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Multi-stage hybrid model for supplier selection and order allocation considering disruption risks and disruptive technologies

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ABSTRACT

In recent times, Supply chains are required to undergo the structural changes in order to adapt to the positive events such as Industry 4.0 and negative events such as natural and man-made disasters. Both positive and negative events tend to cause disruptions and affect business operations continuity. Supplier selection, being the critical and foremost activity must ensure that selected suppliers are capable of supporting the organizations against disruptions caused by these events. Hence, supplier selection and order allocation must be restructured considering the dynamics of Industry 4.0 and disaster events to ensure undisrupted flow of materials across supply chain. The paper proposes a multi stage hybrid model for integrated supplier segmentation, selection and order allocation considering risks and disruptions. The suppliers are then evaluated based on set of criteria suitable in Industry 4.0 environment using Data Envelopment Analysis (DEA) and are further prioritized using Fuzzy Analytical Hierarchical Process and Technique for Order of Preference by Similarity to Ideal Solution (FAHP-TOPSIS). The risk associated with each supplier is computed. The paper also proposes a Mixed Integer Program (MIP) as to optimize multi-period, multi item order allocation to suppliers in such a way that overall cost and risk of disruption is simultaneously minimized. In event of any disruption either from supply or demand side, the multi-stage hybrid model tends to reduce its economic impact by allocating emergency orders, thus, ensuring business operations continuity. The proposed multi-stage hybrid model is illustrated using a case of an automobile company.

1. Introduction

The fourth industrial revolution-Industry 4.0 has led to a significant change in every business function not just manufacturing. The business organizations are in the process of re-structuring their supply chains using the three main components of Industry 4.0: cyber-physical systems, Internet of things and smart factories to meet highly volatile and uncertain demand (Ghadimi et al., 2019). The disruptive technologies must be embedded into the entire supply chain structural design (Dolgui et al., 2018; Tjahjono et al., 2017) because an organization cannot truly benefit from disruptive technologies if its other supply chain partners are still functioning in conventional ways. In addition to disruptive technologies, ensuring business continuity in the event of disaster is also an equally important concern for the global and complex supply chains. The natural and manmade disasters lead to supply shortages and disruptions across supply chains (Sheffi, 2001, 2015) and supply chains must be re-structured in order to avoid the potential risks of disruptions as a part of their disaster preparedness (Wunnava, 2011; Sahebjamnia et al., 2015). Both the industrial revolution (positive events) and natural and manmade disasters (negative events) can cause disruptions if supply chains are not continuously adapted or aligned towards them. The disruption is the temporary or permanent loss in business functionality due to any unprecedented event (Tierney, 2007). Therefore, there is a need of supply chain structural design changes to protect against the risk of technological advancements as well as disruptions caused by disasters.

Suppliers plays a vital role in efficient functioning of entire supply chain. The organizations evolving into Industry 4.0 may not successfully realize the benefits of Industry 4.0 (such as transparency, visualization and automation) if the suppliers are still functioning in the conventional manner. The supplier base much be technically as well as technologically competent to match the requirements of an interconnected value chain (Müller, 2019). The process of selecting the supplier base and allocation of the final orders must be re-structured to incorporate the

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potential challenges caused by disruptive technologies as well as the disruption risks caused by disasters (Bhutta and Huq, 2002; Ivanov and Sokolov, 2012). In addition, the suppliers must be selected based upon their potential ability to support the organization during any crisis or disaster (Parmar et al., 2010). Hence, the supplier selection process must also consider the supplier's resilience or ability to mitigate risks. The research frameworks for resilient supplier selection proposed in literature are mostly proactive in nature (Torabi et al., 2015; Haldar et al., 2014). However, the occurrence of disaster is inevitable and it can disturb the entire supply chain dynamics if not handled efficiently. Therefore, process of supplier selection and order allocation must also be adaptive in nature and be able to minimize the impact of disruptions from propagating downstream.

In view of this, the paper proposes a multi-stage hybrid model for structural design of supplier selection and order allocation in presence of disruptive technologies and disruption risks. The entire structure of supplier selection and order allocation process is redesigned starting from criteria definition to final order allocations. The technological criteria for supplier selection in identified and evaluated using Fuzzy AHP in order to match the dynamics of Industry 4.0 as well as the growing need of business resilience. The suppliers are segmented using the Data Envelopment Analysis (DEA) as efficient and inefficient suppliers based on their performance on the set of criteria. The inefficient suppliers are not considered for further evaluation and order allocations. The efficient set of suppliers is further evaluated and prioritized using Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). The paper proposes the method to compute the average risk percentage for each supplier which is associated with each supplier. Finally, the paper proposes a Mixed Integer Program (MIP) considering disruption risk in Industry 4.0 environment and allocates the orders to the suppliers for multiple items over a multi period planning horizon such that total cost of procurement and risk associated can be minimized. The proposed MIP is further extended to model the demand and supply side disruption scenarios and emergency order allocation to optimize the overall cost and risk. The proposed multi-stage hybrid model is demonstrated using a case illustration of an automobile company where supplier selection process in being upgraded to address the dynamics of disruptive technologies and disaster caused disruptions. The findings of the study suggest that proactive segmentation and selection of suppliers to reduce the risk of disruption can actually support an organization to handle actual disruption scenarios to minimize the cost impact of disruptions and ensure the continuity of business operations. However, it has also been observed that in case of disaster, when demand unexpectedly fluctuates or supplier capacity is disrupted, the regular orders may not meet the demand. Therefore, the extended MIP proposed in paper attempts to ensure business continuity by allocating emergency orders in cost efficient manner. The research attempts to highlight the role of supplier's technological capabilities in the business resilience and ensuring business operations continuity.

The rest of the paper as structured as follows. Section 2 presents the review of literature. Section 3 discusses the problem statement and the proposed multi-stage hybrid model. Section 4 demonstrates the proposed model with the help of a case illustration. Section 5 discuss the managerial implications and theoretical contributions of the paper. Section 6 presents the conclusion and future scope of the study.

2. Literature review

This section reviews the literature on supplier selection problem. Section 2.1 reviews the supply chain models considering disruption risks, Section 2.2 reviews the supply chain models from Industry 4.0 perspective and Section 2.3 studies the supplier selection models under disruptive technologies and disruption risks. Section 2.4 identifies research gaps and research objectives are framed.

2.1. *Supply chain models under disruption risks*

In early 2000's, it was realized that ability to manage supply chain disruptions can act as a competitive edge for any organization. (Sheffi and Rice, 2005). The researchers have also investigated the role of flexibility of supply chain structures in order to minimize the impact of disruptions. Skipper and Hanna (2009) have identified the attributes helpful in contingency planning contributing to the organizational flexibility in order to minimize the risk exposure. Wu et al. (2007) have proposed a disruption propagation framework to assess the disrupted functions of a supply chain and effect of these disruptions on performance measures.

The risk management is an important concern in supply chains as organizations must not select the supply chain partners which increase any kind of risk for them. Barroso et al. (2010) have identified the sources of supply chain disruptions and have discussed the strategies to manage the disruptions and achieve resilience across supply chain. Colicchia et al. (2010) have proposed a simulation-based framework for inbound supply chain risk management in a global sourcing context. Schmitt and Singh (2012) suggested that in order to capture disruption risks the supply chain networks must be considered as a whole and strategic inventory placement and backup capacity throughout several supply chain links must be used for mitigating the risks. Zhu (2013) have proposed joint replenishment and production model under uncertainties. Backordering is allowed for higher and unfulfilled demand in order to mitigate disruption. However, the occurrence of any disaster is an inevitable event, and can affect any organization. Therefore, the supply chains must respond to the disruptions in order to avoid their propagation to other supply chain functions. Ivanov et al. (2014) have studied the phenomenon of ripple effect caused by supply chain disruptions and have compared its characteristics to bullwhip effect. Kim et al. (2015) have studied the supply chain network disruptions and the structural relationships among entities in the network. Any disruption in any node or arc may or may not disrupt entire supply chain network depending upon its structural relationships with other entities. This concept can be used for managing level of resilience in supply chain networks. Dubey et al. (2015) have proposed a multi objective mixed integer linear program considering uncertainties and have compared the results using several numerical experiments to study the effect on supply chain resilience. Gupta et al. (2015) have analysed the classic dilemma or single vs dual sourcing in presence of possible disruption risks. Dubey et al. (2017) have investigated the role of behavioural dimensions such as trust and cooperation on supply chain resilience. Khalili et al. (2017) have suggested the integrated production and sourcing planning considering extra capacities of production facilities, prepositioning or inventories and backup logistics are some structural changes suggested to improve supply chain resilience. Ivanov and Dolgui (2018) have suggested the need to develop resilient as well as efficient supply chain design. The low certainty need supply chains can be developed by incorporating more flexibility in process and resource utilization. Altay et al. (2018) have conducted an empirical study exploring the effect of the resilience and agility efforts of business organizations on the pre-disaster and post-disaster supply chain performance. Hosseini et al. (2019a) have conducted a systematic review of literature and studied the mathematical/quantitative models developed for supply chain resilience. Ivanov et al. (2019a) have studied that how digitization of supply chains can help in managing disruption risk and ripple effect mitigation by coordinating material and information flow between cyber and physical supply chains. Ivanov et al. (2019b) have studied in their book that how one failure propagates through supply chain structures and what supply chain structures are prone to ripple effect and have explored the mitigation strategies. Ivanov (2018) have explained the concepts of resilience along with structural dynamics. The methodologies and models for recovery and stabilization of supply chain structures are also proposed.

2.2. Supply chain models considering disruptive technologies

The new technologies can also disrupt the way business organizations functions and the supply chains must be re-structured from time to time in order to keep up with changing dynamics. Fawcett et al. (2011) have studied why information sharing among several supply chain functions is not improved despite the infrastructure and have suggested changes required to improve the same. Prajogo and Sohal (2013) have studied the competencies and skills required by supply chain managers for the changes expected in supply chain functions due to adoption of technology and automation. Schröder et al. (2014) is one of the initial papers mentioning the need of transitioning in supply chain required for Industry 4.0. The change in risk management system and the new potential risks that supply chains are likely to encounter in Industry 4.0 are also studied in literature. Brettel et al. (2014) have studied and identified the major areas from the supply chain which needs to be developed and supported for fourth industrial revolution. Parreño-Marchante et al. (2014) have proposed a system architecture using RFID to enhance flexibility and traceability in supply chain. Khajavi et al. (2014) have investigated the impact of additive manufacturing in case of distributed production scenario and have identified major challenged in its adoption by the industry. Mohr and Khan (2015) have suggested the use of flexible structural changes in supply chain to take advantage of 3D printing. Gnimpieba et al. (2015) have proposed an architecture for collaborative supply chain structure. With manufacturing industries gradually transitioning into Industry 4.0, it has been realized that several supply chain functions must also be upgraded from an Industry 4.0 perspective. Schlüter et al. (2016) have proposed a risk mitigation framework for decentralized supply chain networks by considering Industry 4.0 factors and finance indicators. Ivanov et al. (2018) have also proposed a risk mitigation research framework to control ripple effect in a cyber-physical systems-based supply chain. Duarte and Cruz-Machado (2017) have identified the gaps in incorporating lean and green supply chain characteristics in Industry 4.0. Gamage and Rupasinghe (2017) have simulated the impact of Industry 4.0 applications such as information sharing, prediction, resource allocation & cross functionality of the impact of sustainability in carbon emissions of an apparel industry.

In context of factories in industries, Ivanov et al. (2016) have proposed an integrated model for machine selection and job assignment for dynamic short-term scheduling for Industry 4.0. Stentoft and Rajkumar (2018) have studied the reorganization of manufacturing structures due to technological advancements leading to back-shoring or re-shoring. Barreto et al. (2017) have explored the effect of Industry 4.0 in distribution networks. Logistics domain is undergoing several technological changes involving a lot of sensor technologies and automation. Hence, the managerial requirements for efficient operation of logistics domain for Industry 4.0 are identified. Tjahjono et al. (2017) have studied several domains within supply chain such as procurement, logistics etc. and have identified the key performance indicators affected by the disruptive technologies. Hoffman and Rusch (2017) have explored that how logistics sector can be developed to the support industries of the fourth revolution. Barata et al. (2018) have reviewed the work done for supply chains in Industry 4.0 in order to identify emerging research areas. Stentoft and Rajkumar (2018) have investigated how the innovations in supply chain functions affect the market and operational performance of an organization. Panetto et al. (2019) have identified the technology enabled strategies and challenges faced by these strategies in design of innovative and resilient networks. Dubey et al. (2019) have investigated the relationship between data analytics, supply chain resilience, organizational flexibility and competitive advantage. Ardito et al. (2019) have studied the digitization of supply chain functions in order to provide an interface between supply chain and marketing functions.

2.3. Supplier selection models under disruption risks and disruptive technologies

Suppliers have a vital role to play in ensuring business operations continuity. Efficient and reliable supplier base is an essential requirement in order to respond and recover from natural or man-made disruptions. Therefore, the sourcing practices carried out by an organization have an important role in ensuring the supply chain resilience and an organization's overall preparedness. In this direction, Tomlin (2006) studied several mitigation strategies for disruptions coming from supplier side and have compared them by proposing an ordering policy model considering volume flexibility. Yu et al. (2009) have conducted a comparative analysis between single and dual sourcing methods considering disruption probability and profit. Parmar et al. (2010) have proposed an algorithm for effective supplier base management in order to minimize the supply side disruptions. Haldar et al. (2012, 2014) have proposed resilient supplier selection models using fuzzy MCDM methods. Supplier selection and order allocation is a core business function that requires continuous structural changes from time to time. Sawik (2013) proposed supplier portfolio selection model considering the risk of disruption and suggested the use of inventory pre-positioning with protected suppliers to mitigate the disruptions. Torabi et al. (2015) have proposed a supplier selection and order allocation model considering several disruption scenarios. The total resilience level can be calculated for various strategies considered. Kamalahmadi and Mellat-Parast (2016) have proposed a flexible sourcing model integrating supplier selection and transportation decisions for resilience in supply chain. The study suggested that to reduce the disruption risk, sourcing must be done from a fewer, however, more resilient suppliers. Hosseini and Barker (2016) have proposed the resilience criteria to be used for supplier selection along with primary and sustainable criteria and have used Bayesian network model to study the causal relationship among criteria. Parkouhi and Ghadikolaei (2017) have proposed a fuzzy ANP- Grey VIKOR based model to evaluate the resilience of suppliers. The model is developed for a wood and paper industry. In recent times, supply failure risk as an important measure for supplier selection (Lee, 2017). Hosseini and Al Khaled (2019) have identified eight criteria contributing to supplier resilience and have proposed a regression and AHP based hybrid model for supplier selection. Hosseini and Ivanov (2019) and Hosseini et al. (2019b) have modelled the ripple effect in the supply chain by considering supplier disruption probability using Bayesian network approach considering different levels of supplier capacity and stages of disruptions. Hosseini et al. (2019c) have also proposed a model for resilient supplier selection by considering the probability of disruption of suppliers Valipour Parkouhi et al. (2019) have proposed joint supplier selection and segmentation framework by identifying the resilient criteria and classifying them as enhancers or reducers. The grey DEMATEL and grey simple additive weight methodology has been used. It is not possible for any organization to realize the benefits of Industry 4.0 without technologically upgrading its end to end supply chain. Real-time information sharing and technical assistance among supply chain partners is the key feature of Industry 4.0. Therefore, supply chain partners must be selected to match the requirements of Industry 4.0 infrastructure. To address this concern, Müller (2019) have studied the challenges of supplier integration in Industry 4.0. The strategies of supplier integration are proposed by drawing insights from expert interviews. Recently, Ghadimi et al. (2019) have developed a multi-technology based architecture for automated supplier selection process. Cavalcantea et al. (2019) have proposed a simulation and machine learning based supplier selection considering risk profiles of suppliers in a digital manufacturing environment. The reviewed literature is summarized in Table 1.

