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COVID-19 pandemic: Supply chain risk management by integrating Interpretive Structural Modeling and Bayesian belief network

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Abstract: The paper proposes a theoretical framework, based on a literature review, that analyzes the links between COVID-19 impacts and supply chain risk mitigation strategies, investigating the role of digitalization as a potential key resource to improve the effectiveness of supply chain resilience. Then, the paper empirically tests the framework through a hybrid causal mapping technique using the frameworks of Interpretive Structural Modelling and Bayesian Belief Networks methods to support supply chain decision making approaches. The findings of this paper can support managers in developing simple and traciable models for assessing interdependences among supply chain disruption sources and to invest effectively in resilience strategies.

Keywords: COVID-19 pandemic, SC disruption, SC resilience, digitalization, SC risk mitigation

1. INTRODUCTION

The supply chains of several companies, in most of the industries, are growing complex and globalized, and are more likely to be exposed to the detrimental effects of disruptive events. Particularly over the last two years, the 94% of the companies of the Fortune 1000 list faced supply chain disruptions due to the COVID-19 pandemic (Fortune (2020). Scholars have increasingly studied the topic of resilience (Ivanov and Dolgui, 2020). However, the literature is still highly fragmented (Queiroz et al. (2020). Deloitte (2020) recently emphasized the need for organizations to in-depth understand the correlation between potential disruptive events, supply chain strategies and supply chain performance, to support robust decision-making approaches to enhance SC Resilience (SCR) (Chowdhury et al. (2021). Several studies have analyzed the disruptions' impact on SCR and main strategies adopted by firms to respond to it (Orlando et al., 2022). Authors, in particular, described the SC risk mitigation strategies based on flexibility, efficiency, agility, information and knowledge sharing, and responsiveness in managing SC disruptions to assure SCR (Vanany et al. (2021; Moosavi and Hosseini (2021)). Sturm et al. (2021), for example, reported the employment of flexibility or agility as key practices to react to pandemic. Efficiency is inherently linked to agility, being an operational element of agility, along with quality and productivity (Agarwal et al. (2007); Braunscheidel & Suresh (2009)), and serves therefore as a key adaptive resilience capacity. Agility and responsiveness together serve to ensure the capability to cope with risks, typically in the short-term and in the long-term (Gligor et al. (2020). Moreover, Acioli et al. (2021) highlighted the role of information sharing to achieve SCR. Insurance investments and government supports can be also listed as additions risk financing strategies (Chopra et al. (2021)).

In addition, several studies are emphasizing the importance of digital technology adoption to achieve SCR (Modgil et al. (2021); Balakrishnan end Ramanathan (2021); Dubey et al. (2021); Nayal et al. (2021)). However, there is the need to empirically investigate how firms may in practice deploy SC risk mitigation strategies, and digitalization, to cope with disruptions and improve SCR (Ivanov and Dolgui (2020); El Baz and Ruel (2022); Craighead et al. (2020)).

1.1 Paper goals

The scope of this paper is twofold.

First, the paper proposes a theoretical framework, based on a literature review, that analyzes the links between the recent COVID-19 pandemic's impacts and supply chain risk mitigation strategies (Butt (2021); Chopra et al. (2021); Magableh (2021)), also investigating the role of digitalization as a potential key resource to improve the effectiveness of SCR. This framework can also support companies in better

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facing other types of disruptions, such as the sourcing and supply chain shortages related to the recent conflict between Russia and Ukraine.

Second, the paper empirically tests the framework through a hybrid causal mapping technique using the frameworks of Interpretive Structural Modelling and Bayesian Belief Networks to support supply chain decision making approaches, developing simple and tractable models for assessing interdependences among supply chain disruption sources and strategies.

In particular, we investigate the following research questions:

RQ1. What are the relationships between the impacts of SC disruptions, mitigation strategies, digitalization and firms' performances?

RQ2. How to simulate and quantify the impacts of SC disruptions on firms' performance as well as the effect of the adoption of supply chain risk mitigation strategies?

2. RESEARCH METHOD AND KEY RESULTS

In this section we describe the methodology employed in this study.

Through a structured literature review on SC disruptions' impacts, supply chain risk mitigation strategies and firms' performances (Butt (2021); Chopra et al. (2021); Magableh, (2021); Ivanov and Dolgui (2020)), we built our theorical conceptual model (Fig. 1).

