Chapter 2

Quantifying the Supply Chain Resilience

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1. Introduction

In the current economic environment, increasingly global, there is the general awareness that companies are able to better compete if they act together, in supply chains, and thereby competitiveness can be increased [1]. Therefore, supply chains are becoming vital to the competitiveness of many companies and businesses.

The adoption of modern management paradigms, philosophies, strategies, policies and/or practices to improve effectiveness and reduce operating costs, such as lean manufacturing, Just-In-Time, strategic inventory, reduced product lifecycle and outsourcing, have created highly efficient supply chains. Although these new ways of managing have yielded attractive business benefits, they reduced the slack available to deal with uncertain events [2] and promoted the business globalization, increasing complexity of the extended networks, which amplifies the adverse impact of problems that can arise. In addition, the interconnection and interdependence among companies in a global supply chain makes them more vulnerable to a range of risks [3-6].

Supply chains are subjected to more risks than ever, which are numerous and constantly evolving, and derive both from within and outside of the company. Avoiding such risks or reducing their negative effects is a challenge for today management. Nevertheless, some risks cannot be avoided [2] and with today's complex global supply chains, fragmentary solutions and specific initiatives are no longer enough to cope with the multifaceted nature of risks.

One way to deal with supply chain risk is to increase confidence in the supply chain [7], i.e. confer to the supply chain the ability to be resilient. A resilient supply chain must develop resilience capabilities [8] to react to the negative consequences of unexpected events and to return quickly to its original state, the one before the risk occurrence, or to move to a new best state after being affected by the risk [9-11], and continue business operations as efficiently as

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possible. Increase resilience and reduce the likelihood of risk events occurring is the aim of supply chain risk management [12].

Although some recent studies highlighted the importance of quantifying the ability of companies and supply chains to overcome the negative effects of risks [13], the assessment of the supply chain resilience has not been attempted so far [2]. The main goal of this chapter is to fill this gap by proposing a quantitative index to measure the supply chain resilience to a risk based on the resilience index of its companies.

The chapter begins by defining and discussing central concepts in the scope of supply chain management, such as risk, sources of risk and supply chain risk. Since numerous risks that can occur and their characteristics and possible adverse effects to both company and supply chain, some strategies used to mitigate the negative effects of risk on a supply chain and make it more resilient are discussed. Then, the resilience index of a company to a risk is presented based on the concept of the resilience triangle. Finally, the resilience index of a supply chain to a risk is determined by aggregating the resilience index of companies that constitute the supply chain.

To illustrate how the proposed resilience index in both the individual company and the supply chain can be determined a case study is presented. The case study is the continuation of other case study developed in a previous work and is a real sub-set of companies which belong to a Portuguese automotive industry supply chain composed by one automaker, two 1st-tier suppliers, two 2nd-tier suppliers, and one outsource entity, structured in three-echelons [14]. The supply chain is disrupted due to a transportation interruption of material between two suppliers. To make resilient both the company and the supply chain, one strategy widely used to mitigate the negative effects of risk on supply chains based on the creation of redundancy is considered. Based on the results of the simulation of two scenarios developed in the previous work, the resilience indexes of companies and supply chain are determined. The two scenarios analysed consider the transportation interruption of material between two suppliers but in one scenario no strategy mitigation is adopted, whereas in the other scenario a strategy is adopted. In each scenario the resilience indexes of each company are determined based on the order fulfilment that is one of the important criteria to judge the level of the customer service of the company. This is the relative ability of the company to satisfy the customer. The fulfilment rate is a performance measure of the order fulfilment, expressed as a percentage of the total order. Finally, the resilience index of the supply chain is computed depending on the aggregation method implemented and then analysed.

The chapter proposes a tool that allows to quantifying the resilience of a company and a supply chain to a risk. The uncertainty of the future is usually modelled using scenarios [15]. So, by the comparison of scenarios, this proposal allows to help managers improving the decision making regarding the selection of mitigation strategies that promote greater supply chain resilience to a risk.

2. Supply chain risk

The body of literature on risks and supply chain risks has increased since events such as 9/11 and Hurricane Katrina. Additionally, the susceptibility of supply chains to risk is increased by

globalisation and certain management initiatives such as the increased use of outsourcing, dependence on single suppliers, complexity and interdependency of supply base, increased competition and customers more demanding and with higher expectations, tendency toward increase regulation, and more unpredictable threats. Not all risk is negative if it provides a competitive advantage, but companies should be aware how much risk they can handle.

2.1. Risk

Supply chains are subjected to more risks than ever, which are numerous and constantly evolving, and derive both from within and outside of the company. They are also becoming more costly. Avoiding such risks or reducing their negative effects is a challenge for today management. Nevertheless, some risks cannot be avoided and with today's complex global supply chains, fragmentary solutions and specific initiatives are no longer enough to cope with the multifaceted nature of risks.

Multiple definitions of risk exist in the literature. Reference [16] consider risk "in line with common usage in the sense that it relates to supply chain vulnerability, as at risk: vulnerable; likely to be lost or damaged" and propose a classification in three classes: i) Internal to the organization, ii) External to the organization but internal to the supply chain, and iii) External to the supply chain. However, there are some definitions of risk, most of which related to its influence on business outcomes, as can be visualised in Table 1.

Reference	Risk definition
[16]	Risk is used in line with common usage in the sense that it relates to supply chain vulnerability, as at risk: vulnerable; likely to be lost or damaged
[17]	Risk is the negative deviation from the expected value of a certain performance measure, resulting in undesirable consequences for the local company
[18]	Risk is the expected outcome of an uncertainty event, i.e. uncertain events lead to the existence of risks

Table 1. Some risk definitions

2.2. Sources of risk

There is a consensus that the sources of risk become more important as the complexity of modern supply chains increases. The adoption of more suitable actions for mitigating the negative effect of risks depends on the risk source. Knowing its source, it may be possible to act in order to avoid or reduce the probability of occurrence of the risk and consequently its negative effect on business outcomes. There are a high number of sources of risk that have the potential to adversely affect both revenue and cost, reducing the performance and competitiveness of the supply chain. Classification clarifies the relevant dimensions of potential sources of risk in supply chain.