Table 1
Summary of literature reviewed.

References	Main theme	Methodology			Resilience		Disruption Technologies		Cost efficiency
		Conceptual/ theoretical/ Literature based Framework	Empirical Study	Algorithmic/ Simulation/ Mathematical Model	Pre-disaster	Post-disaster	Single	Multiple	
Sheffi (2001), Sheffi & Rice Jr. (2005), Tomlin (2006), Ivanov et al. (2014), Sahebjamnia et al. (2015), Sheffi (2015)	Conceptualizing Supply chain resilience	✓			✓	✓			
Bhutta and Huq (2002), Yu et al. (2009), Parmar et al. (2010) Barroso et al. (2010) Colicchia et al. (2010) Haldar et al. (2012, 2014), Sawik (2013), Parkouhi and Ghadikolaei (2017), Valipour Parkouhi et al. (2019)	Selection of suppliers considering disruption risk		✓	✓	✓				
Skipper and Hanna (2009), Lee (2017)	Identification of factors in risk planning	✓	✓		✓				
Wu et al. (2007)	Assessment of disrupted functions			✓		✓			
Zhu (2013)	Strategies for replenishment during disruptions		✓			✓			✓
Schmitt and Singh (2012), Kim et al. (2015),	Supply chain network design under disruption risk			✓	✓	✓			
Torabi et al. (2015), Kamalahmadi and Mellat-Parast (2016),	Effect of supply chain disruption on business performance			✓	✓	✓			✓
Gupta et al. (2015), Khalili et al. (2017)	Effect of mitigation strategies on business performance		✓		✓	✓			✓
Fawcett et al. (2011), Khajavi et al. (2014), Mohr and Khan (2015), Gnimpieba et al. (2015)	Study of Role of a disruptive technology across supply chain	✓					✓		
Prajogo and Sohal (2013), Brettel et al. (2014), Parreño-Marchante et al. (2014), Stentoft and Rajkumar (2018), Duarte and Cruz-Machado (2017), Gamage and Rupasinghe (2017), Barreto et al. (2017), Tjahjono et al. (2017), Hofmann and Rüsch (2017),Barata et al. (2018), Müller (2019)	Study of changes in certain supply chain functions due to Industry 4.0	✓						✓	
Schröder et al. (2014), Ivanov et al. (2018)	Conceptualizing the supply chain resilience using disruptive technologies	✓			✓			✓	
Dubey et al. (2015)	Multi objective optimization	✓		✓		✓			✓
Dubey et al. (2017)	Behavioural dimensions for supply chain resilience		✓		✓				
Altay et al. (2018)	Agility and Resilience		✓		✓	✓			
Schlüter et al. (2016)	Role of disruptive technologies in	✓			✓			✓	✓
Ivanov et al. (2016)	Scheduling model for Industry 4.0				✓			✓	✓
Ghadimi et al. (2019)	Model for supplier integration in Industry 4.0			✓				✓	
Panetto et al. (2019)	Challenges for IOT based supply chains	✓			✓			✓	
Stentoft and Rajkumar (2018), Hosseini et al. (2019a), Ivanov and Dolgui (2018), Ardito et al. (2019) Hosseini et al. (2019b), Hosseini & Ivanov (2019)	Effect of disruptions of supply chain performance	✓			✓	✓			✓
Ivanov *et al.*, (2019)a,b	Managing disruption risk using digital supply chains	✓			✓	✓		✓	

(*continued on next page*)

Table 1 (*continued*)

References	Main theme	Methodology			Resilience		Disruption Technologies		Cost efficiency
		Conceptual/ theoretical/ Literature based Framework	Empirical Study	Algorithmic/ Simulation/ Mathematical Model	Pre-disaster	Post-disaster	Single	Multiple	
Hosseini and Barker (2016), Hosseini and Al Khaled (2019), Hosseini et al. (2019c)	Resilient supplier selection			✓	✓				✓
Proposed model	Proposed hybrid model for supplier selection			✓	✓	✓		✓	✓

2.4. Research gaps and research objective

The supply chains are subjected to continuous transition owing to increased complexity, globalization, technological advancements and the risk of disruptions from natural and manmade disasters. The structure of supply chains cannot remain static anymore, it needs to go through continuous evolution and must be adaptive to both positive and negative events in the business environment. It is observed that most of the literature study the effect of disruptive technologies on the functioning of an organization. However, the companies cannot work in isolation, therefore, the real value of these disruptive technologies cannot be realized if the changes are not adopted among all the supply chain. Moreover, most of the papers have considered one technology and its potential for supply chains. But, Industry 4.0 is driven by a set of technologies interacting with each other. There is very limited literature available on the study of structural changes required in entire supply chain design in order to adopt the disruptive technologies. Moreover, it is also realized that the literature on disruption risks and supply chain resilience is studied for the conventional supply chain structures. There is a very limited literature addressing on the managing the disruption risk for a highly digitized supply chain. The disruptions in supply side are minimized using resilient supplier selection. However, with the emerging disruptive technologies, there is a need to redesign the process of supplier selection and order allocation. The conventional criteria and methods used for supplier selection and handling the disruption risks may not do well in presence of disruptive technologies. In view of the gaps identified from literature following are the research questions (RQ):

RQ1. What are the technological criteria for supplier selection in presence of disruption risks for Industry 4.0?

RQ2. How to identify the most important criteria?

RQ3. How to create a technologically competent supplier base?

RQ4. How supplier risk can be computed?

RQ5. How supplier selection and order allocation is done for Industry 4.0?

RQ6. How to handle disruptions from supply side in Industry 4.0?

Based upon the above research questions, following are the research objectives (RO) framed for this paper:

RO1. To identify and prioritize the criteria for technologically competent supplier selection for Industry 4.0

RO2. To develop supplier segmentation methodology for Industry 4.0

RO3. To propose a method to calculate supplier risk.

RO4. To develop a Mixed Integer Program for final supplier selection and order allocation for Industry 4.0

RO5. To develop an extended Mixed Integer Program for handling disruptions in Industry 4.0

3. Problem statement and proposed multi-stage hybrid model

3.1. Problem statement

The paper addresses the restructuring of the supplier selection and order allocation process of a global manufacturing company which is in process of transition into an Industry 4.0 and the company also intend to minimize the risk of disruptions due to any disaster event. Therefore, the suppliers must be selected in such a manner that they are technologically competent so that the company can realize the actual benefits of Industry 4.0 and ensure the undisrupted flow of materials to its manufacturing facility in order to respond to the market demand. If any of the supply chain partner is not technologically competent, it acts as a source of risk and can lead to supply chain disruption. It is important for the company to restructure its supply chain networks so that the information is shared across the channels on real-time basis to gain the flexibility and responsiveness required in Industry 4.0 environment. Therefore, the company needs to identify and evaluate the technology driven as well as resilient criteria and develop a supplier segmentation, selection and order allocation methodology jointly considering both disruptive technologies as well as disruption risks. The supplier selection and order allocation structure must be adaptive to absorb the real time demand fluctuations as well as unexpected disruptions such that total cost as well as risk can be simultaneously minimized considering demand fluctuations, risk and disruptions.

3.2. Research framework

The research framework for the problem stated in section 3.1 is shown in Fig. 1. The initial step is to identify the set of technology driven criteria from an Industry 4.0 perspective for restructuring of supplier selection process. The identified criteria are then studied for their interrelationship and are evaluated using expert opinions. The suppliers are initially segmented into the efficient and inefficient suppliers using data envelopment analysis (DEA). The motivation to use DEA is to reduce the supplier base before applying the more exhaustive method for supplier prioritization and risk calculation. The inefficient suppliers are, therefore, not considered for the further process selection and order allocation. The efficient suppliers further evaluated and prioritized using FAHP-TOPSIS. There are other multi criteria decision making tools which can be used for the supplier prioritization, however, TOPSIS is used because it is relatively less complicated and easy to understand (Roszkowska, 2011). The set of criteria for supplier selection is supposed to protect the organization against certain risks that can cause disruptions in entire supply chain. Therefore, the criteria-risk mapping is done to understand how various criteria are protecting the organization against various risks. Using the ratings given to suppliers against various criteria in TOPSIS, the average risk percentage is calculated for each supplier. The MIP is proposed to optimize supplier selection and order allocation such that the demand is met with minimum cost (including cost of risk). However, due to any unforeseen/disaster event if any supplier is disrupted or the demand for any product suddenly fluctuates,

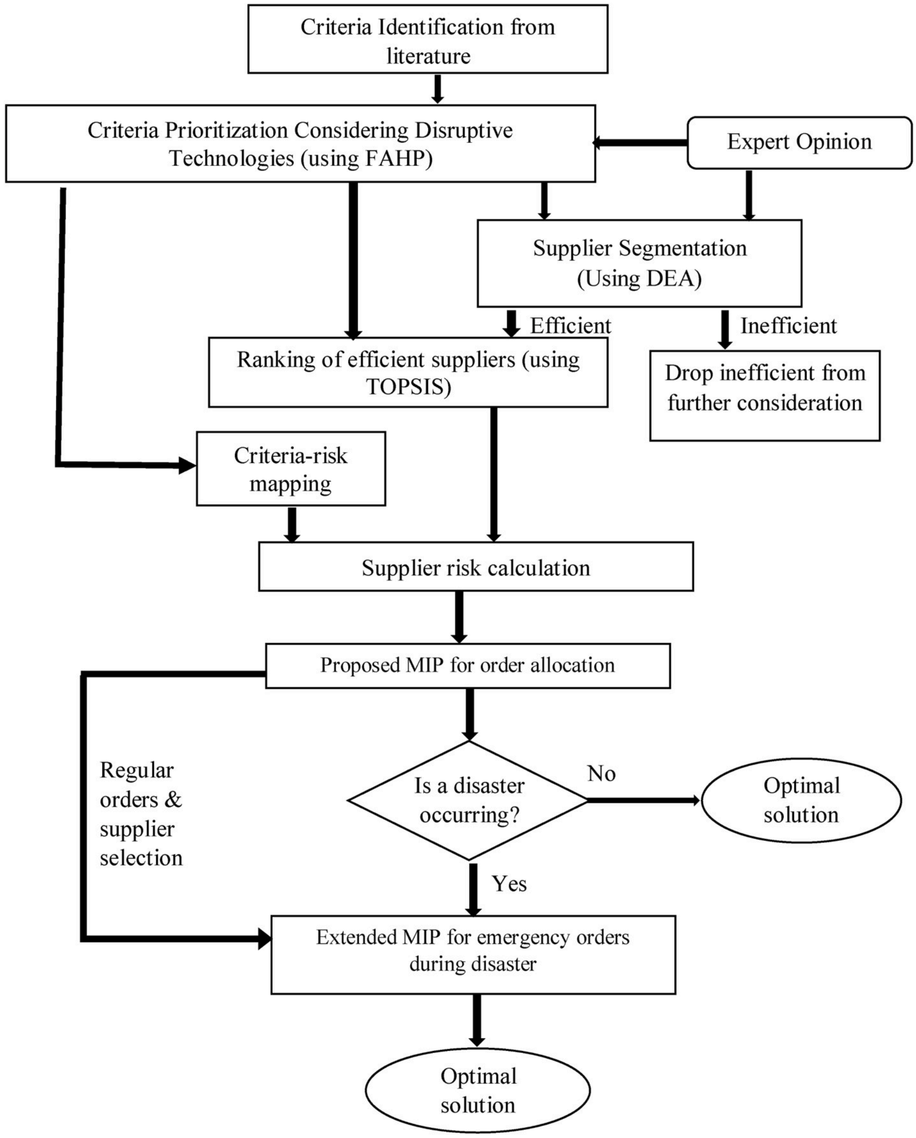

Fig. 1. Proposed Multi-stage hybrid model for supplier selection and order allocation.

the system must be adaptive enough to handle this situation using emergency orders minimizing the total cost and stockouts. Therefore, the MIP is further extended for a disaster scenario, where supplier disruptions and unexpected demand fluctuations are considered and managed using emergency orders and backup capacities keeping the total cost of procurement, stockouts and risks at a minimal level.

3.3. Identification of criteria & priorities

The technologically driven criteria are identified using the review of literature and the field survey. The conventional set of criteria used in literature need to be revised to incorporate the technological requirements expected from supplier's side for industries investing into disruptive technologies. Moreover, the technological criteria must also ensure the undisrupted flow of information and materials even during the disasters. The priority of these criteria is established by conducting pairwise comparison among the criteria. As, the adoption of disruptive technologies is relatively new in industry, therefore, here is a there is a slight fuzziness in clarity about the inter-relationship among various technological criteria. Hence fuzzy-scale is used to capture these uncertainties. The criteria weights are hence obtained using FAHP. The fuzzy scale used for FAHP can be referred from Appendix A1. The steps to convert fuzzy weights into crisp weights can be referred from Opricovic and Tzeng (2004).