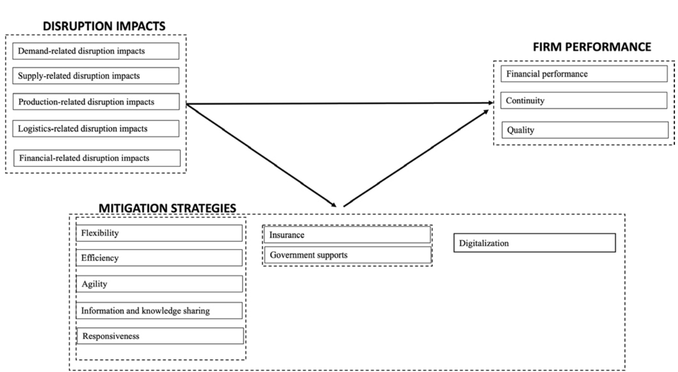


Figure 1. Conceptual model.

Once developed the conceptual framework, we selected two case studies. Since the ISM models rely on experts' knowledge, the process of case selection and participant recruitment is crucial to obtain a generalizable and representative model. We refer to two large multinational companies in the FMCG industry and in the automotive industry. Respondents have been selected in order to ensure they have a comprehensive knowledge of the risk issues, resilience, and strategies ranging across the supply chain from the perspective of the focal company (Qazy et al. (2018)).

In the present work we present the outcomes from the FMCG case study.

2.1 Interpretive structural modeling (ISM) technique

ISM has been selected since it is a well-known technique for solving complex decision-making problems based on complex relationships among specific variables (Sage (1977); Ruiz-Benitez et al. (2018)).

As a first step we built a Structural Self-Interaction Matrix (SSIM) which reports the relationships of pair elements (i.e., disruptions, strategies, performances). Experts were asked to fill the pairwise relationships among elements of the system in a quadratic SSIM (Tab. 1) The relationship between different elements i and j were expressed by using four symbols: V – element i enables/leads to/ impacts on element j; A – element j enables/leads to/ impacts on element I; X – element i and j are mutually interdependent; O – no relationship between elements i and j.

Table 1. Structural Self-Interaction Matrix

		D1 Demand-related disruption	D2 Supply-related disruption	D3 Production-related disruption	D4 Logistics-related disruption	D5 Financial-related disruption	D6 Flexibility	D7 Efficiency	D8 Agility	D9 Information and knowledge sharing	D10 Responsiveness	D11 Insurance	D12 Government support	D13 Digitalization	D14 Financial performance	D15 Continuity	D16 Quality
D1	Demand-related disruption		V	V	V	V	A	A	A	A	A	O	O	A	V	V	V
D2	Supply-related disruption			V	V	V	A	A	A	A	A	O	O	A	V	V	V
D3	Production-related disruption				V	V	A	A	A	A	A	O	O	A	V	V	V
D4	Logistics-related disruption					V	A	A	A	A	A	O	O	A	V	V	V
D5	Financial-related disruption						A	A	A	A	A	A	A	A	X	V	O
D6	Flexibility							O	O	A	X	O	O	A	V	V	V
D7	Efficiency								O	A	X	O	O	A	V	V	V
D8	Agility									A	X	O	O	A	V	V	V
D9	Information and knowledge sharing										V	O	O	A	V	V	V
D10	Responsiveness											O	O	A	V	V	V
D11	Insurance												O	O	V	V	O
D12	Government support													O	V	V	O
D13	Digitalization														V	V	V
D14	Financial performance															V	V
D15	Continuity																X
D16	Quality																

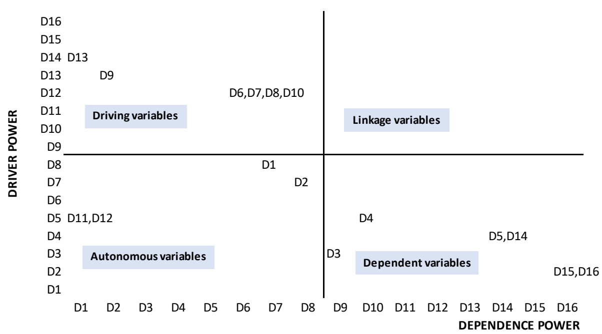
Then, it is converted in a binary matrix, obtaining the initial reachability matrix. After checking the transitivity property, it is converted into the final reachability matrix. From the final reachability matrix, the reachability and anteceded set for each variable is found, in order to divide the factor relationships of the reachability matrix into different levels. Based on these levels, we establish the ISM levels structure (Tab. 2).

