Calculating supply chain resilience: a critical review of the literature

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Abstract: The ability of a system to withstand disruptive events and quickly restore operational status by recovering initial capacity is called resilience. A resilience analysis allows to consider long term effects of disruptions and track the time trend of residual capacity allowing to estimate business interruption losses. However, no standard and comprehensive methodology for resilience assessment of industrial systems is available yet. To provide guidance to researchers and practitioners, in this paper an attempt is made to develop a framework to categorize and critically appraise resilience estimation approaches for supply chains. A critical review of the literature is here carried out, to evaluate the state of the art and identify the best available approaches. In particular, in reviewing the literature we focused on five main issues, namely: adopted computational approach, resilience quantification metric, point of view of the analyst, flow modeling, transport failures modeling. Additionally, resilience estimation has been decomposed into a set of independent subproblems, namely: the characterization of the disruptive events, their probability of occurrence estimation, the generation of scenarios, the definition of the failure state for the elements of the supply chain, the calculation of the time trend of capacity recovery and the definition of the economic loss. Previous approaches in tackling each subproblems are compared and discussed. A morphological matrix is finally suggested as an operational tool to support the definition of appropriate combinations of approaches to subproblems that allow the development of new more effective models for assessing the resilience of the supply chain. The above approach marks the novelty if this critical literature review as compared to existing ones.

Keywords: Resilience, Supply Chain, Literature review

I. INTRODUCTION

Resilience is the ability of a system to resist a disruptive event which impairs its capacity, and to recover quickly from the resulting loss. Supply chains (SC) are networks of economic actors (suppliers, manufacturers, logistic providers etc.) allowing to produce and distribute products or services to the final customer. Failure of one or more nodes in a SC may disrupt its operations causing possible delays and interruption of physical, information and financial flows, thus preventing the goods and services to reach in a timely and economically sustainable manner the final user. In recent years, some important disruptive events, such as the COVID-19 epidemic, the Russian-Ukrainian war events, and the Suez Canal blockage have shown how SCs in these cases can suffer serious decreases in performance, and slowly recover the original condition, causing huge economic losses globally.

The study of the resilient behavior of systems is often carried out adopting the perspective of the trend of the residual capacity C(t) over time (fig. 1). In the curve it is possible to note in the period $t_0 \div t_d$ the initial capacity loss CL = $C(t_d)-C(t_0)$, in the period $t_d \div t_c$ the planning of restoration activities, and in the period $t_c \div t_r$ the recovery process.

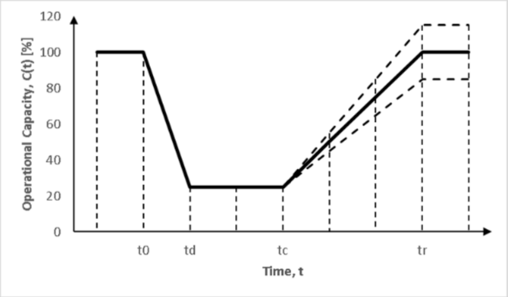

Fig. 1. Trend of capacity vs Time

In general, the capacity recovery trend is not linear and is discontinuous owing to discrete capacity recovery of single components. In addition, the post-recovery capacity can reach a lower or higher level than the initial one, depending on the interventions performed.

The literature on SC resilience is very wide, however a standard approach to its estimation has not been agreed upon. The following work aims to analyse the state of the art of the literature on SC resilience, by focusing on the comparison of alternative approaches available to solve some specific subproblems in resilience computation. Existing literature reviews instead are based on the comparison between papers (Bier et al., 2019; Hosseini et al., 2019; Hosseini and Ivanov, 2020).

The paper is structured as follows. Section II describes the criteria adopted to select articles. In section III the reviewed papers are classified and compared on the basis of five relevant categories. In section IV the problem of calculating the SC resilience is decomposed into simpler subproblems. Techniques adopted in the literature to solve the subproblems are then classified resorting to a morphological matrix and discussed in detail in section IV. In the Conclusions section results of the analysis are resumed, limitations of this analysis are discussed and perspectives for future research are identified.