3.4. Supplier segmentation using DEA

The suppliers are evaluated to be included in the pool of suppliers for the company. The suppliers are rated for their expected performance on the identified criteria (in section 4.1). The output-oriented DEA model is used for evaluation. The outputs of all the DMU's are evaluated for a virtual output. Since, the ratings of the suppliers against all the criteria are their performance measure and hence are considered to be the output. The formulation of the model is given as follows:

In any system, let's assume that there are r outputs and i inputs, and u_r is the weight if the output Y_{ro} for any particular DMU. Similarly, v_i is weight of input X_{ij}, then in order to have better performing units, total output should be maximized if input is fixed. The objective function is to maximize the total output as shown in equation (1). For detailed explanation, Lovell and Pastor (1999) can be referred.

$$Max \sum_{r=1}^{s} u_r Y_{ro} \tag{1}$$

Subject to,

$$\sum_{r=1}^{s} u_{rj}Y_{rj} - \sum_{i=1}^{m} v_i X_{ij} \leq 0 \qquad \forall r \tag{2}$$

$$\sum_{i=1}^{m} v_i X_{io} = 1 \tag{3}$$

$$u_r, v_i \geq 0 \qquad \forall\, i, r \tag{4}$$

The model is solved for each supplier one by one and the suppliers having efficiency 1 are considered in the pool, the inefficient suppliers are not considered. If an organization is keeping technologically inefficient suppliers in the pool, the chances of supply chain disruptions are more during any disaster event. Hence, as a proactive measure, it is important to carefully select technologically competent and compatible suppliers for transparency and responsiveness across the supply chain.

3.5. Supplier prioritization using TOPSIS

Supplier selection is followed by supplier segmentation. After the criteria are identified and suppliers are evaluated to be efficient or inefficient on these criteria, the final selection of suppliers need to be done. The efficient suppliers are only considered for further evaluation using TOPSIS. TOPSIS stands for technique for preference by similarity to the ideal solution is a multi-criteria decision-making method proposed by Hwang and Yoon (1981) rank the set of alternatives. The steps involved in TOPSIS are described below:

Step-I: Performance data is obtained for j alternatives over i criteria as shown in equation (5)

$$a_{ij} = \begin{vmatrix} d_{11} & d_{21} & d_{i1} \\ d_{12} & d_{22} & d_{i2} \\ d_{1j} & d_{j2} & d_{ij} \end{vmatrix} \tag{5a}$$

Step-II: obtain a standardized matrix S_{ij} by using equation (6)

$$S_{ij} = \frac{d_{ij}}{\left(\sum_j d_{ij}^2\right)^{1/2}} \qquad \forall i, j \tag{6}$$

Step III: Develop weights (w_i) for each criterion. Construct the weighted normalized matrix using equation (7)

$$V_{ij} = w_i S_{ij} \qquad \forall i, j \tag{7}$$

However, if all the criteria are equally weighted than it will be exactly same matrix as step II.

Step-IV: Identify the ideal solution and negative-ideal solution using equations (8) and (9).

$$\textit{Ideal solution } V^* = \{\max(V_{ij}) \quad \forall i\} \tag{8}$$

$$\textit{Negative Ideal solution } V^{'} = \{\min(V_{ij}) \quad \forall i\} \tag{9}$$

Step V: Calculate Separation Measure (S_i*) from ideal solutions for each alternative as shown in equation (10)

$$S_i^* = \sum_j V^* - V_{ij}\Big)\left(V^* - V_{ij}\right)\left(V^* - V_{ij}\right)^2\Big)^{1/2} \quad \forall i \tag{10}$$

Step VI: Calculate the separation measure ($S_i^{'}$) from negative ideal solution for each alternative as shown in equation (1

$$S_i^{'} = \sum_j V^{'} - V_{ij}\Big)\left(V^{'} - V_{ij}\right)\left(V^{'} - V_{ij}\right)^2\Big)^{1/2} \quad \forall i \tag{11}$$

Step VII: The closeness index is computed using equation (12) and suppliers are ranked in descending order of the index value.

$$C_i^* = \frac{S_i^{'}}{(S_i^{'} + S_i^*)} \quad \forall i \tag{12}$$

By allocating orders to the most preferred or top ranked suppliers, the risk of supply chain disruption due to disasters for an Industry 4.0 can be minimized. The company can also develop strategic alliance with the top-ranked suppliers to ensure the business continuity in the time of crises. Hence, this methodology is also used to identify suppliers worth to be further developed for collaborative projects.

3.6. Criteria-risk mapping and supplier risk calculation

The criteria used for supplier selection are supposed to protect the organization against one or more supply chain risks. Therefore, it is important to understand how the criteria used for supplier selection are linked to the supply chain risk. For the purpose of this study, the risk is classified into five types namely forecast risk, procurement risk, capacity risk, inventory risk and system's risk. Each kind of risk is briefly defined below. Chopra and Sodhi (2004) can be referred for further explanation.

Forecast risk: Mismatch between expected and actual demand within supply chain. ***Procurement risk***: Unexpected fluctuation in cost, quality & time of delivered items due to supplier price hikes, improper contract conditions or any inefficiency at supplier's end.

Capacity risk: Risk of having excess or short capacity.

Inventory risk: Holding of excess inventory throughout supply chain can affect the financial efficiency of the entire supply chain.

System's risk: In integrated cyber physical systems, any threat or failure anywhere in supply chain can affect entire supply chain.

Step I: The criteria-risk matrix is prepared to identify which criteria is mitigating which risk. The matrix uses binary variable (W_{ki}) which takes value 1 if criteria i is covering the risk k for the organization, otherwise it takes value 0. Hence The matrix W is shown below in equation (13):

$$W = \begin{vmatrix} w_{11} & w_{21} & w_{k1} \\ w_{12} & w_{22} & w_{k2} \\ w_{1i} & w_{2i} & w_{ki} \end{vmatrix} \quad w_{ki} \in \{0, 1\} \quad \forall k,\ i \tag{13}$$

Also compute the column sum ($\sum_i w_{ki}, \forall k$) to determine how many total criteria are covering each kind of risk for the organization.

Step II: The suppliers are rated against these criteria already for TOPSIS (equation (5)).

$$a_{ij} = \begin{vmatrix} d_{11} & d_{21} & d_{i1} \\ d_{12} & d_{22} & d_{i2} \\ d_{1j} & d_{j2} & d_{ij} \end{vmatrix} \tag{5b}$$

Step III: The risk of supplier noncompliance is calculated using these ratings. The risk percentage for non-compliance of each supplier against each criterion is computed with the help of following equation:

$$R_{11} = \frac{(max\ rating - d_{11})}{\max rating} * 100 \qquad \forall s,\ \forall i \tag{14}$$

Now, the supplier-criteria risk matrix is obtained as equation 15

$$R_{ij} = \begin{vmatrix} R_{11} & R_{21} & R_{i1} \\ R_{12} & R_{22} & R_{i2} \\ R_{1j} & R_{2j} & R_{ij} \end{vmatrix} \tag{15}$$

Step IV: Total risk matrix (TRkj) can be obtained by matrix multiplying Wki and Rij as shown in equation 16

$$TR_{kj} = [w_{ki}] * [R_{ij}] \tag{16}$$

Step V: Normalize the total risk matrix by diving each value in the column with column sum computed in equation X. The normalized matrix is obtained as shown in equation (17):

$$NR_{kj} = \begin{vmatrix} TR_{11} \Big/ \sum_i w_{1i} & TR_{21} \Big/ \sum_i w_{2i} & TR_{k1} \Big/ \sum_i w_{ki} \\ TR_{12} \Big/ \sum_i w_{1i} & TR_{22} \Big/ \sum_i w_{2i} & TR_{k2} \Big/ \sum_i w_{ki} \\ TR_{1j} \Big/ \sum_i w_{1i} & TR_{2j} \Big/ \sum_i w_{2i} & TR_{kj} \Big/ \sum_i w_{ki} \end{vmatrix} \tag{17}$$

Step VI: The average risk percentage for each supplier is computed by taking the row average of values in normalized risk matrix using equation (18). In equation (18), k is the total number of risk types considered.

$$Risk_j = \sum_k NR_{ik} \Big/ k \quad \forall j \tag{18}$$

Hence, average risk associated with each supplier is computed.

3.7. Mixed integer program for supplier selection & order allocation (With and Without disruptions)

In this section, the mixed integer program is proposed for supplier selection and order allocation jointly considering the disruptive technologies and disruption risks. The model is proposed for multi-item and multi-period planning of order allocation to the suppliers. The orders can only be allocated to the efficient set of suppliers identified at screening stage. The prices and capacities offered by the suppliers are already known. The objective of the supplier selection and order allocation is to ensure that demand is met with minimum total cost including the cost of risk. If there is no disaster, the regular orders must be released in such a manner that total cost and risk can be minimized. However, if there is a disaster scenario, the regular orders should remain as such and disruption must be handled using emergency orders to the same or different supplier. The assumptions and notations used in the model are described below:

Assumptions for the model:

1. Demand is stochastic in nature. However, the mean and variance tend to change before and after the disaster.
2. Suppliers have limited capacity and known with certainty. In case, disaster occurs, suppliers can support with an additional 20% backup capacity
3. All orders must be fulfilled in same period. Late deliveries are not allowed. Penalty cost is incurred for any shortages in case of disaster caused disruptions.
4. Emergency orders can be executed to prevent the disruptions.

Decision Variables.

X_{pst} Quantity of order for product p ordered from supplier s in time period t.

$X^{'}_{pst}$ Quantity of Emergency order for product p ordered from supplier s in time period t.

Y_{pst} Binary variable taking value 1 if product p is ordered from supplier s in time period t ELSE 0.

U_{pst} Binary variable taking value 1 if emergency order for product p is ordered from supplier s in time period t ELSE 0.

I_{pt} Inventory carried for product p in time period t.

Sh_{pt} Shortage for product p occurred in time period t.

Notations.

UPC_{pst} Unit price of product p ordered from supplier s in time period t.

$UPC^{'}_{pst}$ Surged Unit price for emergency orders for product p ordered from supplier s in time period t.

R_s Risk of disruption associated with supplier s.

RC_s Cost of risk associated with supplier s.

OC_{pst} Cost of ordering product p from supplier s in time period t.

UTC_{pst} Unit Transportation cost incurred receiving product p from supplier s in time period t.

HC_{pt} Unit holding cost of product p in time period t.

C_{pst} Capacity offered by supplier s for product p in time period t.

EC_{pst} Extended suppliers offered by supplier s for product p in time period t.

$F^{-1}{}_{Dpt}$ Constant inverse cumulative function of demand for given mean, standard deviation and probability of meeting the demand.

Pen_{pt} Penalty cost incurred for shortages for product p in time period t.

MIP: Supplier selection and order allocation without disruptions

$$Zmin = \sum_p \sum_s \sum_t \left(UPC_{pst} X_{pst} + Y_{pst} OC_{pst} + UTC_{pst} X_{pst} + R_s RC_s Y_{pst} \right) + \sum_p \sum_t HC_{pt} I_{pt} \tag{19}$$

Subject to,

$$I_{p(t-1)} + \sum_s X_{pst} - F^{-1}_{Dpt}(\alpha_{pt}) - I_{pt} = 0 \quad \forall p,\ t \tag{20}$$

$$\sum_s X_{pst} \le \sum_t F^{-1}_{Dpt}(\alpha_{pt}) \quad \forall p, t \tag{21}$$

$$X_{pst} \le C_{pst} {}^{*} Y_{pst} \qquad \forall p, s, t \tag{22}$$

$$\sum_s R_s * Y_{pst} \le 0.4 \qquad \forall p.\forall t \tag{23}$$

$$X_{pst}, I_{pt} \text{ are integers} \quad \forall p, s, t \tag{24}$$

$$Y_{pst} \in \{0, 1\} \quad \forall p, s, t \tag{25}$$

The objective function of the model shown equation (19) is the minimization of total cost of procurement comprising of unit price, ordering cost, transportation and holding cost along with the total risk coming from selected suppliers over the entire planning horizon. Equation (20) represents the inventory balance equation balancing inventory from previous period and total orders received to the demand and inventory left over in current period. Equation (21) restricts the maximum order to be placed in any period to the total demand over planning period. Equation (22) is the supplier capacity constraint restricting the order quantity with the available supplier capacity. Equation (23) restricts the maximum risk coming from suppliers for any product in any period to be less than 40%. The integer nature of order quantity X_{pst} and inventory I_{pt} and the binary nature of variable Y_{pst} for supplier selection is shown in equations (24) and (25) respectively.

Extended MIP: Supplier Selection and Order Allocation with disruptions.

If any disaster event occurs model II is used to execute emergency orders from the selected or backup suppliers. The purchase price of emergency orders is higher than regular orders. The emergency orders from suppliers are also associated with risk. In model II shortages can occur and a penalty cost is incurred corresponding to the same. The regular orders already finalized using model I must remain as such and can be used as given data in Model II. The model is formulated as following:

$$Zmin = \sum_p \sum_s \sum_t \left(UPC_{pst} X_{pst} + UPC^{'}_{pst} X^{'}_{pst} \right) + \sum_p \sum_s \sum_t OC_{pst}\left(Y_{pst} + U_{pst}\right) + \sum_p \sum_s \sum_t UTC_{pst}\left(X_{pst} + X^{'}_{pst}\right) + \sum_p \sum_t HC_{pt} I_{pt} + \sum_P \sum_T Pen_{pt} Sh_{pt} + \sum_p \sum_s \sum_t R_s RC_s \left(Y_{pst} + U_{pst}\right) \tag{26}$$

Subject to,

$$I_{p(t-1)} + \sum_s X_{pst} + \sum_s X^{'}_{pst} - F^{-1}_{Dpt}(\alpha_{pt}) - I_{pt} + Sh_{pt} = 0 \quad \forall p,\ t \tag{27}$$

$$X^{'}_{pst} \le \left((C_{pst} - X_{pst}) + EC_{pst} \right) * U_{pst} \quad \forall p, s, t \tag{28}$$

$$\sum_s R_s * U_{pst} \le 0.3 \quad \forall p, \forall t \tag{29}$$

$$X^{'}_{pst}, Sh_{pt} \text{ are integers} \quad \forall p, s, t \tag{30}$$

$$U_{pst} \in \{0, 1\} \quad \forall p, s, t \tag{31}$$

Equation (26) represents the objective function of the model which minimizes the total cost of procurement comprising of purchase price, ordering cost, transportation cost of regular as well as emergency orders, holding cost, penalty cost for the shortages occurring, and the cost of risk from regular orders and emergency orders. Equation (27) represents the inventory balance equation, balancing the inventory on hand, the regular orders and the emergency orders to the demand, current inventory and the shortages. Equation (28) is the capacity constraint for emergency orders. During any disaster event, the suppliers offer 20% more capacity as extended support. Emergency orders can be placed from the same supplier as regular orders or the different one. The risk for each product in each time period for extended orders should be less than 30% as shown in equation (29). Equation (30) describes the integer nature of emergency orders and shortages and equation (31) describes the binary nature of variable for supplier selection for emergency orders.

