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The resilience of on-time delivery to capacity and material shortages: An empirical investigation in the automotive supply chain

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ABSTRACT

Supply chains around the globe are susceptible to disturbances that negatively impact their performance. Generally, supply chain disturbances lead to failure modes that impact the ability of the supply chain to deliver the promised goods and services on time. Therefore, companies operating in different supply chains are willing to become resilient to disturbances and their ensuing failure modes to be able to deliver on time and remain competitive. In light of this willingness, this study aims to propose an index that enables companies to assess their resilience of on-time delivery to supply chain failure modes based on the resilience practices they deploy. To this end, drawing on the knowledge derived from case study data analysis and literature, eight propositions and an explanatory framework are put forward that theorize the identified relationships between supply chain disturbances, failure modes, resilience practices, and on-time delivery as the primary indicator for measuring supply chain performance. Next, considering the resilience practices companies tend to deploy, an index capable of assessing the companies' resilience of on-time delivery to two prevalent supply chain failure modes, namely capacity shortage and material shortage is modelled and tested using a case study in an upstream automotive supply chain in Portugal. The results indicate high resilience levels of on-time delivery to the aforementioned failure modes, mainly due to the high cost of production halt in the automotive industry. Additionally, a set of supply chain capabilities and their related resilience practices and supply chain state variables are identified that can be deployed and controlled to improve supply chain resilience.

1. Introduction

With supply chains (SCs) crossing several countries and continents, incidents that cause material flow interruptions are more likely to cause large-scale disturbances. These disturbances can ripple throughout the SC causing critical negative effects and SC failure modes (Ivanov & Dolgui, 2020; Ivanov, Sokolov, & Dolgui, 2014). When struck by disturbances, many companies cannot sustain their productivity level and lose their competitiveness (Ghavamifar, Makui, & Taleizadeh, 2018). The COVID-19 pandemic is an instance of how unforeseen disturbances negatively impact the global SCs (Ivanov, 2020). In the meantime, SC management is expected to adopt innovative practices to foster appropriate responses to disturbances and proceed with delivering customer orders on time (Carvalho, Azevedo, & Cruz-Machado, 2012; Huq, Pawar, & Subramanian, 2021). However, such expectation requires companies and SCs to become resilient to unexpected disturbances and their ensuing SC failure modes (Carvalho, Cruz-Machado, & Tavares, 2012; Goldbeck, Angeloudis, & Ochieng, 2020), and this is why different methods of assessing supply chain resilience (SCR) present an important research stream (Hosseini, Ivanov, & Dolgui, 2019; Ponomarov & Holcomb, 2009; Ribeiro & Barbosa-Povoa, 2018) as they can help companies determine the extent to which they need to develop resilience.

Although the existing research is valuable, quantitative methods to assess resilience are scarce (Heckmann, Comes, & Nickel, 2015; Hohenstein, Feisel, Hartmann, & Giunipero, 2015; Ivanov, Dolgui, Sokolov, & Ivanova, 2017; Ribeiro & Barbosa-Povoa, 2018; Zavala, Nowicki, & Ramirez-Marquez, 2019), particularly at individual company level (Caputo, Pelagagge, & Salini, 2019; Kamalahmadi & Parast,

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2016). The existing research tends to concentrate on the qualitative (conceptual) characteristics of resilience (Hosseini et al., 2019; Ribeiro & Barbosa-Povoa, 2018) and none clearly explain how companies can assess their resilience level based on the practices they deploy to deal with SC disturbances (Ribeiro & Barbosa-Povoa, 2018). Thus, the primary objective of this research is to address this knowledge gap through an innovative method. To do this, drawing on the insights derived from a case study in an upstream automotive SC and the existing knowledge in the literature, propositions and an explanatory framework are put forward that reflect the main variables outlining the resilience of on-time delivery. Next, an index is modelled that enables companies to assess their resilience of on-time delivery to the two most common SC failure modes (i.e., capacity shortage and material shortage) by holistically taking into consideration the resilience practices they tend to deploy, thus allowing them to make the right modifications to increase their SCR level. However, to model the proposed resilience index, it is necessary to first understand in detail 1) what SC disturbances are and how they can affect the performance of the companies, and 2) what resilience practices companies utilize to avert the negative impacts of such SC disturbances.

This research is exploratory, and a theory-building methodology is adopted by making use of a case study. In the first phase of the research, a case study was conducted in a Portuguese automotive SC to understand what SC disturbances (and their negative effects) are, and how they can be dealt with. Subsequently, a second research phase was performed to gain further insights into the resilience practices that companies utilize to encounter the negative effects of SC disturbances. Thus, the variables outlining the resilience phenomenon in this study transpire from empirical data laying out the rationale for modelling the resilience index.

This paper is comprised of seven sections. Section one introduces the underlying research objective. Section two presents the relevant theoretical background regarding the underlying variables of the research. In section three, the research methodology is described by elaborating the employed research design, case study selection and data collection, as well as data analysis, leading to the identification of the main research variables and the formation of the explanatory framework. Section four explains the underlying rationale for the formulation of the resilience index, followed by its validation using case study data. In section five, the case study findings and results are presented and discussed. Section six explains the research contributions compared with the existing literature, followed by a discussion on the theoretical and managerial implications of the research. Finally, section seven presents the limitations and directions for future research.

2. Theoretical background

In the wake of the COVID-19 outbreak, the research community has once again focused its attention on SCR by looking into more practical ways to address this phenomenon (Belhadi et al., 2021). For instance, recently, Burgos and Ivanov (2021) investigated the impacts of the COVID-19 pandemic on the resilience of the food retail SC. In doing so, they drew on the importance of on-time delivery as an integral measure to assess the performance of the SC in the face of SC failure modes caused by the COVID-19 pandemic. Their observations suggest that material/inventory shortages as well as supplier capacity shortages are among the SC failure modes that have the highest negative impact on the on-time delivery of the SC. The importance of on-time delivery in the face of SC disturbances and failure modes is also emphasized by Adenso-Díaz, Mar-Ortiz, and Lozano (2018) who state that “Supply chain networks need to respond efficiently to operation disruptions, as one of their aims is to guarantee the on time delivery of products.”, or by Tarafdar and Qrunfleh (2017) who “define SC performance as the extent to which the supply chain is able to meet end-customer requirements of product availability and on-time delivery”. Table 1 presents a general overview of some of the works in the past decade (in chronological order from the most recent to the oldest) that refer to the importance of on-time delivery as a prominent performance measure in the context of SCR, some of which also point out two prevalent SC failure modes, i.e., capacity shortage and material shortage, among others.

Table 1
Illustrative research that emphasize the importance of on-time delivery in the context of SCR.

Authors	On-time delivery	Capacity shortage	Material shortage
Burgos and Ivanov (2021)	X	X	X
Gu, Yang, and Huo (2021)	X		X
Mishra, Dwivedi, Rana, and Hassini (2021)	X	X	X
Huq et al. (2021)	X		X
Dolgui et al. (2020)	X	X	X
Kinra, Ivanov, Das, and Dolgui (2020)	X	X	X
Adenso-Díaz et al. (2018)	X	X	
Ghavamifar et al. (2018)	X	X	
Fattahi, Govindan, and Keyvanshokooh (2017)	X	X	
Chen, Tai, and Li (2016)	X	X	
Gunasekaran, Subramanian, and Rahman (2015)	X	X	X
Brandon-Jones, Squire, Autry, and Petersen (2014)	X		X
Azevedo et al. (2013)	X	X	X
Carvalho, Barroso, et al. (2012)	X	X	X
Spiegler, Naim, and Wikner (2012)	X	X	X

While all these works mutually highlight the significance of on-time delivery in the context of SCR, to the best of our knowledge, none has come up with a method to specifically assess the resilience of on-time delivery to capacity and material shortages that follow SC disturbances. Thus, in this study, we try to address this knowledge gap through derived insights from industry and extant literature that help us model an index capable of assessing the resilience of on-time delivery to capacity and material shortages.

2.1. Supply chain disturbances and failure modes

Disturbances in SCs are inevitable and if they are not addressed in time, they can instigate SC failure modes (Carvalho, Cruz-Machado et al., 2012; Goldbeck et al., 2020). Hence, managers are expected to focus on developing resilience in their SCs in order to effectively respond to SC disturbances (Carvalho, Azevedo, et al., 2012; Huq et al., 2021). Resilience is referred to as a capability that not only empowers the SC to react to unexpected disturbances but also helps it to recover from the ensuing SC failure modes (Ponomarov & Holcomb, 2009). Moreover, the capability to avert failure modes that follow SC disturbances is crucial for an SC's success and is considered an important SCR property (Hosseini et al., 2019). According to Carvalho, Cruz-Machado et al. (2012) “The goal of SC resilience analysis and management is to prevent movement to undesirable states, i.e., the ones where failure modes could occur.” Since SCs are networks comprised of many companies, it is important that they deploy the necessary resilience practices to avoid SC failure modes from taking place, and in cases where they do, seek to minimize their negative impacts and quickly recover from them before they propagate throughout the SC (Dolgui, Ivanov, & Rozhkov, 2020; Wang, Dou, Muddada, & Zhang, 2018).

It is believed that while there are many SC disturbances, the failure modes caused by them are limited in number (Rice & Caniato, 2003). The negative effects of SC disturbances normally lead to SC failure modes, which prevent SCs from fulfilling the on-time delivery of the products and services to their customers (Adenso-Díaz et al., 2018; Carvalho, Maleki, & Cruz-Machado, 2012). The most commonly cited SC failure modes in the literature are material shortages, capacity shortages, labour shortages, quality issues, transportation delays, demand variations, and supply ruptures (Carvalho, Maleki, et al., 2012; Huq et al., 2021; Ivanov et al., 2017; Paul, Sarker, Essam, & Lee, 2019; Shishebori & Babadi, 2018; Shukla & Naim, 2017).

