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Supply Chain Resilience Triangle: The Study and Development of a Framework

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***Abstract*—**Supply Chain Resilience has been broadly studied during the last decade, focusing the research on many aspects of Supply Chain performance. Consequently, different definitions of Supply Chain Resilience have been developed by the research community, drawing inspiration also from other fields of study such as ecology, sociology, psychology, economy et al. This way, the definitions so far developed in the extant literature are therefore very heterogeneous, and many authors have pointed out a lack of consensus in this field of analysis. The aim of this research is to find common points between these definitions, through the development of a framework of study: the Resilience Triangle. The Resilience Triangle is a tool developed in the field of civil engineering, with the objective of modeling the loss of resilience of a given structure during and after the occurrence of a disruption such as an earthquake. The Resilience Triangle is a simple yet powerful tool: in our opinion, it can summarize all the features that authors have captured in the Supply Chain Resilience definitions over the years. This research intends to recapitulate within this framework all these heterogeneities in Supply Chain Resilience research. After collecting a various number of Supply Chain Resilience definitions present in the extant literature, the methodology approach provides a taxonomy step with the scope of collecting and analyzing all the data gathered. The next step provides the comparison of the data obtained with the plotting of a disruption profile, in order to contextualize the Resilience Triangle in the Supply Chain context. The tool and the results developed in this research will allow to lay the foundation for future Supply Chain Resilience modeling and measurement work.

***Keywords*—**Supply chain resilience, resilience definition, supply chain resilience triangle.

I. Introduction

To survive in the turmoil of the present world, companies need to improve their processes, systems and technologies in order to be dynamic and flexible and meet the ongoing changes in the global market. [1] Nowadays, in fact, strong business competition, along with the non-trivial level of technology of modern industrial sectors [2], leads to a high risk of uncertainty. If these risks become real, they can have a negative impact on every Supply Chain (SC) resulting in deformations that could lead to a decline in both profitability and competitive advantages.

Many studies have shown that modern SCs are at greater risk than their managers recognize [3]-[5]. Nevertheless, in today's uncertain and turbulent markets, SC vulnerabilities have become an important issue for many companies [3]. The numbers and types of threats that can undermine a SC are now multiple: companies are faced with major risk management challenges [6].

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Creating a resilient SC could be the answer to this phenomenon. However, this is an area of study that still needs to be adequately researched.

Supply Chain Resilience (SCR) has been broadly studied during the last decades [7]-[9], [5] based, on the different perspectives of "resilience" that the various disciplines to which the resilience concept is relevant.

This study carefully analyzes the concept of resilience applied to business SCs, studying multiple SCR definitions and developing a framework of study in order to lay the basis for further development of this methodology.

This paper is organized as follows: Section II outlines the literature review from the concept of resilience to SCR. Section III outlines the Resilience Triangle framework tool, while section IV contextualizes the Resilience Triangle into the performance profile of a SC. Finally, Section V shows the research conclusion.

II. Literature Review: From Resilience to Supply Chain Resilience

The concept of resilience is multidimensional and multidisciplinary, since it has been the subject of scientific research for many years in disciplines such as psychology and ecosystems.

The word “resilience” has its roots in the Latin word “resiliens”, present participle of resilire "to rebound, recoil," from re- "back" (see re-) + salire "to jump, leap and nowadays, according to the “Oxford Advanced Learners Dictionary”, “resilience” is the ability of a substance to return to its original shape after it has been bent, stretched or pressed. Many fields of science borrowed then the term “resilience”.

In ecology, Holling proposed systems to have two distinct properties: resilience and stability. He associated in fact “resilience” to the ability of systems to absorb changes, opposed to “stability” as the ability of the latter systems to return to a state of equilibrium after a temporary disorder [10].

From a social point of view, Timmerman [11] was one of the first to define the resilience as “the measure of a system’s, or part of a system’s capacity to absorb and recover from the occurrence of a hazardous event”. This definition has been then evolving: the United Nations Office for Disaster Risk Reduction, for example, provided a more complete definition. According to the UNISDR, in fact, resilience is “the capacity of a system, community or society potentially exposed to hazards to adapt, by resisting or changing in order to reach and maintain an acceptable level of functioning and structure" [12].

