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ORIGINAL RESEARCH

Evaluating the impacts of COVID-19 outbreak on supply chain risks by modified failure mode and effects analysis: a case study in an automotive company

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Abstract

Supply chains have been facing many disruptions due to natural and man-made disasters. Recently, the global pandemic caused by COVID-19 outbreak, has severely hit trade and investment worldwide. Companies around the world faced significant disruption in their supply chains. This study aims to explore the impacts of COVID-19 outbreak on supply chain risks (SCRs). Based on a comprehensive literature review on supply chain risk management, 70 risks are identified and listed in 7 categories including demand, supply, logistics, political, manufacturing, financial and information. Then, a modified failure mode and effects analysis (FMEA) is proposed to assess the identified SCRs, which integrates FMEA and best–worst method to provide a double effectiveness. The results demonstrate the efficiency of the proposed method, and according to the main findings, "insufficient information about demand quantities", "shortages on supply markets", "bullwhip effect", "loss of key suppliers", "transportation breakdowns", "suppliers", "on-time delivery", "government restrictions", "suppliers' temporary closure", "market demand change" and "single supply sourcing" are the top 10 SCRs during the COVID-19 outbreak, respectively. Finally, the practical implications are discussed and useful managerial insights are recommended.

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1 Introduction

Risks associated with supply chains have been a main issue for companies as they can cause serious damages to the company's performance. Since a supply chain includes a network of related actors, a disruption in one part of the chain can significantly affect the other actors as well (Rezaei Vandchali et al., 2020; Vandchali et al., 2021a). The numerous examples such as $400 million loss for Ericsson due to a fire in 2000 (Chopra & Sodhi, 2004), losing $72 million in profit for Toyota due to tsunami in 2011 (Pettit et al., 2013), and losses of profits by Boeing ($2 billion), Cisco ($2.25 billion) and Pfizer ($2.8 billion) because of the poor decisions associated with supply chain risks (Oliveira et al., 2017) shows the importance of having a robust approach to manage those risks. Companies find that to have a competitive advantage in long-term, they should improve their abilities in responding and mitigating a wide variety of supply chain risks (Baryannis et al., 2019). Supply chain risk management (SCRM) plays a critical role in companies' operations as it can help them to overcome the challenges caused by real-world uncertainties in a proactive manner (Tang & Musa, 2011). For example, to manage disruptions caused by sustainability violations, firms need to collaborate with their supply chain network actors to manage the negative consequences (Vandchali et al., 2021b). Thus, SCRM is increasingly gaining attention from academicians and practitioners as it is responsible for identifying, assessing, mitigating, and monitoring potential disruptions in the supply chain to reduce the negative impact of risk events in supply chain operations (Munir, 2020; Yang et al., 2021).

The recent COVID-19 outbreak has caused drastic changes in global supply chains (Queiroz, 2020; Tirkolaee et al., 2021a). Countries have faced lockdown and border closure which makes it more difficult to supply enough products and services. Markets and industries have confronted predicaments and many factories have shut down due to financial difficulties in affected regions. For example, many countries in Southeast Asia imposed lockdown in March and April 2020 to reduce the fast spread of the pandemic (e.g. Indonesia on March 15, Malaysia on March 18, Philippines on March 25, Singapore on April 3, Thailand on April 30) (Salcedo et al., 2020). As a result, global supply chains have been impacted profoundly due to their high dependency on their vulnerable suppliers (Tirkolaee et al., 2021b). For example, around 200 firms listed in Fortune Global 500 firms are working with factories in Wuhan where the outbreak was initiated (Kilpatrick & Barter, 2020). This type of disruption can have huge impacts on other parts of supply chains; i.e., ripple effect (Pavlov, 2019). For instance, 50 to 70 percent of global demand for copper, iron ore, metallurgical coal, and nickel are covered by suppliers located in China, as reported by Chopra and Sodhi (2004); LINDA & L., 2020). Additionally, the COVID-19 outbreak has caused considerable fluctuations in customers' demand patterns. For example, a sudden increase in the demand for toilet papers caused a temporary shortage in some grocery stores. These issues can certainly put a supply chain in a risky and uncertain environment.

Previous studies in the SCRM were mainly focused on natural disasters, wars and terrorism, political environment, fire accidents, economic instability, economic downturns, social and cultural grievances as the source of disruptions in supply chains (Kilpatrick & Barter, 2020; Linda, 2020; Pavlov, 2019; Salcedo et al., 2020; Tirkolaee et al., 2021b). However, the COVID-19 outbreak can be seen as a turning point in SCRM, which can raise the awareness of experiencing similar outbreaks in the future. To avoid facing the next shocking moment and its negative consequences, immediate and effective responses to such disruptions via SCRM are key points for companies. Previous works have identified various types of risks that need to be taken into account by companies to mitigate their impacts on the supply chains. However, due to the limitation in time and budget, responding to all the identified risks is a challenging task, thus, firms need to prioritize their practices by focusing on the management of those risks which can be more affected by the future pandemic.

As identifying the comprehensive side effects of the COVID-19 outbreak in SCRM is at early stage (Baz & Ruel, 2021; Ivanov, 2021), there is a strong need to explore which types of supply chain risks can be most affected by the COVID-19 outbreak to provide more insights for companies in their future SCRM endeavors (Ardjmand, et al., 2021). In this regard, this paper aims to fill this gap by identifying potential risks in supply chains and investigate how those risks may be affected by the COVID-19 outbreak. We propose a modified Failure Mode and Effects Analysis which integrates the traditional FMEA and Best–Worst Method (BWM) to assess the impacts of the COVID-19 outbreak on identified supply chain risks. To address this issue, the following research questions are developed:

- What are the most important supply chain risks during the COVID-19 outbreak?
- How the identified risks can be mitigated?

FMEA is a valid risk assessment technique (Mangla et al., 2018) and is used as a structured and proactive risk management method to identify potential risks and estimate their impacts and relevance in various industries (Huang, 2019). It has the ability to eliminate and mitigate known or potential failures and is able to enhance the reliability and safety of complex systems (Choudhary, 2021; Liu et al., 2013). FMEA is an important method that provides insights for managers in making appropriate risk management decisions to face real-world uncertainties. To assess the risks via FMEA, the risk priority number (RPN) for each failure mode is calculated by multiplying the scores of risk factors like occurrence (O), severity (S), and detection (D) (Chen & Wu, 2013). However, calculating RPN via the traditional FMEA method has received several criticisms such as creating quite the same value of RPN (Chang & Cheng, 2010). Based on a comprehensive analysis conducted by Liu et al. (2013), there are 3 major issues associated in using the traditional FMEA method. First, the relative importance of O, S, and D is not considered within the final output (RPN). Second, the same RPN can be achieved by having different scores for each of these three factors without considering their different implications. Third, evaluating the three factors can be a challenging task as it is difficult to precisely find the related scores. Hence, a wide range of methods has been proposed to overcome the shortcomings and improve the effectiveness of the traditional FMEA. This elaboration modified FMEA methods by using BWM to overwhelm the drawbacks of traditional FMEA. BWM has been applied to calculate risks' weight. The main reasons to select BWM among other MADM methods can be seen as follows (Rezaei, 2015):

- BWM is a "vector-based MADM method that needs fewer comparisons in comparison with other pairwise comparison matrix-based MADM methods such as AHP".
- The final weights derived from the BWM are highly reliable due to the less input needed from the experts.

The rest of this paper is structured as follows: Sect. 2 reviews previous studies in SCRM. In Sect. 3, the methodology is presented providing more information regarding the classic FMEA and BWM. In Sect. 4, the impacts of the COVID-19 outbreak on supply chain risks are investigated. Section 5 discusses the top 10 risks and also provides recommendations to respond to these risks, and Sect. 6 presents concluding remarks, limitations and highlights several future research directions.

2 Survey on the literature

In this section, we review the most relevant papers/reports published in the literature in two complementary streams including supply chain disruptions and risk assessment.

