A conceptual framework for supply chain resilience estimation

Caputo A.C.[a], Donati L.[b], Salini P.[c]

a. Dipartimento di Ingegneria Industriale, Elettronica e Meccanica, Università degli Studi Roma Tre, Via Vito Volterra, 62, 00146 – Roma – Italy (antoniocasimiro.caputo@uniroma3.it)

b. Dipartimento di Ingegneria civile, informatica e delle tecnologie aeronautiche, Università degli Studi Roma Tre, Via Vito Volterra, 62, 00146 – Roma – Italy (lorenzo.donati@uniroma3.it)

c. Dipartimento di Ingegneria Industriale e dell'Informazione e di Economia, Università degli Studi dell'Aquila, Piazzale Ernesto Pontieri – Monteluco di Roio (AQ) – Italy (paolo.salini@univaq.it)

Abstract: Resilience, i.e. the ability to absorb the impact of disruptive events and quickly recover functionality is increasingly perceived as an important requirement of supply chains (SC). In fact, over the past decade, multiple disruptive events, such as the Covid 19 pandemic and the war in Ukraine demonstrated the fragility of many SC. However, in order to assess resilience of a SC and plan improvement actions one has to be able to quantify it. While scholars and practitioners have suggested several methods to address this issue, no widely agreed approach exists. Current approaches are affected by a number of limitations. For instance, the calculation of the resilience index is not based on the temporal trend of the SC performance, a global SC resilience performance measure is not identified, the response of companies to the perturbation are not taken into account, the perturbating event can impact a single company at a time, and, finally, the affected company can not show degraded operations but is assumed to lose its entire capacity. The objective of this work is to propose a comprehensive and analytical SC resilience calculation model, which fills the gaps of existing approaches. The model consists of 4 main phases. In the first one, the SC is modeled by considering three superimposed layers, representing namely: nodes, paths connecting nodes, and transporters, to allow a proper assessment of interactions between the whole set of involved players and geographically located physical assets and infrastructures. In the second, disruptive events and their consequences are modeled. In the third, the SC operation in degraded conditions is modeled, and in the fourth, starting from the simulated performances, the resilience of the SC is calculated. In this paper the entire conceptual framework and data structures describing the above SC resilience estimation method is described.

Keywords: Resilience, Supply Chain, Black Swan Events

I. INTRODUCTION

In industrial practice resilience is the ability to withstand major disruptive events, and to quickly restore functionality of a system. Resilience of supply chains (SC) is a topic gaining an increasing attention from scholars, especially after several unexpected events, i.e. the COVID 19 pandemic, the Russia-Ukraine war and the blockage of Suez channel, showed in recent times the vulnerability of global SCs. The key to build more resilient SC lies in understanding the weak points, applying proper protective and preventive measures as well as develop reactive strategies. This asks for being able to quantify the resilience of a SC under a wide array of disruptive scenarios. However, while numerous attempts are available in the literature an agreed approach to estimate SC resilience is not yet available. In this paper, in order to attempt to improve the available SC resilience modeling a framework and underlying model to compute resilience for a SC of arbitrary configuration, exposed to generic disruptive scenarios is described. The novelty of the model lies in focusing on assessing the impact of disruption on the SC structure and modeling performances under degraded operational conditions. While space limitations prevent from providing full modeling details here we focus on describing the adopted data structure and the general computational framework, based on a critical appraisal of the existing literature.