According to Carvalho, Cruz-Machado et al. (2012), the state of the SC can help understand its vulnerabilities to disturbances and the ensuing SC failure modes. They define the state of the SC as "a specific arrangement of SC entities and relational links between them and others SCs, material and information flows, management policies and lead times". Considering this definition, they identify "SC entities", "relational links", "material flow", "information flow", "management policies" and "lead times" as the main SC dimensions and classify various SC state variables accordingly (Table 2).

2.2. Resilience practices and supply chain capabilities

The overall level of resilience in an SC is based on the resilience practices that each company in that SC implements to deal with SC disturbances (Azevedo, Govindan, Carvalho, & Cruz-Machado, 2013; Hosseini et al., 2019). Resilience practices can be divided into two categories, i.e., proactive and reactive (Tukamuhabwa, Stevenson, Busby, & Zorzini, 2015). Proactive resilience practices are deployed before a disturbance takes place, and therefore incur the cost of implementation regardless of whether a disturbance occurs or not (Wang et al., 2018), whereas reactive resilience practices are expected to be implemented after SC disturbances take place. Thus, the reason for deploying resilience practices is twofold: 1) try to avert performance loss by minimizing the severity of potential disturbances; 2) help the company recover to its desired performance level within a reasonable timeframe and at a reasonable cost (Carvalho, Cruz-Machado et al., 2012). Resilience practices are a means of achieving SC capabilities (aka core competencies), which consequently determine the level of SCR against SC disturbances (Han, Chong, & Li, 2020; Pettit, Croxton, & Fiksel, 2019).

The severity of disturbances is associated with the presence of certain capabilities in the SC that help absorb possible damages and reduce the magnitude of the ensuing SC failure modes (Hosseini et al., 2019). While they are more than a handful, the most commonly referred to SC capabilities in the extant literature are flexibility, redundancy, visibility, collaboration, and velocity/responsiveness, which are affected by certain resilience practices (Han et al., 2020; Hohenstein et al., 2015; Kamalahmadi & Parast, 2016; Kochan & Nowicki, 2018). For instance, the constitution of safety stock throughout the SC is one common resilience practice that affects redundancy (Carvalho, Barroso, Machado, Azevedo, & Cruz-Machado, 2012; Hosseini et al., 2019). Responsiveness is affected by the resilience practices that are aimed at reducing the lead times, whereas visibility and collaboration capabilities are affected by performing information sharing and risk sharing practices among the SC partners (Han et al., 2020; Tukamuhabwa et al., 2015). Flexible sourcing, flexible supply base, and flexible transportation are resilience practices that affect the flexibility of the SC (Tukamuhabwa et al., 2015). Hence, resilience practices generate the capabilities that the SC needs to reduce the severity of disturbances as well as the recovery time while keeping the costs at a reasonable level.

Table 2
SC state variables in Carvalho, Cruz-Machado et al. (2012).

SC Dimension	SC State Variables
SC entities	Number of available alternatives for each entity, type and number, and geographic localization.
Relational links	Channel leader at dot end, collaboration, bilateral extensive coordination, buying-selling, preferred suppliers, long term partnership, among others.
Material flow	Transport mode, number of units and delivery frequency, number of customers, and time to supply.
Information flow	Type (manual or electronic), and frequency.
Management policies	Overall process description (capacity for extra orders, lot size, percentage of defects, number of operations, strategy – make to order vs. make to stock), stock type and stock level.
Lead times	Delivery lead time and production lead times.

2.3. Resilience assessment

Even though there is a multitude of publications regarding resilience, there are not many studies that aim to measure resilience using quantitative methods, especially when considering the resilience practices that companies tend to deploy in their SCs (Ribeiro & Barbosa-Povoa, 2018). Since SCR is a multidimensional and hierarchical concept (Chowdhury & Quaddus, 2017) and it traverses across different SC tiers (Munoz & Dunbar, 2015), there is no consensus regarding a specific set of rules, measures, or methods for its assessment. This is evident when searching through the existing literature. According to Golan, Jernegan, and Linkov (2020), only 22% of the publications that targeted resilience assessment and modelling put forward an explicit quantitative method. Table 3 briefly describes (in chronological order from the most recent to the oldest) some of the studies that have used different quantitative methods to assess resilience. As stated earlier, what differentiates this study from the others is the conception of a resilience index that can assess the resilience of on-time delivery to two very frequent SC failure modes, i.e., capacity shortage and material shortage.

3. Research methodology

3.1. Research design

An inductive research approach was followed in this study. This approach starts by collecting data that describe the phenomenon from the informant's point of view; and normally leads to adopting a substantive theory based on the descriptive data, identifying the research variables and establishing connections between them (Golicic, Davis, & McCarthy, 2005). In order to build the theory to support the development of the explanatory framework, case study was chosen as the research method. Case studies are normally recommended for theory building (Eisenhardt & Graebner, 2007) as they empirically describe a specific phenomenon in which various sources of evidence are employed. This research makes use of an in-depth single case study, which means that only one SC (with multiple embedded companies) is the object of the study. This approach is appropriate for the objective of this research since an in-depth single case study is a suitable way to build theory (Eisenhardt & Graebner, 2007) as well as provide enough insights to identify the underlying variables of the research (Voss, Tsikriktsis, & Frohlich, 2002; Yin, 2003).

In order to ensure the quality of the research design, four tests were applied, i.e., internal validity, external validity, construct validity and reliability (Yin, 2003):

- To ensure construct validity, the literature review results were incorporated into the development of the questionnaires. Moreover, the case study design was based on the utilization of various sources of evidence, e.g., secondary data sources, interviews, and ethnographical observations. Also, the chain of evidence was established by using a case study database. Lastly, the informants were asked to review and confirm the interview reports.
- To ensure internal validity, the case study findings were examined with the help of the principal informants to make sure that the data was analysed properly, and that all the related variables were incorporated.
- To ensure external validity, case studies were conducted in several companies embedded in the same SC to identify the patterns that emerge from cross-case analysis. Furthermore, data coding was performed to add rigour to the cross-case analysis.
- To ensure reliability, structured interview questionnaires were used. Moreover, the interviews were conducted by several researchers.

Table 3
Studies addressing resilience assessment using quantitative methods.

Author(s)	Research Description	Method
Mohammed, Naghshineh, Spiegler, and Carvalho (2021)	Develop A hybrid integrated DEMATEL-TOPSIS-bi objectives optimization model that allows evaluating the resilience of the existing suppliers.	Probabilistic bi-objective programming
Goldbeck et al. (2020)	Consider the speed of recovery as a metric and propose a mathematical model to optimize the allocation of repair resources.	Mathematical modelling - Optimization
Kinra et al. (2020)	Develop a model that assesses the ripple effect within a multi-echelon SC considering maximum possible loss.	Quantitative modelling
Hosseini and Ivanov (2019)	Propose an SCR measure based on the ripple effect by considering disturbance and recovery stages and examining SCR as a function of supplier susceptibility and recoverability using a Bayesian network.	Probabilistic Graphical Modelling - Bayesian network
Tan, Zhang, and Cai (2019)	Use graph theory to propose a conceptual model to evaluate the structural redundancy within the SC as an element that can be controlled to improve resilience.	Graph theory
Adenso-Díaz et al. (2018)	Propose a resilience metric by considering robustness as an antecedent of resilience and carrying out numerical trials to ascertain how different design elements influence robustness and consequently SCR.	Mathematical modelling – bi-objective optimisation
Zavala, Nowicki, and Ramirez-Marquez (2019)	Provide a mathematical model in the context of multi-echelon, post-production support networks to demonstrate the post-disruption resilience at the SC network nodes and the investments required to restore the network.	Mathematical modelling
Valenzuela, Fu, Xiao, and Goh (2018)	Formulate a measure based on the network typology to assess the impact of a disturbance that propagates from one node downstream of the SC.	Mathematical modelling
Pavlov et al. (2017)	Develop a resilience index for SC design by considering the structural attributes of SC design to measure SCR, using the hybrid fuzzy-probabilistic method.	Hybrid fuzzy-probabilistic approach
Han and Shin (2016)	Propose a model to analyse resilience based on risk and network configuration, incorporating risk propagation concepts after a disturbance takes place.	Mathematical modelling - Quantitative evaluation model
Cardoso et al. (2015)	Develop an optimization model for a closed-loop SC, where eleven indicators are proposed to measure SCR.	Mathematical modelling - Mixed Integer Linear Programming (MILP)
Munoz and Dunbar (2015)	Propose a multidimensional, multi-tier metric for quantifying resilience by characterizing the response to a disturbance over a specific period.	Simulation modelling - Structural Equation Modelling (SEM)
Kim, Chen, and Linderman (2015)	Propose a metric for the resilience of the supply networks by considering the number of arc/node disruptions.	Graph theory
Soni et al. (2014)	Use graph theory to propose a model considering the major drivers of SCR and their interconnections resulting in a single numerical index for SCR.	Deterministic modelling using Graph theory
Azadeh, Salehi, Arvan, and Dolatkhah (2014)	Use Fuzzy Cognitive Maps to explain the relationships among resilience factors and assess resilience in high-risk environments.	Fuzzy Cognitive Maps (FCMs)
Carvalho et al. (2013)	Propose a composite index to measure the resilience and agility of automotive companies and SCs.	Mathematical modelling
Azevedo et al. (2013)	Propose a hierarchical index to measure the level of resilience (along with greenness) based on a set of resilience practices in automotive companies.	Integrated assessment model
Spiegler et al. (2012)	Propose a method based on Integral of the Time Absolute Error (ITAE) to assess the resilience of the SC by considering inventory levels and shipment rates.	Simulation - System dynamics
Wang and Ip (2009)	Develop an index for the assessment of the network resilience in aircraft servicing by performing a weighted sum of each node's resilience.	Mathematical modelling - Optimization
Datta, Christopher, and Allen (2007)	Use the agent-based computational modelling to examine ways to enhance operational resilience to deal with demand variability as well as production/distribution capacity shortages.	Agent-based computational framework
Carvalho and Machado (2007)	Propose a resilience index and a resilience indicator based on adaptability, diversity and cohesion as the three main SC capabilities.	Simulation-based framework

Also, the collected data were stored and kept track of in the case study database.