Table 2. Level partitions in the ISM Model

Level	Reachability set	Antecendent set	Intersection set	Variable Code	- Description
VI	D1,D2,D3,D4,D5,D14,D15,D16	D1,D6,D7,D8,D9,D10,D13	D1	D1	Demand-related disruption
V	D2,D3,D4,D5,D14,D15,D16	D1,D2,D6,D7,D8,D9,D10,D13	D2	D2	Supply-related disruption
IV	D3,D4,D5,D14,D15,D16	D1,D2,D3,D6,D7,D8,D9,D10,D13	D3	D3	Production-related disruption
III	D4,D5,D14,D15,D16	D1,D2,D3,D4,D6,D7,D8,D9,D10,D13	D4	D4	Logistics-related disruption
II	D5,D14,D15,D16	D1,D2,D3,D4,D5,D6,D7,D8,D9,D10,D11,D12,D13,D14	D5,D14	D5	Financial-related disruption
VII	D1,D2,D3,D4,D5,D6,D7,D8,D10,D14,D15,D16	D6,D7,D8,D9,D10,D13	D6,D7,D8,D10	D6	Flexibility
VII	D1,D2,D3,D4,D5,D6,D7,D8,D10,D14,D15,D16	D6,D7,D8,D9,D10,D13	D6,D7,D8,,D10	D7	Efficiency
VII	D1,D2,D3,D4,D5,D6,D7,D8,D10,D14,D15,D16	D6,D7,D8,D9,D10,D13	D6,D7,D8,D10	D8	Agility
VIII	D1,D2,D3,D4,D5,D6,D7,D8,D9,D10,D14,D15,D16	D9,D13	D9	D9	Information and knowledge sharing
VII	D1,D2,D3,D4,D5,D6,D7,D8,D10,D14,D15,D16	D6,D7,D8,D9,D10,D13	D6,D7,D8,D10	D10	Responsiveness
III	D5,D11,D14,D15,D16	D11	D11	D11	Insurance
III	D5,D12,D14,D15,D16	D12	D12	D12	Government support
IX	D1,D2,D3,D4,D5,D6,D7,D8,D9,D10,D13,D14,D15,D16	D13	D13	D13	Digitalization
II	D5,D14,D15,D16	D1,D2,D3,D4,D5,D6,D7,D8,D9,D10,D11,D12,D13,D14	D5,D14	D14	Financial performance
I	D15,D16	D1,D2,D3,D4,D5,D6,D7,D8,D9,D10,D11,D12,D13,D14,D15,D16	D15,D16	D15	Continuity
I	D15,D16	D1,D2,D3,D4,D5,D6,D7,D8,D9,D10,D11,D12,D13,D14,D15,D16	D15,D16	D16	Quality

Finally, in order to provide a better understanding of the relationship between SC disruptions, risk mitigation strategies and performances, we develop a MICMAC matrix (Tab. 3), by diving the variables into four cluster according to the driving and dependence power (Mandal and Deshmukh (1994); Sharma and Gupta (1995)).

Table 3. MICMAC matrix



Answering the RQ1, the MICMAC matrix reveals the following classification for the variables (disruptions, strategies, and performances) under investigation:

Quadrant I (autonomous variables). In this quadrant we found D1 (demand-related disruption), D2 (supply-related disruption), D11 (insurance) and D12 (government support). Elements in this quadrant are weak drivers and weak dependents. This implies that D1, D2, D11 and D12 do not have high connection degree with other variables, hence they are "autonomous variables". This does not mean that these variables have no impact on performances or other disruptions. Instead, as ISM diagraph shows, both D1 and D2 influence financial performance, continuity and quality. Also, looking at the ISM model, D1 may lead to supply-related disruption (D2). In fact, D1 is close to the limit between quadrant I and quadrant IV. D11 (insurance) and D12 (government support) (which can be considered "external mitigation strategies" or risk transfer strategies) may impact on financial performance and, by acting on financial related disruption, it may also help to ensure continuity and quality. However, none of the disruptions or SC strategies act as driver of these two practices (D11 and D12).

QUADRANT II (dependent variables). Most of disruptions (D3, D4, D5) and all the performances (D14, D15, D16) are here. D3 (production-related disruption), D4 (logistic-related disruption) and D5 (financial-related disruption), D14 (financial performance), D15 (continuity), D16 (quality) have low driver power and high dependent power. Looking at the ISM diagram, it is possible to observe that D3, D4, D5 are influenced by D2 and D1 (demand and supply-related disruption). Additionally, they are influenced by SC strategies (D6, D7, D8, d10) as well as information sharing (D9) and digitalization investment (D13). All performances measures (D14, D15, D16) are impacted by disruptions as well as by mitigation strategies (either SC strategies or digitalization and information sharing).