Based on literature review, two main categories of sources of supply chain risk are defined: i) external and ii) internal to the supply chain. Each of them is, in turn, segmented by some authors.

The external to the supply chain category encompasses the sources of risk arising from the environment in which the supply chain is involved. It includes, on one hand, aspects that influence demand at the level of the end customer and, on the other hand, events that, when they materialize, have a severe impact on the area of their occurrence. Examples of these are i) the natural catastrophes such as tsunamis, earthquakes, hurricanes, and floods [17]; ii) the human-made catastrophes which are acts, intentional or not, caused by humans such as computer viruses, destructive competitive acts, sabotage and terrorist attacks [19-21]; iii) the implementation of laws and policies affecting the supply chain, such as trade and transportation laws, as well as the degree and frequency of changes in these laws and policies [17, 22-23]; and iv) a significant increase in the product demand (volume) or an unforeseen change in the specifications of the product considered [24-25]. However, this category relates to events which are outside the sphere of influence of supply chain managers.

Sources of risk within supply chain can arise from within of each company's supply chain or from the interaction between them. However, regardless of the place of origin, sources of risk can be generated in: i) resources-human, financial, infrastructure, material, energy, and equipment-such as vandalism, sabotage, labour strikes, industrial accidents [26-27], loss of a supplier [28], information technology problems or breakdowns [26], breakdown in machinery, equipment malfunctions and systemic failures [29]; and ii) management processes which include all sources of risk resulting from the decision making at management process.

For a thorough review on supply chain risk and risk management literature we recommend [5, 30-33].

3. Supply chain risk management

As the goal of risk management is ultimately to mitigate negative influences and ensure the company’s success [34], supply chain risk management aims to identify the potential sources of supply chain risk and implement appropriate actions or strategies through a coordinated approach among supply chain members, to avoid or reduce supply chain vulnerability [18, 35-36].

3.1. Supply chain risk management process

The supply chain risk management process entails a systematic application of management policies, procedures and practices in carrying out a sequence of activities of identifying, analysing, evaluating, treating, monitoring and communicating risk. It is an iterative process composed by four main activities, Risk Identification, Risk Assessment, Responding to Risk, and Monitoring and Review. This process can be used to provide the supply chain with some characteristics that make it more resilient to risk.

After the Risk Identification activity the Risk Assessment activity is done, being critical in the supply chain risk management process. In this activity is performed the analysis and the evaluation of risk. In addition, is determined the degree of exposure of assessed risks, expressed as likelihood and impact, and also the risks are ranked. Having identified and assessed the relevant risks, management should determine how to respond (next activity in the process).

According to reference [12] the aim of supply chain risk management is to increase resilience and reduce the likelihood of risk events occurring, which is a different perspective of [18, 35-36]. Thus, the Responding to Risk activity of the supply chain risk management process should identify and analyse the actions that minimize the adverse effects of risk, i.e. those that allow mitigating the risk, and also select and implement the most appropriate regarding the resilience of the supply chain.

3.2. Mitigation strategies to respond to risk

Generally, risk responses can include risk avoidance, acceptance, transference and mitigation. When possible, risk avoidance option is appropriate if the risk has been evaluated as unacceptable or intolerable. Responding to risk can be made through risk mitigation, which requires specific strategies to reduce or even eliminate the risk likelihood, or the risk impact, or both. There is much literature that suggests strategies to deal with company and supply chain risks [10, 29, 37-42].

There are many means available to control the negative effects in performance outcomes caused by risks within supply chains. A fundamental strategy would be to try to maintain supply chain performance measures of consistent fulfilment of orders, delivery reliability, and customer satisfaction.

Supply chain companies may also take a proactive or reactive strategy to respond to risk. A proactive strategy makes changes to its practices before the risk occurrence. Supply chain entities that adopt this approach are often trying to avoid a potential future threat or to capitalize on a potential future opportunity. When a supply chain entity makes changes in its practices only after the risk has already occurred, it reacts to a risk and a reactive change occurs.

Reference [43] describes two general approaches for dealing with risks: contingency and mitigation strategies. Contingency strategies are, in essence, more reactive in nature, whereas mitigation strategies are more proactive [41, 44-45]. Mitigation strategies imply taking actions before the risk occurs in order to reduce this event's occurrence or to reduce its impact. Therefore, the company or the supply chain incurs the cost of the mitigating action whether or not an unanticipated event or outcome occurs [29].Conversely, contingency strategies involve actions taken only after a disruptive event has happened. Reference [43] also highlights that more than one strategy can be used to manage risks.

Multiple potential sources of risk produce varying effects on a supply chain and complicate the selection of a risk mitigation strategy. There are eight risk mitigation strategies addressed by reference [26], which can be classified into either redundancy or flexibility strategies and utilized in practice [24, 43, 46-47]. Specifically, increase capacity, increase inventory and have

redundant suppliers are redundancy strategies. Increase responsiveness, increase flexibility, aggregate demand, increase capacity and have more clients are flexibility strategies. Reference [26] developed a matrix that shows how each strategy acts in mitigation of the seven types of risks (these risks do not include systems risk and intellectual property risks). An analysis of the matrix proposed by these authors reveals that the implementation of some strategies mitigate some types of risk, but increase the likelihood of other types.

As the lack of redundancy makes companies vulnerable to changes in business environment, reference [48] posits redundancy as a good risk management strategy. However, some strategies based on redundancy can get very costly and supply chains should re-examine the trade-offs between efficiency and redundancy [16].