II. RESEARCH METHODOLOGY

The literature research on SC resilience was conducted through scientific databases (Scopus, Web of Science and Science Direct) and search engines (ResearchGate and Google Scholar), focusing on works published since 2010. Considering that resilience, even in the sole domain of industrial applications has multiple meanings (i.e. also pertaining to organizational, psychological, and safety-related issues, often treated in a qualitative manner), to restrict the search to meaningful contributions it was decided to use only the keywords "Supply Chain Resilience", "model", "quantification/computation" contained in title, abstract and keywords. 247 articles were initially identified. Only 89 of these were focused on calculating the resilience of supply chains, while the others dealt with other issues (e.g. individuation of the parameters that influence resilience, surveys on the perception of resilience). Eventually 31 papers were selected containing more relevant quantitative models to calculate the resilience.

III. LITERATURE CLASSIFICATION

The selected articles were classified into the five categories indicated in Table II and discussed below.

A. *Computational approach*

The main characteristic that distinguishes the reviewed papers is the adopted computational approach. Three distinct computational approaches have been identified. A process-based one, characterized by discrete event simulations, which analyses the process inside the SC to derive the measure of resilience. Mathematical programming, which through the constraints calculates the performance of the supply chain and subsequently the resilience index (optimizing it or not). Finally, a probabilistic approach can be adopted resorting to Bayesian Networks, which do not describe the physical structure of the system but map the logical structure of "cause-consequences" between damage caused by the disruptive event and its consequences. They often provide only an aggregate indicator of system resilience.

B. *Resilience quantification*

Many authors do not identify an explicit resilience metric but indirectly base the assessment of the resilience of the SC on certain cost or time indicators. Among the articles analysed, 15 different indicators of this type were identified. This type of approach does not allow a clear development of the SC resilience calculation associated with the definition of resilience. Many authors, instead, explicitly identify a resilience index, but express it through a "proxy indicators" (e.g.: time down, backorders...), and do not refer to the trend of the residual capacity curve (fig. 1).

To the last category belong the authors who, with different formulations, compute a performance measure based on the residual capacity curve of the SC (fig. 1), for example measuring the area under the curve. However, while this latter approach requires the plot the capacity recovery curve, it appears the referable method as it computes a performance measure explicitly based on the resilience definition and taking into account the actual time to recover and the disruption level.

C. *Point of view of the analyst*

In some cases, the resilience indicators are computed with reference to a specific company, or component of the SC arbitrarily selected as the focal point. This appears as quite limitating, as the point of view of a single actor does not describe adequately the resilience of the entire SC and its overall response to a disruption. In fact, given a disruption different actors may experience different impacts. A second type of approach considers a global perspective. In this case, the resilience indices are associated with measures of the "health" level of the entire SC (e.g.: average inventory, average capacity of nodes etc.). Nevertheless, indicators of this type can distort the assessment of resilience, as they can hide localized criticalities that affect the entire functionality of the SC. In the last group the evaluation is based on the level of service offered to customers, or on the level of performance of retailers. This approach can be considered preferable as it bases performance on SC output, which is the factor generating the external revenues that feeds the SC and allows its survival.

D. *Flow modelling*

A relevant feature of SC resilience models in the number of distinct materials flows considered. Papers that consider a single flow cannot include the interaction between the different raw materials and semi-finished products. Multiple product flows are considered in many articles, which sometimes use the bill of materials to represent each flow necessary to a production. Only a few articles, in addition to considering multiple production flows, also introduce information flows. Information flows can allow to better represent the dynamics of procurement between SC actors. Finally, only one paper considers the financial flow that goes up the SCs. The recent ban from the SWIFT circuit of some Russian banks following the war in Ukraine demonstrate how this flow must be considered, as can be the target of the disruptive event.

E. *Transport failures modeling*

The category concerning transport modeling does not deal with how transport is represented in SCs, but with how disruptions in transportation are modeled. Most of the articles do not include transportation disruptions in the study of SC resilience. This is a serious shortcoming, as it neglects an important category of risk for global SCs, as demonstrated by the blockade of the Suez channel in March 2021. It is indeed useful to note how transport failures can affect both different SCs and several elements of the same SC, without production companies having undergone any disruptive event.