QUADRANT III (linkage variables). This quadrant has instable variables, this means that elements in this area will affect other elements and may also have a feedback effect on themselves. No elements are found in this area. This means that none of the disruptions or strategies act as driver/receiver at the same time.

QUADRANT IV (driving variables). All the SC strategies and the digitalization are here. These variables have high driver power and low dependence power. This imply that all SC strategies as well as digitalization are important enables for disruption and performance. From ISM model, they act on all the disruptions and positively impact on firm's performance. It is also interesting to observe that all SC strategies (D6, D7, D8, D10) are positively drown by information sharing (D9) and digitalization ((D13). In fact, they are closer to the intersection between quadrants (towards quadrant III) showing that they act as linkage variables between digitalization and disruption/performance.

2.2 Bayesian Belief Network (BBN)

We developed a multi-layer Bayesian Belief Network (BBN) model, built on causal relationship between SC disruptions, risk mitigation strategies and performances (Qazy et al. (2018); Hosseini et al. (2020)). For this scope, we used GeNIe software. BBNs allow to in-depth understanding the correlation between potential disruptive events, supply chain strategies and supply chain performance, to support robust decision-making approaches to enhance resilience.

The BBN model, with variables and probabilities, is described in Figure 2. The target nodes are the performances variables, namely continuity, quality and financial performance.

Briefly, our results show that in the firm, given the different disruptions and investments on mitigation strategies, the final probabilities of continuity being good (yes) or bad (no) were 31% and 69% respectively. The model also shows that the probability of good or bad financial performance, during the pandemic, was the same (50%). The probability of having a good quality is 44%, while the probability of getting a bad quality is 56%.

The results have been also validated through a sensitivity analysis (Fenton and Neil (2013)).

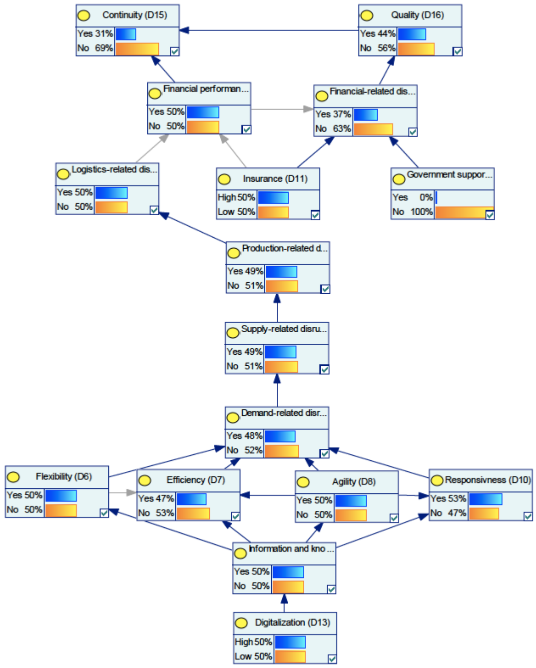


Figure 2. BBN model

Answering the RQ2, we simulated and quantified the impacts of SC disruptions during the pandemic outbreak on firms' performance as well as the effect of the adoption of supply chain risk mitigation strategies. In particular, we found that the most affected performance for the company was the business continuity. In fact, we found that the probabilities of experiencing a reduction in business continuity (69%) was higher than getting good continuity level (31%). The impact of disruption and the effect of mitigation strategies was instead almost neutral (even chance to have good or bad performances) in terms of quality and financial performance.

3. CONCLUSIONS

The two selected firms differently faced SC disruptions linked to the COVID-19 pandemic (Sharma et al. (2020)), namely disruptions related to supply management, production management, demand management, logistics management, relationship management and financial management. To cope with the negative effect of these disruptions, five resilience strategies (namely, flexibility, visibility, agility, reactivity and inventory management) (Paul and Chowdhury (2020)) have been differently applied by the case study firms, according to their specific characteristics. In addition, the role of government incentives has been investigated in the paper among the other five supply chain resilience strategies (Chopra et al. (2021)). Digitalization is confirmed to be a key driver for accelerating the applicability and effectiveness of the above-mentioned resilience strategies, particularly during the crisis of these last two years (Yang et al., 2021). The paper investigates and describes different combinations of exposures, resilience strategies, and demographic characteristics across the selected companies, and how firms differently cope with the challenges generated by COVID-19 pandemic.

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