3.2. Case study selection and data collection

A case study of an automotive SC in Portugal was selected to investigate various SC disturbances that impact the automotive companies with dissimilar positions and sizes within the SC and to identify the relevant resilience practices they use to counter the SC disturbances. Apart from the economic importance of this industry sector, the pressures to reduce lead times and costs along with customer demand for customized products add to the susceptibility of the automotive SC to disturbances (Fartaj, Kabir, Eghujovbo, Ali, & Paul, 2020; Thun & Hoenig, 2011). Hence, the automotive SC is a suitable example of an SC that needs to be (re)designed in a resilient way. Selecting a research design based on an in-depth single case study including seven embedded case companies allowed us to comprehensively research the variables that are relevant to understanding the resilience phenomenon in the context of the automotive SC. Table 4 summarizes the profile of the participating companies in the selected SC. The names of the companies were not mentioned due to the non-disclosure agreement.

The data collection was comprised of two phases. In the first phase, the main objective was to identify the principal variables that describe the resilience phenomenon. Subsequently, an explanatory framework along with a resilience index was developed using the findings in this phase. In the second phase, the applicability of the resilience index was assessed in the case study setting using a subset of four companies from the sample (Table 4), which represents a real-life situation.

Table 4
Sample characteristics.

Company descriptor	Product lines	Position in the SC	Company size (No. of employees)	Manager interviewed
Company 1	Vehicles	Automaker	More than 1000	SC manager
Company 2	Logistic services	Logistics provider	50–100	Operations manager
Company 3	Logistic services	Logistics provider	50–100	Project manager
Company 4	Front rear	1st tier supplier	50–100	Logistics manager
Company 5	Plastic parts	1st tier supplier	200–500	Product engineer
Company 6	Cockpit	1st tier supplier	200–500	Logistics manager
Company 7	Exhaust systems	1st tier supplier	50–100	Lean manager

Since the first phase of this research is exploratory, an in-depth interview approach was chosen as the principal method for collecting data as it provides the opportunity to capture the underlying variables of the research in detail (Miles & Huberman, 1994). According to the subject of the research, in each company, the most appropriate person to be interviewed was suggested by the chief executive officer of the company. In order to curb expert bias, data related to the participants' opinions were collected via twenty-one structured interviews. In the first research phase, an interview questionnaire (Appendix A) was adopted to maintain a mutual analysis path that allowed the results to be compared between the companies. Also, data regarding SC disturbances was gathered and used from secondary sources like news reports or company websites. Additionally, the case study database included data resulting from the observations of the researchers on the companies' processes. In phase two, an exhaustive questionnaire (Appendix B) was adopted and administered among four companies in the sample (Table 4) by considering the findings in phase one.

3.3. Data analysis

Analysing the field data and their interpretation is the nucleus of building theories from case studies. Nevertheless, it is the least systematized and the most challenging part of the method (Eisenhardt & Graebner, 2007). Data analysis in this research started after the first structured interview with the SC manager of the automaker and subsequently continued across the whole data collection phase. By doing this, the focus of the research was preserved, and the load of excessive data was controlled. The utilized techniques for data analysis are summarised in Table 5. Miles and Huberman (1994) claim that analysing the data is an interrelated process comprised of reducing the data, displaying it, and drawing conclusions. Reducing the data means focusing, simplifying, condensing and structuring the data into manageable units. Data display is about how the data is displayed and communicated. The last step in analysing data is to derive explications from the data displays while assuring analytical validity.

Since each company and manager would perceive SC disturbances differently, in a first step, all managers of the companies were requested to state their definition of SC disturbances. Diverse answers were given, e.g., shortage of materials at the right time; internal or external factors that delay the deliveries; internal or external factors that change the production plans; and issues leading to changes in the normal operations of the company. From these answers, it could be inferred that the managers did not associate the disturbances with specific events. In other words, the managers were not concerned with the events per se, but rather with the offsetting effects that they caused in their companies and consequently in the SC. When the interviewees were asked about the effects of the SC disturbances, the majority of the answers were

Table 5
Data analysis techniques.

Research phase	Study purpose	Data reduction	Data display
Phase one	Understanding what SC disturbances are and how they affect the companies' performance.	Coding the responses from the interviews, notes from on-site observations, and news reports.	Analysing the data regarding cross-case perspectives; Determining the number of responses in the sample.
	Identifying the resilience practices that companies use to avert or reduce the negative impacts of the SC disturbances.	Coding the responses from the interviews and notes from on-site observations.	
Phase two	Measuring how resilient companies are to SC disturbances.	Assessing the values of the SC state variables using the Likert scale, where 0 means the value of the SC state variable is zero/non-existent and 5 means the value is very high.	Analysing data related to cross-case perspectives; Modelling an aggregate index.

attributed to "capacity shortage" and "material shortage". When any of these two circumstances occurred, the company would fail to proceed with the "on-time delivery" of the products. For instance, unscheduled changes in the production plans of the automaker would impact the production plans of the first-tier supplier, and consequently, it may face "capacity shortage" to provide a timely response to the new orders placed by the automaker. Also, when the automaker made unscheduled changes to the production plans, a breach in the inventory of the first-tier supplier could occur that would disrupt the "on-time delivery" of the products due to possible "material shortage". In summary, the case study data showed that the most evident SC failure modes caused by the negative impacts of SC disturbances were "material shortage" and "capacity shortage", which compromise the "on-time delivery" of the products.

When the managers were asked about the practices they deployed to avoid or minimize the negative effects of disturbances, they mentioned different practices such as safety stock for critical materials, alternative or urgent transportation, use of dummy components, traceability of materials and components, alternative means of communication, flexible workforce, temporal workforce, extra shifts, or rapid response to equipment failures. Additionally, the automaker referred to alterations in the production planning, development of a common response plan with suppliers, and financial collaboration to assist insolvent suppliers. From the case study data, the following practices are suggested to avoid and overcome the identified SC failure modes:

- Capacity shortage: use alternative production paths, use maximum capacity, reduce response time, reallocate resources, increase capacity, and change the production schedule.
- Material shortage: use materials buffers, deliver a temporary substitute product, use an alternative delivery paths, use alternative suppliers/strategic sourcing, reduce supply lead time, reduce delivery lead time, change delivery schedules, and find new suppliers.
- Capacity shortage and Material shortage: create SC visibility, align SC information systems, and SC common response.

The principal variables that originated from the case study are as follows:

- SC disturbances are events that impact the SC state variables and are likely to trigger failure modes that result in failure to fulfil "on-time delivery". In other words, when a company encounters the negative

effects of an SC disturbance, its ability to manage "on-time delivery" will be compromised. The negative effects of the SC disturbances are mainly characterised by the following two SC failure modes: 1) "Capacity shortage", which occurs when the available resources are not enough to meet the demand, for instance, when the production equipment fail or are not sufficient. 2) "Material shortage", which occurs when there is not enough material to meet the demand, for instance, when the suppliers do not deliver on time, or the delivered materials/components are erroneous.
- Resilience practices are actions that are deployed by managers and decision-makers to prevent or mitigate SC disturbances and failure modes. These practices are normally deployed to 1) reduce the "disturbance severity" by improving the visibility and redundancy SC capabilities, for instance, sharing information with SC partners and using substitutes for production; 2) minimize the "recovery time" by improving the flexibility, responsiveness, and collaboration SC capabilities, for instance, altering the production/delivery schedules, or planning an SC common response.

3.4. Framework

Resilience is a notion that cannot be observed, which is in line with the description of a construct by Meredith (1993). In his work, he describes a construct as a notion that cannot be observed either directly or indirectly, however, it can be deduced by observable items. As mentioned earlier, there are certain capabilities in a company's SC that help reduce the "disturbance severity" and expedite the "recovery time". "Disturbance severity" is associated with the presence of certain SC capabilities, i.e., visibility and redundancy (according to the case study findings), which reduce the magnitude of SC failure modes. Whereas "recovery time" is associated with the presence of certain SC capabilities, i.e., responsiveness, collaboration, and flexibility (according to the case study findings), which help SCs to recover faster. These SC capabilities are associated with certain resilience practices that are represented by various SC state variables, which can be used as observable items to help assess SCR (Carvalho, Cruz-Machado et al., 2012). Drawing on the case study findings, we deemed it appropriate to use an explanatory framework to describe the identified associations between the main research variables.

Resilience needs to be assessed with reference to an incident or event, i.e., the resilience of "what" to "what" (Carpenter, Walker, Anderies, & Abel, 2001). To this end, we used the SC failure modes "Material shortage" and "Capacity shortage" that transpired from the case study findings. Hence, in this study, resilience is assessed based on the resilience of "on-time delivery" to "capacity shortage" as well as the resilience of "on-time delivery" to "material shortage". After analysing the case study findings, we put forward eight propositions that describe how the main research variables are interrelated. The propositions are as follows:

- Proposition 1a: SC disturbances instigate "capacity shortage" in companies.
- Proposition 1b: SC disturbances instigate "material shortage" in companies.
- Proposition 2a: "capacity shortage" negatively affects "on-time delivery".
- Proposition 2b: "material shortage" negatively affects "on-time delivery".
- Proposition 3: a higher level of resilience to "capacity shortage" reduces the risk of capacity shortages after a disturbance takes place.
- Proposition 4: a higher level of resilience to "material shortage" reduces the risk of material shortages after a disturbance takes place.
- Proposition 5a: deploying resilience practices to reduce the "disturbance severity" increases the level of resilience to "capacity shortage" as well as "material shortage".
- Proposition 5b: deploying resilience practices to reduce the "recovery time" increases the level of resilience to capacity and material shortage.

Using the aforementioned propositions, an explanatory framework was proposed (Fig. 1), which depicts the potential relationships between the variables of the research (Meredith, 1993), outlining the resilience of on-time delivery to capacity and material shortages.