Some articles model transport failure by breaking the arcs that connect the nodes that make up the SC. However, using this approach, it is necessary to evaluate the possibility of events that may affect not a single arch, but a family of arcs sharing some common characteristic (e.g. transit through a specific bottleneck, or failure of a company performing transportation over multiple arcs). In this case, a single event must cause damage to all the related arcs. Obviously, the arc is not necessarily totally destroyed, but only a reduction of its capacity can occur. Imagining, for example, a long-term blockade of the Suez Canal, which forces the African circumnavigation. The transport of goods continues to be possible, but lengthening the times, obviously keeping constant the number of ships used, the quantity of goods transportable per unit of time is reduced. Clearly the longer route will have its obvious repercussions also in terms of costs.

The modeling of complex dynamics such as these can alternatively take place by representing the transports as if they were real nodes. In this way, disruptive events affecting several transport companies can be considered, such as the blocking of straits and infrastructures, for example through "risk portfolios". Furthermore, it is possible to take into consideration the specific risks of the single transport company, and to include in the SC structure also back-up transport companies. In such a representation, each tier made up of the actual manufacturing and storage nodes of the SC alternates with a tier made up of the transport companies that connect them.

IV. DECOMPOSITION OF THE RESILIENCE CALCULATION PROBLEM

The heterogeneity in the approaches used to calculate resilience, highlighted in the previous section, necessitated a more detailed study to formalize the SC resilience calculation problem under a unified framework. In order to clarify this point it has been chosen to subdivide the entire process of resilience calculation into a number of separate sub-problems (see Table I), here listed as A to F, as already made for the case of the resilience of industrial plants in Caputo et al. (2021).

A. *Disruptive event characterization*

Most authors (Baghersad and Zobel, 2015; Behzadi et al., 2020; Bottani et al., 2019; Burgos and Ivanov, 2021; Dixit et al., 2016, 2020; Hosseini et al., 2016; Ivanov and Dolgui, 2020; Lohmer et al., 2020; Moosavi, and Hosseini, 2021; Olivares-Aguila and El Maraghy, 2020; Rajesh, 2016; Shi et al., 2019; Simchi-Levi et al., 2015; Tian et al., 2021; Wagner and Neshat, 2010) adopt a simplified approach referring to a “generic” disruption, and do not consider any specific type of disruptive event or, when specific events are considered, there is no possibility of specifying the characteristics of the event. A second group of articles considers transportation delay as a disruptive event (Carvalho et al., 2011; Colicchia et al., 2010). This kind of event is certainly not negligible in globalized SCs. However, to consider only this type of event is reductive. Some articles consider multiple types of risks (Ojha et al., 2018; Shi and Mena, 2021; Taghizadeh et al., 2021). The approach is interesting, as it can involve the failure of multiple nodes following a single event. This aspect cannot be overlooked in SC dynamics.

Only one paper accounts for different categories of events for each node (Schmitt and Singh, 2012), requiring the specification for each node of a distinct "risk portfolio". This approach allows both to consider the damage of multiple nodes caused by an event present in more portfolios, and to consider multiple simultaneous events that damage the nodes that concern them. According to this approach, the nodes can be linked by common risks inherent for example to geography, sector, nationality and many other levels, with the possibility that they occur simultaneously.

B. *Probability of disruption occurrence*

This subproblem relates to the source of information as far as the probability of occurrence of the disruption is concerned. Hernandez et al. (2013) only assume a ”worst case” event neglecting its probability of occurrence. As a result a lower bound resilience is obtained. However, if the worst case had a negligible probability, the related measurement of performance would not be indicative of the average resilience. From this we deduce the importance of identifying a probability of occurrence of the disruptive event, to assign the right relevance to the obtained resilience indicator or to allow the computation of a weighted average in case of multiple scenarios. Taghizadeh et al. (2021) relies on third parties and agencies to assume probabilities of occurrence. These sources can be useful in the case of geographical risks related to natural events, political or economic instability. However, for specific risks that may have different probabilities of occurrence even between neighboring companies that are part of the same SC (e.g. strike risk) these tools do not offer solutions. Some authors derive the probability of occurrence of events from past data (Das and Lashkari, 2015; Shi and Mena, 2021). This can be useful only for phenomena characterized by a specific frequency, but not for others.