During the last decades, the resilience concept was then adopted by SC specialists researchers to outline the new performance requirement of companies, given the evolution of modern business society, the characteristic of resilience has become a very important competitive factor [13], [14]. This also in the light of the factor that disruption can easily propagate, even with amplifications [15], due to the presence of the Domino Effect or Cascading Effect exacerbated by the highly interconnection of nowadays Supply Networks [16]-[18].

A. SCR Definitions Literature Review

In order to best conduct this study, a literature review on the various SCR definitions has been conducted. The concept of SCR has in fact emerged several times in literature.

Some 25 definitions have been found (see Table I), supporting the hypothesis that there is a lack of consensus among the scientific community regarding the definition of SCR [19], [20]. Among these definitions, for example, Christopher and Peck [3] offers the most concise one, defining resilience as 'the ability of a system to return to its original state or move to a new, more desirable state after being disturbed'.

Ponomarov and Holcomb [14] define SCR as the SC adaptation capability to prepare for unexpected events, respond to interruptions, and recover from them to maintain continuity of operations at the desired level of connection and control over the structure and function. Ponomarov and Holcomb also state that SC managers strive to reach the fully integrated, efficient and effective SC ideals that can create and sustain a competitive edge. To this end, they must balance the downward pressure on costs and the need for efficiency, with effective means, all to handle market demands and the risks of bankruptcy in the SC.

According to Ponis and Koronis [21], SCR is the ability to plan and design the SC network in order to anticipate disruptive and unexpectedly negative events, proactively respond in an adaptive manner to interruptions, maintain control over structure and function and arrive at a robust final state of operation, if possible, more favorable than before the interruption, thus gaining a competitive edge.

Arguably, the latter two definitions are the most complete: these two definitions incorporate in fact the most features, including adaptation, preparation, response, connection, and control capabilities, as well as timely recovery to return to the original state, or preferably, to a better state.

An additional point of view is offered by Wieland and Wallenburg [22], which claim that a SC can be resilient if its conditions remain stable at the original state or if a new stable situation is obtained. Resilience is therefore understood as the ability of a SC to cope with change. In Wieland and Wallenburg's paper, compared to other authors, relationship skills are deepened. If companies build collaborative relationships with other members of the SC, in order to gain a competitive advantage, these relationships can be exploited to improve SCR. Consequently, relational vision is applied, which results in three types of relational skills, namely communication, cooperation and integration that facilitate the resilience of a SC. The two authors distinguish proactive and reactive strategies to achieve resilience, which can be referred to as robustness and agility, respectively.

Carvalho et al. [23] in one of their works offer a study of SCR, defining it as the system's ability to return to its original state or to a new more desirable one after experiencing a disturbance and avoiding occurrence of failure modes. The goal of SC resilience analysis and management is to prevent the shifting to undesirable states, i.e., the ones where failure modes could occur.

III. Resilience Triangle

According to the various definitions previously shown, SCR can be linked to the development of readiness to an unexpected event, and into providing an effective and efficient response that supports fast recovery to the desired state of the system. This behavior can be illustrated with the "resilience triangle" (see Fig. 1), a plotting tool first introduced by Bruneau et al. [43].

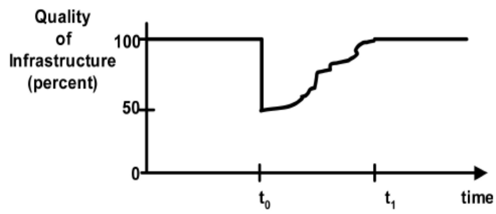

Fig. 1 The Resilience Triangle

The concept of "triangle of resilience" according to Tierney and Bruneau [44] can represent "the loss of functionality from harm and discomfort".

The "resilience triangle" helps in visualizing the magnitude of the disorder and the negative impact on system performance. It is useful to assess the resilience of a system after an unexpected disorder. It represents a measure of both the loss of functionality of a system after a disaster and the amount of time it takes for the system to return to normal performance levels. Resilience enhancement measures are designed to reduce the resilience triangle size by improving performance (vertical axis) strategies and reducing recovery time (horizontal axis).