Reference [19] encourages companies to examine their risk levels and consider keeping strategic inventory reserves to protect against catastrophic events. Reference [5] provides a review of supply chain risk management and classifies strategies for supply chain robustness in two categories: those that increase the supply chains efficiency, and those that increase its resilience. Strategies which make the supply chain more efficient increase a facility's operational ability to handle a risk; business continuity planning within single sites tends to focus on this approach. Resilience, however, focuses on the ability of the company to sustain operation and recovery quickly in the face of a risk.

Reference [49] proposed similar strategies and expanded Tang's list to include expansion of capacity whereas reference [50] proposed risk insurance, information sharing, and relationship development.

4. Supply chain resilience

One way to deal with supply chain risk is to increase confidence in the supply chain, i.e. confer to the supply chain the ability to be resilient. Probably, in the long term, the key to supply chain remaining competitive is to be resilient. A resilient supply chain must develop resilience capabilities to react to the negative consequences of unexpected events and to return quickly to its original state, the one before the risk occurrence, or to move to a new best state after being affected by the risk, and continue business operations as efficiently as possible. Increase resilience and reduce the likelihood of risk events occurring is the aim of supply chain risk management [12].

The increase in the occurrence of risks that has been observed in the last few years at the global level, and the need for the supply chain to be ever more competitive, has created the need, on the part of managers, to take measures in order to make supply chains resilient to risk.

Supply chain resilience is receiving increased attention in the business, as well as in the academic press. There seems to be widespread recognition that supply chain risks have the potential to cause significant negative economic impacts [38, 51]. So, resilience helps to recover system states after incidents take place rather than prevent incidents from occurring [52].

In a supply chain company context, resilience is defined as the ability of a supply chain entity to react to risk and return to its original state or a more desirable one [16, 53-54]. Multiple definitions of supply chain resilience exist in the literature and some of these are presented in Table 2.

Reference	Supply chain resilience definition
[8]	The capacity for complex industrial systems to survive, adapt, and grow in the face of turbulent change.
[16]	The ability of a system (supply chain) to return to its original state or move to a new, more desirable state after being disturbed.
[53]	The ability to react to the negative effects caused by disturbances that occur at a given moment in order to maintain the supply chain's objectives.
[54]	"The adaptive 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."
[55]	The ability to maintain control over performance variability in the face of disturbance and a property of being adaptive and capable of sustained response to sudden and significant shifts in the environment in the form of uncertain demands.
[56]	Supply chain resilience is the ability to maintain operations and connectedness under the loss of some structures or functions
[57]	"The ability of a supply chain to both resist disruptions and recover operational capability after disruptions occur."

Table 2. Definitions of supply chain resilience

4.1. Supply chain resilience assessment

The question on "how to assess the supply chain resilience" still has no answer. Reference [58] specify some resilience properties: i) amount of change the system can undergo and still retain the same controls on function and structure; ii) degree to which the system is able of self-organization; and iii) ability to build and increase the capacity for learning and adapting. Reference [58] also argues that to understand the resilience of a system, it must be clearly defined – resilience of "what to what". It is vital to define what system state is being considered and what failure modes are involved.

4.2. Resilience triangle

Reference [20] outlined a graph that illustrates how risks would affect companies' performance which can be measured by sales, production levels, profits and customer service. Additionally, the graph shows different phases of the system's performance response: after a risk the performance decreases but as actions are taken the system's performance will gradually be

restored. Reference [20] characterizes companies' response to risk in eight phases, including i) eventual preparation to risk, ii) disruptive event occurrence, iii) first response, iv) initial impact, v) full impact, vi) recovery preparation, vii) recovery and viii) long term impact. These phases can be observed plotting the company response to risk along the time as can be illustrated using the "resilience triangle" (Figure 1), which helps to visualize the magnitude of the risk negative impact on system (company or supply chain) performance. The concept of a "resilience triangle" emerges from disaster research and represents the loss of functionality from damage and risk [59]. Therefore, the company's performance evolution along the time can be used to analyse supply chain resilience.

References [59-60] highlight the relation between a disruptive event and business indicators. When deciding which supply chain performance should be analysed we consider the supply chain's objective, which is satisfying customers.

The depth of the triangle represents the disruption severity, i.e., the severity or magnitude of loss damage, and the length of the triangle represents the recovery time, i.e., the damping time. The smaller the triangle is, the more resilient the company or supply chain is. Therefore, the "resilience triangle" should be minimised. Actions, behaviours, and properties of companies and networks can contribute for reducing the area of the "resilience triangle" [59].

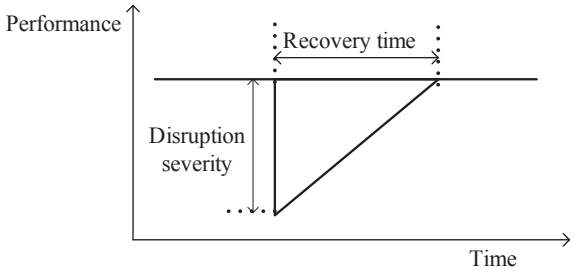

Figure 1. "Resilience triangle"

In this approach it is necessary to use proper performance measures which should be done according to the supply chain type. To analyse different scenarios in an automotive supply chain, the authors in prior simulation studies, see [14, 61], proposed the next performance measures: i) lead time ratio (average value of the ratio between the actual and the promised lead time for all the orders delivered by a company to its direct customers), ii) total cost (sum of production, material, holding inventory and transportation cost), and iii) fulfilment rate.