2.1 Supply chain disruptions

Disruptions are imminent in a world where uncertainty is increasing and changes occur rapidly. All markets and industries may face different types of disruptions and there is no exception for supply chains. Supply chain disruptions are unplanned events that may occur and affect the normal (or expected) flow of material (Blackhurst et al., 2008; Svensson, 2000). These disruptions may occur at one level of a supply chain and quickly propagate to the entire supply chain or even other supply chains (Samvedi et al., 2013). The critical impacts of disruptions on supply chains' performance stimulate researchers to put focus on SCRM/supply chain disruption management and identify a wide range of risks (Sharma, 2021a; Wagner & Bode, 2008; Xie, 2011). Those risks mainly occur due to natural disasters like tsunami, earthquake, bushfires or man-made disasters, such as sanctions, war, oil spills and terrorist attacks (Chopra & Sodhi, 2004; Ho et al., 2015; Jüttner et al., 2003; Sodhi et al., 2012; Thun & Hoenig, 2011; Xie, 2011). A comprehensive overview of the importance of SCRM and identified SCRs is given in Tables 1 and 2, respectively. There are many views to categorize risks in the supply chain management literature. However, this paper follows the study of Ho et al. (Ho et al., 2015) as they conduct an extensive literature review to identify various SCRs, and provide deep insights into how they can be categorized. The categories are briefly described below:

(i) *Demand-side risks* Demand risk stands for the possibility of an event related to outbound flows which may influence the probability of customers placing orders with the focal firm, and/or variance in the amount and variety wished by the customer (Manuj & Mentzer, 2008).
(ii) *Supply-side risks* Supply risk represents the possibility of an event concerning inbound supply from individual supplier failures or the supply market occurring, such that its outcomes bring about the inability of the purchasing firm to fulfill customer demand or lead to the threats to customer life and safety (Zsidisin, 2003a).
(iii) *Logistics risks* Logistics risks happen when there are disruptions in planning and implementing the efficient transportation and storage of products from the origin point to the consumption point.
(iv) *Political risks* Political risks are those risks related to changes that occur within a country's policies, investment regulations or business laws. Other influential elements contain international relationships and other situations that can have an impact on the economy of a certain country or organization.
(v) *Manufacturing risks* Disruptions in the internal operations of a firm cause manufacturing risk. Examples of manufacturing risks are labor shortage, downtime or loss of own production capacity, etc.

Table 1 An overview of the importance of SCRM

Reference	Risk management is important because…
Sheffi (2001)	Supply chain is vulnerable to man-made disasters
Hendricks and Singhal (2003)	Supply chain disruption decreases shareholder value and declines stock price
Finch (2004)	Firms face risks when working with small- and medium-size enterprises as partners
Norrman and Jansson (2004)	Supply chain vulnerability is increasing
Barry (2004)	Globalization increases SCRs like transportation risks or exchange rate risks
Chopra and Sodhi (2004)	Supply chain is complex and vulnerable to natural and man-made disasters
Peck (2005)	As time goes on supply chains become more complex, dynamic and interconnected
Sheffi (2007)	Some suppliers are prone to bankruptcy
Tang (2006)	Firms become vulnerable to risks when they consider initiatives like outsourcing and product variety in order to increase performance
Coleman (2006)	The frequency of disasters increased exponentially
Thun and Hoenig (2011)	The concept of just-in-time that is used by firms makes supply chain vulnerable
	Suppliers may provide defective materials/components
Xie (2011)	Risk adversely influences supply chain operations and then its desired performance measures, such as chain-wide service levels, responsiveness and cost
	Supply chain becomes complex
Giannakis and Louis (2011)	Supply chain is complex and also demand and supply are inherently uncertain
Lavastre et al. (2012)	Market globalization, reduced product lifecycles, complex international networks of industrial partners, unpredictable demand, uncertain supply, etc. cause supply chain to face risk
Colicchia and Strozzi (2012)	Uncertainty in customer demand, the unpredictability of the business environment along with market dynamics, etc. imply that the supply chain never actually reaches a stable steady state
Ho et al. (2015)	Supply chain is facing a variety of uncertainties
	Disruptions have negative effects on supply chain performance
Heckmann et al. (2015)	Supply chain is complex and uncertain
Aqlan and Lam (2015)	Globalization of sourcing, production, and sales, increased complexity and competitiveness put supply chain at risk
Wiengarten et al. (2016)	Supply chain globalization have increased its complexity and uncertainty
Li and Zeng (2016)	Having suppliers from across the world incur additional risk
Behzadi et al. (2018)	Globalizing, implementing Lean and JIT method made supply chain vulnerable to both natural or man-made disasters
Baryannis et al. (2019)	

Table 2 An overview of SCRs

Risk category	Reference	Identified risks
Demand risks	Wagner and Bode (2008)	Unanticipated or very volatile customer demand
		Insufficient or distorted information from your customers about orders or demand quantities
	Chopra and Sodhi (2004)	Bullwhip effect due to lack of supply chain visibility
		Demand uncertainty
		Inaccurate forecasts
	Wu et al. (2006)	Sudden shoot-up demand
	Samvedi et al. (2013)	Market demand change
	Manuj and Mentzer (2008)	Inability to fulfill customers' demand
	Blackhurst et al. (2008)	Product demand variations
	Schoenherr et al. (2008)	Order fulfillment risk
		Demand uncertainty
	Oke and Gopalakrishnan (2009)	Demand variability and unpredictability
	Christopher and Lee (2004)	Inaccurate demand forecasting
Supply risks	Gaudenzi and Borghesi 2006)	Lack of supplier visibility
	Samvedi et al. (2013)	Sudden hike in cost
	Wagner and Bode (2008)	Poor logistics performance of suppliers
		Supplier quality problems
		Supplier bankruptcy
		Capacity fluctuations or shortages on supply markets
	Chopra and Sodhi (2004)	Supplier bankruptcy
		Supplier responsiveness
		Delays because of supplier Inflexibility
		Poor quality or yield at supply source
		Supply uncertainty
		Supplier of a key part or raw material shuts down plant
		Reduction in supplier capacity
	Blackhurst et al. (2008)	Supplier bankruptcy
		On-time delivery from Supplier
		Supplier lead time variance
		Supplier manufacturing capacity
	Schoenherr et al. (2008)	Supplier fulfillment risk
	Zsidisin (2003b)	Supply uncertainty
	Oke and Gopalakrishnan (2009)	Loss of key suppliers (Supplier bankruptcy)
	Christopher and Lee (2004)	Increase in supplier lead time

Table 2 (continued)

Risk category	Reference	Identified risks
	Radivojević and Gajović (2014)	Component /material shortages
Logistics risks	Wagner and Bode (2008)	Poor logistics performance of logistics service providers
	Tuncel and Alpan (2010)	Stress on crew
	Xie (2011)	Higher cost of transportation
	Schoenherr et al. (2008)	Transportation breakdowns
		On-time/on-budget delivery
	Svensson (2000)	Inbound and outbound risk sources
	Radivojević and Gajović (2014)	Transportation risks (non-delivery risks, delays, re-routing, etc.)
		Storage/warehousing risks (incomplete customer order etc.)
	Chopra and Sodhi (2004)	Delay in distribution
	Blackhurst et al. (2008)	On-time delivery to customers
Political risks	Wagner and Bode (2008)	Changes in the political environment
		Political instability, war, civil unrest or other socio-political crises
		Administrative barriers for the setup or operation of supply chains
	Blackhurst et al. (2008)	Political issues/unrest
		Legislative action related to importing / global sourcing
	Oke and Gopalakrishnan (2009)	Safety regulations by government agencies
	Radivojević and Gajović (2014)	New regulations
		Governmental restrictions
Manufacturing risks	Kleindorfer and Saad (2005)	Imbalance between demand and supply
	Chopra and Sodhi (2004)	Rate of product obsolescence
	Blackhurst et al. (2008)	
	Christopher and Lee (2004)	Over order to hold buffer stocks for key customers
	Manuj and Mentzer (2008)	stock-outs or excess stock
	Tuncel and Alpan (2010)	Operator absence
		Instable manufacturing process
		Technological changes
	Wagner and Bode (2008)	Downtime or loss of own production capacity
	Chopra and Sodhi (2004)	Delay in production
		Inventory holding cost
	Manuj and Mentzer (2008)	Inability to produce
		Firms going out of business/bankrupt
	Schoenherr et al. (2008)	Product cost
		Product quality (defective rate)