The concept of the triangle of resilience can be applied in various fields, but it is born primarily because of the need to measure the resilience of infrastructures in case of natural disasters.

Still according to Bruneau et al. [43], considering for example the happening of an earthquake, the "loss of resilience", R_1, with respect to that specific event, can be measured by the size of the expected degradation in quality, over time (that is, time to recovery). Mathematically, it can be defined by (1):

Loss of resilience equation:

$$R_1 = \int_{t_o}^{t_1} [100 - Q_t]\, dt \quad (1)$$

Yu et al. [45] exemplify these concepts applied to one of the most frequent catastrophes in the world, the earthquake. In their research, the Resilience Triangle was used to compare services performance after an earthquake in Chile and Japan with that of the US state of Oregon.

The Resilience Triangle shown in Fig. 3 indicates that Chile and Japan have high levels of resilience to earthquakes, while at the time of the study, Oregon had almost none.

TABLE I
SCR DEFINITIONS

#	Source	Definitions
1	Carvalho et al. [7]	To survive, organizations and their supply chains must be resilient: they must develop the ability to react to an unforeseen disturbance and to return quickly to their original state or move to a new, more advantageous one after suffering the disturbance.
2	Brandon-Jones et al. [24]	SCR is defined as the ability of a system to return to its original state, within an acceptable period of time, after being disturbed.
3	Carvalho et al. [23]	SCR is concerned with the system's ability to return to its original state or to a new more desirable one after experiencing a disturbance and avoiding occurrence of failure modes. The goal of supply chain resilience analysis and management is to prevent the shifting to undesirable states, i.e., the ones where failure modes could occur.
4	Christopher and Peck [3]	The ability of a system to return to its original state or move to a new, more desirable state after being disturbed.
5	Closs and McGarrell [25]	SCR refers to the supply chain's ability to withstand and recover from an incident. A resilient supply chain is proactive – anticipating and establishing planned steps to prevent and respond to incidents. Such supply chains quickly rebuild or re-establish alternative means of operations when the subject of an incident.
6	Datta [26]	SCR is not only the ability to maintain control over performance variability in the face of disturbance but also a property of being adaptive and capable of sustained response to sudden and significant shifts in the environment in the form of uncertain demands.
7	Datta et al. [27]	Resilience of the supply network is the ability of the production–distribution system to meet each customer demand for each product on time and to quantity.
8	Erol et al. [28]	Resilience is a response to unexpected or unforeseen changes and disturbances, and an ability to adapt and respond to such changes.
9	Falasca et al. [29]	Resilience is defined as the ability of a supply chain to reduce the probabilities of a disruption, to reduce the consequences of those disruptions when they occur and to reduce the time to recover normal performance.
10	Gaonkar and Viswanadham [30]	SCR is the supply chain with the ability to maintain, resume and restore operations after a disruption.
11	Guoping and Xinqiu [31]	SCR is the ability of the supply chain to return to its original or ideal status under emergency risk environment.
12	Longo and Oren [32]	Resilience is a critical property that, in a context of supply chain change management, allows the supply chain to react to internal/external risks and vulnerabilities, quickly recovering an equilibrium state capable of guaranteeing high performance and efficiency levels.
13	Ponis and Koronis [21]	SCR is the ability to proactively plan and design the supply chain network for anticipating unexpected disruptive (negative events), respond adaptively to disruptions while maintaining control over structure and function and transcending to a post robust state of operations, if possible a more favorable one than that prior to the event, thus gaining a competitive advantage.
14	Ponomarov and Holcomb [14]	The adaptive capability of the supply chain to prepare for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations at the desired level of connectedness and control over structure and function.
15	Sheffi [33]	Reducing vulnerability means reducing the likelihood of a disruption and increasing resilience - the ability to bounce back from a disruption. Resilience, in turn, can be achieved by either creating redundancy or increasing flexibility.
16	Shuai et al. [34]	Resilience as the rapidly recovery ability to equilibrium after the supply chain is attacked by a disturbance and we use the recovery time to measure the ability.
17	Xiao [35]	SCR can be defined as the supply chain's ability of returning to the original or ideal status when this supply chain system has been disturbed by external interruption, and resilient supply chain shows that this supply chain has the two abilities on adaptability to environment and recovering ability of the system.
18	Yao and Meurier [36]	Supply resilience is defined as the ability to bounce back from disruptions and to permanently deal with and respond to the changing environment.
19	Ambulkar et al. [37]	Firm's resilience to supply chain disruptions is defined as the capability of the firm to be alert to, adapt to, and quickly respond to changes brought by a supply chain disruption.
20	Hohenstein et al. [38]	SCR as the ability to avoid/reduce the probability of disruptions and to respond and recover quickly.
21	Purvis et al. [39]	Supply chain resilience increases a firm's readiness in dealing with risks that can emerge from the customers' side, the suppliers' side, the internal processes adopted and the supply chain integration mechanisms employed.
22	Wieland, A. and Wallenburg, C.M. [22]	A supply chain can be resilient if its original stable situation is sustained or if a new stable situation is achieved. The resilience is understood as the ability of a supply chain to cope with change.
23	Blackhurst et al. [40]	A firm's resiliency enhancers are defined as: attributes that increase a firm's ability to quickly and efficiently recover from a disruptive event.
24	Scholten, K., Schilder, S. [41]	As the frequency and impact of supply chain disruptions remain stubbornly high, resilient supply chains that are able to absorb such shocks via visibility, velocity, flexibility and collaboration.
25	Stevenson, M., and Busby, J. [42]	SCR is the ability to build resilience to natural disasters, terrorist attacks and other fundamental threats to the supply chain, it is the ability to cope, recover or maintain continuity in the face of vulnerability or interruption of operations.