Finally, many authors use expert estimates or employee interviews for probability estimation (Collicchia et al., 2010; Goldbeck et al., 2020; Hossain et al., 2019; Ojha et al., 2018; Schmitt and Singh, 2012; Shi and Mena, 2021). These approaches, if structured in a risk analysis, can make it possible to identify the probabilities of occurrence of events for which it would be practically impossible to do otherwise. In conclusion, no method seems adequate for each type of event, but the right source of the probability of occurrence must be sought for each type of event considered.

C. Scenario generation

This subproblem does not refer to the assessment of the damage level of the nodes, but the strategy for deciding how many and which different damage scenarios to use in the calculation of resilience. The simplest approach is one in which the scenarios are determined by the user (Carvalho et al., 2011, Collicchia et al., 2010; Hernandez et al., 2013; Ivanov, 2017; Lohmer et al., 2020; Moosavi and Hosseini, 2021; Olivares-Aguila et al., 2020; Simchi-Levi et al., 2015; Tan et al., 2019; Zavala et al., 2018). Very often this approach is contained in papers that are more focused on solving others of the identified subproblems. Some authors, on the other hand, analyse all the computationally possible scenarios (Das and Lashkari, 2015; Goldbeck et al., 2020). In this case the probability of occurrence of each given scenario combination is essential, as it assigns a proper weight to each. The flaw of this approach is its computational cost which, especially in the case of complex SCs, can become very high. The computational cost is reduced in some cases by means of Monte Carlo Simulation (Dixit et al., 2020; Ojha et al., 2018) allowing to consider only a statistically significant but smaller number of scenarios.

D. Definition of the faults

The assessment of the state of damage of the system components is typically neglected in the examined literature, and the state of damage is determined by the user (Burgos and Ivanov, 2021; Carvalho et al., 2011; Das and Lashkari, 2015; Hernandez et al., 2013; Ivanov, 2017; Lohmer et al., 2020; Moosavi and Hosseini, 2021; Olivares-Aguila et al., 2020; Simchi-Levi et al., 2015; Tan et al., 2019; Zavala et al., 2018). The widespread use of this approach denotes a clear difficulty within the SC in characterizing the interaction of disruptive events and the related vulnerability of the elements of the SC. Furthermore it is frequent that binary damage states are considered. This approach is not adequate, as it is unrealistic that entire companies have only two levels of residual capacity without considering at least some intermediate states between total disruption and normal operations. Other authors propose a probabilistic approach (Collicchia et al., 2010; Dixit et al., 2020; Goldbeck et al., 2020; Ojha et al., 2018; Shi et al., 2019; Tan et al., 2021). Some of them randomly and independently extract both the damaged nodes and the damage level associated with it. Other authors instead extract random numbers and compare them with a probabilistic vulnerability index of the component (i.e. fragility curves), to define its failure state. In this way the damage state is related to the probability of damage of the element, to a given disruptive event. For this reason, this latter approach proves to be the most suitable for calculating the resilience of a SC.

E. Capacity curve calculation

The most important subproblem is that relating to the calculation model of the capacity curve (fig. 1). The curve represents the performance of the system during the period under consideration, and from this derives the resilient behavior of the system. Some authors employ a Bayesian network for the calculation of residual capacity (Hossain et al., 2019; Hosseini et al., 2016; Hosseini and Ivanov, 2020; Shi and Mena, 2021). This interesting tool does not appear particularly suitable for the purpose of calculating SC resilience for several reasons. The first resides in the fact that it does not model quantitatively the flows, but represents a series of logical-probabilistic links between system states and events. This prevents from obtaining a quantitative measure of the system output, which can only derive from the modeling of the complex dynamics of flows. Second, in general, this tool is not designed to generate a temporal trend of the residual capacity of the SC, but it provides an aggregate indicator, representing the overall probability that the SC can perform at an assigned service level instead of assessing the variation of SC output over time.