Table 2 (continued)

Risk category	Reference	Identified risks
	Xie (2011)	Design change
	Kleindorfer and Saad (2005)	Disruptions of normal activities
	Radivojević and Gajović (2014)	Machine failure/downtime
		Imperfect yields
		Process/product changes
		Bankruptcy of partners
		Labor shortages
		Loss of key personnel
		Decreased labor productivity
		Quality problems
Financial risks	Cucchiella and Gastaldi (2006)	Price fluctuation
	Wu et al. (2006)	Loss of contract
		Financial and insurance issues
	Manuj and Mentzer (2008)	Changes in exchange rates
		Wage rate shifts
	Blackhurst et al. (2008)	Exchange rate risk
		Financial strength of customers
	Radivojević and Gajović (2014)	Budget overrun
		Currency fluctuation
		Global economic recession
Information risks	Xie (2011)	Information structure breakdown
	Cucchiella and Gastaldi (2006)	Information delays
	Gaudenzi and Borghesi (2006)	Lack of information transparency between supply chain members

(vi) *Financial risks* Supply chain may occasionally experience situations in which its financial health face risk and lead a supply chain into disruption or bankruptcy. Examples of financial risks are changes in exchange rates, wage rate shifts and so on.

(vii) *Information risks* Information creates a connection between supply chain members. Lack of proper information management in the supply chain can lead a supply chain into disruption. For instance, all supply chain operations face uncertainty and risk when there is a lack of information transparency between supply chain members.

According to Table 1, all studies have one thing in common. They all mention the point that supply chains are complex and tainted with uncertainty. Hence, risk may occur in both upstream and downstream of a supply chain and significantly affect its performance. However, the COVID-19 outbreak is a rare event in both scale and intensity compared to outbreaks, such as Severe Acute Respiratory Syndrome (SARS), Middle East Respiratory Syndrome (MERS), H1N1 influenza virus, and the severity of supply chains' disruption is high in this outbreak (Ivanov, 2020; Kapoor, 2021). Since the beginning of the COVID-19 outbreak, the SARS-CoV-2 coronavirus that causes COVID-19 has mutated, resulting in different variants of the virus. The current COVID-19 and its new variants resulted in massive damage to all fields and organizations' businesses and brought panic worldwide (Qayyum, 2021; Queiroz & Fosso Wamba, 2021; Sharma, 2021b). One of the unique characteristics of the COVID-19 outbreak is that it is the first long-term supply chain disruption in decades (Ivanov, 2021).

2.2 Risk assessment

An overview of risk assessment methods in supply chains is given in Table 3. As Table 3 shows, various combinations of different methods including FMEA, simulation, fuzzy logic, and multi-attribute decision making (MADM) techniques have been used in SCRM studies. To assess SCRs in this study, we propose a modified FMEA method by which the FMEA is enhanced by the recently developed MADM techniques-BWM (Rezaei, 2015). FMEA is a popular risk management tool and is widely used by companies and organizations for SCRM (Christopher & Lee, 2004; Zsidisin, et al., 2004). However, it has been recently criticized by researchers on the way that it prioritizes the risks (Barends et al., 2012; Li & Zeng, 2016). To overcome this weakness, this paper integrates the BWM with the traditional FMEA. BWM is a reliable MADM method to assess the weight vector of current SCRs caused by the COVID-19 outbreak. It is a vector-based MADM technique that needs fewer pair-wise comparisons against other pair-wise comparison-based MADM techniques such as Analytical Hierarchy Process (AHP), and also the final weights stemmed from BWM are highly reliable as the result of less inconsistency led by less pair-wise comparisons (Rezaei, 2015).

3 Methodology

The framework for the proposed methodology is presented in Fig. 1 to assess the impacts of the COVID-19 outbreak on SCRs. The framework has four phases which are elaborated in the following sub-sections.

3.1 Phase 1: identifying supply chain risks and establishing panel of experts

Based on a comprehensive literature review on SCRM, 70 risks have been identified and listed in 7 categories including demand-side risks, supply-side risks, logistic risks, political risks, manufacturing risks, financial risks and information risks suggested by Ho et al. (Ho et al., 2015) (Table 2). After identifying SCRs, a panel of experts was formed to assess the validity and importance of the identified risks. The panel consisted of 10 experts, three from academia who work as a business consultant and seven from the automotive industry. Each expert had around 9 to 15 years of experience in the supply chain area including supply planning, transportation planning, export planning, quality management and production planning.

3.2 Phase 2: conducting a survey

After developing a comprehensive list of supply chain risks, a two-part questionnaire was developed. The first part of the questionnaire sought the required data for calculating weights of identified risks via BWM and the second part was designed to collect data for calculating RPN via FMEA. Using several online skype meetings, the purpose of the study, identified supply chain risks and methodology were explained to each expert in the panel. Then, the first

Table 3 An overview of the literature on SCR assessment methods

References	Method(s)
Sinha et al. (2004)	FMEA
Schoenherr et al. (2008)	AHP
Levary (2008)	AHP
Moeinzadeh and Hajfathaliha (2009)	Fuzzy VIKOR, Fuzzy ANP
Schmitt and Singh (2009)	Monte Carlo simulation, Discrete-event simulation
Tuncel and Alpan (2010)	FMECA, Petri Net (PN) simulation
Finke et al. (2010)	Discrete-event simulation
Berle et al. (2011)	FMEA
Giannakis and Louis (2011)	Multi agent-based decision support system
Wang et al. (2012)	Two-stage FAHP
Samvedi et al. (2013)	Fuzzy AHP, Fuzzy TOPSIS
Chaudhuri et al. (2013)	FMEA
Radivojević and Gajović (2014)	AHP, Fuzzy AHP
Liu and Zhou (2014)	FMEA, Fuzzy set theory, Grey relational theory
Mangla et al. (2015)	Fuzzy AHP
Jaberidoost et al. (2015)	AHP, Simple Additive Weighting (SAW)
Rajesh and Ravi (2015)	Grey theory, DEMATEL
Li and Zeng (2016)	FMEA
Dong and Cooper (2016)	Orders-of-magnitude AHP (OM-AHP)
Mavi et al. (2016)	Shannon Entropy, Fuzzy TOPSIS
Nakandala et al. (2017)	Fuzzy Logic (FL), Hierarchical Holographic Modelling (HHM)
Gul et al. (2017)	Fuzzy AHP, Fuzzy VIKOR, Fine-Kinney approach
Mohaghar et al. (2017)	Best–Worst Method
Song et al. (2017)	Rough logic, DEMATEL
Er Kara and Oktay Fırat (2018)	Best Worst Method, K-Means Clustering
Arabsheybani et al. (2018)	Fuzzy MOORA, FMEA
Mangla et al. (2018)	Fuzzy FMEA
Rostamzadeh et al. (2018)	Fuzzy TOPSIS, CRITIC approach
Wan et al. (2019)	Fuzzy Bayesian-based FMEA