4. Case illustration: XYZ automobiles private limited

In this section, the proposed multi stage hybrid model for supplier selection and order allocation is illustrated using the case of XYZ Automobiles Pvt. Ltd. XYZ has been a market leader in automobiles for several years despite encountering some disruptions from time to time. In recent years, the company has been investing heavily in disruptive technologies and hence bringing in major structural changes in its overall functioning. XYZ has realized that it has not been able to gain any significant improvement as the technologies under the umbrella of Industry 4.0 has been installed and implemented at a company's level. The other supply chain functions of the company are not yet fully integrated with the technologies available within the company. Therefore, the company has not been able to realize the potential benefits of Industry 4.0 like supply chain visibility and transparency. Supplier selection and order allocation is one key function for the company which needs structural transformation. The company has been using the conventional criteria and methods for supplier evaluation and therefore, are not able to capture the technological competency of suppliers which is now an important requirement by the company. The other major concern for the company to integrate the supply chain is to minimize the disruptions which are caused by the natural disasters such as floods, cyclones & earthquakes as well as manmade disasters such as terrorist attacks or protests. Hence, the company is required to identify and update the supplier evaluation criteria capturing the technological competency of the suppliers. The suppliers which are not technologically competent may not provide the necessary visibility to the company in terms of capacity and lead-times, increasing the risk of disruption and hence cannot be considered for order allocations. The company is required to maintain and develop a pool of suppliers based on the technological criteria to ensure the efficient use of disruptive technologies in order to fulfil the uncertain demand and to handle disaster caused disruptions. The disaster events in past have caused two types of disruptions for the company in the past i.e. huge fluctuation in demand and/or capacity failure from supplier side. The company needs to design a supplier segmentation, selection and order allocation process such that the suppliers suitable to adapt to the changes in technology ongoing with the company are identified and developed and can also help the company in handling the sudden fluctuations in demand/capacity due to disasters by providing real time visibility. The company intends to develop the supplier segmentation & selection process so that overall cost of procuring items over a planning horizon can be minimized. At the same time, the supplier selection process is expected to be adaptive to handle the potential disruption by allocating emergency orders to other suppliers such that cost impact and risk is kept minimum. In order to address the company's concerns the multi-stage hybrid model for supplier selection and order allocation considering disruptive technologies and disruption risks is implemented. The steps are explained in following subsections.

4.1. Criteria identification & prioritization

The criteria for evaluating suppliers for their technological competence are identified from literature and from expert opinion (top & middle management of the company). The identified criteria are briefly described in Table 2. The criteria are compared amongst themselves using Fuzzy-AHP. The aggregated fuzzy pairwise comparison matrix is provided in Appendix A2. Final priorities of the criteria are shown in Table 3. It has been observed that manufacturing flexibility, cyber security, use of RFID & data visibility are important technological requirements from the suppliers in today's digitized supply chains. The

Table 2
Technological Criteria for supplier selection.

Criteria		Description
C_1	Disaster sensing using BDA	Use of Big Data Analytics can help to predict the impact of disaster/market so that the organizations can prepare themselves accordingly
C_2	**RFID/Barcodes**	It helps in visualizing the levels of inventory at all levels of supply chains, having real time information can help the organization to manage disruptions from alternate/backup suppliers
C_3	**Public-Private Partnership**	Public-private partnerships can help in data access from government agencies and organizations can know the actual impact of disaster
C_4	**Smart contracts using Block chain**	Can help manage the capital and resources and maintains a transparency at all supply chain links
C_5	**Data Visibility across value chain**	Each supply chain link must be also to provide all necessary information on real time basis to other supply chain partners to prevent any chance to disruption
C_6	**IOT Infrastructure**	Cyber-physical systems can help reduce the lead times and increase responsiveness
C_7	**Shared platforms**	Shared and compatible platforms can help manage and reallocate the resources to manage supply chain disruptions
C_8	**Resource efficiency using cloud computing**	Cloud computing at real time basis can help in effective allocation & reallocation of the resources on real time
C_9	**GIS/GPS enabled Logistics**	Real time tracking of inventory in transitioning at several stages of the supply chain
C_{10}	**Manufacturing Flexibility**	The suppliers should be flexible to support the supply chain in disaster events
C_{11}	**Additive Manufacturing**	Can help in reducing the lead time and the cost of production
C_{12}	**Cyber security**	As several companies are sharing a lot of information across the supply chain, cyber security is an important criterion for all supply chain partners

Table 3
Fuzzy & Defuzzified Criteria Weights obtained after using Fuzzy AHP.

Criteria	Fuzzy criteria weights	Defuzzified criteria weights (Opricovic and Tzeng, 2004)
C_1	(0.0215,0.039,0.0735)	0.042438
C_2	(0.0883,0.140,0.231)	0.14971
C_3	(0.0266,0.044,0.082)	0.048201
C_4	(0.038,0.0715,0.138)	0.079866
C_5	(0.068,0.107,0.173)	0.115199
C_6	(0.0351,0.0618,0.108)	0.066774
C_7	(0.0446,0.075,0.120)	0.079148
C_8	(0.0319,0.0625,0.108)	0.066929
C_9	(0.0235,0.039,0.070)	0.042177
C_{10}	(0.134,0.221,0.352)	0.224593
C_{11}	(0.0093,0.0137,0.0215)	0.013973
C_{12}	(0.0834,0.1235,0.189)	0.13034

technological criteria are used for supplier selection process in order to adapt to the changing supply chain dynamics and to mitigate the risk of disruption by natural and man-made disasters.

4.2. Supplier segmentation

In supplier segmentation process, the initial pool of suppliers is evaluated against the identified set of criteria using Output-oriented DEA model. The rating of each supplier's potential to perform on the given criteria is taken from the historic data as well as from expert's judgements. All ratings measure supplier's performance on given criteria, therefore, are considered to be the output. The suppliers are then segmented into efficient and inefficient ones. After using the model for all the suppliers, the efficiencies calculated are shown in Table 4.

Hence, efficient supplier set is $\{S_2, S_3, S_4, S_7, S_8\}$ is considered for further selection process whereas the inefficient set of suppliers $\{S_1, S_5, S_6, S_9, S_{10}\}$ are not further considered. By dropping the inefficient suppliers unable to adapt to the dynamics caused by the use of disruptive technologies in supply chain, the risk of disruption likely to be caused by inefficient suppliers can be avoided.

4.3. Supplier prioritization using TOPSIS

After supplier segmentation, the efficient set of suppliers are considered for further procedures, whereas the inefficient suppliers are dropped. The efficient suppliers are further prioritized using TOPSIS. Appendix A3 shows the detailed steps of the TOPSIS for given data. The weights used in TOPSIS for criteria have already been computed using FAHP. Finally, using FAHP-TOPSIS, the final closeness index is computed and the suppliers are ranked as shown in Table 5. The supplier S_4 is found to be best ranked followed by S_7. Supplier S_3 is ranked third followed by S_8 and S_2.

4.4. Criteria-risk mapping and supplier risk calculation

The criteria used for supplier selection are supposed to protect the company against one of the supply chain risks. The criteria-risk mapping is done using expert opinions and the insights drawn from literature. In Table 6, the criteria-risk matrix is shown indicating which criteria is protecting the organization against which risk. For example: the for criteria C_1 the value is 1 against forecasting risk, indicating that criteria C_1 is protecting the organization against that particular risk. If the value of cell is zero, it indicates no relationship.

Using the steps describes in section 3.6, The average risk associated with each supplier is calculated. It can be observed from Table 7 that supplier S_3 is having least risk associated with it which is 18% and supplier S_2 is having highest risk percentage out of all five suppliers.

Table 5
Final Supplier Ranking using TOPSIS.

Suppliers	Closeness Index	Rank
$\mathbf{S_2}$	0.12552	5
$\mathbf{S_3}$	0.6065	3
$\mathbf{S_4}$	0.69317	1
$\mathbf{S_7}$	0.64545	2
$\mathbf{S_8}$	0.50795	4

4.5. Supplier selection and order allocation using MIP

The multi-period and multi-product planning of detailed order allocations to respective suppliers has to be done by the company. The problem considers the order allocation problem for ten different items to the five suppliers over a planning horizon of six months. The orders must be allocated to the suppliers in such a way that demand is fully met at minimum cost of procurement including the purchase cost, ordering cost, transportation cost, holding and risk cost. The supplier capacities, prices offered by suppliers and the forecast of mean and deviation for stochastic demand are known to the company. The complete data for the problem is given in Appendix A4. The problem is solved using mixed integer program when there is no disaster/unforeseen event. The complete supplier selection and order allocation obtained for the given problem in absence of any disruption is provided in Table 8. It can be noted that at this stage all the orders are the regular orders. The total cost of procurement is 3002984. It can be seen from the table that dynamic lot sizing is followed for all the products to match the stochastic demand.

4.5.1. Disaster scenario I: demand fluctuations

Now, considering a scenario when there is a disaster occurrence in second time period. Due to disaster, there is a fluctuation in demand of all the parts from second period onwards. In this case regular orders alone will not be able to satisfy the increased demand. In this case, the problem is again solved using extended MIP, which considers regular orders as input and minimizes the disruptions by allocating emergency orders over and above the regular orders. It is assumed that in case of disaster all suppliers are bound to offer 20% more capacity than they were offering initially. If demand is still not met using emergency orders it will result in a stockout for which company incur the huge cost of stockout. The price for emergency orders charged by the suppliers is also higher than the price for regular orders. It can be seen from Fig. 2 that demand has increased from time period 2 onwards and the emergency order are allocated in addition to regular orders. The regular demand is shown using the solid line and fluctuated demand is shown using the dotted line. The regular orders and emergency orders are shown using bars. It can also be seen from Fig. 2 that in most of the cases the emergency orders are given to the suppliers already given regular orders. It is because it is more cost effective to order in emergency situations from same supplier already supplying the regular orders. However, in some cases, due to cost or capacity restrictions the emergency orders are given to other suppliers as well. The total cost incurred in this case is 3267580 including the incremental cost of managing disruption. In this case, the increased demand is fully met using emergency orders and hence no shortage cost is incurred. However, if the demand fluctuations are not

Table 4
Supplier efficiency obtained using DEA.

Supplier	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}
Efficiency computed using DEA	.819	1	1	1	.857	.738	1	1	.8	.917

Table 6
Criteria-risk matrix.

	Forecast risk	Procurement risk	Capacity risk	Inventory risk	systems risk
Disaster sensing using BDA	1	0	0	1	0
RFID/Barcodes	0	0	0	1	0
Public-Private Partnership	0	1	0	0	0
Smart contracts using Blockchain	0	1	0	0	0
Data Visibility across value chain	1	0	0	0	0
IOT Infrastructure	0	0	1	0	1
Shared platforms	1	0	0	0	1
Resource efficiency using cloud computing	0	0	0	1	0
GIS/GPS enabled Logistics	0	0	0	1	0
Manufacturing Flexibility	0	0	1	0	0
Additive Manufacturing	0	0	1	0	0
Cyber security	0	0	0	0	1

Table 7
Supplier Average Risk calculation.

Suppliers	Forecast risk	Procurement risk	Capacity risk	Inventory risk	systems risk	Average Risk
$\mathbf{S_2}$	48%	39%	78%	50%	63%	**56%**
$\mathbf{S_3}$	4%	39%	33%	8%	7%	**18%**
$\mathbf{S_4}$	11%	33%	63%	17%	33%	**31%**
$\mathbf{S_7}$	33%	39%	33%	28%	48%	**36%**
$\mathbf{S_8}$	30%	33%	33%	17%	37%	**30%**

managed using emergency orders, it would have resulted in shortages/ disruption. It would have cost the company 1390900, which is 54% higher than cost of regular orders. On the other hand, the cost of managing disruptions using incremental orders is merely 9% of regular cost. The ordering patterns for each product time over entire planning horizon with or without disaster occurrence are also shown in Appendix A5.

4.5.2. Disaster scenario II: capacity disruption

In this section, another disaster scenario is considered where the supplier capacity of one of the supplier's is disrupted. In this case, disaster does not affect the demand, however, the capacity of supplier 2 is disrupted. It is assumed that disaster occurred in time period 2, therefore supplier 2 would not be able to fulfil its regular orders from period 2 onwards. Therefore, in this scenario, the extended MIP is again used to allocate emergency orders for the disruption caused. In this case, the regular orders for supplier 2 will become zero from second period onwards. The results obtained are shown in Fig. 3. It is observed from the figure that corresponding to demand, the regular and emergency orders placed. The incremental cost of procurement is incurred for emergency orders. The ordering pattern for all the items over entire planning horizon for regular and emergency orders is tabulated in detain in Appendix A6. It is estimated that total cost of procurement including the cost of emergency orders for this scenario is 3269683. However, in case this disruption in supplier capacity cannot be managed using emergency order allocation to other suppliers, it all would have resulted in shortages. And the total penalty cost for shortages would amount to 4423800, which is 47% more than total cost of procurement (see Fig. 4).

4.5.3. Disaster scenario III: demand fluctuation and capacity disruption (Exhibit A)

In third scenario, it is assumed that disaster has two-fold effect, it caused demand fluctuations in addition to the capacity disruption. In this scenario, it is considered that both scenario I and scenario have occurred together. There is a demand fluctuation due to disaster and also there is a capacity disruption from supplier side. Again, it is assumed that disaster occurs in period 2, the demand for all the products fluctuates from period 2 onwards. Also, the supplier 2 is disrupted from period 2 onwards and will not be able to fulfil the regular orders allocated for all the parts. In order to manage both the disruptions, the extended MIP is used. The regular orders are kept as it is, however, the regular orders pertaining to the disrupted supplier (S2) will become zero from second period onwards. The emergency orders are allocated to the suppliers with remaining & extended capacity in order to manage the regular orders which supplier S2 was unable to meet and also to meet the demand fluctuations as much as possible. The results obtained are shown in Fig. 5. It can be seen that the demand has increased during disaster as well as regular orders have reduced due to disruption. Therefore, in this case the quantity and number of emergency orders have significantly increased as compared to other orders. The ordering pattern for all the products over the planning horizon is provided in Appendix A7. In case, there is not enough backup capacity to handle disruptions, it can result in shortages. For this case example, no shortages are incurred. The total cost of procurement incurred for this scenario is 3565577. However, if these disruptions were not handled using emergency orders, they would have resulted in shortages and cost of penalty would be 5840480 which is 94% higher than the total cost of procurement in this case.