A second category of approaches calculates the residual capacity of the system in terms of constraints of mathematical programming models (Baghersad and Zobel, 2015; Bottani et al., 2019; Dixit et al., 2016; Goldbeck et al., 2020; Ivanov et al., 2016; Razavian et al., 2021; Simchi-Levi et al., 2015). In general, these impose the balance of flows between the nodes of the SC, placing further constraints on maximum capacity, based on the damage status of the elements. Among mathematical programming models the structure of the constraints is very heterogeneous. However, it is possible to note how this type of approach is based on the physical structure of the system, thus can provide a realistic analysis of the behaviour of the SC. On the other hand, the constraints that represent the structures are often complex and may not be suited to peculiar SC architectures. Finally, this type of approach has the advantage that, in addition to providing a measure of the residual capacity, it generates an optimization of at least one performance measure (changing according to the author) of the resilient behaviour of the system. Discrete event simulation is a popular approach for calculating the residual capacity of SCs (Burgos and Ivanov, 2021; Carvalho et al., 2011; Collicchia et al., 2010; Ivanov, 2017, 2020; Lohmer et al., 2020; Moosavi and Hosseini, 2021; Ojha et al., 2018; Olivares-Aguila and El Maraghy, 2020; Schmitt and Singh, 2012; Taghizadeh et al., 2021; Tian et al., 2021) as it allows to replicate the actual functioning of the SC during the occurrence of the disruptive event. Time trends of the output performance measure or state variable of interest can be easily generated, and proper modelling allows replication of any structural complexity of the network. The simulation also allows to easily include the random component in production and transport times, generating models that are more realistic. In conclusion, considering the complexity of global SCs, discrete event simulation is the approach that allows to include the most detailed modelling.

F. Economic loss definition

In all the examined papers, the economic loss is accounted for in terms of business interruption. This consist in the loss of income generated by the blocking of the production flow. Restoration costs are never considered in the articles analysed. However, these may be also relevant. This shortcoming is probably due to the lack of integration with models for calculating the resilience of the individual elements. In fact, the estimate of business interruption is an immediate consequence of the calculation of the SC performance. The estimate of restoration costs, on the other hand, derives from a study more focused on the individual company, which must be dealt with by a specific model, integrated with a model dedicated to the SC. Based on the above analysis, the morphological matrix depicted in Table I summarizes the available solution approach for each of the subproblems. Please note that some authors only address some subproblems, so not all papers provide solutions for every subproblem. The structure of the morphological matrix reflects the fact that resilience computation implies a sequence of distinct independent tasks which can be carried out according to different conceptual paradigms and computational tools. The variety of available approaches generates a combinatorial explosion of possible SC resilience computational models. The matrix does not indicate a priority among the subproblems, but highlights the computational steps offering a compact overview of options. In this respect this matrix may also act as a practical tool helping researchers to choose the preferred approach when modeling SC resilience taking into account pros and cons of each option.

V. CONCLUSION

This paper tried to offer a critical review of available approaches to computation of SC resilience. While other reviews available, the novelty of this contribution lies in the analysis of distinct issues and subproblems related to SC resilience computation and in the establishment of a reference framework to classify existing and future models. The decomposition of SC resilience computation into sub-problems allows a clearer comparison of alternative options, and highlights the heterogeneity that characterizes the existing literature. The resulting morphological matrix also acts as a practical tool to synthesize novel resilience estimation models. Based on the review findings the following limitations of existing literature in SC resilience computation can be pointed out. No single metric for resilience assessment is agreed upon, and traditional metrics conceived for industrial plants and other networked systems such as communication networks and utilities fail to capture the complexities of SCs. While it is conceptually simple to assess resilience from the point of view a single actor, the problem of representing resilience of an entire SC is open to discussion. The impact of SC structure on resilience has not been studied in detail given that most existing models are conceived for very, maybe excessively, simple networks. Modeling of information flows across the SC is still quite scarce. Quite surprisingly, most of the literature neglects modeling disruption in the transportation activities. Disruption events characterization is quite crude in most cases and often the damage level is not related to the type of disruption and the affected actor. The state of each component is often modelled in a binary state. This prevent to analyze partial loss of capacity. Scenarios generation is often left to arbitrary choice of the analyst and is carried out in a deterministic manner. Integrated and systematic probabilistic scenario generation and related damage estimation is still uncommon and requires further research. This may also call for integration of SC models and single business units resilience modelling, adopting a multi-level approach still non existent. Economic loss estimation is only linked to business interruption, provided that duration of the interruption can be estimated in a reliable manner, while capacity recovery costs are neglected. This confirms that there is a strong need for more realistic and sophisticated SC resilience estimation modeling. Overall, it seems that process flow-based probabilistic approaches are more suitable to provide detailed resilience estimation, including the assessment of time-dependent residual capacity. This, in turn, allows a quantitative computation of resilience performance measures. This approach can even be supplemented by mathematical programming models for optimization purposes. As compared to other literature reviews, this paper has the limitation that the adopted problem-based approach differs from the traditional paper-based review. In this respect the paper by paper description is not explicit. As a future work research will be aimed at developing novel SC resilience modelling tools filling the numerous gaps highlighted above.