4. Modelling the resilience index

The most acknowledged way to assess the resilience of a system is by means of the "resilience triangle" (Tukamuhabwa et al., 2015), which originates from research regarding disasters and denotes the loss of functionality/performance caused by disruptions/disturbances (Bruneau et al., 2003; Tierney & Bruneau, 2007). It has been used in different research fields such as disaster resilience (Zobel, 2011), freight resilience measures (Adams, Bekkem, & Toledo-Durán, 2012), business continuity (Sahebjamnia, Torabi, & Mansouri, 2015), and SCR (Bevilacqua, Ciarapica, & Marcucci, 2018; Carvalho, Azevedo, & Cruz-Machado, 2014) to name a few, indicating its wide range of applicability. Due to its simplicity, the resilience triangle provides a solid foundation for adopting quantitative measures that apply to both general and specific cases (Falasca, Zobel, & Cook, 2008; Zobel, 2011). Hence, it was used in this study as the underlying rationale for modelling the resilience index.

The characteristics of the resilience triangle are in accordance with the definition of SCR by Ponomarov and Holcomb (2009), who posit that SCR is mainly about providing effective responses to reduce the severity of the disturbance and promote recovery time. The resilience triangle in Fig. 2 shows how "Severity" and "Recovery time" together reflect the impact magnitude of disturbance on "Performance".

The depth of the triangle (marked as h in Fig. 2) shows the magnitude or severity of the disturbance, whereas the length of the triangle (marked as b) indicates the time the system needs to recover. A smaller triangle area implies a more resilient system. The resilience triangle area is computed using severity and recovery time, which in this case are the basis for modelling the resilience index (Eq. (1)).

$$\text{Resilience index} = (\text{severity} \times \text{recovery time})/2 \tag{1}$$

In this study, severity and recovery time are associated with specific resilience practices that are represented by different SC state variables, which as stated earlier can be used as observable items to assess SCR (Carvalho, Cruz-Machado et al., 2012). Also, resilience needs to be assessed with reference to an event, i.e., the resilience of "what" to "what" (Carpenter et al., 2001). According to the case study findings, the suggested SC performance measure is "on-time delivery" and since two principal failure modes were identified in the case study, two resilience indices are modelled: 1) resilience of "on-time delivery" to "capacity shortage"; and 2) resilience of "on-time delivery" to "material shortage". In order to model these indices, the main practices for avoiding or minimizing the negative effects of disturbances as well as their related SC state variables were obtained from analysing the case study data. It should be noted that three of the identified resilience practices (i.e., "create SC visibility", "align SC information systems" and "SC common response") were used by the companies to increase the resilience of "on-time delivery" to both "capacity shortage" and "material shortage". Fig. 3 presents the proposed resilience practices and their related SC state variables that are used to model the resilience indices. It is worth noting that many of these SC state variables have already been used in different works such Carvalho, Cruz-Machado et al. (2012) and Naghshineh and Carvalho (2021).

Indices are normally modelled by adding or multiplying different indicators related to the phenomenon under study (Fetscherin, 2010; Zhou, Ang, & Poh, 2006). Among the existing aggregation methods,

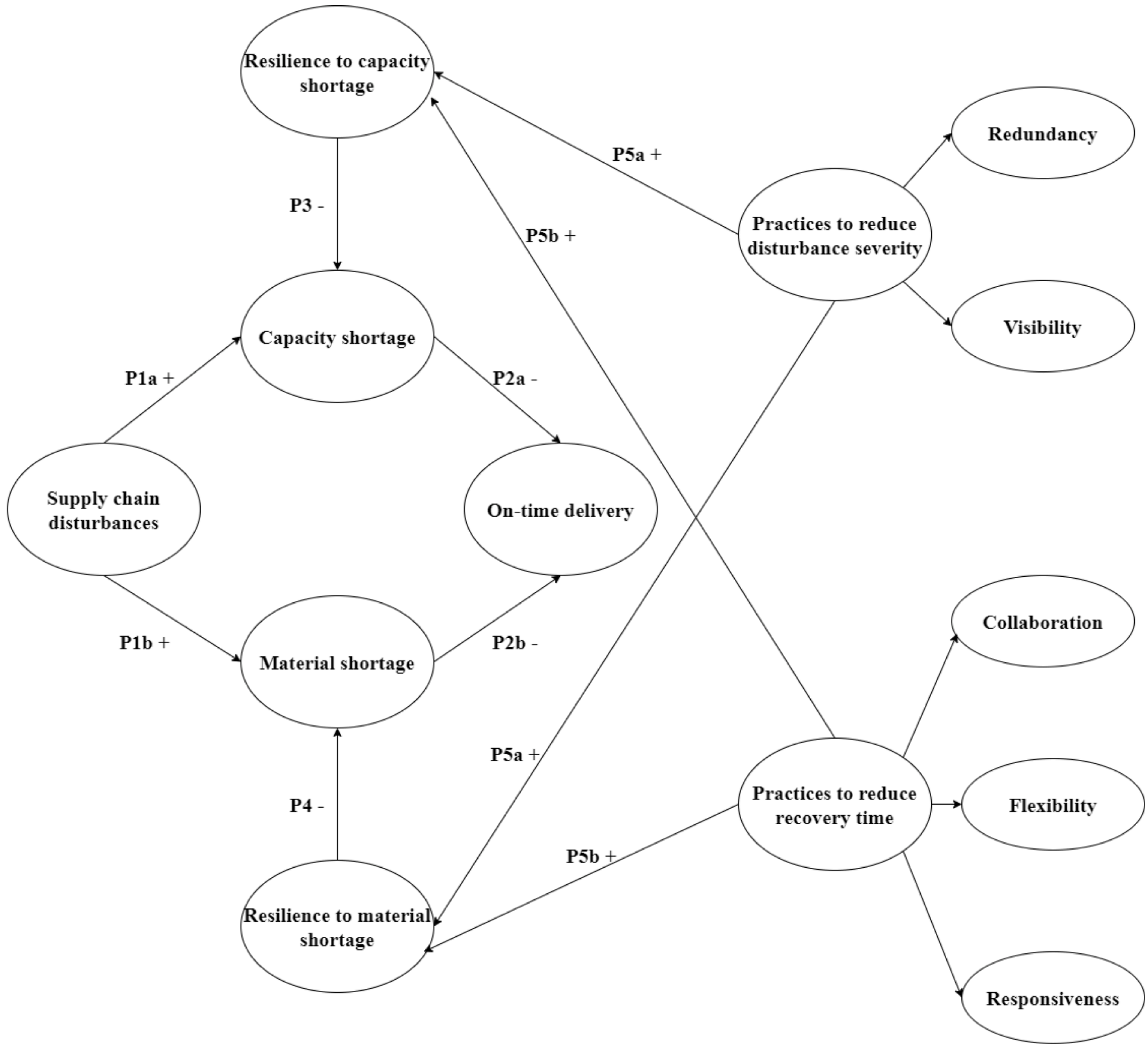

Fig. 1. Framework for modelling the resilience of on-time delivery to capacity and material shortages.

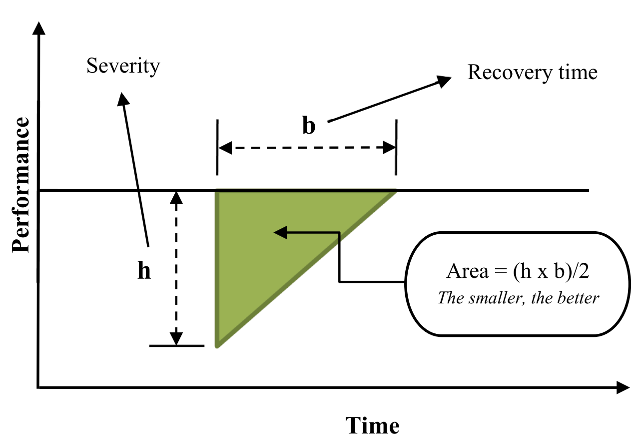

Fig. 2. Resilience triangle.

Simple Additive Weighting (SAW) is widely used in practice because of its simplicity and transparency (Jaberidoost et al., 2015; Sahu, Narang, Rajput, Sahu, & Sahu, 2018; Zhou et al., 2006). Even when the assumption of independence between the variables is not fitting, SAW would still yield relatively accurate results. Therefore, SAW was chosen as the aggregation method to model the indices for severity and recovery time via Eqs. (2) and (3):

$$\text{Severity}_z = 1 - \frac{\sum_{S=1}^{N_{ZS}} X_{ZS}}{5N_{ZS}} \tag{2}$$

$$\text{Recovery time}_Z = 1 - \frac{\sum_{r=1}^{N_{zr}} Y_{zr}}{5N_{zr}} \tag{3}$$

where

- z denotes the failure mode ("material shortage" or "capacity shortage").
- X_{zs} denotes the SC state variable s, which contributes to minimizing the severity of failure mode z.
- N_{zs} denotes the number of SC state variables, which contribute to minimizing the severity of failure mode z.
- Y_{zr} denotes the SC state variable r, which contributes to minimizing the recovery time for failure mode z.
- N_{zr} denotes the number of SC state variables, which contribute to minimizing the recovery time for failure mode z.