4.3. Company resilience index

In two simulation studies covering a three echelon of an automotive supply chain, the authors verified that when a supply chain is affected by a risk the performance of the supply chain companies is jeopardized [14, 61]. Moreover, even when the risk affects only one company, its

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negative effects are propagated along the supply chain creating performance patterns analogous to the resilience triangle [59].

From a resilience perspective it is important to analyse the companies' behaviour in a specific time period, for example between t0 and t1, in which the performance was affected and also recovered, Figure 2. Out of this range the company performance is no affected by the risk negative effects. Therefore, the triangle area is proposed as a proxy to assess the individual companies' resilience.

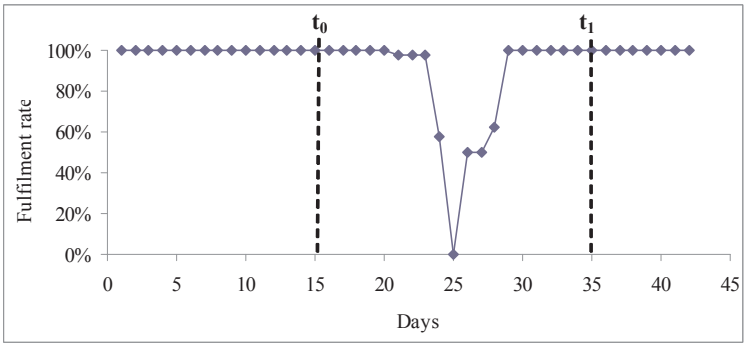

Figure 2. "Resilience triangle" pattern in simulation results (Adapted from reference [14])

Considering that company performance is measured at the end of each period t (between t_0 and t_1), a curve is generated with the performance along time (P_{it}). If there are no risks, the performance level of each company i is given by P_i. When a company is affected by the risk, a triangle pattern emerged showing the loss of company performance. However, some periods after the company performance recovers to the initial state P_i. To compute the triangle area a simple algorithm based on straight line approximations between the performance measure values for consecutive time periods is used [62]. The resilience index for a company i is computed using Equation 1:

$$R_i = 1 - \frac{\int_{t_0}^{t_1} (P_i - P_{it})\,\partial t}{P_i(t_1 - t_0)} \cong 1 - \frac{\sum_{t=t_0}^{t_1} (P_i - P_{it})}{P_i(t_1 - t_0)} = 1 - \frac{\sum_{t=t_0}^{t_1} \left(1 - P_{it}/P_i\right)}{P_i(t_1 - t_0)} \quad (1)$$

where,

R_i: is the resilience index of company i;

P_i: is the performance level of company i when it is not affected by the negative effects of a risk;

P_{it}: is the performance level of company i in time period t;

t_0: is the lower limit of the time period based on which the company resilience index is determined; usually prior to the time instant at which the performance level is affected by the negative effects of the risk;

t_1: is the upper limit of the time period based on which the company resilience index is determined; generally corresponds to a time instant at which the performance level is already recovered from the negative effects of the risk;

The resilience index of company i (R_i) is from 0 to 1. The value of R_i equal to 0 means that company i is no resilient to the disruption, i.e., performance P_{it} of company i is null during the period of time from t_0 to t_1. The value of R_i equal to 1 means that company i is resilient to the disruption and is able to sustain its performance, i.e. performance P_{it} of company i is equal to P_i during the period of time from t_0 to t_1.

4.4. Supply chain resilience index

Since the supply chain is a network of companies, the assessment of supply chain resilience to risks needs to reflect the perspective of the network. In this line, reference [63] proposed a hierarchical index to measure companies' and supply chain level of greenness and resilience, considering that the overall supply chain behaviour is affected by the aggregation of the supply chain company behaviour. In this paper, the same hierarchical approach will be used; the intention is to develop an index to assess the overall supply chain resilience (R_{SC}) based on the supply chain companies' resilience indexes.

Aggregation is always a potential area of methodological controversy in the field of composite index construction [64-65]. There are various linear methods for aggregation; the most common are additive, multiplicative and additive weighting [64-66]. However, for modelling the supply chain resilience based on a linear model is necessary to admit that there are no synergy and conflict effects among the supply chain companies' performance indicators [64], i.e. they should be independent [66-67]. Moreover, linear additive aggregation only can be applied when all indicators have the same measurement unit, and implies that poor performance in some indicators can be compensated by sufficiently high values of other indicators [64]. The multiplicative aggregation is appropriate when it entails partial (non-constant) compensability, i.e. compensability is lower when the composite indicator contains indicators with low values [64].

The right selection of the components of composite indexes and their weights are also critical for the aggregation process. Despite these concerns, reference [68] suggest that composite indexes should remain relatively simple in terms of their construction and interpretation. The choice of the most adequate aggregation method depends on the purpose of the composite indicator, as well as the nature of the subject being measured [69].

In literature there are few attempts to develop an overall supply chain resilience index. Reference [63] proposes an additive function of the individual companies' indexes for the supply chain resilience. According with reference [70] the reliability of a supply network is

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computed by multiplying the individual reliability of each company. To those authors the reliability can be used as a measure of the ability of a supply network to withstand disruption risks, which is a resilience property.