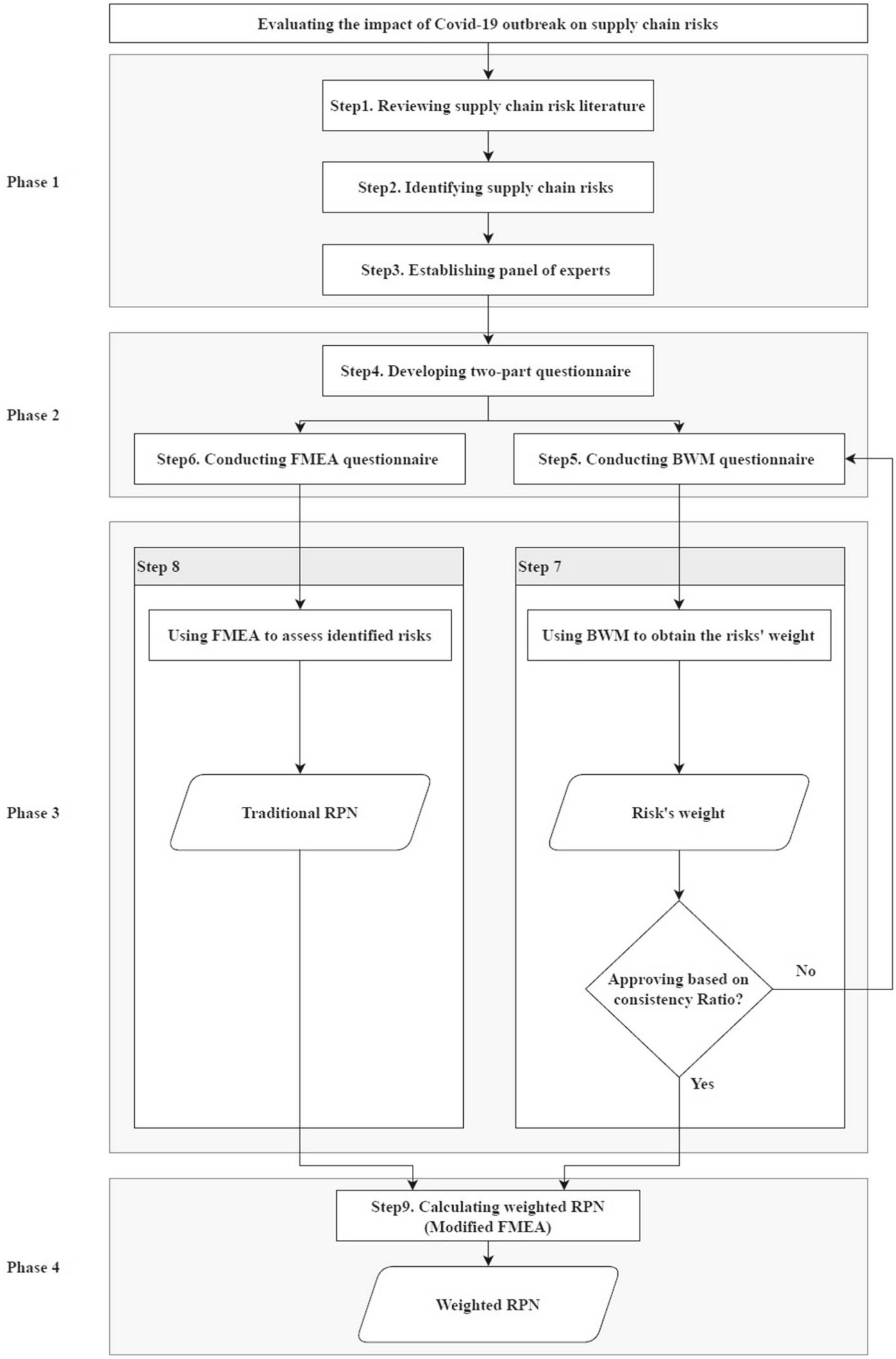

Fig. 1 Framework for the proposed methodology

round of surveys began by sending the first part of the questionnaire (BWM questionnaire) to each expert. Within a period of three days, the completed responses were received from the panel of experts. Then, the second part of the questionnaire (FMEA questionnaire) was sent to the panel of experts and the completed responses were received within 4 days.

Within the BWM questionnaire, the weights of each risk were obtained by asking each expert to answer the questions about which risks have the most important priority to be mitigated during the COVID-19 outbreak. Then, using collected data from the FMEA questionnaire, grades for three factors including O, S and D for each risk were obtained based on the 10-point Likert scale.

3.3 Phase 3: Calculating risks' weight and traditional RPN

This phase includes two main steps (Step 7 and 8) which have been conducted simultaneously.

3.3.1 Step 7: Using Best–Worst Method to identify the risks' weights

In this step, BWM was applied for calculating risks' weights. The two main reasons to apply BWM are as follows:

BWM is a "vector-based MADM method that requires fewer comparisons in comparison with other pairwise comparison matrix-based MADM methods such as AHP".

- The final weights resulted from the BWM are highly reliable since it needs less input required to be provided by the experts.

The execution sub-steps to implement the BWM are as follows (Rezaei, 2015):

Sub-step 1 Specify a set of decision criteria: In this step, we identify a set of decision criteria $\{c_{1,}c_{2,}c_{3,} \ldots, c_n\}$ to make a decision.
Sub-step 2 Determine the best and worst criteria: Experts identify the best (i.e. the most important, or desirable) and the worst (i.e. the least important, or desirable) criteria.
Sub-step 3 Determine the Best-to-Others vector: Experts identify the preference of the best criterion against all other criteria through a number between 1 and 9, where score 1 stands for equal preference between the best criterion and another criterion and score 9 denotes the extreme preference of the best criterion against the other criterion. The consequential Best-to-Others vector would be $A_{B=}(a_{B1,}a_{B2,}a_{B3,} \ldots, a_{Bn})$, where a_{Bj} represents the preference of the best criterion B against criterion j, and $a_{BB} = 1$.
Sub-step 4 Determine the Others-to-Worst vector: Experts identify the preference of all the criteria against the worst criterion using a number between 1 and 9. The consequential Others-to-Worst vector would be $A_{W=}(a_{1W,}a_{2W,}a_{3W,} \ldots, a_{nW})^T$, where a_{jW} represents the preference of criterion j against the worst criterion W, and $a_{WW} = 1$.
Sub-step 5 Calculate the optimal weights $(W_1^*, W_2^*, \ldots, W_n^*)$: The optimal weights of the criteria will provide the following requirements: For each pair of W_B/W_j and W_j/W_W the ideal situation is where $W_B/W_j = a_{Bj}$ and $W_j/W_W = a_{jW}$. Hence, to receive a weight vector as close as possible to the ideal situation, we must minimize the maximum deviation among the set of $\{|W_B - a_{Bj}W_j|, |W_j - a_{jW}W_W|\}$ and the problem can be formulated according to Model (1):

$$\text{minimize } \max_j \left\{ \left| \frac{W_B}{W_j} - a_{Bj} \right|, \left| \frac{W_j}{W_W} - a_{jW} \right| \right\}$$

subject to

Table 4 Consistency index table

a_{BW}	1	2	3	4	5	6	7	8	9
Consistency index	0.00	0.44	1.00	1.63	2.30	3.00	3.73	4.47	5.23

$$\sum_j W_j = 1,$$
$$W_j \geq 0 \quad \forall j. \tag{1}$$

Model (1) can be converted into the linear programming Model (2):

$$\begin{aligned}
&\text{minimize}\, \xi \\
&\text{subject to} \\
&\left|W_B - a_{Bj} W_j\right| \leq \xi \quad \forall j, \\
&\left|W_j - a_{jW} W_W\right| \leq \xi \quad \forall j, \\
&\sum_j W_j = 1, \\
&W_j \geq 0 \quad \forall j.
\end{aligned} \tag{2}$$

Sub-step 6 The optimal weight vector $\left(W_1^*, W_2^*, \ldots, W_n^*\right)$ and ξ^* are determined by solving Model (2). Here, ξ^* stands for the consistency ratio. The closer ξ^* to zero, shows the more reliable comparisons made by the decision maker leading to the higher consistency. The consistency index is given in Table 4. Then, the consistency ratio is calculated using ξ^* and the corresponding consistency index:

$$\text{Consistency ratio} = \frac{\xi^*}{\text{Consistency index}} \tag{3}$$

Considering the above sub-steps, once the final risk's weights were identified, the consistency ratio was calculated for each risk. If the ratio was close to zero, the weight was approved and would be considered as an input for Step 9 in the next phase. Otherwise, step 5 should be conducted again. This process was continued until all the calculated weights were approved via consistency ratio.