4.5.4. Disaster scenario IV: demand fluctuation and capacity disruption (Exhibit B)

In the fourth scenario, it is assumed that the disaster leads to both the demand and supply disruptions simultaneously. This scenario is similar to scenario III, however, the intensity of the disruption varies in this case. It is assumed that disaster event has led to unexpectedly high demand fluctuations and on the other side some suppliers are affected by the disaster leading to complete capacity loss by those suppliers. The initial supplier selection and order allocation.

Again, it is assumed that disaster occurs in time period T_2, the demand for all the products experiences huge fluctuations from time period T_2 onwards. The suppliers S_2 and S_8 are also disrupted which means that they will not be able to fulfil any regular orders for any item product allocated to them. The extended MIP is used to manage the disruptions and revise the regular orders to meet the demand which may have increased significantly due to disaster and allocate emergency orders to undisrupted suppliers in case in case some of the suppliers are disrupted. Now in this case, the company will be able to manage disruptions on the real time basis only if the supplier base is technologically competent to share the effect of disruptions with the company and allows the revision of regular orders. In order to achieve the real-time coordination between suppliers and buyers is only possible if real-time information sharing is there between two parties. Therefore, in order to minimize the impact of disruptions, the suppliers must be

Table 8
Supplier selection and order allocation for Stochastic demand.

		T1	T2	T3	T4	T5	T6
P1	Normal equivalent of stochastic demand	2581	896	3155	1673	1307	3029
	Regular order	2581	1561	2490	4000	0	2009
	Supplier Selection	X (1, 1, 3) = 2581,X (2, 1, 5) = 1561,X (3, 1, 3) = 2490,X (4, 1, 2) = 4000,X (6, 1, 3) = 2009					
P2	Normal equivalent of stochastic demand	2689	2923	1330	1014	1732	2632
	Regular order	3042	2570	2388	0	4320	0
	Supplier Selection	X (1, 2, 5) = 3042 X (2, 2, 2) = 2570 X (3, 2, 4) = 2388 X (5, 2, 4) = 4320					
P3	Normal equivalent of stochastic demand	2215	2723	2055	1513	3132	881
	Regular order	2750	2188	4760	1580	360	881
	Supplier Selection	X (1, 3, 2) = 2750 X (2, 3, 4) = 2188 X (3, 3, 4) = 4760 X (4, 3, 2) = 1580 X (5, 3, 3) = 360 X (6, 3, 3) = 881					
P4	Normal equivalent of stochastic demand	1071	1547	3263	2614	1215	2704
	Regular order	1071	4360	450	2860	969	2704
	Supplier Selection	X (1, 4, 2) = 1071 X (2, 4, 5) = 4360 X (3, 4, 2) = 450 X (4, 4, 5) = 2860 X (5, 4, 5) = 969 X (6, 4, 3) = 2704					
P5	Normal equivalent of stochastic demand	2796	2997	1104	1622	1507	1914
	Regular order	2796	2997	3807	0	2340	0
	Supplier Selection	X (1, 5, 5) = 2796 X (2, 5, 5) = 2997 X (3, 5, 3) = 3807 X (5, 5, 3) = 2340					
P6	Normal equivalent of stochastic demand	2223	2748	1232	2707	1829	1504
	Regular order	3221	1750	2578	3190	0	1504
	Supplier Selection	X (1, 6, 3) = 3221 X (2, 6, 3) = 1750 X (3, 6, 5) = 2578 X (4, 6, 5) = 3190 X (6, 6, 2) = 1504					
P7	Normal equivalent of stochastic demand	1456	2988	732	2899	1221	963
	Regular order	2310	2134	732	2899	2184	0
	Supplier Selection	X (1, 7, 3) = 2310 X (2, 7, 2) = 2134 X (3, 7, 4) = 732 X (4, 7, 4) = 2899 X (5, 7, 2) = 2184					
P8	Normal equivalent of stochastic demand	2948	2871	1815	1715	1007	1799
	Regular order	2984	4650	0	4280	0	241
	Supplier Selection	X (1, 8, 5) = 2984 X (2, 8, 2) = 4650 X (4, 8, 2) = 4280 X (6, 8, 4) = 241					
P9	Normal equivalent of stochastic demand	1221	2056	2647	3032	964	2347
	Regular order	1527	1750	4300	3080	1610	0
	Supplier Selection	X (1, 9, 2) = 1527 X (2, 9, 5) = 1750 X (3, 9, 2) = 4300 X (4, 9, 3) = 3080 X (5, 9, 2) = 1610					
P10	Normal equivalent of stochastic demand	1699	1797	2482	904	1882	982
	Regular order	4940	0	1942	0	1882	982
	Supplier Selection	X (1, 10, 4) = 4940 X (3, 10, 3) = 1942 X (5, 10, 5) = 1882 X (6, 10, 5) = 982					

technologically competent with the firm transitioning inti Industry 4.0.

The results of the extended MIP suggest that all the regular orders except the orders pertaining to the disrupted suppliers (S2 & S8) will become zero from second time period onwards. The emergency orders are allocated to the remaining undisrupted suppliers by utilizing their remaining or extended capacity available such that the demand is met as much as possible and the shortages are minimized. The results obtained are charted in Fig. 5. In this case, due to the huge fluctuation in the demand and two suppliers being disrupted, the high amount of emergency orders allocated to the rest of the suppliers. The detailed ordering plan and the emergency order allocations are provided in Appendix A8. The company is able to handle the disruptions and allocate emergency orders because of real time information sharing and transparency between the company and the suppliers in Industry 4.0 environment. In this case the total cost of the procurement is 3887198. However, if this information sharing is not there, it can result in shortages. For this case example, no shortages are incurred. However, if these disruptions were not handled using emergency orders, they would have resulted in shortages and cost of penalty would be 5840200 which is 1844% higher than the total cost of procurement in this case.

Table 9 shows that some flexibility in supply chain structure can help the company in preventing the disruptions by allocating emergency orders to other suppliers. It can be seen from the table that cost of procurement including the emergency orders is significantly less than the penalty cost for shortages for all the disaster scenarios. It is also realized from this case example that careful selection of suppliers in this era of disruptive technologies is extremely important. In this case, the suppliers are technologically competent to the organization and hence the information sharing and flow of material is transparent. The supplier capacity is visible to the organization and hence the emergency orders can be placed. In absence of technologically competent suppliers, such responsiveness and flexibility cannot be achieved. Therefore, disruptive technologies play a significant role in managing disruption risks in a supply chain. This case also indicates the importance of supplier-buyer relationships along with the role of information sharing across supply chain. The demand fluctuations in this case can be managed using supplier backup capacity during disaster.

5. Managerial implications and theoretical contributions

5.1. Managerial implications

The outcomes of the proposed research can help supply chain managers to reconfigure their conventional supplier selection and order allocation process to match the changing dynamics of the industry. The proposed framework can be used as a decision making tool by the business organization which can assist supply chain managers in evaluation of supplier alternatives on their technological capabilities as well as their ability to ensure business continuity against disruptions from disasters. The findings reveals that the supplier segmentation and prioritization process proposed in the paper helps business organizations to proactively design a pool of reliable suppliers minimizing the supplier risk and hence the impact of disruptions in event of disaster. The proposed MIP is a unique model to assist the supply chain managers to optimally design their order allocation policies from multiple sources to meet the uncertain demand while keeping the overall cost and risk at minimum level. Moreover, the proposed model can be also of high sustainable value to business organizations in handling the disaster caused disruption scenarios such as unexpectedly high demand fluctuations or supplier capacity failures in a cost-efficient manner. Another unique and interesting aspect of the proposed MIP is its application in the event of disruption where business organizations can be benefited by the proposed extended MIP enabling them to efficiently revise the regular orders and allocate emergency orders in an attempt to minimize the cost impact of disruptions and ensure business continuity. The case-illustration provided in the paper can also help managers to understand and relate to the structural dynamics of the supplier selection process in presence of disruptive technologies and disaster caused

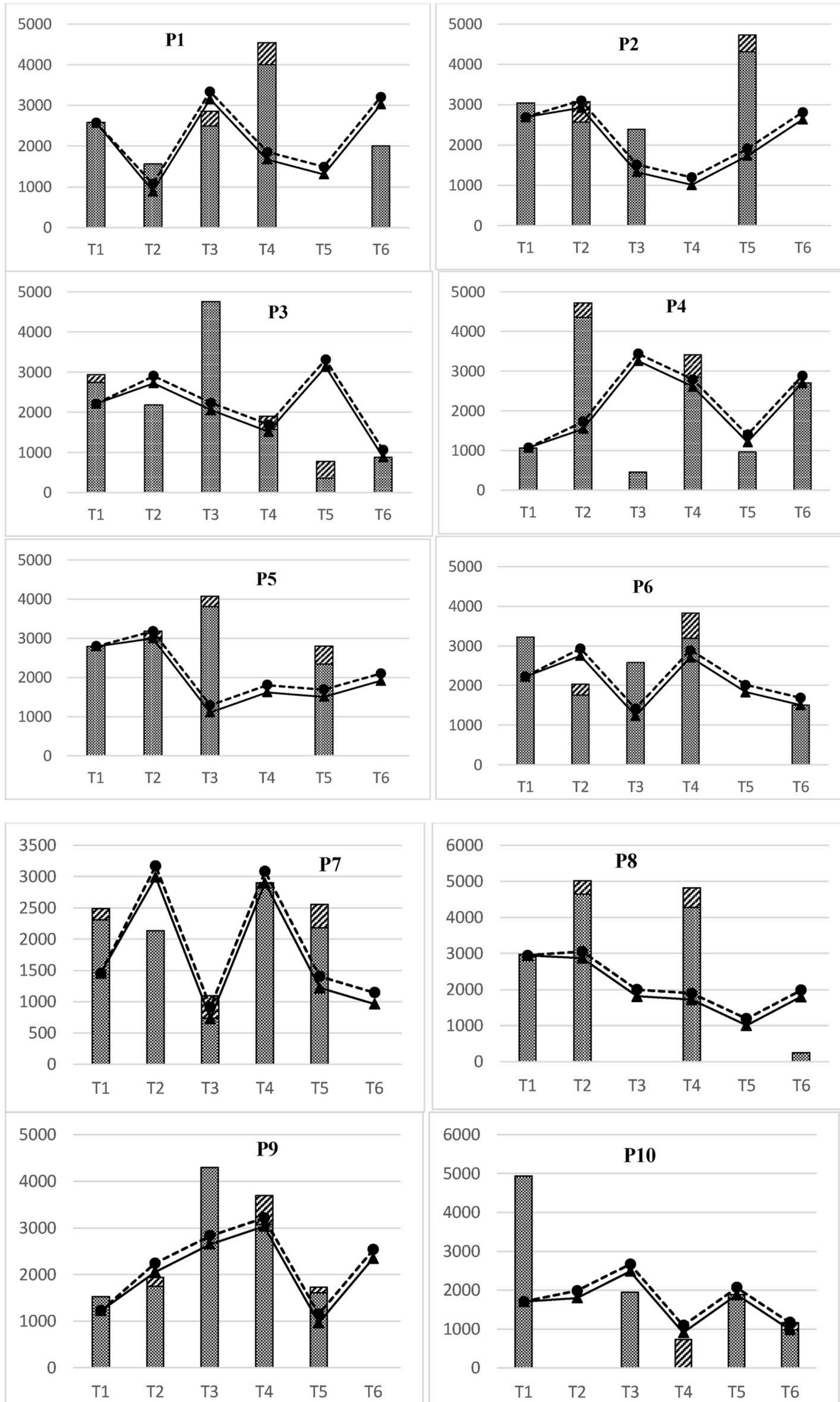

Fig. 2. Ordering pattern for disaster scenario I.

disruptions.

5.2. Theoretical contributions

This paper contributes to the widely and extensively researched field of supplier selection. The contribution made in the paper is technically and theoretically a novel attempt as an integrated supplier segmentation, selection and order allocation in Industry 4.0 environment considering the disaster caused disruptions. The proposed model presents how the supplier selection decisions are affected when a conventional industry transition into Industry 4.0. The requirements from the suppliers in industry 4.0 to handle the disaster caused disruptions are

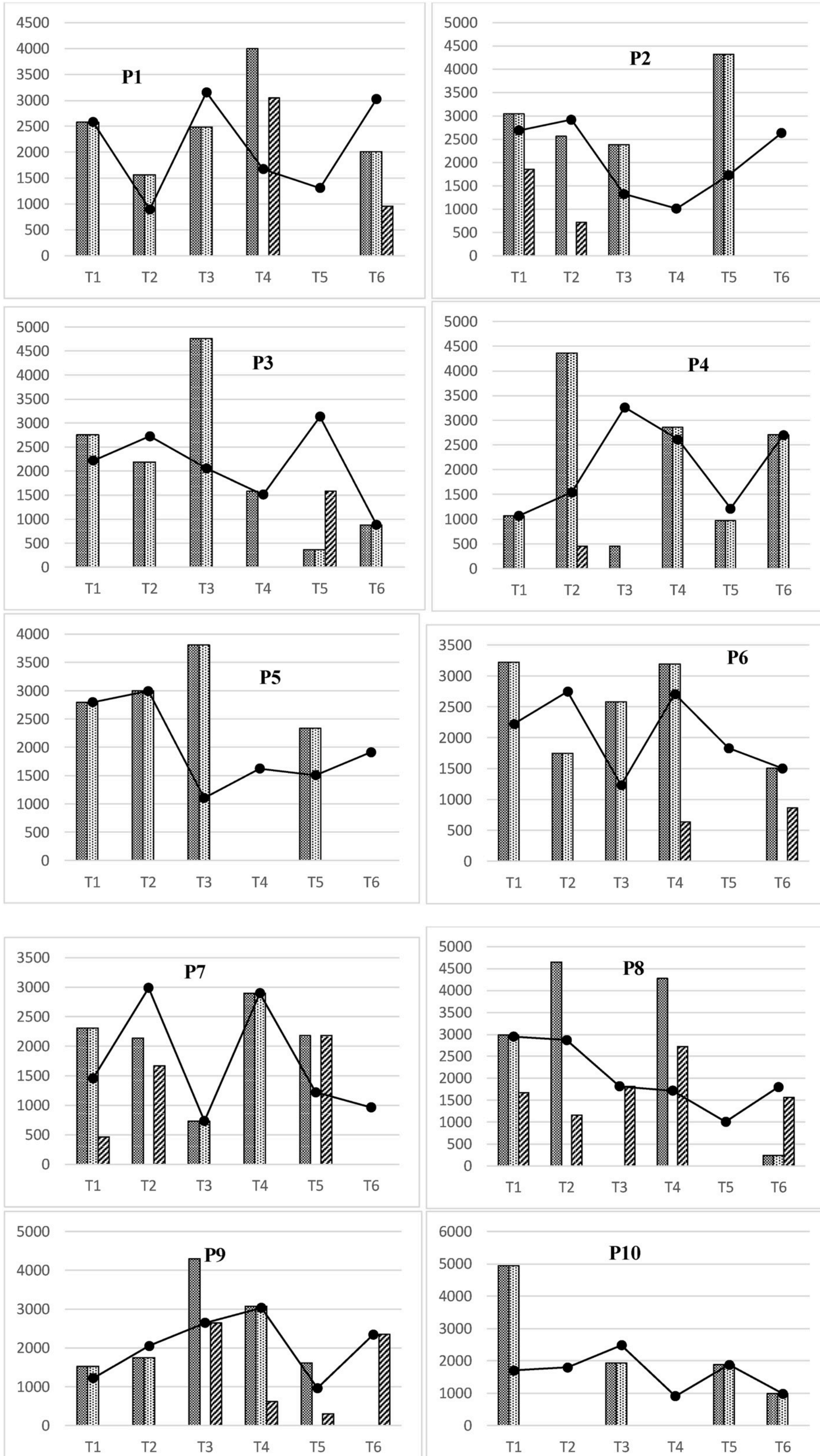

Fig. 3. Ordering pattern for disaster scenario II.

