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 Vampchali et al., 2020; Vampchali 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 (Vampchali 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 can the identified risks 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                                                                                      |
| Norrmann 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                                                                                         |
| Xie (2011)                  | Risk adversely influences supply chain operations and then its desired performance measures, such as chain-wide service levels, responsiveness and cost                        |
| Giannakis and Louis (2011)  | Supply chain becomes complex                                                                                                                                                |
| 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                                                                                                                        |
| Heckmann et al. (2015)      | Disruptions have negative effects on supply chain performance                                                                                                            |
| Aqlan and Lam (2015)        | Supply chain is complex and uncertain                                                                                                                                    |
| 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                                                               |
|                 | 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                           |
|                 | Blackhurst et al. (2008)         | Reduction in supplier capacity                                                    |
|                 |                                  | 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                                                    |
| Risk category         | Reference                                      | Identified risks                                                                 |
|----------------------|------------------------------------------------|----------------------------------------------------------------------------------|
| Logistics risks      | Radivojević and Gajović (2014)                  | Component /material shortages                                                    |
|                      | 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                                                        |
|                      | Svensson (2000)                                 | Inbound and outbound risk sources                                                |
|                      | Radivojević and Gajović (2014)                  | Transportation risks (non-delivery risks, delays, re-routing, etc.)              |
|                      | Chopra and Sodhi (2004)                         | Delay in distribution                                                            |
|                      | Blackhurst et al. (2008)                        | On-time delivery to customers                                                    |
|                      | Blackhurst et al. (2008)                        | Changes in the political environment                                             |
|                      | Blackhurst et al. (2008)                        | Political instability, war, civil unrest or other socio-political crises          |
|                      | Blackhurst et al. (2008)                        | Administrative barriers for the setup or operation of supply chains               |
|                      | Oke and Gopalakrishnan (2009)                   | Legislative action related to importing / global sourcing                         |
|                      | Radivojević and Gajović (2014)                  | Safety regulations by government agencies                                         |
|                      | Radivojević and Gajović (2014)                  | New regulations                                                                  |
|                      | Oke and Gopalakrishnan (2009)                   | Governmental restrictions                                                        |
| Political risks      | Wagner and Bode (2008)                          | Imbalance between demand and supply                                               |
|                      | Chopra and Sodhi (2004)                         | Rate of product obsolescence                                                     |
|                      | Blackhurst et al. (2008)                        | Over order to hold buffer stocks for key customers                               |
|                      | Christopher and Lee (2004)                      | stock-outs or excess stock                                                       |
|                      | Manuj and Mentzer (2008)                        | Operator absence                                                                |
|                      | Tuncel and Alpan (2010)                         | Instable manufacturing process                                                   |
|                      | Christopher and Lee (2004)                      | Technological changes                                                            |
|                      | Wagner and Bode (2008)                          | Downtime or loss of own production capacity                                       |
|                      | Chopra and Sodhi (2004)                         | Delay in production                                                              |
|                      | Blackhurst et al. (2008)                        | Inventory holding cost                                                           |
|                      | Manuj and Mentzer (2008)                        | Inability to produce                                                             |
|                      | Schoenherr et al. (2008)                        | Firms going out of business/bankrupt                                              |
|                      | Schoenherr et al. (2008)                        | Product cost                                                                     |
|                      | Schoenherr et al. (2008)                        | Product quality (defective rate)                                                 |
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

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**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.
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
| 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

| $a_B W$ | 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 |

\[
\sum_j W_j = 1, \\
W_j \geq 0 \quad \forall \ j.
\]  

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

\[
\begin{align*}
\text{minimize } & \xi \\
\text{subject to } & |W_B - a_B j W_j| \leq \xi \quad \forall \ j, \\
& |W_j - a_j W_W| \leq \xi \quad \forall \ j, \\
& \sum_j W_j = 1, \\
& W_j \geq 0 \quad \forall \ j.
\end{align*}
\]

Sub-step 6 The optimal weight vector $(W^*_1, W^*_2, \ldots, W^*_n)$ and $\xi^*$ are determined by solving Model (2). Here, $\xi^*$ stands for the consistency ratio. The closer $\xi^*$ 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 $\xi^*$ and the corresponding consistency index:

\[
\text{Consistency ratio} = \frac{\xi^*}{\text{Consistency index}}
\]

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).

\[
RPN = O \times S \times D. \tag{4}
\]