3.3.2 Step 8: Using FMEA to assess identified risks

As mentioned earlier, step 8 was conducted with step 7 in parallel. FMEA is a well-known risk assessment approach that has been widely used by practitioners and researchers to assess the impacts of failure modes. In the traditional FMEA technique, experts typically use a 10-point scale (in which the larger points indicate higher risks), to provide a score to each risk by determining three factors including occurrence (O), severity (S) and detection (D). The risk/probability that the failure mode would occur as a result of a specific cause is referred to as occurrence. Severity is an assessment of the seriousness of a potential failure mode's effect on the supply chain after it has occurred. The probability that a potential failure will be detected before it causes damage to the supply chain is referred to as detection.

The final output of the FMEA method is RPN which has been considered as the second input for Step 9. RPN is computed for each risk by the multiplication of these three factors as

Table 5 General evaluation scheme

Level	Severity (S)	Occurrence (O)	Detection (D)
1	No	Almost never	Almost certain
2	Very slight	Remote	Very high
3	Slight	Very slight	High
4	Minor	Slight	Moderately high
5	Moderate	Low	Medium
6	Significant	Medium	Low
7	Major	Moderately high	Slight
8	Extreme	High	Very slight
9	Serious	Very high	Remote
10	Hazardous	Almost certain	Almost impossible

Eq. (4). Items with a high RPN will need to be investigated thoroughly. The higher number shows the high intensity of the failure mode. The general evaluation scheme for FMEA is shown in Table 5 (Shahin, 2004).

$$\mathrm{RPN} = \mathrm{O} \times \mathrm{S} \times \mathrm{D}. \tag{4}$$

3.4 Phase 4: Calculating weighted RPN using modified FMEA

Finally, in Step 9 the modified RPN was calculated using two inputs received from Step 7 and 8 in the previous phase. As mentioned in the introduction section, the final RPN resulted from the traditional FMEA method has been criticized by many scholars as it does not consider the relative importance, implications, and accuracy of the three risk factors (Lolli et al., 2015). In this regard, the risk assessment has to be more accurate to provide reliable insights for researchers and managers. As suggested by Rezaei (2015), BWM, which is an MADM method, can provide highly reliable weights compared to the other popular weighting methods such as the AHP method. Therefore, we integrated BWM and FMEA to rank risks based on a weighted RPN measure. Equation (5) is applicable in this study but instead of obtaining weights (W) by AHP, we obtain weights by BWM.

$$R_i = RPN_i \times w_i \quad \forall i. \tag{5}$$

4 SCRM and COVID-19: case study

This paper investigated the impact of the COVID-19 outbreak on an auto part supply chain in Iran. The case company is a well-known auto spare-part company which manufactures several spare parts such as disc brake, control arm, etc. and supplies them to the domestic and foreign markets. The company's main raw materials include ferrosilicon, copper, fire clay, and bentonite. The purchasing department can provide these raw materials from both local and global suppliers. The main foreign suppliers of the case company are from India, China, Germany and Spain. The COVID-19 outbreak highlights the need for SCRM because many countries across the world including the case company's international partners (India, China, Germany, Russia and Spain) have been affected adversely by the COVID-19 outbreak. Considering the global supply chain of the company and the role of automotive industry in Iran's economy, it has been an ideal case to investigate the impact of the COVID-19 outbreak on SCRs.

4.1 Results

According to the comprehensive review of literature, 70 risks were selected and grouped in 7 categories in Sect. 2 (see Table 2). 10 experts reviewed the identified risks and answered two questionnaires. In the first questionnaire, the experts were asked to determine the best and worst criteria in each category. Then, they were asked to determine the preference of the best criterion against all other criteria and also the preference of all the criteria against the worst criterion in each category. The geometric mean has been used to obtain the average of the experts' scores. For the sake of brevity, the weights for the top 10 risks are just given in Table 6 while the weights of all risks are given in Table 10 in the Appendix.

As can be seen in Table 7, the average consistency ratio for all categories is close to zero, therefore, the comparisons are highly reliable and consistent.

Table 6 Risks' weights

Risk factors	Weight
Insufficient information from customers about demand quantities	0.052815468
Shortages on supply markets	0.042702619
Bullwhip effect	0.040470682
Loss of key suppliers	0.034816649
Transportation breakdowns	0.024845145
On-time delivery from Supplier	0.024901878
Government restrictions	0.019608837
Supplier temporary closure	0.025707869
Market demand change	0.043425187
Single sourcing	0.026479916

Table 7 Consistency ratio

Categories	Average consistency
Main categories	0.027975098
Demand	0.039951342
Information	0.033427863
Political	0.03796177
Logistic	0.028505429
Financial	0.024307036
Supply	0.011962651
Manufacturing	0.012222432

Table 8 Risk assessment

Risk factors	O	S	D
Insufficient information from customers about demand quantities	6.866409357	6.480740698	4.314173986
Shortages on supply markets	8.058327045	7.081223839	3.019607297
Bullwhip effect	5.957892136	6.021651011	4.733420285
Loss of key suppliers	5.649167974	7.487482597	4.382523843
Transportation breakdowns	6.480740698	8.273404568	4.750117742
On-time delivery from Supplier	7.449373164	6.677183706	4.954164
Government restrictions	6.718030748	7.344588652	6.148025993
Supplier temporary closure	6.344227581	7.567216457	4.711951203
Market demand change	5.709325706	6.424755835	3.590938482
Single sourcing	6.932422864	7.024327185	4.195501726

In the second questionnaire, the experts were asked to assess risks by answering the questions about occurrence, severity and detection of each risk. Geometric mean was used to calculate the average score of O, S and D. Risk assessment of the top 10 risks is given in Table 8 and also risk assessment of all risks is given in Table 11 in the Appendix.

Finally, we used the proposed FMEA method to calculate the weighted RPN (R_i). A comparison between the top 10 risks is given in Table 9 and Fig. 2. Risks were ranked from 1 to 70. The first rank (1) is the most important risk and the last rank (70) is the least important one. All details of the ranking procedure are presented in Table 12 in the Appendix. According to Table 9, "Insufficient information from customers about demand quantities" is 26th important risk when we used the traditional FMEA and it is the first important risk when we used the proposed FMEA technique. Also, "Shortages on supply markets" is the 33rd important risk in the traditional FMEA, while it is the second important risk in the proposed method. As we discussed earlier, supply and demand uncertainty are critical challenges a supply chain faces during man-made or natural disasters like earthquakes or the COVID-19 outbreak. Thus, these types of risks are more harmful than other risks.

5 Discussions and recommendations

In this section, we discuss the top 10 risks which can significantly threaten the supply chains during the COVID-19 outbreak, and provide some recommendations to respond to these risks. The discussion is based on the categories of the risks which are ranked in the top 10.