II. LITERATURE REVIEW

Literature abut SC resilience modeling is quite heterogeneous and has been recently reviewed by Caputo et al. (2022). A classification can be attempted by referring to the manner each single modeling issue has been addressed. As far as the resilience performance measure is concerned, in most of the existing models, the resilience of the SCs is indicated by means of proxy indicators, based on time and costs which only provide a static figure (Burgos and Ivanov, 2021; Colicchia et al., 2010; Dixit et al., 2020). The chosen indicators are very heterogeneous, but none of these can describe properly the behavior of the system's performance. Only a few authors propose indices that derive from plotting the trend of SC performance over time (Goldbeck et al., 2020; Moosavi and Hosseini, 2021), but they disagree on choice of performance measure. A complex sub-problem is the definition of the state of damage and the residual capacity of the individual nodes following the disruptive event. The main approaches propose the definition of the state of damage by the users (Moosavi and Hosseini, 2021), or they propose probabilistic approaches (Collicchia et al., 2010; Dixit et al., 2020; Goldbeck et al., 2020). The first approach can be considered valid for specific "What-if" analyses, but it has the drawback of being uncorrelated to the hypothesized disruptive event. Probabilistic approaches, such as those that employ fragility curves, remain the only alternative approach. However, the trends of the residual capacity of individual disrupted nodes are rarely considered. Instead, their capacity follows a binary logic (operational/disrupted). This is unrealistic, as a disrupted node can show a degraded performance instead of total interruption. The third main sub-problem is the method for calculating the performance curve over time. Some models provide a calculation through Bayesian networks others through mathematical programming models (Goldbeck et al., 2020). Both approaches do not allow to easily represent the complex SC dynamics. On the other hand, approaches based on simulations (discrete event or agent based) are more suitable and widely adopted. In fact, this allows to better represent the complexity of the structure and connections of a SC, (Burgos and Ivanov, 2021; Colicchia et al., 2010; Moosavi and Hosseini, 2021; Schmitt and Singh, 2012). However, even in the case of simulations, in most cases to nodes are not given the ability to adopt reactive strategies, for example by allocating greater production capacity to more requested products, to the detriment of others. The last sub-problem is the disruptive event characterization. It links the state of damage of the SC to the actual risks occurring. Existing models sometimes neglect the problem and apply completely generic failures or simple transport delays (Burgos and Ivanov, 2021; Colicchia et al., 2010; Dixit et al., 2020; Moosavi, and Hosseini, 2021). Only more complex approaches introduce one or more risks, which can cause damage to the SC as a whole or to specific nodes (Schmitt and Singh, 2012). Existing works almost never consider events that can damage more than one node, a very usual situation for events that can damage a SC. In summary, the gaps encountered in the existing literature consist of: not using a SC performance trend to perform the calculation of the resilience index; not considering the residual capacity of individual disrupted nodes as a continuous but as a binary value; use of unsuitable SC performance calculation methods or not considering the nodes' reaction to supply and demand trends; not considering that disruptive events can generate failures across multiple the nodes.

III. Calculation model

The model consists of 4 main steps:

a) Supply chain structure modeling;
b) Disruptions generation;
c) Supply chain operations simulation;
d) Resilience index calculation.

A. Supply chain structure modeling

This paragraph describes the structure of the model necessary to calculate SC performance irrespective of the damage state of the nodes. The structure of the SC in modeling plays an essential role. In fact, too trivial modeling does not allow to suitably represent the complex dynamics of modern SCs. However, structures that are too complex are difficult to comprehend and cumbersome to apply in practice. The adopted modeling structure of the SC includes three overlapping layers: namely nodes, paths, transporters.

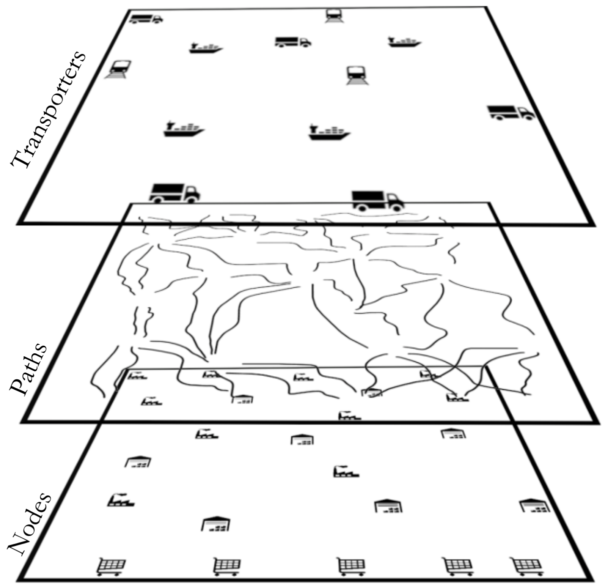

Fig. 1. Nodes, Paths and Transporters layers overlapping.

This allows to establish interactions and associations between the elements of the distinct layers without being forced to assign a univocal geographical location to the entities. For instance, while nodes (i.e. plants and warehouses) have a unique geographical location, transporter companies do not necessarily have a fixed location, while connections between nodes do not necessarily imply a terrestrial route among them, and the same transportation route can be shared by different transporter or can be interrupted for a specific transport mode while being allowed for other modes. The different entities populating the layers are detailed below.

