RE is the area under the recovery effort curve. And, α is a weighting factor to give more or less importance to RE. RDR (RE) gives a relative dimensionless result.

$$RDR(RE) = \frac{\int_{t_0}^{t_f}[TSP(t) - SP(t)]dt + \alpha \int_{t_0}^{t_f}[RE(t)]dt}{\int_{t_0}^{t_f}|TSP(t)|dt} \quad (1)$$

Looking for a measure that can have an absolute meaning, this resilience cost metric was transformed to get the Company Resilience Index (CRI). For simplicity, summations instead of integrals are used. Additionally, in this research TSP is defined as the assigned cost to produce 100% of the planned demand. Furthermore, we propose to add SI and RE to TSP in the denominator. As a result, the denominator represents the total cost spent during the evaluation period. And the numerator characterises the system impact and recovery costs. The CRI as given in Eq. (2) has a scale from 0 to 1. Having 0 for a company with null resilience and 1 for the most resilient.

$$\mathrm{CRI} = 1 - \frac{\sum_{t=t_0}^{t_f}[\mathrm{TSP(t) - SP(t)}] + \alpha \sum_{t=t_0}^{t_f}[\mathrm{RE(t)}]}{\sum_{t=t_0}^{t_f}|\mathrm{TSP(t)}| + \sum_{t=t_0}^{t_f}[\mathrm{SI(t)}] + \alpha \sum_{t=t_0}^{t_f}[\mathrm{RE(t)}]} \quad (2)$$

In order to measure SI, RE and TSP, costs of the associated company fulfilling rate (FR) are used. The FR represents the ratio between the units fulfilled and the total demand in each period as presented in [2]. Where $Q_{delivered,j}$ is the quantity delivered and $Q_{ordered,j}$ the quantity ordered from order j. And $J_{i,t}$ corresponds to the number of orders placed to supplier i during time period t. Costs for fulfilling rate are accounted as shown in Eq. (3). Consequently, the system performance (SP) corresponds to the cost spent in each period. The target system performance is the cost considered to fulfil the orders during a period of time. When there is not a disruption, SP and TSP should be equal.

$$FRCost_{i,t} = Cost_{i,j} \times \left[\frac{1}{J_{i,t}} \sum_{j=1}^{J_{i,t}} \frac{Q_{delivered,j}}{Q_{ordered,j}} \right] \tag{3}$$

FRCosts are decomposed to evaluate the CRI. SI is the cost for the area where the fulfilling rate falls below TSP (Fig. 2). RE is the cost invested in getting the area that exceeds TSP as shown in Fig. 2. α can be used to weigh SI and RE [3]. However, when α is 1, we can compare CRIs of each company in different scenarios as we are dealing with monetary units. That is, when CRI=1 the cost is the least expensive strategy and when CRI=0, the cost is the most expensive. For that reason, we keep α=1. CRI is used to evaluate the performance of each company within the SC. Then, three approaches (average method, multiplicative method and worst case scenario) as presented in [2] are used to obtain the supply chain resilience index (SCRI).

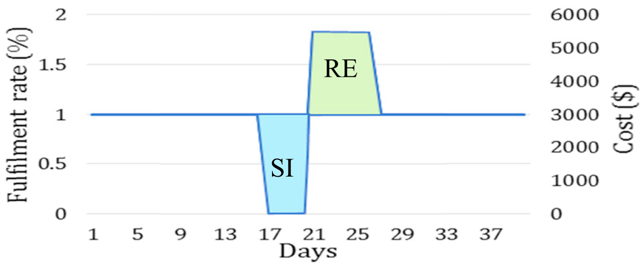

Fig. 2. System impact (SI) and recovery effort (RE) areas.

4.2. Network topology

Metrics to measure structural characteristics in the networks have been proposed previously. But they do not consider the physical location in the SCs. The importance of defining locations zones resides that each country/province or location zone has different regulations. So, the increase in zones will increase the number of transactions to deal with. The definition of location zones will help to detect zones with risk concentration. Accordingly, location zones with a higher number of nodes or SC entities would be more predisposed to a disruption. It is important to mention that just material flows links are discussed, for that the SC network is directional.

In this research, location zones to calculate density and scale indices were included. A location zone is defined as the geographical location of the nodes in the SC network. The location zones can be countries, provinces, cities or territories. But, the granularity of the SC zones will depend on the size of the SC. For example, in a global SC, each country can be considered a zone. Another alternative to defining the location zones can be using the standard country or areas codes used by the United Nations Statistics Division [6].