A Likert scale of 0 to 5 is used to measure each SC state variable, where 0 signifies that the SC state variable value is zero or non-existent

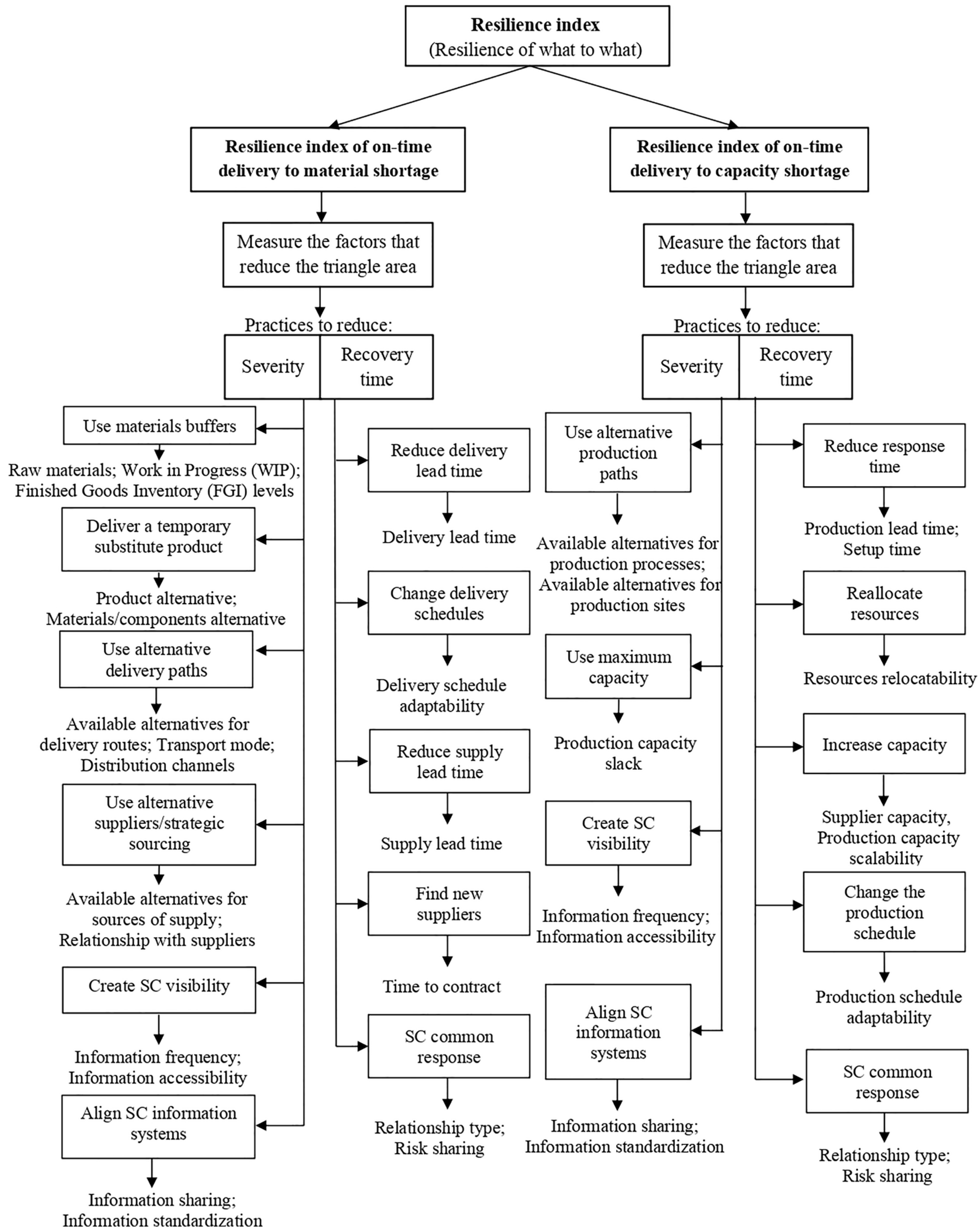

Fig. 3. Resilience practices and supply chain state variables used for modelling the resilience index.

and 5 signifies that the SC state variable value is very high. These SC state variables are then aggregated to output values for severity and recovery time. Severity (Eq. (2)) outputs values ranging from 0 to 1, where 0 signifies "No impact on performance" and 1 signifies "High-performance loss". Similarly, recovery time (Eq. (3)) outputs values ranging from 0 to 1, where 0 signifies "Instantaneous recovery" and 1 signifies "High recovery time".

A multiplicative aggregation method is used to build the resilience index for a specific failure mode (denoted by z) by multiplying the output values for severity and recovery time respectively (Eq. (4)).

$$\text{Resilience Index}_z = \underbrace{\left(1 - \frac{\sum_{s=1}^{N_{zs}} X_{zs}}{5N_{zs}}\right)}_{\text{severity}} \times \underbrace{1 - \frac{\sum_{r=1}^{N_{zr}} Y_r}{5N_{zr}}}_{\text{recovery time}} \times \frac{1}{2} \quad (4)$$

The resilience index yields values ranging from 0 to 0,5. Since smaller values represent better outcomes for resilience (i.e., smaller resilience triangle area), 0 signifies "Highly resilient" and 0,5 signifies "Not resilient". The resilience index is 0 when recovery time and/or severity is/are 0. This implies that if severity is non-existent or recovery time is instantaneous, the disturbance will not impact the normal performance of the company.

In order to assess the SC state variables (represented in Fig. 3), metrics were identified from the literature. Tables 6, 7 and 8 contain the SC state variables and their designated metrics to constitute each resilience index. Upon determining the metrics' values, Eqs. (5) and (6) can be used to compute each resilience index respectively. Eq. (5) allows for the computation of "on-time delivery" to "capacity shortage" (Resilience Index $_{CS}$), whereas Eq. (6) allows for the computation of "on-time delivery" to "material shortage" (Resilience Index $_{MS}$).

$$\text{Resilience Index}_{CS} = \underbrace{\left(1 - \frac{S_{CS1} + \ldots + S_{CS5} + S_{C1} + \ldots + S_{C5}}{5 \times 10}\right)}_{\text{severity}} \times \underbrace{\left(1 - \frac{R_{CS1} + \ldots + R_{CS8} + R_{C1} + R_{C2} + R_{C3}}{5 \times 11}\right)}_{\text{recovery time}} \times \frac{1}{2} \quad (5)$$

$$\text{Resilience Index}_{MS} = \underbrace{\left(1 - \frac{S_{MS1} + \ldots + S_{MS13} + S_{C1} + \ldots + S_{C5}}{5 \times 18}\right)}_{\text{severity}} \times \underbrace{\left(1 - \frac{R_{MS1} + \ldots + R_{MS4} + R_{C1} + R_{C2} + R_{C3}}{5 \times 7}\right)}_{\text{recovery time}} \times \frac{1}{2} \quad (6)$$

where

- Resilience Index$_{CS}$ indicates the company's resilience of "on-time delivery" to "capacity shortage".
- Resilience Index$_{MS}$ indicates the company's resilience of "on-time delivery" to "material shortage".
- S_{CSi} is the SC state variable i that contributes to minimizing the "capacity shortage" severity.
- S_{MSj} is the SC state variable j that contributes to minimizing the "material shortage" severity.
- S_{Ck} is the SC state variable k that contributes to minimizing both the "capacity shortage" and the "material shortage" severity.
- R_{CSl} is the SC state variable l that contributes to minimizing the "capacity shortage" recovery time.
- R_{MSm} is the SC state variable m that contributes to minimizing the "material shortage" recovery time.
- R_{Cn} is the SC state variable n that contributes to minimizing both the "capacity shortage" and the "material shortage" recovery time.

In order to test the applicability of the resilience index, data were collected from four companies of the SC under study that agreed to take part in the second phase of the research, using the exhaustive questionnaire (Appendix B). The resulting scores for each SC state variable are shown in Tables 6, 7 and 8. In order to calculate the two resilience indices for each company, the scores for the SC state variables were aggregated based on Eqs. (5) and (6) as shown in Table 9. It should be noted that the obtained scores were presented and discussed with each company to ensure they projected valid results.

5. Case study findings

The findings regarding the implemented resilience practices by the case study companies provide useful insights for managers and decision-makers as explained next.

5.1. Resilience practices for capacity shortage

The automaker (i.e., company 1) reported that it did not have alternative production processes in place. Also, the possibility to outsource the production processes was low mainly due to the strict quality requirements at the automaker. Only in some instances, if necessary, production would be outsourced, e.g., body painting. However, having a versatile assembly line was considered a very useful practice since it enabled the automaker to simultaneously assemble four different vehicle models. The case study findings also showed that the automaker ensured its production equipment operated seamlessly to avoid the need for redundancy in production processes. In addition, the automaker exercised an extensive maintenance program to ensure equipment availability and operability. Regarding the availability of alternative production sites, the informant for company 5 mentioned that the

Table 6
Capacity shortage: scores for the SC state variables.

Triangle side	Resilience practice	Supply chain state variable	Metrics (0 "Very low/difficult" and 5 "Very high/easy")	SCORE – Company descriptor 1	4	5	7
Severity	Use alternative production paths	Available alternatives for production processes	S_{CS1}: Possibility to outsource production processes [c]	2	0	5	0
			S_{CS2}: Operations versatility (number of operations a workstation can perform) [a]	4	2	5	4
			S_{CS3}: Redundancy in production processes [b][c]	2	2	5	4
		Available alternatives for production sites	S_{CS4}: Number of available alternatives for production sites [c]	1	1	5	4
	Use maximum capacity	Production capacity slack	S_{CS5}: Ease (time and cost) of adjusting the production capacity [f]	3	3	5	5
Recovery time	Reduce response time	Production lead time	R_{CS1}: Ease (cost) of reducing production lead time [c][d]	3	3	5	3
		Setup time	R_{CS2}: Ease (cost) of reducing setup or changeover times [a][c]	3	3	4	3
	Reallocate resources	Resources relocatability	R_{CS3}: Ease (cost and time) of relocating equipment from one cell, site, or business partner to another [b]	2	2	5	3
			R_{CS4}: Ease (cost and time) of reallocating workers [c][a]	4	2	5	5
			R_{CS5}: Ease (cost and time) of disabling equipment and re-commissioning if necessary [b]	2	1	3	4
	Increase capacity	Supplier capacity	R_{CS6}: Possibility to influence the short-term capacity of suppliers [c]	3	2	4	3
		Production capacity scalability	R_{CS7}: Ease (time and cost) of increasing production capacity [c]	3	3	4	4
	Change the production schedule	Production schedule adaptability	R_{CS8}: Ease (cost and time) of changing the production schedules [b]	4	3	4	4

Sources: [a] Tsourveloudis and Valavanis (2002); [b] Ramasesh, Kulkarni, and Jayakumar (2001), [c] Swafford, Ghosh, and Murthy (2006); [d] Lin, Chiu, and Chu (2006); [e] Bottani (2009); [f] case study findings.