A.1 Nodes layer and entities

The first layer contains the node entities, which represent transformer companies and warehouses. The transformer companies have the function of procuring the necessary raw materials, producing, and supplying downstream the finished products for which they are qualified. Warehouses have the function of intermediate storage of materials.

The two types of nodes can act both as customers for upstream nodes and as suppliers for downstream nodes. The first tier of the SC is made up of transformers who extract and supply raw materials, without needing to be replenished. Final nodes are retailers (i.e. point of sales) which are modeled as warehouses nodes. Customer orders are generated with a dedicated process. These are directed to a specific retailer to give geographical relevance to the orders and define the physical delivery point of the goods. In the event of a node failure, customer nodes will be able to divert orders to companies capable of supplying the needed product, if any.

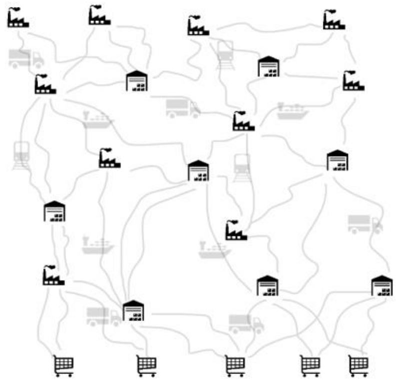

Fig. 2. Nodes layer example

All the data structure composing the layer are contained in the following table..

TABLE I. NODES LAYER DATA STRUCTURE

Nodes/Capacity Vector	In this vector the i-th element specifies the nominal daily capacity C_i of each i-th node. In case of transformer nodes, C_i is expressed in terms of aggregate resource-hours per day, which can be freely allocated between the current production orders to be fulfilled. In case of WH nodes capacity is represented by available storage volume in terms of Pallet unit loads.
Production Lot Vector	A production lot vector is associated to each production order of a transformer node, including all relevant data useful to characterize it: [Internal Lot ID, referring customer order ID, product ID, number of pieces, production start date, production advancement percentage, actual production end date, planned production end date]. Production advancement percentage is updated daily and depend on the allocated capacity.
Nodes/Material/ Process Data matrix	This matrix associates the i-th nodes to each the k-th output material they can produce. The cell corresponding to each pair Node/Material has a null value when the node cannot supply the product, conversely, it holds the corresponding "Process Data Vector".
Process data vector	This vector includes information about processing lead time and unit resources consumption for each which can be processed/stored by each node. In particular, for Transformer nodes it specifies the Minimum Lead Time, and the Unit Capacity Utilization Coefficient (resource-hours/unit), while for warehouse nodes it specifies the Unit space Consumption (pieces/pallet unit load).
Node Input Order list	This list includes all current unfulfilled orders received by a node from its customer nodes. Each time a new order is generated by a customer it is appended to the corresponding supplier order list. Each time an order is fulfilled it is cancelled from the list.
Node Output Order list	This list includes all current unfulfilled orders generated by a node. Each time a new order is generated by the node it is appended to the list. Each time an order is fulfilled it is cancelled from the list. This refers to materials supply orders issued from transformer or warehouse nodes to the respective supplier nodes.

Orders vector	The Order Vector is the individual record included in the Node Order Lists and includes all information required to characterize the order: [Order ID, sender customer node, recipient supplier node, material ID, quantity, order issue date, planned fulfillment date]. The planned fulfillment date results from adding a predefined lead time to the issue date or can be the result of a negotiation between customer and supplier.
Nodes / Input/ Output matrix	This is a 3D matrix represents for each transformer node (i.e. the third dimension) the Bill of Material of the output material it can produce. For each node, represented by its corresponding 2D, matrix the input and output materials codes are correlated by the amount of input material per unit output.
Nodes/Materials /Orders matrix	The three-dimensional matrix performs the function of database on the inventory present in each transformer and warehouse nodes. The nodes are represented by the third dimension. For each node, the inventory of each material is indicated in the columns, while the amount reserved for each order is indicated in the rows. This allows the nodes reserve a portion of the overall inventory of a given material to specific customer orders. The first row is associated to inventory not reserved for any specific order. The overall inventory of a given material is obtained by summing over the corresponding column the partial inventories.