As we intend to propose an index for the overall supply chain resilience (R_{SC}) based on the resilience indexes of individual companies, the subsequent four approaches are considered. Following the suggestion of reference [63], the additive model is used to compute the overall supply chain resilience index (Equation 2). The resilience of each company has equal importance in determining the supply chain resilience. In this approach the lower values of resilience indexes of some supply chain companies are compensated by the higher values of other companies.

$$R_{SC} = \frac{1}{n} \times \sum_{i=1}^{n} R_i \tag{2}$$

If a reliability perspective is considered, R_{SC} should be computed by multiplying the resilience indexes of supply chain companies (Equation 3). This approach assumes that a company with a low resilience to risk implies low resilience of the supply chain in which it operates, i.e. if a company is vulnerable to a risk the supply chain will be vulnerable too. Thus, from the viewpoint of the supply chain, low resilience index value of a company promotes low resilience of the remaining companies, leading to low supply chain resilience index value.

$$R_{SC} = \prod_{i=1}^{n} R_i \tag{3}$$

A third approach to determine the R_{SC} is considering a network perspective where the system resilience is function of the lower value of company resilience (Equation 4). This approach considers that the resilience of a supply chain is given by its weakest link. It does not take in consideration possible interactions among companies to improve the overall resilience.

$$R_{SC} = Min\left(Ri\right) \tag{4}$$

The overall resilience index can be also constructed considering a constraint approach. Companies of the supply chain that could interrupt the material flow to the customer are critical. In this approach only the sub-set of these critical companies (designated by m) is considered for calculating the resilience of supply chain (Equation 5). When one of these companies is not able to sustain its performance the whole supply chain fails.

$$R_{SC} = \prod_{y=1}^{m} Ry \tag{5}$$

5. Resilience index of an automotive supply chain: Case study

To illustrate the application of the proposed resilience index in both the individual company and the supply chain, some results of the case study developed by [14] will be used. The case is based on a simulation study that will be briefly described below.

The simulation study developed by [14] was conducted within a Portuguese automotive supply chain characterized by a lean production environment. The pressures to reduce costs and lead time, as well as the globalization and trend in consumer demand for highly customized products, makes this type of supply chain extremely vulnerable to risks [71-72].

The supply chain under study, represented in Figure 3, incorporates six companies in three echelons:

- One automaker;
- Two 1st-tier suppliers: Supplier 1 and Supplier 3, and one outsource company: Supplier 2; and
- Two 2nd-tier suppliers: Supplier 4 and Supplier 5.

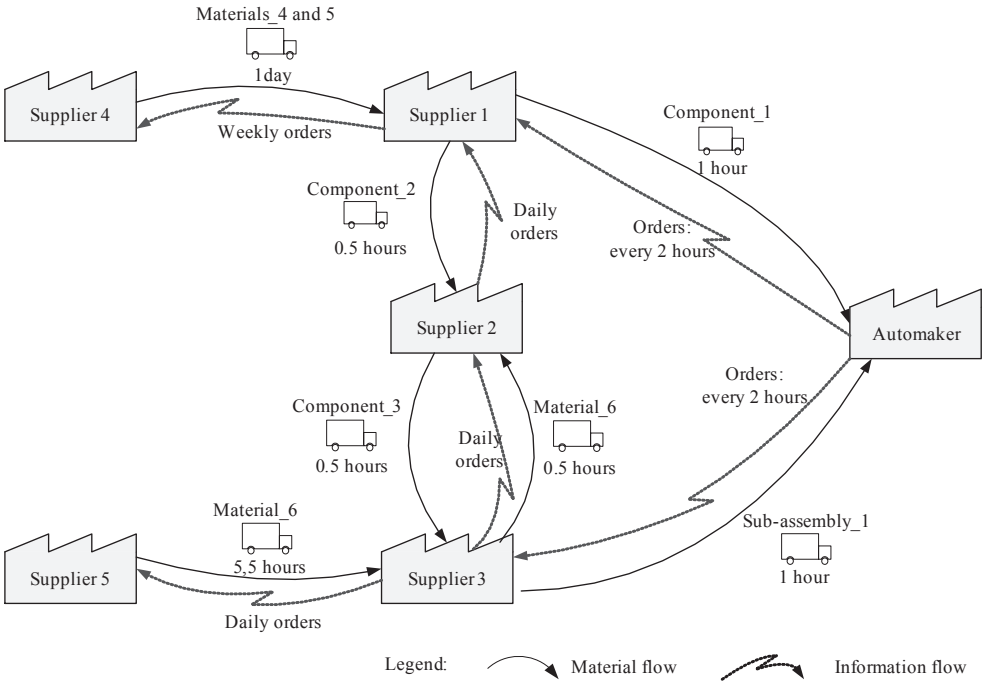

Figure 3. The automotive supply chain under study (Adapted from [14])

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The automaker is the supply chain final customer and pulls the material from suppliers. Every two hours the automaker places an order of Sub-assembly_1 to Supplier 3 and an order of Component_1 to Supplier 1. If it is not possible to deliver the complete order, these suppliers supply the order partially. Due to lean production environment a risk occurrence, like a delivery failure, can cause the halts of the automaker production line, which represents a high cost to the supply chain. So, the supply of Component_1 and Sub-assembly_1 is critical.

To evaluate the performance of each supply chain company during a time period the fulfilment rate is used (Equation 6). The fulfilment rate of a supplier i in a time period t is defined by the ratio between the number of units delivered on-time from suppliers to their 1st-tier customers and the total number of units ordered by 1st-tier customers.

$$Fulfilment\ Rate_{i,t} = \frac{1}{J_{i,t}} \sum_{j=1}^{J_{i,t}} \frac{Q_{LTpromised,j}}{Q_j} \tag{6}$$

where,

$J_{i,t}$: is the total number of orders placed by 1st-tier customers to supplier i during time period t;

Q_j: is the number of units of the order j;

$Q_{LTpromised,j}$: is the number of units of the order j delivered in the promised lead time LT;

t: is the analysed time period.

In the study of [14] is considered the disruption in the transportation of Material_6 from Supplier 5 to Supplier 3. As Supplier 3 has inventory to satisfy Material_6 demand for only three days and there are no alternative suppliers for this material, the interruption of the flow of Material_6 between Supplier 5 and Supplier 3 occurs. So, the supply chain is highly vulnerable to this particular risk.