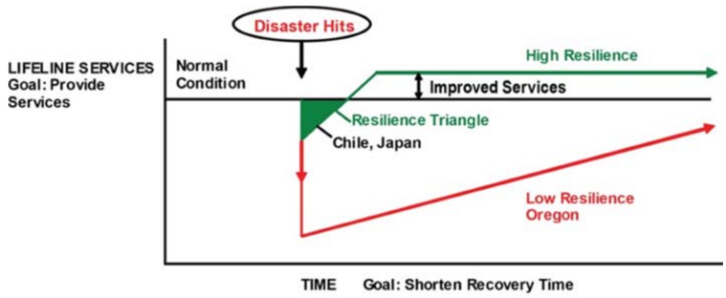

Fig. 2 Resilience Triangle according to Yu et al. [45] analysis

IV. Contextualizing the Resilience Triangle into Supply Chain Performance Profile

To our knowledge, in the extant literature there are only few examples of Resilience Triangle applications into the SC field of study.

One example can be found in the study of Carvalho [46], who applied the Resilience Triangle to SC, providing hence a comprehensive study framework.

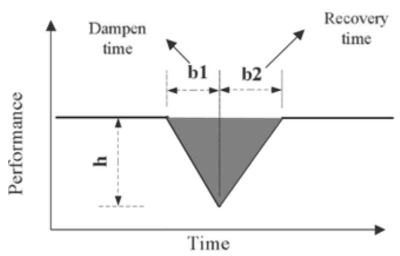

Fig. 3 Resilience Triangle with dampen time

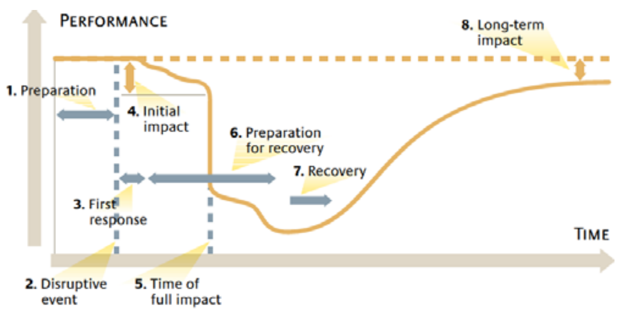

Fig. 4 The disruption profile plotted by Sheffi and Rice [33]

As can be seen from the figure, the depth of the triangle (h) shows the severity and extent of the damage, i.e. the severity of the disturbance, and the length of the triangle (b) shows the damping time (b1) and the recovery time (b2). The smaller the triangle, and the more the system or the SC is resilient to unexpected disturbances. Therefore, the "triangle of resilience" should be minimized. Actions, behaviors and property of companies should be aimed at reducing the area of the triangle.