Table 7
Material shortage: scores for the SC state variables.

Triangle side	Resilience practice	Supply chain state variable	Metrics (0 "Very low/ difficult" and 5 "Very high/ easy")	SCORE			
				Company descriptor			
				1	*4*	*5*	*7*
Severity	Use materials buffers	Raw materials level	S_{MS1}: Availability of raw material strategic buffers (RAW) [c]	0	4	5	3
		WIP level	S_{MS2}: Availability of Work in Progress (WIP) strategic buffers [c]	1	2	5	2
		FGI level	S_{MS3}: Availability of Finished Goods Inventory (FGI) strategic buffers [c]	2	1	5	1
	Deliver a temporary substitute product	Product alternative	R_{MS4}: Availability of product alternatives/ dummies [f]	1	0	3	2
		Materials/ components alternative	R_{MS5}: Ease (time and cost) of using new/ substitute components [a]	2	1	1	2
	Use alternative delivery paths	Available alternatives for delivery routes	S_{MS6}: Number of available alternatives for delivery routes [c]	3	3	5	4
		Transport mode	S_{MS7}: Number of available alternatives for transporting goods and material [c]	2	3	5	4
		Distribution channels	S_{MS8}: Ease (cost and time) of switching between distribution channels [b]	2	3	5	3
	Use alternative suppliers/ strategic sourcing	Available alternatives for sources of supply	S_{MS9}: Number of available alternatives for sources of supply [b]	1	1	4	2
			S_{MS10}: Number of different suppliers contracted per component [c]	1	1	0	2
			S_{MS11}: Ease (cost and time) of switching between suppliers [b] [c]	1	1	3	3
		Relationship with suppliers	S_{MS12}: Close relationship with suppliers [e]	4	4	3	5
			S_{MS13}: The level of expertise in developing supply sources [b]	2	3	2	4
Recovery time	Reduce delivery lead time	Delivery lead time	R_{MS1}: Ease (cost) of reducing delivery lead time [c][d]	3	2	5	2
	Change delivery schedules	Delivery schedule adaptability	R_{MS2}: Ease (cost and time) of changing delivery schedules [c]	3	2	4	2
	Reduce supply lead time	Supply lead time	R_{MS3}: Ease (cost) of changing the supplier lead time [b][c]	3	3	3	2
	Find new suppliers	Time to contract	R_{MS4}: Ease (cost and time) of contracting new suppliers [e]	1	1	3	3

Sources: [a] Tsourveloudis and Valavanis (2002); [b] Ramasesh et al. (2001), [c] Swafford et al. (2006); [d] Lin et al. (2006); [e] Bottani (2009); [f] case study findings.

company had already benefited from this practice in the past by delocalizing its production and transferring to another production site due to equipment failure. However, the automaker and company 4 did not have many alternatives in place for production sites and processes, which consequently made it more difficult for them to adjust and use maximum production capacity, and thus they experienced the negative impacts of disturbances with more severity.

Reducing the response time was reported to be another practice for enhancing resilience. This practice was mainly implemented by company 5 through a lean production setting, where set-up and production lead times were reduced significantly. At the same time, the companies constantly exercised continuous improvement. For instance, the automaker fostered different Kaizen events for reducing and optimizing the production processes. The companies mainly reported a low cost for reallocating workers, whereas the associated costs for equipment reallocation between facilities were much higher. Company 4 emphasized that the primary obstacle in transferring operations between facilities was the high cost and time necessary to constitute material buffers in new locations.

Production capacity was reported to be rather scalable by adding extra work shifts. Contracting additional production capacity was mainly done by the automaker and was reported to be of great importance. Considering that there were at times surges in customer demand that would lead to lost sales due to capacity shortages, it was the automaker's strategy to negotiate approximately 15% extra capacity with its suppliers. Altering the production schedules, especially with regard to the production sequence of the vehicles, was reported to be relatively easy for the automaker since it manufactured only four different models using the same assembly line. However, some restrictions were also present concerning the different vehicle models and their specific parts. For instance, the vehicles that had hardtop convertible roofs faced restrictions in the production sequence as the Takt time (i.e., time to produce/assemble the products to match the demand) of the roofing systems at the supplier was greater than the Takt time of the car assembly at the automaker.

Table 8
Capacity shortage and Material shortage: scores for the mutual SC state variables.

Triangle side	Resilience practice	Supply chain state variable	Metrics (0 "Very low/difficult" and 5 "Very high/easy")	SCORE Company descriptor 1	4	5	7
Severity	Create supply chain visibility	Information frequency	S_{C1}: Availability of real-time information systems (e.g., inventory information, demand information) [d]	5	5	2	4
		Information accessibility	S_{C2}: Information accessibility [d]	4	4	5	4
	Align supply chain information systems	Information sharing	S_{C3}: The level of network connection extensiveness [d]	4	4	5	3
			S_{C4}: Ease (cost and time) of exchanging reliable and timely information with supply chain partners [b]	4	5	5	4
		Information standardization	S_{C5}: The level of information standardization/interoperability [a]	4	3	5	4
Recovery time	Supply chain common response	Relationship type	R_{C1}: Trust-based relationships with suppliers and customers [e]	4	4	2	5
			R_{C2}: The degree of cooperation with other firms in the supply chain [d]	3	4	2	5
		Risk sharing	R_{C3}: Actively share the risk with partners [f]	5	3	5	5

Sources: [a] Tsourveloudis and Valavanis (2002); [b] Ramasesh et al. (2001), [c] Swafford et al. (2006); [d] Lin et al. (2006); [e] Bottani (2009); [f] Pettit, Fiksel, and Croxton (2010).

Table 9
Resilience indices scores.

Company descriptor	The resilience of "on-time delivery" to "capacity shortage"			The resilience of "on-time delivery" to "material shortage"		
	Severity	*Recovery time*	*Resilience index $_{CS}$*	*Severity*	*Recovery time*	*Resilience index $_{MS}$*
Company 1	0.34	0.35	0.06	0.52	0.37	0.10
Company 4	0.42	0.45	0.10	0.48	0.43	0.10
Company 5	0.06	0.22	0.01	0.24	0.31	0.04
Company 7	0.30	0.20	0.03	0.39	0.31	0.06

Severity scale: 0 (No impact on performance) to 1 (High-performance loss)
Recovery time scale: 0 (Instantaneous recovery) to 1 (High recovery time)
Resilience index scale: 0 (Highly resilient) to 0,5 (Not resilient)

5.2. Resilience practices for material shortage

The automaker did not keep any raw material inventory and to make sure that there was a continuous just-in-time (JIT) production flow, it required the suppliers to preserve a three-day inventory. For components with high and erratic delivery lead times, e.g., parts coming from Asia, the automaker used inventory buffers via central intermediaries to avert probable delays in transportation, e.g., a central warehouse situated in France. The management of FGI by the automaker was reported to be challenging since such inventory required more space for storage and was harder to handle due to possible damages. Moreover, maintaining a strategic buffer for FGI was a very difficult task as the JIT suppliers would provide the necessary parts for a specific vehicle model when it was already in the automaker's assembly line. It was only company 5 that managed to keep strategic buffers in stock due to its products' material type, i.e., plastic parts.

In case there was a disturbance, the automaker used alternative/dummy components to avoid the assembly line from shutting down. Later, the alternative/dummy components would be replaced by original parts. However, this practice was quite expensive, time-consuming, and could lead to problems, e.g., damage to the assembled vehicles. Also, there were situations where an alternative product could not be used since it could no longer be replaced with the original part when the vehicle left the assembly line. Thus, whenever the suppliers failed to deliver the product on time, the assembly line at the automaker would halt. In terms of using alternative materials or components, the automaker followed a strict policy (imposed by its parent company) that allowed no alternatives in terms of materials or components, unless in some special cases where higher quality materials/components were used, e.g., altering one type of steel with another that possessed higher performance characteristics.

In the SC under study, it was essential for the suppliers to receive the required components/materials on time since they had to manufacture the parts exactly as per the automakers' requests. Therefore, it was crucial to ensure straightforward transportation of the required components/materials. All the suppliers in the case study were working with logistics companies that had a profound experience in transportation and had access to alternative delivery routes and various modes of transport. This was mainly due to a lack of alternatives for products and materials/components that encouraged the suppliers to partner with such competent logistics companies. This way, in case a disturbance took place in one delivery route/transport mode, the suppliers did not have to be concerned about whether they would receive the required materials/components on time. Normally, the contracted logistics companies would merge the orders from different sources using intermediary facilities (e.g., distribution centres) and then proceed with the shipment of the requested materials/components. Nonetheless, they remained open to requests by their contractors for modifying this process at a higher cost. In general, the shipment of components by producers located in Asia was made by sea, which dictated longer delivery lead times. In cases where there was a defective batch, an urgent shipment had to be made by air as the alternative delivery route. Furthermore, the transport mode could also be altered at a higher cost, e.g., air instead of marine transport.

Regarding strategic sourcing, the automaker's parent company chose the suppliers based on the specifications of materials/components. Normally, only one supplier was contracted per component, making it difficult to switch between alternative suppliers. Also, as there were not too many suppliers available, the companies had developed a close relationship with their suppliers. This type of relationship helped them to coordinate their processes better and avert material shortages. Despite incurring higher costs, the companies preferred to use faster transportation to decrease delivery lead times. The flexibility to change delivery schedules and supplier lead times was moderately high. However, due to a lack of supplier availability, contracting new suppliers was not perceived as a viable practice.

5.3. Resilience practices for capacity shortage and material shortage

Suppliers had visibility over the automaker's processes by exchanging information regarding the status of production through Electronic Data Interchange (EDI). The automaker would send its production plans to the suppliers one week before the start of the production, specifying the number of vehicles to be manufactured each day. This way, the suppliers would know what parts and components the automaker needed to carry out the production. The first-tier suppliers would also receive EDI messages from the second-tier suppliers informing them about the status of the materials/components that were scheduled for shipment. The alignment of information systems between the companies allowed them to share frequent and updated information mainly regarding their stock levels, leading to an extended network connection and a high level of SC visibility. Policies regarding the way information had to be exchanged and how it had to be used were in place and were followed by the companies, e.g., electronic data protocols defined by the automaker.