To analyse the effects of the disruption occurrence on each company and also on the overall supply chain performance, reference [14] designed four scenarios. The base case scenario (scenario 1) corresponding to the representation of the current supply chain (without disruption occurrence). Scenario 2 corresponds to the same supply chain nevertheless affected by the disruption. Scenarios 3 and 4 were designed from scenario 2, based on the implementation of redundancy and flexibility strategies, respectively.

5.1. Scenarios to analyse

The objective of this chapter is to measure the resilience of the supply chain to a risk based on the company's resilience index proposed. With this goal the daily fulfilment rates of the different supply chain company resulted from scenarios 2 and 4 of reference [14] are used. In scenario 2 the current supply chain is affected by a transportation disruption in day 15, which causes an interruption in the flow of Material_6 from Supplier 5 to Supplier 3 during seven days. In Scenario 4 the effects of a mitigation strategy, based on redundancy, on resilience of

the supply chain are analysed. The redundancy strategy is defined by increasing from 3 to 7 days the inventory level of Material_6 in Supplier 2. The two scenarios have the same input values, such as demand patterns, bill of materials, inventory data, resource data, transportation time and cost data, and contemplate the occurrence of the same disruption.

The interruption of the material flow between two supply chain companies, not always all the companies are affected the same way by its negative effects. In scenario 2 the performance of Supplier 1 and Supplier 4 is not affected by the transportation disruption, as the two suppliers are able to sustain the performance level even when the others lost performance after the disruption occurrence. So, Figure 4 shows only the fulfilment rate simulation results of scenario 2, for the supply chain companies which are affected by the disruption occurrence (Suppliers 2, 3 and 5).

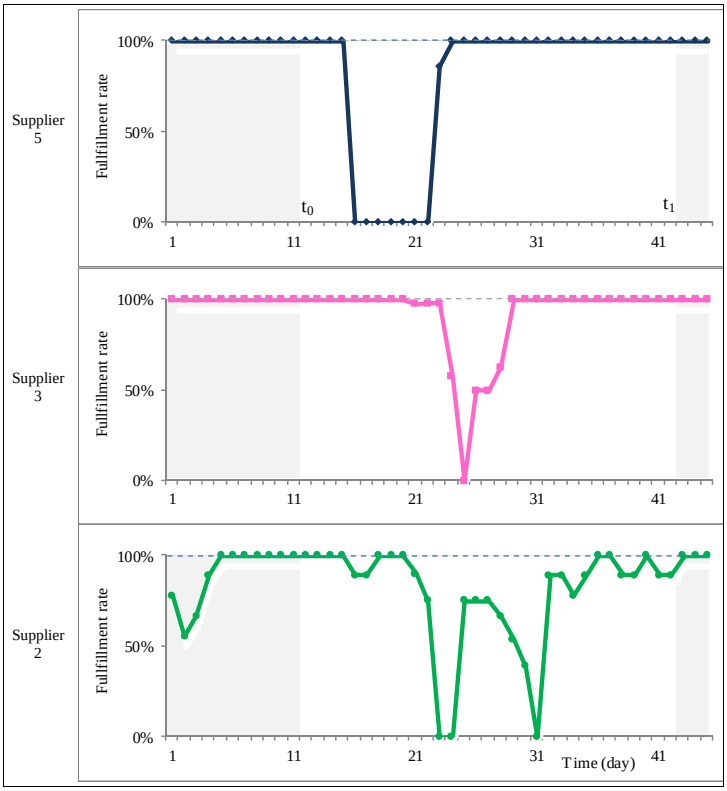

Figure 4. Fulfilment rate results for some supply chain companies of scenario 2

From the analysis of Figure 4 it is possible to verify that the supply disruption of Material_6 affects the performance of supply chain companies in cascade; firstly Supplier 5, and then Suppliers 3 and 2.

The fulfilment rate results, Figure 4, show clearly the inability of Supplier 5 to delivery Material_6 on-time to Supplier 3. During the period that the disruption is active, from day 16 to day 22, Supplier 5 fulfilment rate decreases abruptly to zero, since it is impossible to deliver the Material_6 to Supplier 3. When the risk fades away Supplier 5 is able to recover to the initial state, delivering all the late orders at once and, consequently, increasing the fulfilment rate.

To sustain the supply of Sub-assembly_1 to the Automaker, Supplier 3 uses its safety stock of Material_6 to overcome the delivery failure of Supplier 5; the safety stock of Material_6 in the Supplier 3 is defined by the quantity which allows meeting demand for three days. Therefore, after three days without deliveries of Material_6 from Supplier 5, the Supplier 3 has a shortage of Material_6 and fails to satisfy the Automaker. When the risk fades away Supplier 3 is unable to delivery all the late orders at once. It requires four days to restore its normal behaviour.

Supplier 2 also uses its safety stock to maintain its production, but after three days without deliveries from Supplier 3 the materials have all been used and it cannot fulfil the customer's orders (Supplier 1 and Supplier 3). The low performance of downstream companies of Supplier 2 affects Supplier 2's performance due to not being able to cope with the material shortage. The fulfilment rate of the supply chain upstream companies affects fulfilment rate of Supplier 2, since it is not able to cope with the material shortage. In the time period under analysis the Supplier 2 suffers two waves of material shortage, the first one caused by the disruption occurrence, and the second one when Supplier 3 delivers the first order after the disruption, since Supplier 2 uses all the recently delivered material to produce the late orders, leading to another stockout situation. As shown in Figure 4, Supplier 2 has daily fluctuations due to the daily uncertainties.

Considering the fulfilment rate performance measure and a time window of 30 days (between t_0=12 and t_1=42, Figure 4) the supply chain company resilience index is computed for each scenario using Equation 1.

Afterward, supply chain companies' resilience indexes for scenarios 2 and 4 are analysed.