To extend this research, this paper aims to combine the Resilience Triangle proposed by Bruneau by plotting the profile of a disturbance proposed by Sheffi and Rice [33] in their SCR analysis, in which was introduced the profile that a significant disruption can have over company performances.

As can be seen from Fig. 4, Sheffi and Rice [33] broke the performance profile down into eight different phases:

1. Preparation: the activities of companies with goal of preventing a given disorder, decreasing, when possible, both the likelihood and the impact of a risk;
2. Disruptive Event: the moment in which the disruptive event takes place;
3. First response: the initial response to the event, where a "workaround" solution to the problem is preferred: the aim at this stage is to control the situation and preventing further damage;
4. Initial Impact: This is the first nature that the effect of disruption on company performance can have two natures.
5. Time of full impact: if the disruption is not instantaneous (such as an earthquake or an explosion), it takes time to the event to fully take place;
6. Preparation for recovery: first companies action aimed to resume activities after the destructive event took place;
7. Recovery: all the actions required to bring back company performance to the previous levels as soon as possible;
8. Long term impact: The second nature that a disorder can have. Do not let companies return to the same level of previous performance.

Taking this profile analysis to a next step, these phases can be divided into two categories, as Table II shows:

TABLE II
Disruption Profile Analysis

#	Phase	SC Management	Disruption
1	Preparation	X	
2	Disruptive event		X
3	First response	X	
4	Initial impact		X
5	Time of full impact		X
6	Preparation for recovery	X	
7	Recovery	X	
8	Long term impact	X	

In order to combine the Bruneau Resilience Triangle with the disturbance profile plotted by Sheffi and Rice, the elements from the column "SC Management" are placed into the Resilience Triangle according to their afference.

According to Fig. 5, where:

- t_0-k is the beginning of the preparation activities;

- t_0 is the moment in which the disruption takes place;
- t_1 is the time of full impact;
- t_2 is the moment in which the company consider itself recovered from the event;
- t_2+h is the time horizon in which is analyzed the long term impact of the disruption.

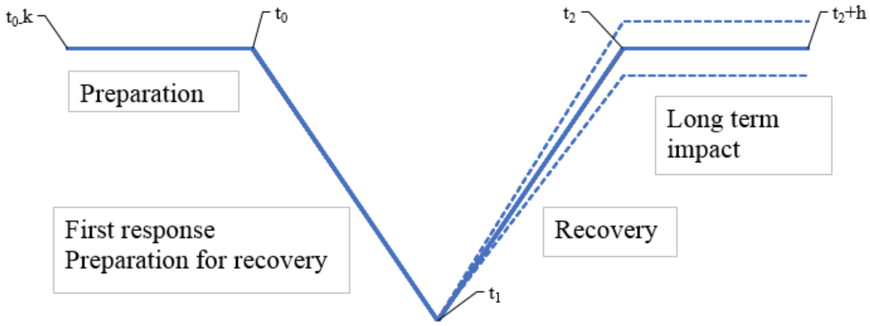

Fig. 5 The Resilience Triangle of a SC plotted according to Sheffi and Rice [33] disruption profile

The preparation phase is associated with all the activities envisaged before the happening of a disruptive event, from t_0-k to t_0. The "first response" and "preparation for recovery" phases are then associated with the second segment, from t_0 to t_1. The "recovery" phase is then associated to the third segment, from t_1 to t_2. The last phase, "long-term impact", refers to the final status of the SC, from t_2 to t_2+k: whether the disturbance causes irreparable damage and therefore long-term effects or, on the contrary, leads the firm to obtaining a competitive advantage over other companies.

A. Resilience Triangle Taxonomy

In order to enhance the study of this framework, a taxonomy analysis was conducted.