A.2 Paths layer and entities

The paths layer contains connections between nodes, an issue often poorly modeled in previous SC resilience models. Paths are physical connection (i.e. transportation routes) crossed by transporters to move materials between an origin and a destination node. Paths can be subject to interruption owing to disruptive events (such as an earthquake destroying a road bridge, the blockage of the Suez Canal caused by a ship aground). The involved nodes could be able to use backup connections, if available, which will be possibly characterized by higher crossing times and costs. Nodes/Nodes/Paths matrix described the interconnection layer structure.

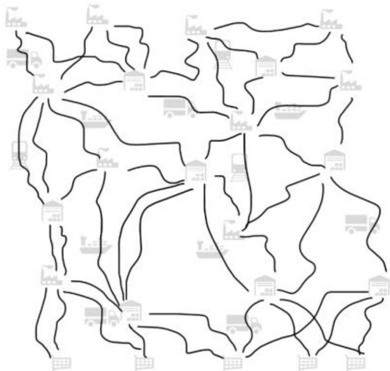

Fig. 3. Paths layers example

TABLE II. PATHS LAYER DATA STRUCTURE

Nodes/Nodes/Paths Matrix	The three-dimensional matrix lists, for each pair of nodes, all the connections between them. The matrix element (i,j,k) indicates the necessary freight days FD for the possible k-th path connecting nodes i and j.

A.3 Transporters layer and entities

This layer includes the transporters entities which are responsible for moving materials from the supplier node to the destination node along the paths. Carriers will have capacity like nodes, but unlike them, they will not have assigned a specific geographic location. In case a path is disrupted, all transporters utilizing that path will not be allowed to perform transportation, unless an alternative path is found, until the path is restored.

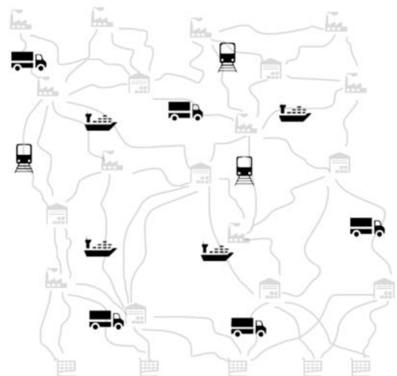

Fig. 4. Transporters layers example

TABLE III. TRANSPORTERS LAYER DATA STRUCTURE

Transporters/ Vehicle matrix	The matrix (i,j) indicates the number of vehicles j, owned by the transporter i.
Vehicle volume vector	The vector indicates the volume of each vehicle j.
Transporters / Paths matrix	The matrix assigns each transporter to a set of available paths defining its allowed routes. This allows carriers to select back up routes, in case the shorter one is disrupted.

B. Disruptions generation

The model includes a library of possible disrupting events of interest (manmade, NaTech, geopolitical, strikes...). Each disruption event is characterized by a magnitude and by the information of the possible target entities, i.e. specific entities or those located in a prescribed geographical impact area (Table IV). For example, all nodes located close together will be subject to the risk of damage caused by a NaTech event that occurs in that area, or the blockage of a strait can interrupt all the paths passing through it. Scenario generation is defined by the user who selects one or more disruptive events and their magnitude. Using the Entities / Events / Magnitude matrix, the entities potentially affected by the selected events are identified.

The assessment of the state of damage of the impacted entity consists in the estimation of its residual capacity. The model includes three options to perform this task. First, to each entity can be assigned a specific vulnerability model which provides the initial loss of capacity and the capacity recovery curve according to the intensity and type of the disruptive event. Specific models exist for this purpose, dedicated to process plants (Caputo et al., 2019, 2021) or manufacturing plants (Caputo et al., 2023). Second, predefined parametric capacity recovery curves can be assigned to entities chosen from proper libraries (Cimellaro et al., 2009; Patriarca et al, 2021). Third, a user-defined capacity curve to simulate a specific "What-if" scenario.

The failure state assessment output consists in the Days/Entities matrix, shown in Table IV.

TABLE IV. DISRUPTIONS GENERATION DATA STRUCTURE

Entities /Events /Magnitude matrix	The matrix indicates the group of entities damageable by an event of a certain magnitude.
Days/Entities matrix	The matrix indicates for each entity (node, path or transporter) the percentage of residual functionality R(t), for each day, starting from the occurrence of the event until the end of its direct consequences.

The perturbed entities undergo an alteration of specific parameters (capacity C for nodes and transporters, and freight days FD for paths) proportional with the residual functionality value R(t) (Table V). In case of vehicles, the transporter's residual percent capacity is defined based on the vehicles state vector δ_j. If R(t) is 0, the altered capacity of the nodes or transporters C'(t) will be zero, forcing it to stop operations. In the case of the paths, on the other hand, it would generate infinite FD'(t), effectively blocking transport on that route.