5.2. Companies' resilience indexes for scenario 2

In scenario 2 Supplier 5 is enable to deliver on-time Material_6 to Supplier 3, between days 16 and 22 (Figure 4), consequently, it fulfilment rate decreases abruptly to zero in that time period, Table 3. As Supplier 5's performance behaviour based on fulfilment rate drops, it means that it is not able to mitigate the overall disruption negative effects.

Period	…	12	13	14	15	16	…	22	23	24	25	…	42
Fulfilment rate	…	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.86	1.00	1.00	1.00	1.00

Table 3. Supplier 5 fulfilment rate and respective resilience index for scenario 2

Being P_i the performance level of company i when it is not affected by the disruption negative effects, P_{it} the performance level of company i in time period t, and using Equation 1, the resilience index of each supply chain company is determined, Table 4.

Considering Supplier 5, and it fulfilment rate performance measure during a time window of 30 days, a resilience index of 0.76 is obtained, Table 4, which translates the level of resilience of Supplier 5 to the disruption.

Supply chain company	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5
Resilience index	1.00	0.78	0.90	1.00	0.76

Table 4. Supply chain companies' resilience index for scenario 2

After the disruption Supplier 3 is able to deliver all the late orders at once, increasing the fulfilment rate to the maximum value. However, Supplier 3's performance is negatively affected by the disruption and, consequently, its resilience index is equal to 0.90. Due to daily fluctuations, resulting from the daily uncertainties, and the behaviour provoked by the transportation disruption Supplier 2 has a low resilience index, 0.78. Not all supply chain companies are affected by the disruption. Supplier 1 and Supplier 4 maintain their normal behaviour, being maximum their resilience index.

Clearly, when there are no mitigation strategy implemented (scenario 2) by supply chain companies and the transportation disruption occurs Supplier 5 is the less resilient supply chain company (the one that is directly affected by the disruption), followed, respectively, by Supplier 2 and Supplier 3, the ones that have greater dependencies of Supplier 5 regarding the supply.

5.3. Companies' resilience indexes for scenario 4

To analyse the effects of the transportation disruption on each supply chain company and on the overall supply chain performance an alternative scenario is considered (scenario 4). Scenario 4 is designed based on scenario 2 and the implementation of a strategy based on redundancy in Supplier 2, corresponding to Supplier 3 demand of Component_3 (that results of the transformation of Material_6 in the Supplier 2) for seven days. When the transportation disruption occurs, the strategy based on redundancy is effective in overcoming the negative disruption effects although Suppliers 5 and 2 continue to be affected their normal behaviour due the disruption effects (Figure 5). So, although the strategy reduces the negative effects of the disruption it continues to propagate its effects along the supply chain. These results are in line with the ones obtained by reference [24] which state also that redundancies can promote inefficiencies in the supply chain.

The resilient index of each supply chain company for each scenario is according to the ability of each company to respond to the transportation disruption (Table 5). With the implementation of redundancy strategy (scenario 4) all supply chain companies increased it resilient index.

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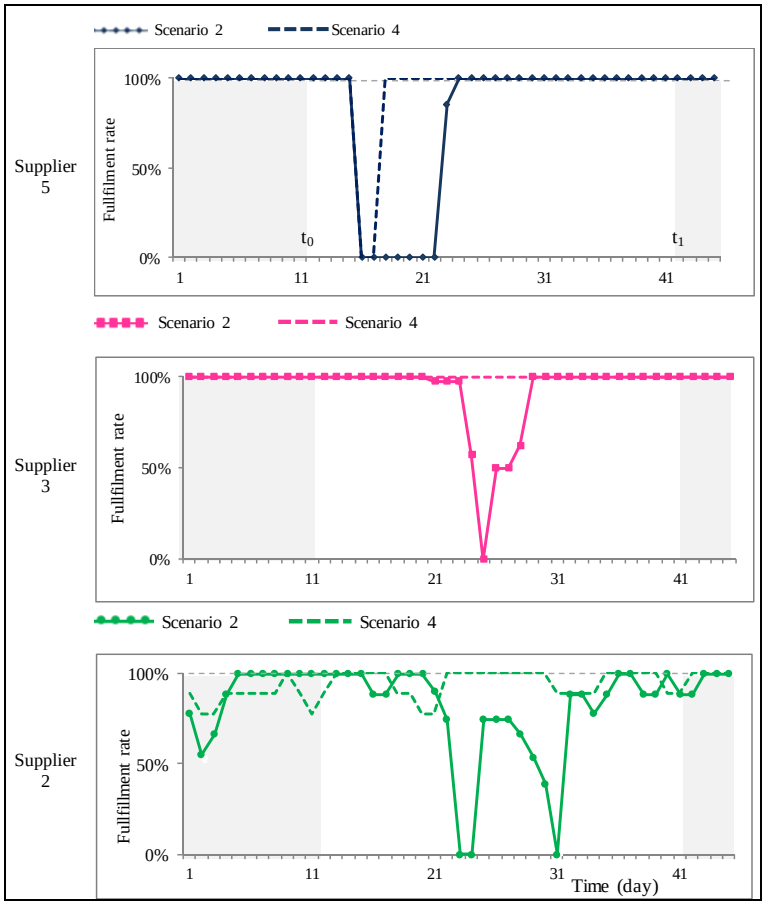

Figure 5. Fulfilment rate results comparison of scenarios 2 and 4

In scenario 4 the resilience index of Supplier 5 increased from 0.73 to 0.93 and the resilience index of Supplier 2 increased from 0.78 to 0.96 (not being the maximum value due to its day-to-day uncertainties). It was maximum the resilience index of the other supply chain companies.