5.1 Demand risks

The first important risk is "insufficient information from customers about demand quantities". As mentioned earlier, during the COVID-19 outbreak, customers' buying patterns have dramatically changed. The automotive industry like other industries is facing problems in the process of production planning as the demand forecast error has increased. The main cause for this increase is the growing concern among customers resulted from the COVID-19 outbreak which can lead to uncertainty in the marketplace. Since the case company does not have proper and integrated information management system, they could not have appropriate

Table 9 Weighted RPN

Risk factors	RPN	Rank (traditional)	Risks' weights	Weighted RPN (R_i)	Rank (modified)
Insufficient information from customers about demand quantities	191.978234	26	0.052815468	10.13942033	1
Shortages on supply markets	172.3073003	33	0.042702619	7.357972933	2
Bullwhip effect	169.8178296	35	0.040470682	6.872643366	3
Loss of key suppliers	185.372199	27	0.034816649	6.454038809	4
Transportation breakdowns	254.6908141	5	0.024845145	6.327830178	5
On-time delivery from Supplier	246.4242447	10	0.024901878	6.136426397	6
Government restrictions	303.3508104	2	0.019608837	5.948356668	7
Supplier temporary closure	226.2120288	16	0.025707869	5.815429124	8
Market demand change	131.7192994	56	0.043425187	5.719935263	9
Single supply sourcing	204.3025006	21	0.026479916	5.409913125	10

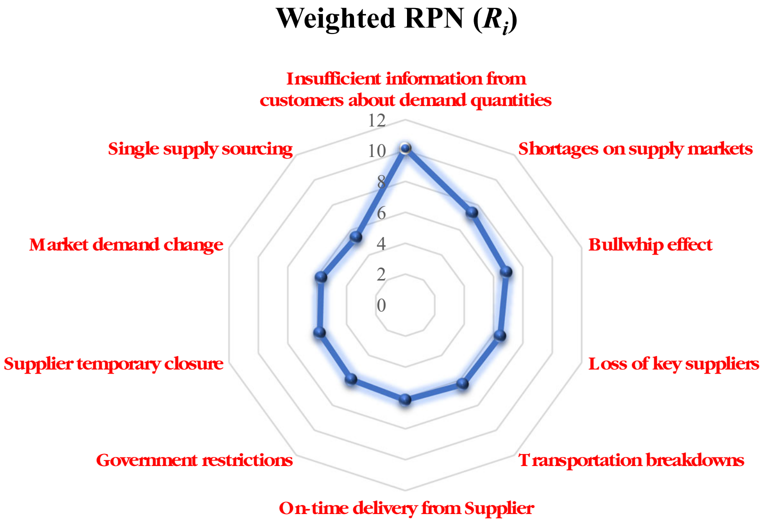

Fig. 2 Ranking the risk factors based on the weighted RPNs

access to the required and real-time information from the market. Insufficient information about customers' demand may trigger the third important risk which is "Bullwhip effect". When customer demand is uncertain or there is a lack of information about customer buying patterns, companies try to mitigate the risk by keeping additional inventory or placing higher order sizes. During the COVID-19 outbreak, customer demand is uncertain, thus the bullwhip effect may occur in the supply chain. "Market demand change" is the 9th important risk. Changes in demand may occur due to different reasons such as changes in customers' expectations, customers' income, customers' preferences, etc. The main reasons for market demand change during the COVID-19 outbreak are changes in customer preferences and a reduction in the financial power of customers. While demand for cleaning and hygiene products is increasing dramatically, industries like the automotive industry may suffer from a decrease in demand. The reason is that customers pay more attention to their essential needs during the outbreaks like the COVID-19 outbreak. Additionally, a decrease in customer financial strength is another reason which causes market demand change. According to Table 12 in the Appendix, decrease in the financial strength of customers is the 12th important risk. The pandemic has put more pressure on blue-collar workers. From the beginning of the COVID-19 outbreak, many small- to medium-sized businesses and companies stopped their operations. As a result, the number of unemployed workers is increasing. Then, the more decrease in the financial strength would lead to less demand for unnecessary products.

5.2 Supply risks

"*Shortages on supply markets*" is the second important risk in Table 9. Sourcing under disruptive situations, like Japanese tsunami and Thailand flood in 2011, is a challenging task for firms. For example, Toyota stopped its production because its raw materials and component suppliers were drastically affected by the earthquake. Sheffi (2001) mentioned the 9/11 terrorist attack as a man-made disaster that caused many companies including Toyota and Ford to stop their routine operations. In case of the COVID-19 outbreak, since many firms across the world are shutting down their production processes as a result of the pandemic, many suppliers are facing difficulties with providing required raw materials and components to their customers. For instance, the closure of some of the biggest slaughterhouses in the U.S. during the COVID-19 outbreak may cause a nationwide meat shortage. This indicates that "Loss of key suppliers" and "Supplier temporary closure", which are the 4th and 8th important risks, could cause shortages in supply markets. Regarding the case company, the suppliers are small- to medium-sized manufacturers which are located in the most affected regions including Iran, China, Spain and Germany. The COVID-19 outbreak has caused some of these companies to terminate their routine operations. Furthermore, it does not have strong supplier relationship management (SRM). Their low performance in SRM program may cause the case company to lose its key suppliers, especially its domestic suppliers, because during disasters like the COVID-19 outbreak, other manufacturers compete strictly to supply more materials or components than they need in a normal situation. According to the aforementioned points, one of the most important risk management strategies for the case company is how to manage shortages in the supply market. Relying on a single supply source for strategic items is another important risk because it puts the entire supply chain in danger even in a normal situation when there are no uncertainties in the markets. During the COVID-19 outbreak supply market is highly uncertain, thus "Single sourcing", which is the 10th important risk, would create problems for the supply chain performance. Many companies around the world have been focusing on Chinese firms because of their lower wages, lower compliance, etc. As a result, China becomes a key player in the global supply chains. However, during the COVID-19 pandemic, Chinese markets faced a significant challenge. The lockdown of Wuhan, which is a major business hub for several international corporations, has put stress on different supply chains. The case company is supplying some specific materials and components such as shifter and drive plate only from Wuhan. Therefore, relying on a single supply source can put the case company's supply chain at severe risk. "On-time delivery from supplier" is also an important risk because during disruptions various delays may occur in a supply chain including delays because of strict inspections, delay in planning routing, etc. In case of the COVID-19 outbreak, transportation breakdown and government restrictions, which are the 5th and 7th important risks, are the main causes of on-time delivery risk. Transportation breakdowns and government restrictions are logistical and political risks, respectively.

5.3 Logistics and political risks

There are many reasons for transportation breakdowns including natural or man-made disasters (Chopra & Sodhi, 2004; Ho et al., 2015). For instance, during a war, different modes of transportation are restricted by governments, or in case of earthquake, there may be the destruction of roads, bridges, etc. which cause transportation breakdown. During the COVID-19 outbreak, many countries have closed their borders to non-residents and restricted or suspended all international flights due to governmental restrictions. According to Salcedo et al. (2020) "China's foreign ministry announced on March 26 that it was suspending practically all entry to the country by foreigners and also stopped almost all international passenger flights", and "India has been barred all incoming passenger traffic by land, air and sea, except for critical goods and services". The case company provides its main raw materials and components from international markets such as India and China. Thus, border closure and countries' lockdown have had significant impacts on the case company's supply flows.

5.4 Recommendations

Most of the identified risks in the demand-side of a supply chain may happen due to a lack of information about the status of supply chain members. For example, the bullwhip effect mainly occurs due to the lack of information sharing and also lack of visibility between members of a supply chain. Therefore, one of the key solutions to reduce the demand-side risks is working on supply chain visibility and also encouraging information sharing among supply chain members. Furthermore, uncertainties in the market cause the supply chain to face fluctuations in demand. In case of the COVID-19 outbreak, demand for some products has been increasing while other industries like automotive experienced demand reduction. Ranking important uncertainties and developing different outcome scenarios can help supply chains properly manage demand-side risks.

Regarding the supply-side risks, diversifying the supply base from the geographic perspective; i.e., following multiple sourcing strategies, is an appropriate solution. The case company can reduce supply-side risks by selecting different suppliers from different countries and regions. One of the most important weaknesses of the case company is its poor supplier relationship management. Building strong relationships with key suppliers and focusing on key suppliers and managing all interactions with them will help them to reduce supply-side risks. Moreover, visibility helps the case to be aware of supplier inventory, production, and purchase order fulfillment status. Therefore, providing visibility in the supply-side of the supply chain is another solution for the case company to mitigate the supply-side risks. Finally, buffering against supply-side disruptions; i.e., considering inventory pre-positioning strategy is another important solution to manage supply-side risks.