All SCR definitions listed in Table I were then studied in order to assign each of the characteristics exemplified by the definitions, to one of the sectors of the Resilience Triangle, as shown in Fig. 6:

I. Prevention;
II. Mitigation;
III. Recovery;
IV. Long term impact;
V. Time: despite Sheffi and Rice [33] not explicitly mentioning the component of time in their analysis, many researchers mention it as a critical measure of the resilience performance of a SC [7] [24], [29], [32], [34], [37], [38], [40].

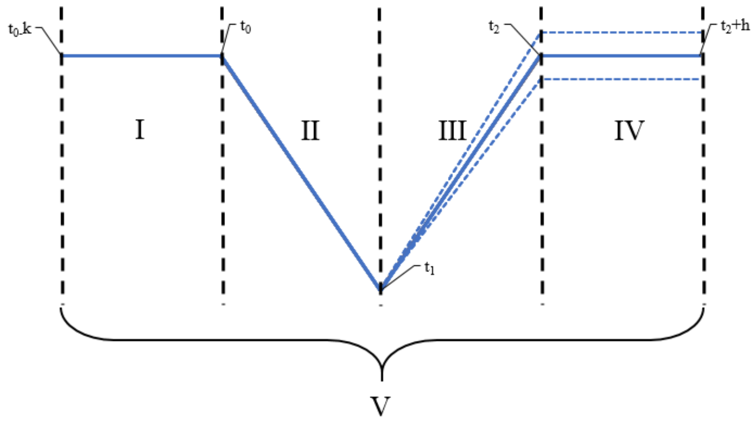

Fig. 6 Resilience Triangle sectors

This step was necessary in order to group the factors exemplified in the five cluster of the Resilience Triangle.

This taxonomy step has been performed following the Delphi method criteria: in order to increase the relevance of this study in fact, experiences and knowledge contributions from both the academic world and from SC management were considered to be fundamental. To this purpose, two academics whose main research field was SC management and three SC managers participated to this classification.

Their task consisted of analyzing Table I and then associating the SCR characteristic exemplified by each definition to one of the five groups.

The results of this step are listed in Appendix (Table III) and summarized in Fig. 7. According to the classification listed in Table II, as Fig. 7 shows, a number of 19 definitions refers to the recovery phase, 14 times mitigation phase, eight times prevention and time, and seven times long term impact.

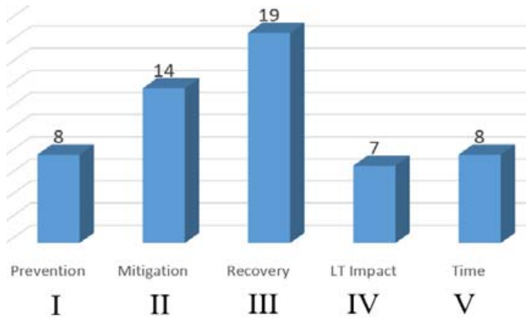

Fig. 7 Characteristics gathered in the 25 SCR definitions

According to the analyzes carried out, 19 out of 25 definitions taken into account explicitly mention the recovery phase. This result is in line with the definition of resilience according to the Oxford Advanced Learners Dictionary. Moreover, in one of the first definitions, which dates back to 2004, Christopher and Peck [3] define SCR as "the ability of a system to return to its original state or move to a new, more desirable state after being disturbed". This definition is perhaps the most faithful to the original definition of resilience, and it is only concerning that phase that we call recovery.

Over the course of the years however, research has expanded to addressing other phases of resilience: preparation, mitigation, and the long-term impact as the result achieved by the ability to be resilient. This is because they are all linked with the goal of maximizing company performance, as shown in Fig. 8.