Supply chain company	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5
Scenario 2	1.00	0.78	0.90	1.00	0.76
Scenario 4	1.00	0.96	1.00	1.00	0.93

Table 5. Supply chain companies' resilience index for scenarios 2 and 4

5.4. Supply chain resilience indexes

The supply chain resilience index can be computed based on the supply chain company indexes using different methods of company indexes aggregation such as proposed in Equations 2 – 4. The supply chain resilience index for both each scenario and each aggregation procedure is presented in Table 6.

Aggregation procedure	Scenario 2	Scenario 4
Additive method	0.89	0.98
Multiplicative method	0.53	0.89
Network perspective	0.76	0.93
Constraint approach	0.90	1.00

Table 6. Supply chain resilience indexes by scenario and aggregation procedure

Regardless the aggregation method used to determine the supply chain resilience index, from Table 6 it can be verified that:

- When the disruption occurs and there are no resilient strategies available to avoid and/or overcome the negative effects caused by it (scenario 2) supply chain companies lose performance, therefore, the supply chain resilience index is low;
- The implementation of a strategy based on redundancy (scenario 4) allows achieving high values for supply chain resilience indexes supporting the development of resilience in supply chain to the disruption.

From the resilience indexes computed for the case study we note that:

- Different scenarios result in different resilience indexes for each supply chain company;
- Different scenarios result in different supply chain resilience indexes for the same aggregation method of supply chain company resilience indexes;
- Different aggregation methods of supply chain company resilience indexes result in different supply chain resilience indexes for the same scenario;
- Supply chain resilience indexes are higher for the scenario where is applied a strategy to mitigate the disruption negative effects.

6. Conclusions

Supply chain risks are increasing in number and frequency, affecting the normal operation and stability of the supply chain and hence the ability of supply chains to fulfil commitments. Therefore, supply chains must be resilient to risks to overcome their vulnerabilities and to react effectively to its negative effects.

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The resilience of a supply chain company to risks may be obtained by reducing the probability of occurrence of the disturbance and/or reducing its negative effects on the supply chain entity. Thus, managers must take measures in order to mitigate the potentially negative effects of risks, whether on the directly affected company, or on other supply chain companies that may be affected, due to the relationship of dependency between supply chain companies. So, the strategies adopted should mitigate the negative impact of determined risks, the ones that have high negative impact and likelihood. However, it is not possible to implement strategies to mitigate any negative effects of risks because the supply chain becomes inefficient. Thus, the strategies adopted should mitigate the negative impact of specific risks, for example, the ones that have high negative impact and the ones that have high probability of occurring. Therefore, to adopt the most suitable mitigation strategies, whether proactive or reactive, it is necessary to identify in advance the risks that can potentially occur and to estimate their potential negative effect(s). Subsequently, it is essential to identify not only the risks that may affect a supply chain, and thus their companies, but the risk sources as well.

It is common sense that is need to measure for improving. To develop suitable supply chain strategies to mitigate risks it is crucial to assess the supply chain resilience to risks. To measure the resilience of a supply chain to a risk based on the company's resilience index, two resilience indexes are proposed, the company resilience index and the supply chain resilience index. The company resilience index is determined based on a performance indicator measured during a time period that entails both the risk occurrence and the recovering from the risk. The resilience index of a supply chain is determined by aggregating its company's resilience index.

Considering that the overall supply chain performance behaviour is affected by the supply chain company performance behaviour, the supply chain resilience should be measure based on the companies' resilience index. In this paper a supply chain resilience index is proposed which follows a hierarchical approach based on the aggregation of supply chain companies' resilience index. As the aggregation is a potential area of methodological controversy in the field of index construction, in this chapter four approaches are proposed.

The resilience index of a supply chain company is determined based on the concept of the resilience triangle. Generally, a key performance measure associated to the customer service level worsens due to the negative effect of the risk and needs some periods of time to recover the value it had before the risk materializes. The behaviour of the key performance measure over time depicts a triangle which area represents the loss of supply chain company performance, i.e. the negative effects of the risk. To achieve the supply chain resilience index the companies' resilience indexes of the supply chain are aggregated using an additive model, a multiplicative model, a network perspective and a constraint approach.

To test and operationalize the supply chain resilience index, the results of a supply chain case study developed previously are used. The case study is related to the Portuguese automotive upstream supply chain in which four scenarios were simulated, the transportation disruption between two companies was considered, and a mitigation strategy based on redundancy was implemented. Scenario 2 corresponds to the current supply chain case study with disruption occurrence. Scenario 4 corresponds to the current supply chain case study with the disruption occurrence under the mitigation strategy. The results of the simulation study allowed to

obtaining the supply chain companies' fulfilment rate along time for each supply chain company and each scenario.

For every company and every scenario, the proposed resilience index based on the company fulfilment rate is computed and its value allows capturing the resilience of company to the disruption considered.

Generally, in the presence of the disruption is expectable that most companies' resilience index are higher when resilience strategies are implemented (case of scenario 4) showing the company's ability to reduce the negative effects of risk. As the scenario 4 shows, implementing a mitigation strategy only one company suffers the negative effects of disruption and only for a short period of time. The companies which depend on it have not been greatly affected by this behaviour.

When a resilience strategy is deployed the supply chain resilience indexes are higher reflecting the system ability in reducing the risk negative effects.

The resilience indexes proposed in this chapter offer a holistic perspective on the supply chain resilience improvement which the decision makers could consider the implementation of mitigation strategies. The resilience indexes also provides managers with a way to assess the resilience of different supply chain redesign scenarios, to improving the decision making process. Moreover, it gives them a dash-board to identify improvement opportunities within the company as well as with their supply chain partners.

There are a number of issues that arise when attempting to create supply chain indexes such as subjectivity, bias, weighting, mathematical combinations, selection of key performance indicators, and source of the data. Future research should focus on these issues and may be carried out to test the proposed index using in-depth longitudinal case studies. It is also necessary a deep study on how to combine the various key performance measures into a supply chain company resilience index.

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