TABLE V. AFFECTED PARAMETERS

Entity	Affected parameters
Nodes	$C'(t) = R(t) * C$
Transporters	$\delta_j \begin{cases} 0 \text{ if j th vehicle is avaible} \\ - \\ 1 \text{ if j th vehicle is not avaible} \end{cases}$ $\quad C'(t) = \frac{\sum_{j=1}^{J} V_j * \delta_j}{\sum_{j=1}^{J} V_j}$
Paths	$FD'(t) = \frac{FD}{R(t)}$

C. Supply chain operations simulation

The SC operations simulation model includes simulation of the following processes, each relating to a type of entity (Table VI).

TABLE VI. SIMULATION PROCESSES

Entity	Processes
Final Customer order	Order generation
Transformer nodes	Incoming product orders management Production management Outgoing orders management
Warehouse nodes	Incoming orders management Outgoing orders management
Transporters	Transports management

Each process runs for each simulated day, once for each of the entities it refers to. Final customer orders are generated by an external routine, given that final customers are not explicitly modeled. During simulation the daily capacity of each entity is updated considering the current residual functionality level as dictated by the occurred disruption and the specific time schedule of capacity recovery as described in Section B.2. Starting from transformers nodes, the received output product orders are fulfilled, either by retrieving from the inventory and/or releasing internal production orders. New production orders are released even to restore a desired minimum inventory level. Stock levels are updated consequent to production advancement and orders fulfillment. Finally, necessary raw materials and components are ordered to external supplier nodes. Subsequently, the processes of warehouse nodes run: first the incoming orders are managed, by shipping the available products, then the outgoing ones, reordering the necessary products from upstream suppliers. Fulfillment of incoming and outgoing order from nodes will require transportation operations performed by issuing a transportation request to transporters nodes. Finally, the process of transport management runs, in which each transporter entity transporters manages its list of requested shipments based on available resources. The delivery date to the final customer is recorded in the corresponding order vector. Owing to space limitations, although transformer nodes operation includes three processes, namely incoming product orders management, Production management, Outgoing orders management, here we focus on the first one only given its importance. The working logic is shown in Fig. 5.