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Appendix A. MORPHOLOGICAL MATRIX

TABLE I
MORPHOLOGICAL MATRIX

Subproblems	**Approaches**				
Disruptive event characterization	Generic	Delay in transport	Multiple types of risks for the whole SC	Multiple types of risks for i-th node of SC	
Probability of disruption occurrence	Expert estimates	Staff interviews	Based on past data	No probability – Worst case	Third parties and agencies
Scenario generation	Determined by the user	All scenarios considered	Monte Carlo Simulation		
Definition of the faults	Determined by the user	Probabilistic			
Capacity curve calculation	Discrete event simulation	Bayesian network	Mathematical programming		
Economic loss definition	Business Interruption				

Appendix B. PAPERS CLASSIFICATION

TABLE II
PAPERS CLASSIFICATION

Papers	Computational approach	Resilience quantification metric	Point of view of the analyst	Flow modelling	Transport failures modelling
Baghersad and Zobel, 2015	MP		ESC	MM	
Bottani et al., 2019	MP		ESC	MM	
Burgos and Ivanov, 2021	PB	PI	ESC	SM+I	DA
Carvalho et al., 2011	PB	PI	PC	MM+I	
Colicchia et al., 2010	PB	PI	PC		
Das and Lashkari, 2015		PI	PC		
Dixit et al., 2016	MP	PI	ESC	SM	DA
Dixit et al., 2020		PI	ESC	SM	DA
Goldbeck et al., 2020	MP	CC	ESC	SM	NT
Hernandez et al., 2013		PI	ESC		
Hossain et al., 2019	BN	PI			
Hosseini and Ivanov, 2019	BN	PI	PC		
Hosseini et al., 2016	BN	PI	PC		
Ivanov et al., 2016	MP	PI	CR	MM	DA
Ivanov, 2017	PB	PI	CR	SM	
Ivanov, 2020	PB	PI	CR & ESC	MM+I	DA
Lohmer et al., 2020	PB	PI	ESC		
Moosavi and Hosseini, 2021	PB	CC	CR	SM	
Ojha et al., 2018	PB	PI	CR		
Olivares-Aguila, El Maraghy, 2020	PB	PI	ESC	SM	
Rajesh, 2016		PI	PC		
Razavian et al., 2021	MP	PI	PC	MM+F	
Schmitt and Singh, 2012	PB		ESC	MM	
Shi and Mena, 2021	BN	PI	ESC		
Shi et al., 2019		PI	ESC	SM	
Simchi-Levi et al., 2015	MP	PI	PC	MM	
Taghizadeh et al., 2021	PB	PI	ESC	SM	
Tan et al., 2019	PB	PI	ESC		
Tian et al., 2021	PB	PI	ESC	MM	DA
Wagner and Neshat, 2010			PC		
Zavala et al., 2018		PI	ESC	SM	

Computational approach: BN= Bayesian Network, MP= Mathematical programming, PB= Process Based (Discrete event Simulation). **Resilience quantification:** CC= Based on the residual capacity curve, PI= Proxy indicators. **Point of view:** CR= Customers / retailers, ESC= Entire supply chain, PC= A particular company. **Flow modelling:** F= Financial flow; I= Information flow, SM= Single material flow, MM= Multiple material flow. **Transport fault modelling:** DA= Damage to arcs, NT= Nodes represent transport companies.