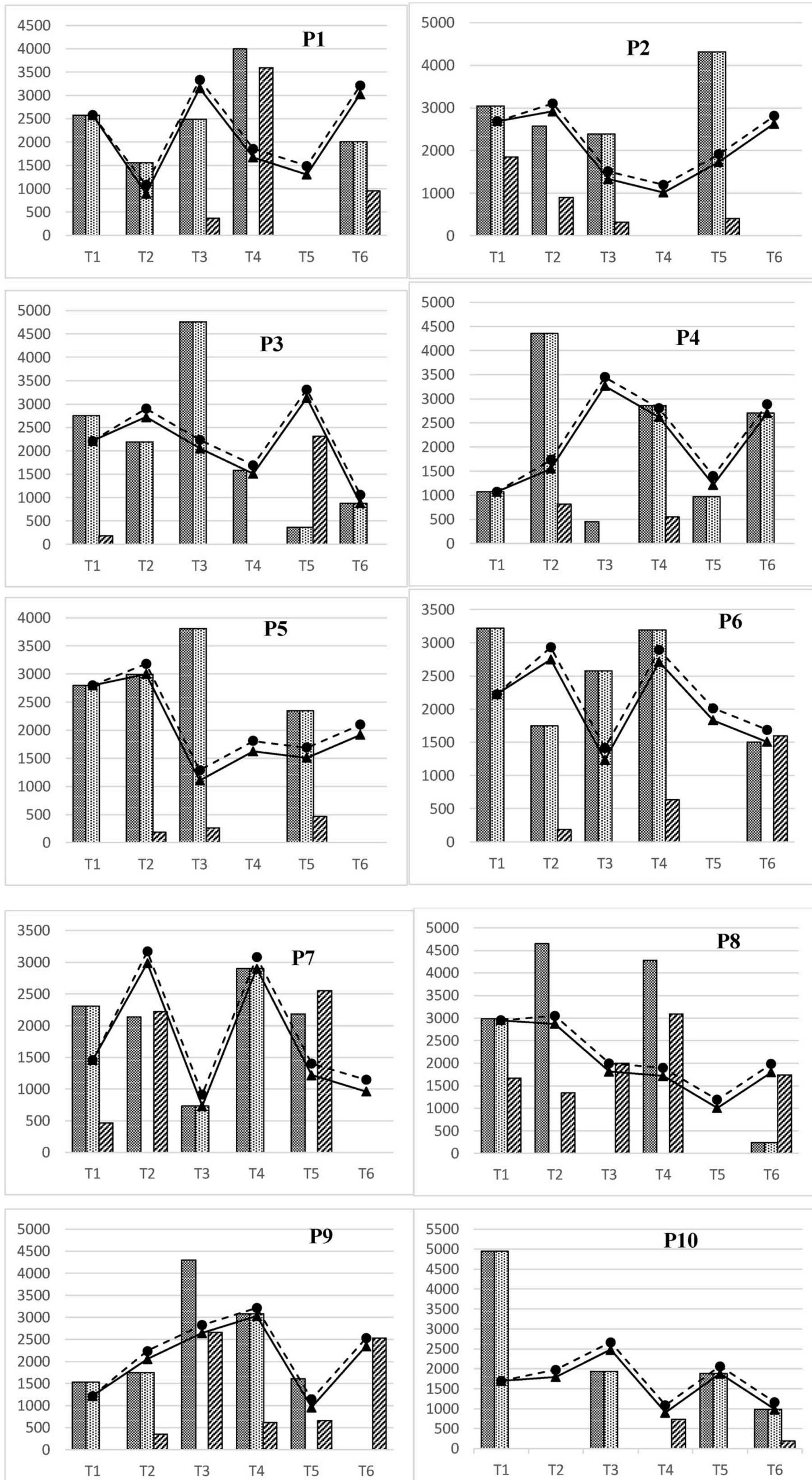

Fig. 4. Ordering pattern for disaster scenario III.

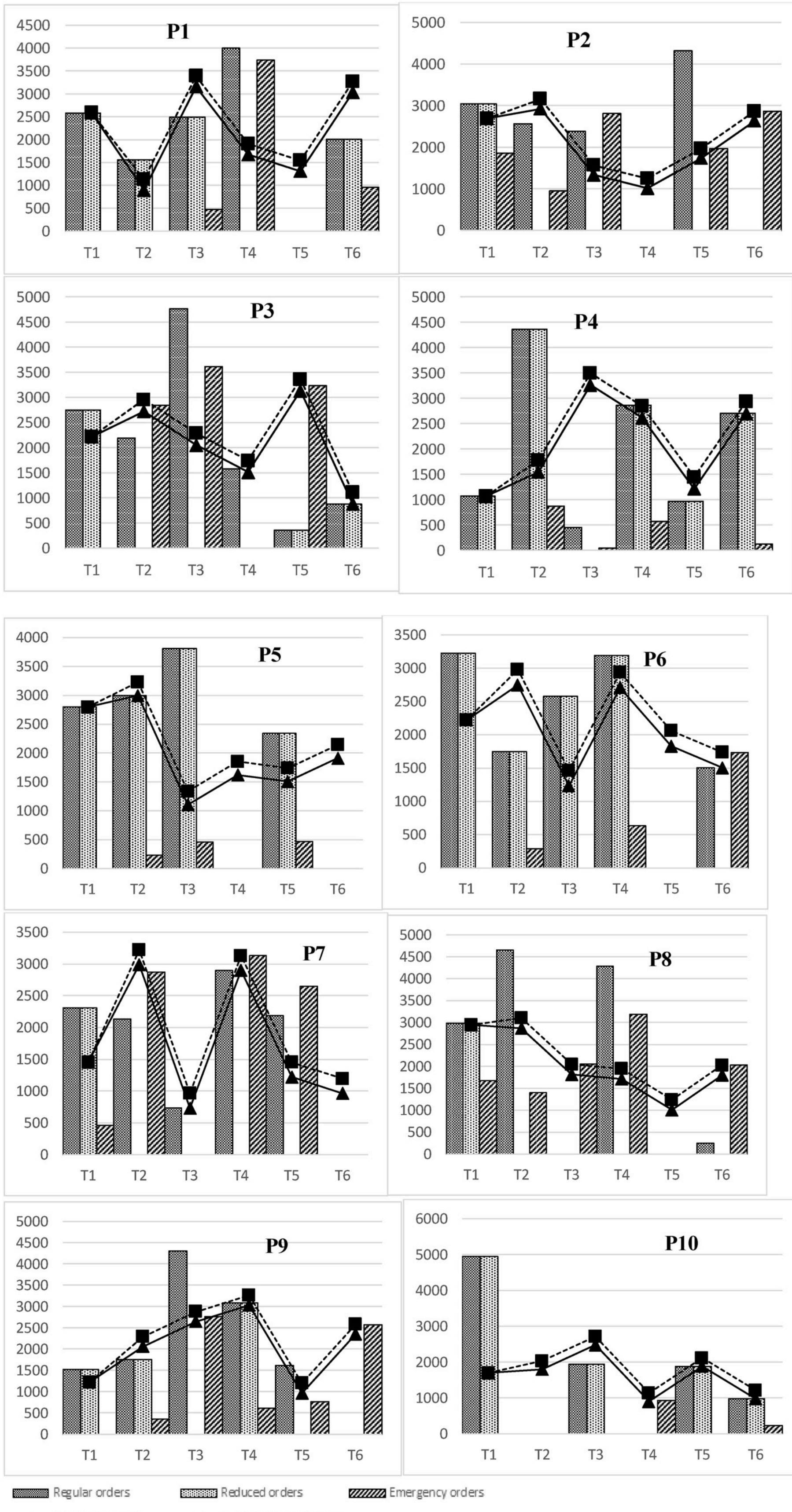

Fig. 5. Ordering pattern for disaster scenario IV.

Table 9
Cost comparison for various scenarios.

	Cost of Procurement with emergency orders	Expressed in % of regular cost	Penalty cost for shortages	Expressed in % of regular cost
Regular	3002984		–	
Disaster Scenario I	3267580	9%	1390900	54%
Disaster Scenario II	3269683	8%	4423800	47%
Disaster Scenario III	3565577	17%	5840480	94%
Disaster Scenario IV	3887198	29.44%	58402000	1844%

different from a conventional industry. To address this concern, the proposed work presents a multi stage hybrid model for supplier segmentation, prioritization and order allocation considering the industry 4.0 environment in presence of demand and/or supply disruptions. The paper identifies the supplier selection criteria relevant to Industry 4.0 environment. The set of criteria identified in the paper evaluates the technical competency of the supplier and the ability to handle disruptions in Industry 4.0 environment. The paper also derives the average supplier risk by mapping their performance of the set of criteria with different kinds of risks involved. The supplier risk is then integrated into mixed integer program where the orders are allocated to the suppliers to meet the uncertain demand over a planning horizon such that total cost and the risk associated is simultaneously minimized. In case of disaster caused disruptions, the extended MIP tends to revise the regular order allocations and allocate emergency orders with the suppliers in such a way that incremental cost handling with the disruptions and overall risk is again minimized. To demonstrate the applicability of the proposed model, a case of an automobile company is also considered under four disaster scenarios.

6. Conclusions and future scope of work

The fourth industrial revolution has led to the need of technologically upgrading the supply chains and for companies to identify the technologically competent partners. In addition to this, global supply chains also have to select the supply chain partners considering the risk of disruptions caused by natural and man-made disasters. Therefore, the paper addresses the reconfiguration of supplier selection and order allocation process broadly from two perspectives i.e. disruptive technologies and disruption risks. The paper proposes a multi-stage hybrid model for re-configuration of supplier selection process involving criteria identification, supplier segmentation, selection and order allocation jointly considering disruptive technologies and disruption risks. The paper identifies and prioritizes the technological criteria used for selecting suppliers for digitized supply chains, which are different from conventional criteria. The supplies are segmented into efficient and inefficient suppliers using DEA and the efficient suppliers are further evaluated and ranked using FAHP-TOPSIS. The paper also proposes a novel method to compute the supplier disruption risk using criteria-risk mapping. The paper proposes an MIP for the detailed supplier selection and order allocation against the uncertain demand considering disruption risk. The extended MIP is also proposed to handle the disaster caused disruptions such as demand fluctuations & supply shortages by revising the initial allocation and allocating emergency orders on real time basis. The proposed multi stage hybrid model is illustrated using a case of an automobile company which is transitioning to Industry 4.0 and investing into disruptive technologies. The proposed model is helpful for the companies undergoing supply chain structural changes in order to adopt to disruptive technologies and how disruptions can be handled in reconfigured supply chain structure. The proposed multi-stage hybrid model can be extended in future to incorporated lead-time constraints, delays and late orders. In addition, the model can also be extended by integrating other supply chain functions such as production, warehousing, logistics etc. with supplier selection.