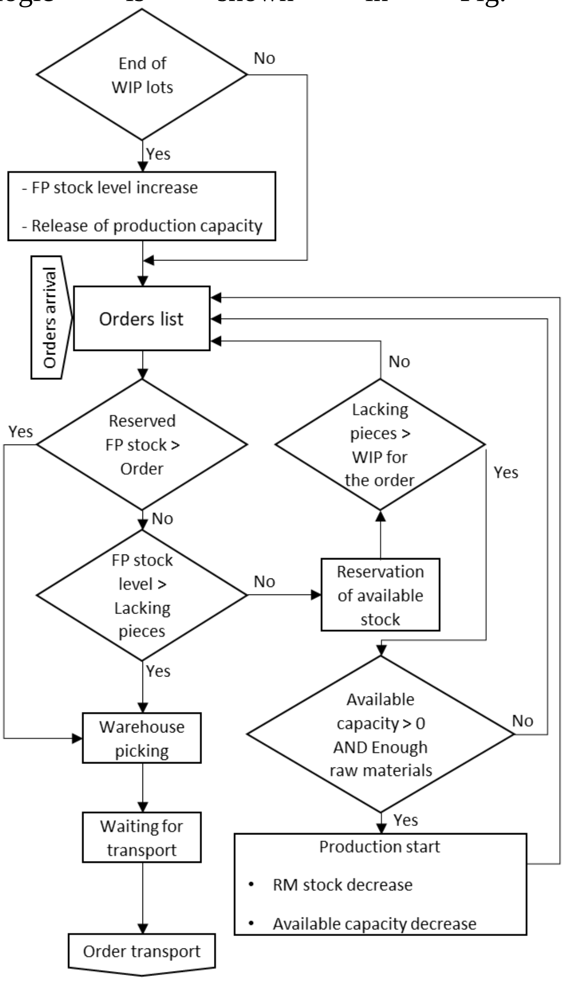

Fig. 5. Incoming product orders management

The following process is repeated for each day in the simulation calendar. Daily simulation starts by checking the possible completion of previously released production lots. In this case, the inventories are increased by the quantity produced, and the corresponding production capacity is released and thus made available for processing further lots. The list of pending is then updated appending new incoming orders. Orders are processed in FIFO logic. First, a check for materials availability in the inventory is performed. If, for a given pending order, the on hand inventory is not enough, then the available quantity is reserved for partial fulfillment of the order, and a new production order is released to produce additional material provided that the required capacity and input materials is available. If those two conditions are not satisfied, order release is delayed until necessary. In case enough materials are already available to fulfill the order, the material is retrieved, the transport is booked, and when available, the shipment is made. As soon as production lot is completed and the on hand inventory is updated, a check is made to verify if pending orders for that materials exist and if some amount of that material had been already reserved for partial fulfillment of that order. The newly produced material is added to the reserved material and the shipment lot is retrieved for transportation. When production starts, raw material inventories (RM) are updated by accounting for its consumption, and available capacity are seized for the duration of the production process. If an order can not be fulfilled in the current day, the simulation skips to the following ordes until the entire list of pending orders is scanned.

D. Resilience index calculation

Resilience is often assessed analyzing the trend over time of the system functionality after the occurrence of a disruption (Fig. 6), while the considered performance measure is system capacity.

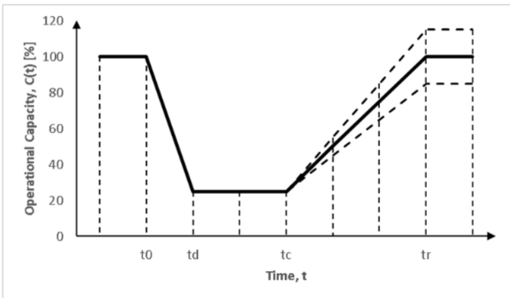

Fig. 6. Trend of functionality vs Time

This time trend is characterized by a first phase of disruption, where the functionality decreases. The second phase consist in the organization of the recovery activities and, finally, the gradual or discontinuous restoration of the functionality. Here we adopt the formulation of Eq. 1 proposed by Cimellaro et al. (2009), already widespread in other engineering fields.

$$Resilience = \frac{1}{t_h - t_0}\int_{t_0}^{t_h} S(t)dt \qquad (1)$$

However, as compared to its original formulation, in Eq. (1) the Service Level S(t) has been substituted to the Operational Capacity C(t) during the perturbed period. In fact, service level, together with the costs, is considered by various authors among the main SC performance indicators (Chopra and Meindl, 2007; Ivanov, 2018). Nevertheless, the computation of service level takes different forms according to the applications (Goetschalckx, 2011). In the case of resilience computation, we propose to use the "in-stock probability" form, where the daily service level represents the ratio between the number of final customer orders timely fulfilled at the current date N(t) and the total number of orders O(t) planned for delivery at current date t (Eq. 2). To obtain a more meaningful computation, N(t) and O(t) refer only to the nodes belonging to the SC portion affected by disruptive events.

$$S(t) = \frac{N(t)}{O(t)} \qquad (2)$$

Being a customer service performance measure, S(t) will refer to the sum of the orders received by the retailers, the last level of the SC. This choice is motivated by the purpose of the model to evaluate the performance of the entire SC by measuring its overall output, without focusing on individual intermediate nodes which may have a negligible impact in global SC performance. Simulation output allows to compute the daily service level as defined by Eq. (1 and 2) during a prescribed time interval.

IV. DISCUSSION AND CONCLUSION

In this paper a cursory description of the conceptual architecture of a novel SC dynamic simulation model for resilience estimation has been carried out. The model attempts to fill the gaps of existing models by allowing a more detailed modeling of the SC during disruptions overcoming the limitations of previous approaches. In particular, the framework allows to simulate the dynamically change of the production logic of all the transformers nodes, reacting to the current SC conditions. For example, in situations where it is difficult to produce a specific product due to lack of materials, it is modeled the shift of the freed up capacity to the production of other products. While the service level of the first product decrease, service level of workable products, which was realistically not equal to one before the disruption, can undergo an increase generated by the higher capacity allocated. This specific feature is not currently included in the available SC simulation tools. Greater detail about entities modeling will be given in subsequent papers as the computer model will be implemented. Furthermore, as a future work it is planned to estimate the economic loss due to the events and contemplate their probability of occurrence in the composition of the damage scenarios.

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