6 Conclusion

In the recent decade, supply chains have been facing several disruptions due to natural and man-made disasters. These disruptions adversely affect the performance of supply chains. Currently, the world is undergoing another disaster which is a virus outbreak called "COVID-19". It has impacted almost every country, taking lives, damaging businesses, and spreading fear in the hearts of people. The COVID-19 pandemic puts different industry sectors at risk. The main contribution of this study is addressing the impact of the COVID-19 outbreak on SCRs and the question that what are the most important SCRs during the COVID-19 outbreak. A comprehensive literature review was performed to identify important SCRs during a pandemic like the COVID-19 outbreak. Seventy risks were identified and listed in seven categories including demand, supply, logistics, political, manufacturing, financial and information. An improved FMEA method, which integrates the traditional FMEA with BWM, was proposed to assess the identified SCRs. Based on final results appeared in Table 9, 'Insufficient information from customers about demand quantities', "Shortages on supply markets", "Bullwhip effect", "Loss of key suppliers", "Transportation breakdowns", "On-time delivery from supplier", 'Government restrictions', "Supplier temporary closure", "Market demand change" and "Single sourcing" were identified as the top 10 SCRs during the COVID-19 outbreak, respectively.

Considering the limitations of conducting this study, few interesting venues for future studies can be suggested for researchers. The main limitation is related to the data obtained from one specific company. Since the data collection for this study was during the early stage of the pandemic, many companies have rejected our calls to participate in this study. The main reason for this reluctance was related to their insufficient knowledge about the COVID-19 related issues as they were still in shock about the received disruptions. Since the current study used a single case study to collect required data, the results may only be generalized to similar companies in this specific situation. Thus, applying the proposed method to different cases can validate the findings. The other future directions would be related to applying this method in different sectors particularly, healthcare industry. Healthcare supply chains are under huge pressures during the recent pandemic as the demand for ventilators, personal protective equipment and drugs have been increasing. Then, researchers can pay specific attention to analyzing the impact of the Covid-19 outbreak on healthcare SCRs. Moreover, according to the result of the current study, insufficient information from customers about demand quantities become the most important risk during the COVID-19 outbreak. Investigating different solutions such as using industry 4.0 technologies to increase the visibility of the supply chain can provide valuable insights in mitigating SCRs.

Appendix

See Tables 10, 11 and 12.

Table 10 Weights of risk factors

Risk factor	Weight
Insufficient information from customers about demand quantities	0.052815468
Shortages on supply markets	0.042702619
Bullwhip effect	0.040470682
Loss of key suppliers	0.034816649
Transportation breakdowns	0.024845145
On-time delivery from Supplier	0.024901878
Government restrictions	0.019608837
Supplier temporary closure	0.025707869
Market demand change	0.043425187
Single supply sourcing	0.026479916
Supplier responsiveness decline	0.030622432
Financial strength of customers	0.019708339
Lack of information transparency between supply chain members	0.017804106
Legislative action related to importing / global sourcing	0.020226009
Inaccurate forecasts	0.035437443
Decrease in supplier manufacturing capacity	0.026499852
Price fluctuation	0.016560285
Sudden shoot-up demand	0.03519166
Sudden hike in cost	0.020728864
Poor logistics performance of suppliers	0.022021084
Supplier bankruptcy	0.023352661
Order fulfillment risk	0.025700512
Currency fluctuation	0.016013771
Supplier lead time variance	0.021188906
Global economic recession	0.01079691
Political uncertainty	0.013540003
New regulations	0.013458296
Poor logistics performance of logistics service providers	0.010563941
Lack of supplier visibility	0.018203246
Transportation risks (delays)	0.011247582
Supplier quality problems	0.025975472
Budget overrun	0.011062507
Changes in exchange rates	0.010509943
Loss of contract	0.009163965
Higher cost of transportation	0.013000251
Safety regulations by government agencies	0.011986025
Loss of key personnel	0.006094513
Firms going out of business/bankrupt	0.005406647

Table 10 (continued)

Risk factor	Weight
Information delays	0.008731026
Imbalance between demand and supply	0.004489327
Stock-outs	0.005998439
Information structure breakdown	0.009552201
Disruptions of normal activities	0.005365076
On-time/on-budget delivery	0.007707918
Delay in production	0.004220098
Bankruptcy of partners	0.003992372
Transportation risks (re-routing)	0.007093126
Storage/warehousing risks (incomplete customer order etc.)	0.007482884
Delay in distribution	0.005802757
Stress on transportation crew	0.006632111
Machine failure/downtime	0.005336704
Inability to produce	0.005207584
Quality problems	0.004797134
Financial and insurance issues	0.006710474
Labor shortages	0.004104014
Operator absence	0.004397661
Product quality (defective rate)	0.004256212
Inventory holding cost	0.00366913
Decreased labor productivity	0.004254281
Excess stock	0.003145386
Instable manufacturing process	0.004687934
Loss of own production capacity	0.003555804
Product cost	0.003846318
Product changes	0.003587473
Process changes	0.003763397
Over order to hold buffer stocks for key customers	0.003308899
Wage rate shifts	0.006381645
Rate of product obsolescence	0.003766064
Technological changes	0.003176571
Design change	0.003140505
Total weight	1

Table 11 Assessment of risk factors

Risk factors	O	S	D
Insufficient information from customers about demand quantities	6.866409357	6.480740698	4.314173986
Shortages on supply markets	8.058327045	7.081223839	3.019607297
Bullwhip effect	5.957892136	6.021651011	4.733420285
Loss of key suppliers	5.649167974	7.487482597	4.382523843
Transportation breakdowns	6.480740698	8.273404568	4.750117742
On-time delivery from Supplier	7.449373164	6.677183706	4.954164
Government restrictions	6.718030748	7.344588652	6.148025993
Supplier temporary closure	6.344227581	7.567216457	4.711951203
Market demand change	5.709325706	6.424755835	3.590938482
Single supply sourcing	6.932422864	7.024327185	4.195501726
Supplier responsiveness decline	5.978908999	5.583788707	5.238390648
Financial strength of customers	6.279990283	8.099551758	5.24871281
Lack of information transparency between supply chain members	7.821250746	7.117449896	5.125459346
Legislative action related to importing / global sourcing	7.434723165	7.625339745	4.413623786
Inaccurate forecasts	6.073806961	5.692425098	4.012556486
Decrease in supplier manufacturing capacity	6.441336429	6.213819601	4.566229395
Price fluctuation	8.694621741	6.731268517	4.318473136
Sudden shoot-up demand	4.733420285	5.683430269	4.418022039
Sudden hike in cost	7.660083112	6.402171746	3.924328152
Poor logistics performance of suppliers	6.589821313	6.154328463	4.221167313
Supplier bankruptcy	4.579786368	6.721772348	5.117506632
Order fulfillment risk	5.829449535	6.623533458	3.481823233
Currency fluctuation	6.085775298	6.776218325	5.206540128
Supplier lead time variance	6.957076243	6.866051815	3.386046885
Global economic recession	8.792562236	6.606483872	5.326560642
Political uncertainty	6.267640002	7.423187374	5.112265941
New regulations	6.96400909	6.402171746	4.467788812
Poor logistics performance of logistics service providers	7.671987043	7.337659008	4.283774801
Lack of supplier visibility	6.296197275	6.021651011	3.631388579
Transportation risks (delays)	7.981176583	6.711342779	3.928238813
Supplier quality problems	4.867307891	5.663452063	3.292905107
Budget overrun	6.619846542	6.694415749	4.603215596
Changes in exchange rates	6.279990283	7.330144722	4.538465758
Loss of contract	6.030694743	7.223014453	5.107442501
Higher cost of transportation	7.382162028	5.709325706	3.386046885

Table 11 (continued)