Appendix A1. Fuzzy scale used for criteria prioritization

Fuzzy rating	Triangular Fuzzy Number	Fuzzy rating	Triangular Fuzzy Number
$\tilde{1}$	(1,1,1)	$\tilde{1}$	(1,1,1)
$\tilde{2}$	(1,2,3)	$\widetilde{1/2}$	(1/3,1/2,1)
$\tilde{3}$	(2,3,4)	$\widetilde{1/3}$	(1/4,1/3,1/2)
$\tilde{4}$	(3,4,5)	$\widetilde{1/4}$	(1/5, 1/4, 1/3)
$\tilde{5}$	(4,5,6)	$\widetilde{1/5}$	(1/6, 1/5, 1/4)
$\tilde{6}$	(5,6,7)	$\widetilde{1/6}$	(1/7, 1/6, 1/5)
$\tilde{7}$	(6,7,8)	$\widetilde{1/7}$	(1/8, 1/7, 1/6)
$\tilde{8}$	(7,8,9)	$\widetilde{1/8}$	(1/9, 1/8, 1/7)
$\tilde{9}$	(8,9,9)	$\widetilde{1/9}$	(1/9, 1/9, 1/8)

Appendix A2. Fuzzy pairwise comparison matrix

		Disaster sensing using BDA	RFID/ Barcodes	Public-Private Partnership	Smart contracts using Blockchain	Data Visibility across value chain	IOT Infrastructure	Shared platforms	Resource efficiency using cloud computing	GIS/GPS enabled Logistics	Manufacturing Flexibility	Additive Manufacturing	Cyber security
C_1	Disaster sensing using BDA	(1,1,1)	(0.25,0.33,0.50)	(0.33,0.50,1)	(0.33,0.50,1)	(0.20,0.25,0.33)	(1,2,3)	(0.25,0.33,0.50)	(1,2,3)	(0.25,0.33,0.50)	(0.11,0.14,0.17)	(4,5,6)	(0.14,0.17,0.2)
C_2	RFID/Barcodes	(2,3,4)	(1,1,1)	(1, 2, 3)	(3,4,5)	(1,1,1)	(4,5,6)	(3,4,5)	(5,6,7)	(3,4,5)	(0.33,0.5,1)	(6, 7, 8)	(1,1,1)
C_3	Public-Private Partnership	(1,2,3)	(0.33,0.50,1)	(1,1,1)	(0.25,0.33,0.50)	(0.14,0.17,0.2)	(0.33,0.50,1)	(1,1,1)	(0.33,0.5,1)	(1,2,3)	(0.14,0.17,0.2)	(6, 7, 8)	(0.25,0.33,0.5)
C_4	Smart contracts using Blockchain	(1,2,3)	(0.20,0.25,0.33)	(2, 3, 4)	(1,1,1)	(0.33,0.5,1)	(2,3,4)	(0.25,0.33,0.5)	(1,2,3)	(2,3,4)	(0.33,0.5,1)	(4,5,6)	(0.14,0.17,0.2)
C_5	Data Visibility across value chain	(3,4,5)	(1,1,1)	(5, 6, 7)	(1, 2, 3)	(1,1,1)	(2,3,4)	(1,1,1)	(1,2,3)	(2,3,4)	(0.20,0.25,0.33)	(6, 7, 8)	(1,1,1)
C_6	IOT Infrastructure	(0.33,0.50,1)	(0.17,0.20,0.25)	(1, 2, 3)	(0.25,0.33,0.50)	(0.25,0.33,0.5)	(1,1,1)	(1,2,3)	(3,4,5)	(1,2,3)	(0.25,0.33,0.5)	(3,4,5)	(1,1,1)
C_7	Shared platforms	(2,3,4)	(0.20,0.50,0.33)	(1,1,1)	(2,3,4)	(1,1,1)	(0.33,0.5,1)	(1,1,1)	(4,5,6)	(2,3,4)	(0.14,0.17,0.2)	(3,4,5)	(0.11,0.14,0.17)
C_8	Resource efficiency using cloud computing	(0.33, .5, 1)	(0.14,0.17,0.20)	(1, 2, 3)	(0.33,0.50,1)	(0.33,0.5,1)	(0.2,0.25,0.33)	(0.17,0.2,0.25)	(1,1,1)	(5,6,7)	(0.17,0.2,0.25)	(2,3, 4)	(1,2,3)
C_9	GIS/GPS enabled Logistics	(2, 3, 4)	(0.20,0.25,0.33)	(0.33, 0.50,1)	(0.25,0.33,0.50)	(0.25,0.33,0.5)	(0.33,0.5,1)	(0.25,0.33,0.5)	(0.14,0.17,0.2)	(1,1,1)	(0.17,0.2,0.25)	(5, 6, 7)	(0.33,0.5,1)
C_{10}	Manufacturing Flexibility	(6, 7, 8)	(1, 2, 3)	(5, 6, 7)	(1,2,3)	(3,4,5)	(2,3,4)	(5, 6, 7)	(4,5,6)	(4,5,6)	(1,1,1)	(6, 7, 8)	(3,4,5)
C_{11}	Additive Manufacturing	(0.17,0.20,0.25)	(0.13,0.14,0.17)	(0.13, 0.14,0.17)	(0.17,0.20,0.25)	(0.13,0.14,0.17)	(0.2,0.25,0.33)	(0.2,0.25,0.33)	(0.25,0.33,0.5)	(0.14,0.17,0.20)	(0.13,0.14,0.17)	(1,1,1)	(0.17,0.2,0.25)
C_{12}	Cyber security	(5, 6, 7)	(1,1,1)	(2, 3, 4)	(5,6,7)	(1,1,1)	(1,1,1)	(6,7,8)	(0.33,0.5,1)	(1,2,3)	(0.20,0.25,0.33)	(4,5,6)	(1,1,1)

Appendix A3. Steps for TOPSIS

	Disaster sensing using BDA	RFID/ Barcodes	Public-Private Partnership	Smart contracts using Blockchain	Data Visibility across value chain	IOT Infrastructure	Shared platforms	Resource efficiency using cloud computing	GIS/GPS enabled Logistics	Manufacturing Flexibility	Additive Manufacturing	Cyber security
S_2	4.0	5.0	7.0	4.0	5.0	3.0	5.0	3.0	6.0	2.0	1.0	2.0
S_3	9.0	9.0	5.0	6.0	9.0	9.0	8.0	8.0	7.0	4.0	5.0	8.0
S_4	8.0	8.0	3.0	9.0	7.0	2.0	9.0	7.0	7.0	6.0	2.0	7.0
S_7	7.0	8.0	8.0	3.0	7.0	5.0	4.0	6.0	5.0	7.0	6.0	5.0
S_8	8.0	7.0	7.0	5.0	8.0	7.0	3.0	9.0	6.0	4.0	7.0	7.0

	Disaster sensing using BDA	RFID/ Barcodes	Public-Private Partnership	Smart contracts using Blockchain	Data Visibility across value chain	IOT Infrastructure	Shared platforms	Resource efficiency using cloud computing	GIS/GPS enabled Logistics	Manufacturing Flexibility	Additive Manufacturing	Cyber security
S_2	0.24165	0.29722	0.50000	0.30953	0.30542	0.23146	0.35806	0.19405	0.42967	0.18182	0.09325	0.14471
S_3	0.54371	0.53499	0.35714	0.46429	0.54976	0.69437	0.57289	0.51748	0.50128	0.36364	0.46625	0.57886
S_4	0.48330	0.47555	0.21429	0.69644	0.42759	0.15430	0.64450	0.45279	0.50128	0.54545	0.18650	0.50650
S_7	0.42289	0.47555	0.57143	0.23215	0.42759	0.38576	0.28645	0.38811	0.35806	0.63636	0.55950	0.36179
S_8	0.48330	0.41611	0.50000	0.38691	0.48868	0.54006	0.21483	0.58216	0.42967	0.36364	0.65275	0.50650

Identification of positive and negative ideal solutions

	Disaster sensing using BDA	RFID/ Barcodes	Public-Private Partnership	Smart contracts using Blockchain	Data Visibility across value chain	IOT Infrastructure	Shared platforms	Resource efficiency using cloud computing	GIS/GPS enabled Logistics	Manufacturing Flexibility	Additive Manufacturing	Cyber security
S_2	0.010255	0.044497	0.024101	0.024721	0.035184	0.015455	0.028339	0.012988	0.018122	0.040835	0.001303	0.018862
S_3	0.023074	0.080094	0.017215	0.037081	0.063332	0.046365	0.045343	0.034634	0.021142	0.081670	0.006515	0.075449
S_4	0.020510	0.071195	0.010329	0.055622	0.049258	0.010303	0.051011	0.030305	0.021142	0.122505	0.002606	0.066017
S_7	0.017947	0.071195	0.027544	0.018541	0.049258	0.025759	0.022672	0.025976	0.015102	0.142923	0.007818	0.047155
S_8	0.020510	0.062295	0.024101	0.030901	0.056295	0.036062	0.017004	0.038963	0.018122	0.081670	0.009121	0.066017
Positive ideal	0.023074	0.080094	0.027544	0.055622	0.063332	0.046365	0.051011	0.038963	0.021142	0.142923	0.009121	0.075449
Negative ideal	0.010255	0.044497	0.010329	0.018541	0.035184	0.010303	0.017004	0.012988	0.015102	0.040835	0.001303	0.018862

Separation from positive Ideal solution

	Disaster sensing using BDA	RFID/ Barcodes	Public-Private Partnership	Smart contracts using Blockchain	Data Visibility across value chain	IOT Infrastructure	Shared platforms	Resource efficiency using cloud computing	GIS/GPS enabled Logistics	Manufacturing Flexibility	Additive Manufacturing	Cyber security
S_2	0.00016433	0.00126717	0.00001185	0.00095487	0.00079229	0.00095545	0.00051400	0.00067473	0.00000912	0.01042189	0.00006112	0.00320202
S_3	0.00000000	0.00000000	0.00010668	0.00034375	0.00000000	0.00000000	0.00003213	0.00001874	0.00000000	0.00375188	0.00000679	0.00000000
S_4	0.00000657	0.00007920	0.00029635	0.00000000	0.00019807	0.00130047	0.00000000	0.00007497	0.00000000	0.00041688	0.00004245	0.00008894
S_7	0.00002629	0.00007920	0.00000000	0.00137502	0.00019807	0.00042464	0.00080313	0.00016868	0.00003649	0.00000000	0.00000170	0.00080050
S_8	0.00000657	0.00031679	0.00001185	0.00061112	0.00004952	0.00010616	0.00115650	0.00000000	0.00000912	0.00375188	0.00000000	0.00008894

Separation from Negative Ideal solution

	Disaster sensing using BDA	RFID/ Barcodes	Public-Private Partnership	Smart contracts using Blockchain	Data Visibility across value chain	IOT Infrastructure	Shared platforms	Resource efficiency using cloud computing	GIS/GPS enabled Logistics	Manufacturing Flexibility	Additive Manufacturing	Cyber security
S_2	0.000000	0.000000	0.000190	0.000038	0.000000	0.000027	0.000129	0.000000	0.000009	0.000000	0.000000	0.000000
S_3	0.000164	0.001267	0.000047	0.000344	0.000792	0.001300	0.000803	0.000469	0.000036	0.001668	0.000027	0.003202
S_4	0.000105	0.000713	0.000000	0.001375	0.000198	0.000000	0.001157	0.000300	0.000036	0.006670	0.000002	0.002224
S_7	0.000059	0.000713	0.000296	0.000000	0.000198	0.000239	0.000032	0.000169	0.000000	0.010422	0.000042	0.000801
S_8	0.000105	0.000317	0.000190	0.000153	0.000446	0.000664	0.000000	0.000675	0.000009	0.001668	0.000061	0.002224