#### 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  | Risks’ weights | Weighted RPN ($R_i$) | Rank (modified) |
|--------------------------------------------------------|------------|-------|----------------|----------------------|-----------------|
| Insufficient information from customers about demand   | 191.978234 | 26    | 0.052815468    | 10.13942033         | 1               |
| quantities                                             |            |       |                |                      |                 |
| 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              |

**Weighted RPN ($R_i$)**

![Fig. 2 Ranking the risk factors based on the weighted RPNs](image-url)
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    |
| 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/warehouse 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            |
| Risk factors                                                                 | O      | S      | D      |
|------------------------------------------------------------------------------|--------|--------|--------|
| Insufficient information from customers about demand quantities              | 6.866 | 6.480 | 4.314 |
| Shortages on supply markets                                                  | 8.058 | 7.081 | 3.019 |
| Bullwhip effect                                                              | 5.957 | 6.021 | 4.733 |
| Loss of key suppliers                                                        | 5.649 | 7.487 | 4.382 |
| Transportation breakdowns                                                    | 6.480 | 8.273 | 4.750 |
| On-time delivery from Supplier                                               | 7.449 | 6.677 | 4.954 |
| Government restrictions                                                      | 6.718 | 7.344 | 6.149 |
| Supplier temporary closure                                                   | 6.344 | 7.567 | 4.711 |
| Market demand change                                                         | 5.709 | 6.424 | 3.590 |
| Single supply sourcing                                                       | 6.932 | 7.024 | 4.195 |
| Supplier responsiveness decline                                              | 5.979 | 5.853 | 5.238 |
| Financial strength of customers                                              | 6.279 | 8.099 | 5.248 |
| Lack of information transparency between supply chain members                 | 7.821 | 7.117 | 5.125 |
| Legislative action related to importing / global sourcing                     | 7.434 | 7.625 | 4.413 |
| Inaccurate forecasts                                                         | 6.073 | 5.692 | 4.012 |
| Decrease in supplier manufacturing capacity                                  | 6.441 | 6.213 | 4.566 |
| Price fluctuation                                                            | 8.694 | 6.731 | 4.318 |
| Sudden shoot-up demand                                                       | 4.733 | 5.683 | 4.418 |
| Sudden hike in cost                                                          | 7.660 | 6.402 | 3.924 |
| Poor logistics performance of suppliers                                      | 6.589 | 6.154 | 4.221 |
| Supplier bankruptcy                                                          | 4.579 | 6.721 | 5.117 |
| Order fulfillment risk                                                       | 5.829 | 6.623 | 3.481 |
| Currency fluctuation                                                         | 6.085 | 6.776 | 5.206 |
| Supplier lead time variance                                                  | 6.957 | 6.866 | 3.386 |
| Global economic recession                                                    | 8.792 | 6.606 | 5.326 |
| Political uncertainty                                                        | 6.267 | 7.423 | 5.112 |
| New regulations                                                              | 6.964 | 6.402 | 4.467 |
| Poor logistics performance of logistics service providers                     | 7.671 | 7.337 | 4.283 |
| Lack of supplier visibility                                                  | 6.296 | 6.021 | 3.631 |
| Transportation risks (delays)                                                | 7.981 | 6.711 | 3.928 |
| Supplier quality problems                                                    | 4.867 | 5.663 | 3.292 |
| Budget overrun                                                               | 6.619 | 6.694 | 4.603 |
| Changes in exchange rates                                                    | 6.279 | 7.330 | 4.538 |
| Loss of contract                                                             | 6.030 | 7.223 | 5.107 |
| Higher cost of transportation                                                | 7.382 | 5.709 | 3.386 |
| 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 | 6.509929296 | 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 | 6.45028976 | 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 | 5.641819842 | 4.463341015 |
| Decreased labor productivity                        | 6.22606383 | 6.279902083 | 3.481823233 |
| Excess stock                                        | 6.967887687 | 5.933644144 | 4.202021625 |
| Insable manufacturing process                       | 5.045785403 | 5.045785403 | 4.456288312 |
| Loss of own production capacity                     | 5.42716983 | 6.267494596 | 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 | 5.808555568 | 3.356970806 |
| Technological changes                               | 3.464101615 | 5.430192486 | 4.979508465 |
| Design change                                       | 4.236057763 | 5.206540128 | 3.878454895 |
| 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              |
| 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    | 3.678943077          | 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              |
| 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 | 0.79535843            | 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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