Risk factors	O	S	D
Safety regulations by government agencies	6.251832058	6.267640002	3.386046885
Loss of key personnel	6.789570751	8.009330718	4.318473136
Firms going out of business/bankrupt	4.911622455	8.16515767	5.77909095
Information delays	5.58935305	5.580680554	4.16179145
Imbalance between demand and supply	8.235879397	7.382162028	4.151294778
Stock-outs	7.318771197	7.5328943	3.292905107
Information structure breakdown	3.7643506	5.600366778	5.313126244
Disruptions of normal activities	7.613508192	7.060262171	3.692510311
On-time/on-budget delivery	4.74563599	6.509929926	4.279510195
Delay in production	6.96400909	7.110161121	4.842534499
Bankruptcy of partners	5.323595671	7.502236558	6.176038269
Transportation risks (re-routing)	6.160461359	5.957892136	3.631388579
Storage/warehousing risks (incomplete customer order etc.)	6.22606383	5.206540128	3.63854417
Delay in distribution	6.981617795	5.535840558	3.71140042
Stress on transportation crew	6.363576551	5.969632064	3.192845983
Machine failure/downtime	4.591605585	7.809115215	4.159474836
Inability to produce	5.397456823	6.925521461	3.984282604
Quality problems	5.356162267	7.204421748	4.126054031
Financial and insurance issues	5.397456823	5.657813953	3.662841501
Labor shortages	7.024327185	6.454028976	3.870827493
Operator absence	6.441336429	5.891527077	4.037102922
Product quality (defective rate)	5.744251968	6.197824657	4.053600464
Inventory holding cost	6.476795995	5.614819842	4.463341015
Decreased labor productivity	6.22606383	6.279990283	3.481823233
Excess stock	6.967887687	5.933644414	4.202021625
Instable manufacturing process	5.045785403	5.045785403	4.456288312
Loss of own production capacity	5.42716983	6.276494596	4.37816093
Product cost	7.363543091	6.318407532	2.864732867
Product changes	4.303292982	6.583260979	4.839838956
Process changes	3.90824505	5.75877648	5.045522664
Over order to hold buffer stocks for key customers	5.211728536	5.076388174	4.340565539
Wage rate shifts	4.148984006	4.881758755	2.783157684
Rate of product obsolescence	4.872158248	5.808655568	3.356970806
Technological changes	3.464101615	5.430192486	4.979508465
Design change	4.236057763	5.206540128	3.878454895

Table 12 Weighted RPN of risk factors

Risk factors	RPN	Rank (traditional)	Risks' weights	Weighted RPN (R_i)	Rank (modified)
Insufficient information from customers about demand quantities	191.978234	26	0.052815468	10.13942033	1
Shortages on supply markets	172.3073003	33	0.042702619	7.357972933	2
Bullwhip effect	169.8178296	35	0.040470682	6.872643366	3
Loss of key suppliers	185.372199	27	0.034816649	6.454038809	4
Transportation breakdowns	254.6908141	5	0.024845145	6.327830178	5
On-time delivery from Supplier	246.4242447	10	0.024901878	6.136426397	6
Government restrictions	303.3508104	2	0.019608837	5.948356668	7
Supplier temporary closure	226.2120288	16	0.025707869	5.815429124	8
Market demand change	131.7192994	56	0.043425187	5.719935263	9
Single supply sourcing	204.3025006	21	0.026479916	5.409913125	10
Supplier responsiveness decline	174.8834861	31	0.030622432	5.355357581	11
Financial strength of customers	266.9763352	4	0.019708339	5.261660082	12
Lack of information transparency between supply chain members	285.3207922	3	0.017804106	5.079881587	13
Legislative action related to importing / global sourcing	250.2184399	8	0.020226009	5.060920366	14
Inaccurate forecasts	138.7329014	47	0.035437443	4.91633932	15
Decrease in supplier manufacturing capacity	182.7647131	28	0.026499852	4.843237774	16
Price fluctuation	252.7422401	6	0.016560285	4.185483461	17
Sudden shoot-up demand	118.8539122	59	0.03519166	4.182666487	18
Sudden hike in cost	192.4536349	25	0.020728864	3.989345196	19

Table 12 (continued)

Risk factors	RPN	Rank (traditional)	Risks' weights	Weighted RPN (R_i)	Rank (modified)
Poor logistics performance of suppliers	171.1933444	34	0.022021084	3.769862947	20
Supplier bankruptcy	157.5387641	39	0.023352661	3.678949307	21
Order fulfillment risk	134.4386059	51	0.025700512	3.455141037	22
Currency fluctuation	214.7101242	18	0.016013771	3.438318776	23
Supplier lead time variance	161.7434888	37	0.021188906	3.427167657	24
Global economic recession	309.4088317	1	0.01079691	3.340659214	25
Political uncertainty	237.8526008	13	0.013540003	3.220524983	26
New regulations	199.1953913	23	0.013458296	2.68083056	27
Poor logistics performance of logistics service providers	241.1526386	11	0.010563941	2.54752223	28
Lack of supplier visibility	137.6786606	48	0.018203246	2.506198542	29
Transportation risks (delays)	210.4138015	19	0.011247582	2.366646525	30
Supplier quality problems	90.77144807	68	0.025975472	2.357831201	31
Budget overrun	203.9961251	22	0.011062507	2.256708614	32
Changes in exchange rates	208.9202727	20	0.010509943	2.195740096	33
Loss of contract	222.4791498	17	0.009163965	2.038791184	34
Higher cost of transportation	142.712285	46	0.013000251	1.855295474	35
Safety regulations by government agencies	132.679649	54	0.011986025	1.590301531	36
Loss of key personnel	234.8382132	14	0.006094513	1.431224613	37
Firms going out of business/bankrupt	231.7656561	15	0.005406647	1.253075063	38
Information delays	129.8162381	57	0.008731026	1.133428971	39
Imbalance between demand and supply	252.3928947	7	0.004489327	1.133074295	40
Stock-outs	181.5428961	29	0.005998439	1.088974003	41
Information structure breakdown	112.0099675	64	0.009552201	1.069941754	42

Table 12 (continued)

Risk factors	RPN	Rank (traditional)	Risks' weights	Weighted RPN (R_i)	Rank (modified)
Disruptions of normal activities	198.4848504	24	0.005365076	1.064886212	43
On-time/on-budget delivery	132.2101512	55	0.007707918	1.019065027	44
Delay in production	239.7791934	12	0.004220098	1.011891804	45
Bankruptcy of partners	246.6640146	9	0.003992372	0.984774428	46
Transportation risks (re-routing)	133.2841779	52	0.007093126	0.945401421	47
Storage/warehousing risks (incomplete customer order etc.)	117.9479617	60	0.007482884	0.882590971	48
Delay in distribution	143.4423711	45	0.005802757	0.832361264	49
Stress on transportation crew	121.2905057	58	0.006632111	0.804412068	50
Machine failure/downtime	149.143698	41	0.005336704	0.795935843	51
Inability to produce	148.9332928	43	0.005207584	0.775582635	52
Quality problems	159.2163872	38	0.004797134	0.76378229	53
Financial and insurance issues	111.8551451	65	0.006710474	0.750601061	54
Labor shortages	175.4847819	30	0.004104014	0.720191998	55
Operator absence	153.2052622	40	0.004397661	0.673744862	56
Product quality (defective rate)	144.3157425	44	0.004256212	0.614238353	57
Inventory holding cost	162.3140498	36	0.00366913	0.595551311	58
Decreased labor productivity	136.1379666	50	0.004254281	0.579169167	59
Excess stock	173.732449	32	0.003145386	0.546455577	60
Instable manufacturing process	113.4568791	63	0.004687934	0.531878307	61
Loss of own production capacity	149.1359319	42	0.003555804	0.530298072	62
Product cost	133.2841779	52	0.003846318	0.512653314	63
Product changes	137.1111894	49	0.003587473	0.491882705	64
Process changes	113.5581137	62	0.003763397	0.427364312	65

Table 12 (continued)

Risk factors	RPN	Rank (traditional)	Risks' weights	Weighted RPN (R_i)	Rank (modified)
Over order to hold buffer stocks for key customers	114.8372882	61	0.003308899	0.379985045	66
Wage rate shifts	56.37101921	70	0.006381645	0.359739846	67
Rate of product obsolescence	95.0045872	66	0.003766064	0.357793324	68
Technological changes	93.66823189	67	0.003176571	0.297543832	69
Design change	85.54011675	69	0.003140505	0.268639197	70

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