Supply Chain Density (SCD) represents the cohesiveness of the network. A highly connected network would cause that the failure of a highly connected node makes the whole network to fail. Density is defined as the number of ties (material flows) divided by the number of potential ties, where $(\#nodes - 1) \leq \#\ ties \leq \#potential\ ties$. The number of location zones z is added to the denominator. Where $1 \leq \#\ z \leq nodes$, as shown in Eq. (4). The addition of location zones to the denominator is done because a disperse network or an increment of location zones reduce the density in the region. Density values tend to 0 when the configuration is increasing density.

$$SCD = 1 - \frac{\#\,ties}{\#z\ *\#potential\ ties} \tag{4}$$

Supply Chain Scale (SCS) is intended to evaluate the structure referring to the number of elements in the SC. Scale index is measured as the ratio of node complexity (number of nodes) and flow complexity (number of flows) plus the number of location zones. As the number of nodes, ties, and location zones increase, the complexity to coordinate the SC would increases. The proposed scale index is shown in Eq. (5). Scale values tend to 0 when the configuration is becoming more complex or larger in scale.

$$SCS = \frac{\#\,nodes}{\#z + \ \#ties} \tag{5}$$

Supply Chain Centralization (SCC): It is the extent to which the cohesion of the network is organized around a particular node. Degree centralization measures how much control some firms execute over the other firms in the network [7]. It is desirable for a structure to have less centralization. So, less central networks will lead to less disruption impact. Centralization is formulated as presented in Eq. (6) [8]. Where $C_{(ni)}$ is defined as the centrality of node *i* which measures how a node is connected to all other nodes as shown in Eq. (7) [8], and $C_{(n*)}$ is the maximum centrality value in the network. Where $x_{ij} = 1$ if there is a link between node ni and nj.

$$SCC = 1 - \frac{\sum_{i=1}^{n}(C_{(n*)} - C_{(ni)})}{\max \sum_{i=1}^{n}(C_{(n*)} - C_{(ni)})} \tag{6}$$

$$C_{(ni)} = \sum_{j} x_{ij} \tag{7}$$

The range of the indices results goes from 0 to 1 in extreme cases. Once the metrics are calculated, a rating system is developed to decide the best alternative. First, the indices values are converted to a linear scale where 0 is the worst value obtained in each metric and 1 is the best value, interpolation is used for in-between values. Objective priority is assigned through weights. The new values are multiplied by their respective weights and added up. The best alternative for the assigned priorities is the one with the highest score.

5. Case study

The considered SC network is based on the case study presented in [9]. A four-echelon SC is used as shown in Fig. 3. Three location zones are considered for the base scenario. In location zone 1, the automaker, supplier 1_3, supplier 1_2 and supplier 1_1 are included. The other two suppliers are located each one in a different location zone.

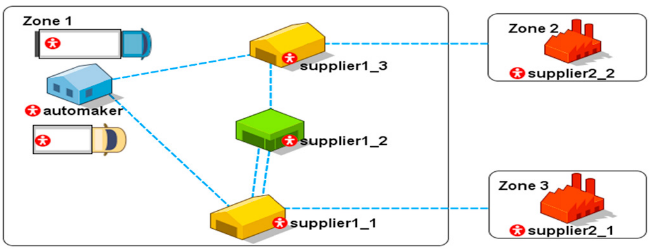

Fig. 3. Supply chain case study (adapted from [9]).

Portugal can be assumed to be location zone 1 and Spain or France can be considered as location zones 2 and 3. A disruption between days 11 to 18 in zone where supplier 2_1 is located was considered as in [2]. Three scenarios were used; scenario I has a disruption in the zone where supplier 2_1 is located. For that, supplier 2_1 cannot produce/deliver material to supplier 1_1. In scenario II the same disruption takes place, but there is a buffer stock of 7 days in supplier 1_2. In scenario III, the same disruption happens, but it considers supplier redundancy. Supplier

2_3 was located in another location zone as a backup. So, supplier 2_3 will work only when the disruption takes place, starting the next day. In this case study, costs for handling extra stock and costs to produce in the alternative supplier were added. For warehousing, extra stock cost of 1.25 dollar/unit/day was assumed during the simulation of 55 days. For the backup supplier, total costs were charged as for the original supplier. In order to measure the recovery effort, 30% increment of total cost was added to achieve extra production during recovery days. This case study should be taken as a guide on how to use the framework, not as the actual SC state.

6. Disruption profile results

Scenario I: Supplier 2_1 had FR=0 during the disruption days due to the disruption was in its zone. The effect was also observed in supplier1_1 and supplier1_2. Both had material shortages that provoked FR=0 for 2 and 4 days respectively. They had to work more than usual to recover their stocks. For that, FR was more than 100% during 6 days for supplier1_2 and 4 days for supplier1_1. Scenario II: Supplier 2_1 had FR=0 during the disruption days. Supplier 1_2 had a material shortage on day 17 and then it had FR higher than 100% during 2 days due to it worked to recover its usual performance. Other suppliers were not affected. Scenario III: Due to there is an alternative supplier, disruption effects are observed just in supplier 2_1. Once the fulfilling rate per each day, supplier, and scenario are calculated, the cost associated with the FR are decomposed into recovery effort costs and system impact costs. Then, CRIs for each scenario/supplier were calculated as shown in Fig. 4.