The development of SC common responses helped to substantially reduce recovery times. For instance, promoting daily and weekly conventions to consider potential SC disturbances (e.g., receiving defective parts or delays in transportation) and coming up with relevant solutions and contingency plans, which required a relatively high level of trust, cooperation, and risk sharing between the SC partners.

5.4. Results discussion

Most of the companies admitted that they had difficulty in using alternative components/materials. This was due to the stringent requirements set by the automaker that restricted the suppliers to deploy this resilience practice. Since the automaker's parent company was in charge of selecting the second-tier suppliers, the number of alternative suppliers to partner with was limited as well. This increased the negative effects of SC disturbances since the companies did not have the freedom to practice multisourcing. Moreover, the production policy set by the automaker was based on lean thinking, which meant that the SC inventory levels had to be reduced to a minimum, i.e., three days of inventory. This production policy also limited the sourcing options of the companies as they were not able to source from suppliers with longer lead times.

Collaboration among the companies was considered crucial for deploying the SC common responses. It provided visibility over the material flow as well as the logistics network, helping the management to make well-informed decisions. The existence of an advanced information technology infrastructure among the companies did not necessarily mean that they had to commit to information sharing. However, it was complemented by collaborative behaviour and trust-based relationships that led to a high level of information sharing and information accessibility between the companies (Naghshineh & Lotfi, 2019). The scores for the resilience indices (as shown in Table 9) translate into a high resilience level of on-time delivery. These results were expected since the cost of production halt was very high for the first-tier suppliers as well as the automaker. Therefore, as discussed earlier, the companies administered the necessary resilience practices and policies based on the needs of their SC to ensure on-time delivery even when SC disturbances took place.

6. Conclusions

6.1. Contribution to the literature

To clarify how this research contributes to the existing literature, we discuss and compare our findings with some of the research mentioned in Table 3 that propose indices for assessing resilience.

Among the early research, Azevedo et al. (2013) suggested a hierarchical index to assess the level of resilience and greenness in SCs. In their study, the resilience practices were selected based on experts' knowledge and evidence from literature, however, they did not develop a framework. In an attempt to be more focused, Carvalho, Azevedo, and Cruz-Machado (2013) also applied a similar methodology to assess resilience, but contrary to the present study, they only considered a limited set of resilience practices and used the Delphi technique to obtain weights for each practice in order to create a composite resilience index. Using a different method, Soni, Jain, and Kumar (2014) utilized graph theory to propose a model that considers the major enablers of SCR and their interrelations, resulting in a single numerical SCR index. While their research findings are valuable, the SCR enablers they have used to compute the resilience index are mainly higher-order constructs, e.g., agility, collaboration, information sharing, etc., and their study does not clearly specify how the values for these SC capabilities can be captured on a granular level. In contrast, this study makes use of a set of specific resilience practices and SC state variables to model an index that focuses on assessing resilience against the two most common SC failure modes (i.e., material shortage and capacity shortage).

Munoz and Dunbar (2015) proposed a multidimensional, multi-tier metric for quantifying resilience by characterizing response to a disturbance over a specific period using simulation modelling and testing it via Structural Equation Modelling (SEM). While their research yields insightful results, it lacks operational detail based on real-world data, whereas the findings of this research are based on actual case study data that overcome this shortcoming. Cardoso, Barbosa-Póvoa, Relvas, and Novais (2015) developed an optimization model for a closed-loop SC, where they proposed different indicators based on network design and operational performance to measure resilience. Their research, however, is based on a limited number of potential SC disturbances and since there are too many different SC disturbances that can take place in reality, instead, considering a limited number of SC failure modes is more plausible when modelling resilience (Rice & Caniato, 2003). Hence, in the current research, we focused on the two most prevalent SC failure modes as mentioned earlier.

Pavlov, Ivanov, Dolgui, and Sokolov (2017) developed a resilience index for SC design by taking advantage of the hybrid fuzzy-probabilistic method. They considered the structural attributes of SC design while measuring resilience. Their proposed method enables the comparison of different SC designs in terms of resilience and recovery capabilities, helping to identify important suppliers whose breakdown would disrupt the entire SC. However, their proposed index does not assess the resilience of the SC to supply failures, particularly at the individual company level. Considering the ripple effect, Hosseini and Ivanov (2019) introduced a resilience measure by considering disturbances and recovery stages. Making use of the Bayesian networks and examining resilience as a function of supplier susceptibility and recoverability, they modelled a measure that can assess the resilience of original equipment manufacturers. However, disturbance possibilities are not explicitly considered, which as mentioned by the authors themselves is a limitation of their work, whereas in this research the resilience index is modelled based on the notion that disturbances lead to SC failure modes that negatively affect the on-time delivery performance of the SC.

More recently, Goldbeck et al. (2020) investigated SCR by mainly considering the capacity for repair logistics in an SC. They considered the speed of recovery as a metric and proposed a mathematical model to optimize the allocation of repair resources. However, a limitation of their work is that distributed and individual decision making by different SC members is not considered to be a factor, which limits the application of the model to mainly analysing well-integrated SCs where all the SC members are committed to collaborating and sharing information. However, the index in this study is capable of measuring resilience at an individual company level, and thus it can also be used by companies that operate in rather disintegrated SC settings.

In summary, after reviewing the existing literature on resilience assessment, evidence suggests that no study by far has proposed a holistic index based on a wide range of resilience practices and relevant SC state variables that can assess a company's resilience of on-time delivery to capacity and material shortages. This research addresses this knowledge gap via an exploratory investigation that is based on knowledge from both industry and extant literature, providing insights into ways resilience can be augmented towards the aforementioned SC failure modes. Additionally, this study contributes to the field of SC management by developing an explanatory framework that shows how the identified resilience practices relate to the SC failure modes, modelling resilience in terms of on-time delivery as the primary performance measure of the SC. At best, the identified set of resilience practices could help to completely avoid capacity and material shortages, and at worst reduce the severity and the time necessary to recover from them. As emphasized in the existing literature, the contributions of this research are in line with the need to identify key variables for mitigating the negative effects of SC disturbances (Blackhurst, Craighead, Elkins, & Handfield, 2005; Ribeiro & Barbosa-Povoa, 2018).

6.2. Theoretical implications

From a theoretical perspective, the explanatory framework in this research provides scholars with new directions on how to conceptualize resilience in different SCs. Particularly, this study highlights a set of resilience practices along with relevant SC state variables that can be deployed or modified to reduce disturbance severity and recovery time, and consequently augment the resilience of on-time delivery. These resilience practices are mainly associated with enhancing flexibility, redundancy, collaboration, visibility, and responsiveness SC capabilities. Existing literature suggests adopting similar SC capabilities to improve SCR, such as adaptability, capacity, recovery, and flexibility in sourcing and order fulfilment (Han et al., 2020; Hohenstein et al., 2015; Kamalahmadi & Parast, 2016; Kochan & Nowicki, 2018; Pettit et al., 2019; Tukamuhabwa et al., 2015), however, it does not specifically clarify how these SC capabilities can contribute to mitigating the negative effects of disturbances. The proposed explanatory framework in this research addresses this shortcoming. Also, as explained earlier, to the best of the authors' knowledge, to date, no research had come up with a holistic index capable of assessing the resilience of on-time delivery to capacity and material shortages.

6.3. Managerial implications

The modelling of the resilience index in this research led to the inference of some managerial implications. The case study responses indicate that when disturbances trigger capacity shortages, the automaker (i.e., company 1) and one of its first-tier suppliers (i.e., company 4) experience the ensuing negative impacts with greater severity mainly due to a lack of alternative production processes/sites as well as low production capacity slack. For instance, in one of our observations, the SC manager of the automaker reported a case where a working shift had to be entirely cancelled due to a shortage of capacity at the engine supplier, whereas in another observation, he reported an incident of a "non-production day" as several suppliers were experiencing capacity shortages. To address such issues and avoid costly halts in the assembly line at the automaker, the SC manager reported that they normally exercise (what he phrased as) "hold actions", which is to hold/retain the production of some vehicles. In this case, the main objective is to change the production planning of the "car body" (i.e., vehicles' frames), or if necessary, change the daily production sequence of the vehicles (i.e., the daily production mix) at the automaker.

However, such "hold actions" can also have negative effects on the SC. For instance, when the automaker changes its daily production mix, the first-tier suppliers may experience difficulties adjusting their production plans accordingly and respond on time. "Hold actions" can thus disrupt the SC and create a negative cycle, where solving one problem at the automaker can lead to other problems at the suppliers. Also, it was reported that in cases where "hold actions" are not viable or there is a part/component shortage, the vehicles can be transferred from the automaker's assembly line to a temporary "park", where the missing parts will be assembled and the dummy components (if any) will be replaced later. However, transferring the vehicles to the "park" poses a challenge as the vehicles can be damaged (e.g., scratches or bumps) apart from increasing the inventory costs. In another instance, where the automaker's production needs cannot be met using regular transport, emergency transport needs to be implemented. This type of transport represents a high additional cost, e.g., an urgent transport van can represent a daily cost of more than €5,000.

Because of all these complexities and interactions among the companies within the same SC, resilience practices are deployed to increase visibility, redundancy, responsiveness, collaboration, and flexibility capabilities in the SC, aiming to increase service levels and reduce costs in the face of capacity and material shortages. Thus, the proposed resilience index along with the identified SC state variables in this study provide an opportunity for managers to analyse and modify the resilience practices they tend to deploy in their SC to increase the resilience of on-time delivery to capacity and material shortages. In more general terms, the derived knowledge from this research allows managers and decision-makers to have a better understanding of the current state of resilience in their SCs, and thus invest their company resources in the right resilience practices. Also, the derived knowledge on how resilience practices and SC capabilities can potentially enhance the resilience of the SC network to failure modes enables managers to make more informed decisions. The proposed resilience index in this research provides a holistic view of how to improve SC performance mainly in terms of on-time delivery, which managers can consider when designing their SCs. Additionally, the proposed resilience index can help managers to assess the resilience of various SC (re)design scenarios, lending support to a more informed decision-making process.