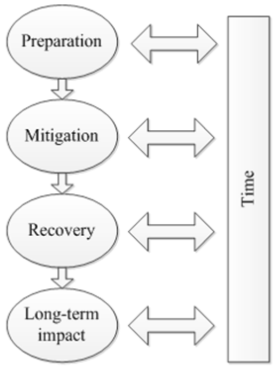

Fig. 8 Connections among the various sectors of the Supply Chain Resilience Triangle

V. Conclusions

Given the trend in recent years of research on SCR, this study has proposed to contextualize all the analyzes so far carried out in the SC Resilience Triangle (SCRT)

As stated by Carvalho [46], a limitation of this structure of study is the fact that it does not capture the probability associated with the disturbance in question: it only complements the performance of the system subject to the disorder. In addition, the "prevention" phase is difficult to measure because it is not directly associated with a precise KPI. Consequently, however, it has many advantages. First of all, if we look at Fig. 9, SCRT allows us to compare the initial status and the company's final status as a result of a performance. This consents to quantitatively evaluate the "long-term effect" caused by a disorder, and then to see if the company has suffered or is growing (thrive) in the meantime.

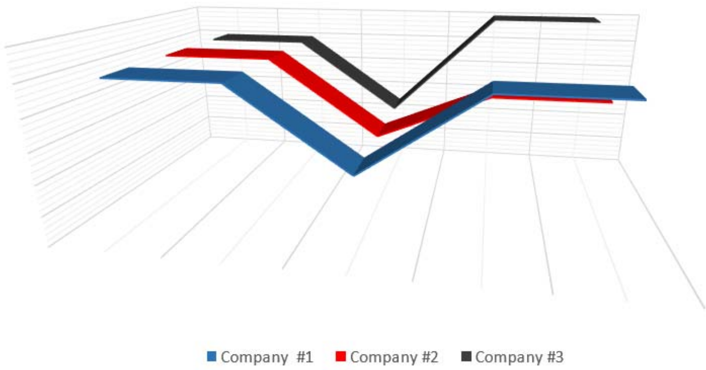

Fig. 9 SCRTs comparison

Additionally, as shown in Fig. 9, SCRT can be used as a comparison tool between the performance trends of various companies.

In each business sector, top management should be aware of the vulnerabilities and capabilities. An efficient management of information can indeed provide consistent benefits and thus creating a resilient environment inside the SC [47]. The SCRT can indeed be a useful tool in order to assess company performances. In fact, a similar benchmark can be conducted by comparing different KPIs internally to a company or to a SC. Comparing the various SCRT can be indeed useful to verify differences at various critical points when dealing with a disorder: preparation, mitigation, recovery, long term impact and time.

APPENDIX

TABLE III
TAXONOMY OF SCR DEFINITIONS

Preparation	#	Mitigation	#	Recovery	#	Long Term Impact	#	Time	#
Prevent	5	React to an unforeseen disturbance	1	Return quickly to their original state	1	Move to a new, more advantageous	1	Quickly	1, 12, 19, 20, 23
Reduce the probabilities of a disruption	9	Withstand and respond	5	Return to its original state	2, 3, 4, 11	A new more desirable	3	Within an acceptable period of time	2
Proactively plan and design the SC network for anticipating unexpected disruptive	13	Maintain control over performance variability in the face of disturbance	6	Recover from an incident, respond and rebuild or re-establish alternative means of operations when the subject of an incident	5	Move to a new, more desirable state	4	Reduce the time to recover normal performance	9
Prepare for unexpected events	14	Response to unexpected or unforeseen changes and disturbances	8	Adapt and respond to such changes	8	Ideal status	11, 17	Rapidly, use the recovery time to measure the ability	16
Reducing the likelihood of a disruption	15	Reduce the consequences of those disruptions when they occur	9	Resume and restore operations	10	If possible a more favorable one than that prior to the event, thus gaining a competitive advantage	13		
To be alert	19		10	Recovering an equilibrium state	12	A new stable situation is achieved	22		
Avoid/reduce the probability of disruptions	20	React to internal/external risks and vulnerabilities	12	Transcending to a post robust state of operations	13				
Increases a firm's readiness in dealing with risks	21	Respond adaptively to disruptions while maintaining control over structure and function	13	Recover from them	14				
		Respond to disruptions	14	Bounce back from disruptions	15, 18				
		Respond to changes brought	19	Recovery ability to equilibrium	16				
		Recover	20	Returning to the original	17				
		Its original stable situation is sustained	22	Adapt	19				
		Absorb such shocks	24	Respond	20				
		Maintain continuity in the face of vulnerability or interruption of operations	25	Efficiently recover	23				
				Ability to cope and recover	25				

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