In order to get the SCRI, the CRIs were aggregated under the additive, multiplicative and network approach. The results are presented in Fig. 5 as well as the strategies costs in thousands of monetary units. Comparing the three approaches, the network approach represents the worst case scenario as it has more extreme values. However, the best and worst scenario are always consistent no matter what approach is used.

Scenario	Supplier 1_1	Supplier 1_2	Supplier 1_3	Supplier 2_1	Supplier 2_2	Supplier 2_3
I	0.92	0.88	1.00	0.89	1.00	
II	1.00	0.64	1.00	0.89	1.00	
III	1.00	1.00	1.00	0.89	1.00	0.53

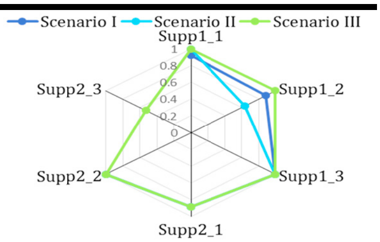

Fig. 4. Company resilience indices for each scenario.

Scenario	Strategy Cost	Average	Multiplicative	Minimum
I	246	0.94	0.72	0.88
II	247	0.91	0.57	0.64
III	250	0.90	0.47	0.53

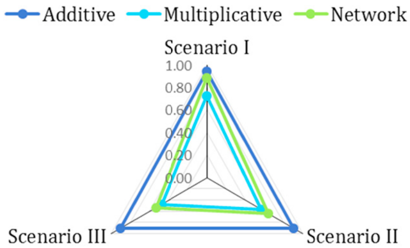

Fig. 5. SCRI results for each scenario/approach.

7. Network configuration results

Scenario I and II have 3 zones, 6 nodes and 7 ties, for that equal results for the 3 indices were obtained. Scenario III has 4 zones, 7 nodes, and 8 ties. The results for the network topology indices are shown in Fig. 6. Because the case study used is small, the results for the network configuration were obtained from a straightforward process. The results could be seen as trivial calculations. However, in network configurations with more nodes, the metrics usage can be better appreciated.

According to the SCRI, scenario I is the most resilient and least costly albeit no recovery strategy is included. This network configuration is denser than the configuration in scenario III. Hence, a disruption happening in the network configuration in scenario I, specifically zone 1, could have a more severe impact. Additionally, scale index in scenario I is lower than in scenario III, resulting in less coordination required in the SC. Scenario I is more centralised than scenario III, this means that the nodes in the network are not equally important or that the power is concentrated. For scenario II the SCRI is higher compared with scenario III. The reason behind this result is that the cost of having safety stock is less than the cost of using an alternative supplier.

Regarding the density, scale, and centralization, scenario II has the same results as scenario I. This result is because they have the same network configuration. Scenario III gives better results in density (relatively low density), making it more resilient to focused disruptions. The reason is that an additional zone was added to the SC network. Scale index in scenario III is higher due to an extra supply flow and another location zone (zone 4) were added. In scenario III, network centralization is diminished. Having less central SC would be beneficial, so suppliers do not depend on other suppliers. Regarding the SC resilience index, it decreases in scenario III as the strategy cost was higher than in scenario I and II. Scenario III is more resilient and less affected by focused disruptions. However, the cost of this strategy is higher.

Scenario	Density	Scale	Centralization
I	0.92	0.60	0.80
II	0.92	0.60	0.80
III	0.95	0.58	0.83

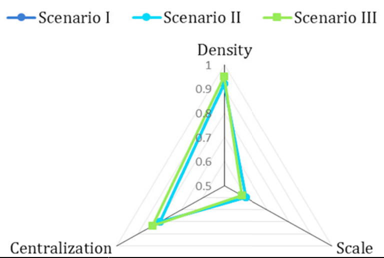

Fig. 6. Topology scenario results.

In order to give more guidance to the decision maker, the rating system was used. Weights for each objective were assigned. For this example, the cost is the dominant factor. The results show that Scenario II is the best option according to the established objectives. However, a change in the objectives could result in choosing another scenario.

8. Conclusion

Decision under uncertainties is challenging to make primarily because many economic factors and lack of information can limit the strategies to deal with these situations. Moreover, SCs looking for strategies that maximise the overall value generated are prone to adopt strategies like outsourcing and offshoring. This internationalisation of the SC boundaries could lead to an underestimation of how risk is compounded. Therefore, this paper proposed a systemic framework to evaluate the SC design. The proposed SC resilience index considers the associated cost to operate at specific delivery performance, the system impact and recover from a disruption. The design characteristics indices proposed, specifically density and scale, incorporate the physical connection of the supply network with the companies' location. Additionally, a rating system was used to determine in a transparent way the best decision. Finally, a case study was presented to demonstrate the applicability of the proposed framework. For future work, robustness quantification and topology indices aggregation would be considered.

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