7. Limitations and future research

Since the SCR theme encompasses a vast range of research topics, in this research, we focused on company behaviour and how to tackle the negative impacts of SC disturbances. In this empirical research, we only focused on one automotive SC despite the notion that the generalizability of results based on a single case study can have some limitations (Voss et al., 2002). However, this issue was mitigated by choosing a case study design where seven case companies were investigated (i.e., one SC with multiple embedded companies), allowing for the cross-case analysis and synthesis of the research results (Yin, 2003). Additionally, more resilience variables might have emerged if different types of SCs were part of the study. Another limitation is that the focus of this research is on the upstream SC of a Portuguese automotive manufacturer. Hence, the results may not always apply to different SC tiers, industry sectors, and countries. Another issue is informant bias as some informants may try to protect their companies' reputation as well as their own image by providing biased information.

In order to generalize the research findings, it is necessary to perform multi-national/cross-cultural research. Hence, future research can aim to assess the propositions that underlie the proposed framework via an extensive survey in different countries and SCs. Also, it is important to conduct empirical research regarding the assessment of the SC state variables. Several issues normally emerge while trying to develop indices and metrics, e.g., bias, subjectivity, selection of indicators, mathematical combinations, weighting, and data sources, among others. Therefore, it is recommended to test the proposed resilience index in other industrial settings. This way the robustness of the proposed index can be put to test. We also suggest testing the proposed resilience index in various industries and SCs where different resilience practices are exercised. To further assess the robustness of the index, future work may as well consider the severity of the disturbances as well as different contingency factors based on process and product characteristics that influence the SC responses to the negative effects of disturbances.

Moreover, a longitudinal study can help to assess the level of resilience over time. This way, the resilience of on-time delivery can be assessed over a specific period and the changes in the SC performance levels can be traced when disturbances occur.

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CRediT authorship contribution statement

Helena Carvalho: Project administration, Conceptualization, Methodology, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Bardia Naghshineh:** Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing. **Kannan Govindan:** Conceptualization, Methodology, Validation. **Virgílio Cruz-Machado:** Supervision, Conceptualization, Methodology, Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Interview questionnaire for phase one

1. General information about the interviewee

-Name (optional)

-Function

-Contact number (optional)

-Email (optional)

General information about the company

-Country

-Sector

-Number of employees: <50; <250; >250

- Main product(s) produced by the company:

-Number of products in production

-Total production in the previous year (units)

-% of production for the domestic market

-% of production for the foreign market

-Approximate sales volume of your company (euros) last year? <2 million; < 10 million; < 50 million; > 50 million

2. Discussion about what supply chain disturbances are and how they can affect the company.

-What do you mean by "disturbance" of the supply chain?

-Indicate examples of supply chain disturbances that have affected your company. What were the characteristics of the disturbances?

Characteristics / Disturbance	Duration	Intensity	Frequency	Other

-For the identified disturbances, what were their negative effects on the company?

Effects / Disturbance	Long term	Short term	Scarcity of materials	Scarcity of capacity	Undelivered products	Rework	Other

3. Discussion about the response practices used by the company to minimize the negative effects of the disturbances.

-For the previously identified disturbances, what are the mitigation practices, policies, or procedures that your company has adopted to minimize their negative effects.

Disturbance	Practices, policies, procedures

Appendix B. Exhaustive questionnaire for phase two

This questionnaire aims to support research in the identification and characterization of potential management practices to avoid and/or minimize the negative effects of disturbances on the supply chain. Your contribution is very important for the development of this study. Please agree to cooperate with this investigation by completing this questionnaire.

A - Characterization of the Company

A.0 Country:

A.1 Sector:

A.2 Number of employees: <50; <250; >250

A.3 Main product(s) produced by the company:

A.4 Main customer activities:

A.5 Function of the person filling out the questionnaire:

A.6 Name of the person filling out the questionnaire: (optional)

A.7 Contact (e-mail): (optional)

A.8 How do you position your company in the supply chain? (Mark the correct answer in the table below).

4th tier Supplier	3rd tier Supplier	2nd tier Supplier	1st tier Supplier	Focal Company	1st tier Customer	2nd tier Customer
☐	☐	☐	☐	☐	☐	☐

B –Management practices to avoid and/or minimize the negative effects of disturbances on the supply chain.

For each of the following practices, mark your perception of the options available to your company for facing the negative effects of disturbances.

B.1 - Practices to minimize the effects of capacity shortages:

B.1. 1 - Use alternative production paths	**Very low** **1**	**2**	**3**	**4**	**Very high** **5**
Possibility to outsource production processes	☐	☐	☐	☐	☐
Operations versatility (number of operations a workstation can perform)	☐	☐	☐	☐	☐
Rredundancy in production processes	☐	☐	☐	☐	☐
Number of available alternatives for production sites	☐	☐	☐	☐	☐

B.1. 2 - Use maximum capacity	**Very difficult** **1**	**2**	**3**	**4**	**Very easy** **5**
Ease (time and cost) of adjusting the production capacity	☐	☐	☐	☐	☐

B.1. 3 - Reduce response time	**Very difficult** **1**	**2**	**3**	**4**	**Very easy** **5**
Ease (cost) of reducing production lead time	☐	☐	☐	☐	☐
Ease (cost) of reducing setup or changeover times	☐	☐	☐	☐	☐

B.1. 4 - Reallocate resources	**Very difficult** **1**	**2**	**3**	**4**	**Very easy** **5**
Ease (cost and time) of relocating equipment from one cell, site, or business partner to another	☐	☐	☐	☐	☐
Ease (cost and time) of reallocating workers	☐	☐	☐	☐	☐
Ease (cost and time) of disabling equipment and re-	☐	☐	☐	☐	☐

commissioning if necessary					

B.1. 5 - Increase capacity	**Very low/difficult 1**	**2**	**3**	**4**	**Very high/easy 5**
Possibility to influence the short-term capacity of suppliers	☐	☐	☐	☐	☐
Ease (time and cost) of increasing production capacity	☐	☐	☐	☐	☐

B.1. 6 - Change the production schedule	**Very difficult 1**	**2**	**3**	**4**	**Very easy 5**
Ease (cost and time) of changing the production schedules	☐	☐	☐	☐	☐

B.2 - Practices to minimize the effect of material shortages:

B.2. 1 - Use materials buffers	**Very low 1**	**2**	**3**	**4**	**Very high 5**
Availability of raw material strategic buffers (RAW)	☐	☐	☐	☐	☐
Availability of Work in Progress (WIP) strategic buffers	☐	☐	☐	☐	☐
Availability of Finished Goods Inventory (FGI) strategic buffers	☐	☐	☐	☐	☐

B.2. 2 - Deliver a temporary substitute product	**Very low/difficult**	**2**	**3**	**4**	**Very high/easy**

	1				5
Availability of product alternatives/dummies	☐	☐	☐	☐	☐
Ease (time and cost) of using new/substitute components	☐	☐	☐	☐	☐

B.2. 3 - Use alternative delivery paths	**Very low/difficult 1**	**2**	**3**	**4**	**Very high/easy 5**
Number of available alternatives for delivery routes	☐	☐	☐	☐	☐
Number of available alternatives for transporting goods and material	☐	☐	☐	☐	☐
Ease (cost and time) of switching between distribution channels	☐	☐	☐	☐	☐

B.2. 4 - Use alternative suppliers/strategic sourcing	**Very low/difficult 1**	**2**	**3**	**4**	**Very high/easy 5**
Number of available alternatives for sources of supply	☐	☐	☐	☐	☐
Number of different suppliers contracted per component	☐	☐	☐	☐	☐
Ease (cost and time) of switching between suppliers	☐	☐	☐	☐	☐
Close relationship with suppliers	☐	☐	☐	☐	☐
The level of expertise in developing supply sources	☐	☐	☐	☐	☐

B.2. 5 - Reduce delivery lead time	**Very difficult 1**	**2**	**3**	**4**	**Very easy 5**

Ease (cost) of reducing delivery lead time	☐	☐	☐	☐	☐

B.2. 6 - Change delivery schedules	**Very difficult** **1**	**2**	**3**	**4**	**Very easy** **5**
Ease (cost and time) of changing delivery schedules	☐	☐	☐	☐	☐

B.2. 7 - Reduce supply lead time	**Very difficult** **1**	**2**	**3**	**4**	**Very easy** **5**
Ease (cost) of changing the supplier lead time	☐	☐	☐	☐	☐

B.2. 8 - Find new suppliers	**Very difficult** **1**	**2**	**3**	**4**	**Very easy** **5**
Ease (cost and time) of contracting new suppliers	☐	☐	☐	☐	☐

B.3- Practices to minimize the effect of capacity shortage and material shortages

B.3.1 - Create supply chain visibility	**Very low** **1**	**2**	**3**	**4**	**Very high** **5**
Availability of real-time information systems (e.g., inventory information, demand information)	☐	☐	☐	☐	☐
Information accessibility	☐	☐	☐	☐	☐

B.3.2 - Align supply chain information systems	Very low 1	2	3	4	Very high 5
The level of network connection extensiveness	☐	☐	☐	☐	☐
Ease (cost and time) of exchanging reliable and timely information with supply chain partners	☐	☐	☐	☐	☐
The level of information standardization/interoperability	☐	☐	☐	☐	☐

B.3.3 - Supply chain common response	Very low 0	2	3	4	Very high 5
Trust-based relationships with suppliers and customers	☐	☐	☐	☐	☐
The degree of cooperation with other firms in the supply chain	☐	☐	☐	☐	☐
Actively share the risk with partners	☐	☐	☐	☐	☐

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