Appendix A4. Data set for case Illustration

		Purchase Cost (S_1,S_2, …S_5)	Ordering Cost (S_1,S_2, …S_5)	Transportation cost (S_1,S_2, …S_5)	Supplier Capacity (S_1,S_2, …S_5)
T_1	P_1	32, 32, 34, 8, 16	1550, 1050, 1050, 1450, 1100	26, 12, 10, 4, 10	4120, 1990, 2610, 2150, 2180
	P_2	28, 22, 14, 8, 8	2250, 2500, 1100, 1250, 1550	12, 26, 30, 28, 16	2390, 1960, 4450, 1560, 4080
	P_3	22, 10, 40, 36, 38	1500, 1450, 1000, 2350, 1100	28, 14, 2, 4, 4	3630, 2750, 4590, 4340, 1540
	P_4	16, 18, 10, 24, 26	2200, 1150, 2300, 2000, 1200	18, 18, 28, 16, 16	4030, 3040, 2610, 1500, 2520
	P_5	36, 40, 12, 32, 18	1400, 2350, 1250, 1600, 1900	26, 10, 16, 6, 16	2390, 2310, 1570, 1980, 4350
	P_6	24, 38, 14, 22, 26	1850, 1800, 2250, 1600, 1450	6, 20, 10, 18, 6	3920, 4160, 4430, 2910, 2370
	P_7	22, 36, 8, 40, 18	1100, 1750, 2150, 1100, 1000	6, 16, 12, 26, 16	3830, 2240, 2310, 4240, 4090
	P_8	12, 14, 12, 30, 10	1950, 1450, 1450, 1850, 2000	12, 16, 24, 12, 12	4710, 2460, 2710, 3290, 3880
	P_9	18, 16, 40, 40, 36	1900, 1850, 2350, 2350, 2300	2, 24, 18, 20, 24	2910, 4730, 2460, 2770, 2270
	P_{10}	8, 8, 40, 10, 22	2000, 2400, 1650, 1200, 1400	30, 30, 6, 2, 4	3060, 3730, 1980, 4940, 3580
T_2	P_1	18, 14, 12, 34, 12	2450, 2050, 1700, 1950, 1400	20, 22, 22, 2, 20	2520, 2600, 2620, 4430, 4970
	P_2	28, 10, 28, 28, 38	2300, 1850, 1100, 2350, 2150	30, 12, 16, 14, 24	2680, 3920, 3000, 1810, 1860
	P_3	8, 30, 18, 18, 32	2500, 2100, 1200, 1050, 2100	22, 6, 16, 16, 6	3710, 3860, 4390, 3240, 4710
	P_4	32, 40, 16, 26, 8	1100, 1450, 1700, 1450, 1500	8, 2, 14, 26, 10	3910, 2580, 1820, 2190, 4360
	P_5	26, 10, 32, 30, 22	1000, 2100, 1650, 1500, 2200	2, 26, 2, 28, 4	2170, 4420, 2800, 2280, 3170
	P_6	24, 18, 22, 32, 36	1950, 2250, 1750, 1650, 2150	4, 22, 4, 24, 20	4400, 2590, 1750, 4580, 2730
	P_7	34, 8, 26, 26, 12	1500, 1950, 1500, 2200, 1100	6, 22, 26, 24, 26	3050, 3340, 2240, 2970, 2430
	P_8	16, 8, 16, 30, 12	1750, 1150, 1100, 1500, 1950	12, 10, 22, 12, 30	2830, 2140, 4720, 3760, 2060
	P_9	16, 12, 12, 36, 8	2200, 2050, 1850, 1950, 1150	14, 28, 24, 8, 22	3380, 1670, 3920, 2580, 1750
	P_{10}	28, 24, 38, 28, 28	1100, 2450, 1200, 1750, 1300	22, 14, 24, 26, 28	3680, 4340, 4060, 1630, 4010
T_3	P_1	22, 28, 20, 30, 32	2300, 1800, 2400, 2450, 1650	30, 4, 2, 12, 22	4990, 4660, 2490, 2170, 1610
	P_2	24, 38, 10, 18, 18	1900, 2250, 1300, 1150, 2000	16, 16, 30, 2, 18	4040, 4170, 2030, 3010, 3000
	P_3	14, 36, 36, 8, 18	2000, 2450, 2300, 2500, 1900	14, 26, 28, 8, 8	4280, 1790, 4950, 4760, 3010
	P_4	18, 16, 32, 10, 10	2100, 1450, 2100, 2350, 1700	28, 12, 22, 28, 30	2330, 3060, 3010, 4070, 1580
	P_5	40, 22, 18, 36, 40	1700, 2250, 1100, 1200, 1300	24, 26, 4, 18, 24	4140, 2520, 4150, 4870, 2830
	P_6	14, 24, 24, 32, 24	1600, 2100, 1700, 1300, 2250	16, 8, 30, 16, 4	4310, 2680, 4080, 3470, 4860
	P_7	18, 10, 28, 14, 34	1950, 1250, 2400, 2200, 1550	30, 12, 16, 2, 20	4800, 3710, 3260, 2090, 2600
	P_8	16, 32, 32, 30, 20	2100, 1350, 1550, 1750, 1400	14, 2, 6, 2, 6	4910, 3910, 3310, 2580, 1780
	P_9	36, 10, 8, 34, 36	2150, 1050, 2400, 1300, 1500	22, 16, 30, 22, 4	2160, 2170, 4690, 3330, 3880
	P_{10}	36, 40, 24, 28, 34	1550, 2050, 2300, 1350, 1650	22, 22, 8, 14, 28	1660, 3060, 4230, 1780, 2580
T_4	P_1	26, 10, 18, 34, 18	1250, 2000, 1950, 1700, 2300	14, 2, 2, 22, 4	2140, 2520, 3400, 2850, 4500
	P_2	12, 18, 40, 40, 24	1000, 1450, 2300, 1500, 1550	6, 26, 4, 22, 20	4370, 2680, 4510, 3360, 2360
	P_3	36, 12, 8, 38, 32	1550, 2200, 2200, 1100, 2050	10, 2, 26, 16, 18	1580, 3710, 3290, 2360, 4230
	P_4	14, 34, 28, 32, 10	2250, 1100, 1650, 1000, 2300	20, 4, 4, 12, 2	2240, 3910, 3250, 4370, 2860
	P_5	34, 20, 16, 40, 12	1400, 1700, 2400, 2250, 1650	14, 26, 24, 10, 18	3110, 2170, 2920, 2400, 3760
	P_6	8, 34, 32, 34, 10	1350, 2350, 1200, 1950, 1450	8, 28, 24, 2, 8	3800, 1820, 4690, 3780, 3190
	P_7	32, 26, 24, 12, 34	2500, 2150, 1000, 2500, 2150	12, 20, 22, 2, 14	3070, 2800, 4750, 3740, 2600
	P_8	36, 10, 28, 34, 40	1450, 1600, 1150, 1150, 2150	24, 6, 2, 2, 30	3720, 1750, 3250, 3350, 3920
	P_9	36, 26, 8, 40, 30	1300, 2250, 1950, 2150, 1050	16, 4, 8, 4, 28	2960, 2240, 3080, 2580, 3860
	P_{10}	18, 20, 16, 34, 32	1050, 2050, 2300, 2350, 1700	8, 18, 28, 12, 2	3210, 4720, 2700, 3380, 2580
T_5	P_1	16, 16, 14, 40, 10	1300, 2100, 2150, 1000, 1650	18, 28, 30, 22, 26	2470, 3920, 2730, 4630, 4420
	P_2	30, 24, 16, 10, 26	1950, 2200, 1950, 1950, 1300	2, 2, 20, 10, 6	2920, 4060, 2720, 4320, 2590
	P_3	20, 38, 16, 22, 32	2500, 2150, 1300, 1650, 1050	4, 20, 10, 16, 6	4910, 2490, 4130, 1530, 3340
	P_4	8, 30, 14, 26, 24	2300, 1350, 1000, 2000, 2500	18, 24, 24, 24, 8	4260, 2030, 3910, 4790, 2140
	P_5	36, 20, 10, 18, 28	2150, 1150, 1400, 2150, 2150	16, 24, 20, 22, 20	1980, 4950, 2340, 4250, 1670
	P_6	36, 38, 38, 28, 14	1000, 2200, 1950, 1400, 1900	30, 28, 28, 24, 22	1910, 3010, 2530, 2600, 4340
	P_7	34, 10, 12, 16, 40	1100, 1850, 2250, 1400, 1400	26, 8, 16, 14, 18	4150, 4150, 3620, 2630, 4660
	P_8	34, 26, 40, 18, 26	2500, 2050, 1250, 2350, 1600	22, 26, 20, 20, 10	4860, 4080, 2010, 1570, 4170
	P_9	36, 22, 38, 8, 38	1200, 2400, 1100, 1500, 1100	22, 2, 6, 28, 16	1630, 3260, 4520, 2040, 1790
	P_{10}	38, 28, 36, 22, 16	2300, 1550, 1650, 1050, 1300	12, 10, 24, 22, 18	2170, 3310, 4060, 2190, 1940
T_6	P_1	8, 12, 10, 8, 38	2000, 1950, 1250, 1300, 1450	28, 12, 12, 20, 2	1740, 4690, 2470, 3350, 3120
	P_2	26, 20, 30, 8, 28	2100, 1150, 1050, 2350, 2300	4, 26, 10, 26, 8	2970, 1580, 2100, 2960, 3870
	P_3	36, 32, 20, 24, 24	1850, 1550, 2050, 1900, 1300	24, 10, 2, 12, 8	4910, 2240, 3760, 1780, 4000
	P_4	18, 34, 22, 30, 14	1250, 1700, 1750, 2050, 1750	2, 10, 14, 30, 28	3760, 3110, 2940, 1610, 2950
	P_5	38, 26, 36, 34, 24	1300, 1500, 1500, 1450, 1900	16, 14, 6, 20, 22	1980, 3800, 3120, 3430, 2180
	P_6	18, 14, 40, 28, 18	1200, 2400, 1750, 2450, 1600	18, 12, 24, 14, 16	4370, 3070, 4480, 3730, 3960
	P_7	22, 28, 30, 20, 40	1300, 1650, 1650, 2150, 1650	30, 10, 6, 26, 6	4880, 3720, 1700, 1980, 3950
	P_8	32, 16, 32, 30, 12	2050, 1150, 1300, 1550, 2350	16, 28, 26, 8, 24	1900, 2960, 4020, 3890, 2940
	P_9	18, 14, 36, 28, 36	1400, 1750, 2300, 1950, 2300	20, 30, 8, 20, 6	3180, 3210, 2250, 3500, 2890
	P_{10}	36, 18, 28, 40, 12	1900, 1700, 2400, 2350, 1000	18, 6, 22, 24, 10	4310, 2470, 4590, 2720, 1670
	Stochastic Demand (mean) (*P_1, P_2..P_{10}*)			Stochastic Demand (Deviation) (*P_1, P_2..P_{10}*)	
T_1	2400, 2500, 2100, 800, 2500, 2100, 1300, 2800, 900, 1600			110, 115, 70, 165, 180, 75, 95, 90, 195, 60	
T_2	600, 2800, 2600, 1300, 2800, 2600, 2700, 2600, 1900, 1600			180, 75, 75, 150, 120, 90, 175, 165, 95, 120	
T_3	2900, 1100, 1800, 3000, 800, 1100, 600, 1700, 2400, 2400			155, 140, 155, 160, 185, 80, 80, 70, 150, 50	
T_4	1500, 800, 1200, 2400, 1400, 2600, 2800, 1600, 2900, 600			105, 130, 190, 130, 135, 65, 60, 70, 80, 185	
T_5	1200, 1600, 3000, 1100, 1400, 1500, 900, 900, 800, 1800			65, 80, 80, 70, 65, 200, 195, 65, 100, 50	
T_6	2700, 2500, 700, 2400, 1700, 1200, 700, 1700, 2100, 900			200, 80, 110, 185, 130, 185, 160, 60, 150, 50	
	Holding cost (*P_1, P_2..P_{10}*)			Penalty cost (*P_1, P_2..P_{10}*)	
T_1	2, 5, 2, 5, 6, 4, 5, 7, 5, 3			160, 170, 160, 200, 160, 180, 170, 170, 150, 160	
T_2	2, 5, 2, 5, 6, 4, 5, 7, 5, 3			180, 180, 170, 190, 100, 180, 100, 180, 160, 190	
T_3	2, 5, 2, 5, 6, 4, 5, 7, 5, 3			160, 190, 120, 110, 170, 140, 100, 100, 150, 110	
T_4	2, 5, 2, 5, 6, 4, 5, 7, 5, 3			160, 120, 140, 130, 130, 110, 200, 100, 170, 140	
T_5	2, 5, 2, 5, 6, 4, 5, 7, 5, 3			190, 190, 190, 100, 150, 120, 180, 120, 180, 160	
T_6	2, 5, 2, 5, 6, 4, 5, 7, 5, 3			170, 200, 140, 180, 110, 160, 170, 110, 180, 100	

Appendix A5. Emergency supplier selection and order allocation during disaster caused demand fluctuations (Disruption scenario I)

		T1	T2	T3	T4	T5	T6
P1	Demand during disaster	2581	1079	3338	1856	1490	3212
	Regular order	2581	1561	2490	4000	0	2009
	Emergency order	0	0	366	549	0	0
	Supplier selection	X (1, 1, 3) = 2581 X (2, 1, 5) = 1561,X (3, 1, 3) = 2490 **E(3, 1, 3)=366**,X (4, 1, 2) = 4000 **E(4, 1, 2)=549**,X (6, 1, 3) = 2009					
P2	Demand during disaster	2689	3106	1513	1197	1914	2814
	Regular order	3042	2570	2388	0	4320	0
	Emergency order	0	505	0	0	408	0
	Supplier selection	X (1, 2, 5) = 3042 X (2, 2, 2) = 2570 **E(2, 2, 2)=505**,X (3, 2, 4) = 2388 X (5, 2, 4) = 4320 **E(5, 2, 2)=408**					
P3	Demand during disaster	2215	2906	2238	1695	3314	1064
	Regular order	2750	2188	4760	1580	360	881
	Emergency order	183	0	0	316	414	0
	Supplier selection	X (1, 3, 2) = 2750 **E(1, 3, 2)=183** X (2, 3, 4) = 2188 X (3, 3, 4) = 4760 X (4, 3, 2) = 1580 **E(4, 3, 2)=316,** X (5, 3, 3) = 360 **E(5, 3, 3)=414**, X (6, 3, 3) = 881					
P4	Demand during disaster	1071	1730	3446	2797	1398	2887
	Regular order	1071	4360	450	2860	969	2704
	Emergency order	0	366	0	549	0	0
	Supplier selection	X (1, 4, 2) = 1071 X (2, 4, 5) = 4360 **E(2, 4, 5)=366**,X (3, 4, 2) = 450 X (4, 4, 5) = 2860 **E(4, 4, 5)=549,**X (5, 4, 5) = 969 X (6, 4, 3) = 2704					
P5	Demand during disaster	2796	3180	1287	1805	1690	2097
	Regular order	2796	2997	3807	0	2340	0
	Emergency order	0	183	264	0	468	0
	Supplier selection	X (1, 5, 5) = 2796 X (2, 5, 5) = 2997 **E(2, 5, 5)=183**,X (3, 5, 3) = 3807 **E(3, 5, 3)=264**,X (5, 5, 3) = 2340 **E(5, 5, 3)=468**					
P6	Demand during disaster	2223	2931	1414	2890	2012	1687
	Regular order	3221	1750	2578	3190	0	1504
	Emergency order	0	276	0	638	0	0
	Supplier selection	X (1, 6, 3) = 3221 X (2, 6, 3) = 1750 E (2, 6, 3) = 276,X (3, 6, 5) = 2578 X (4, 6, 5) = 3190 **E(4, 6, 5)=638,**X (6, 6, 2) = 1504					
P7	Demand during disaster	1456	3171	914	3082	1404	1146
	Regular order	2310	2134	732	2899	2184	0
	Emergency order	183	0	365	0	366	0
	Supplier selection	X (1, 7, 3) = 2310 E (1, 7, 3) = 183X (2, 7, 2) = 2134 X (3, 7, 4) = 732 E (3, 7, 2) = 365,X (4, 7, 4) = 2899 X (5, 7, 2) = 2184 E (5, 7, 2) = 366					
P8	Demand during disaster	2948	3054	1998	1898	1190	1982
	Regular order	2984	4650	0	4280	0	241
	Emergency order	0	366	0	549	0	0
	Supplier selection	X (1, 8, 5) = 2984 X (2, 8, 2) = 4650 **E(2, 8, 2)=366**,X (4, 8, 2) = 4280 **E(4, 8, 2)=549**,X (6, 8, 4) = 241					
P9	Demand during disaster	1221	2239	2830	3214	1147	2530
	Regular order	1527	1750	4300	3080	1610	0
	Emergency order	0	183	0	616	115	0
	Supplier selection	X (1, 9, 2) = 1527 X (2, 9, 5) = 1750 E (2, 9, 5) = 183,X (3, 9, 2) = 4300 X (4, 9, 3) = 3080 **E(4, 9, 3)=616,** X (5, 9, 2) = 1610, **E(5, 9, 2)=115**					
P10	Demand during disaster	1699	1980	2665	1087	2065	1165
	Regular order	4940	0	1942	0	1882	982
	Emergency order	0	0	0	732	0	183
	Supplier selection	X (1, 10, 4) = 4940 X (3, 10, 3) = 1942 E (4, 10, 5) = 732,X (5, 10, 5) = 1882 X (6, 10, 5) = 982, **E(6, 10, 5)=183**					

Appendix A6. Emergency supplier selection and order allocation to manage disaster caused capacity disruptions (Disruption Scenario II)

		T1	T2	T3	T4	T5	T6
P1	Demand	2581	896	3155	1673	1307	3029
	Regular order	2581	1561	2490	4000	0	2009
	reduced quantity after disruption	2581	1561	2490	0	0	2009
	Emergency orders	0	0	0	3045	0	955
	Supplier selection	X (1, 1, 3) = 2581,X (2, 1, 5) = 1561,X (3, 1, 3) = 2490,X (6, 1, 3) = 2009 E (4, 1, 3) = 3045 E (6, 1, 3) = 955					
P2	Demand	2689	2923	1330	1014	1732	2632
	Regular order	3042	2570	2388	0	4320	0
	reduced quantity after disruption	3042	0	2388	0	4320	0
	Emergency orders	1854	716	0	0	0	0
	Supplier selection	X (1, 2, 5) = 3042,X (3, 2, 4) = 2388,X (5, 2, 4) = 4320, E (1, 2, 5) = 1854 E (2, 2, 3) = 716					
P3	Demand	2215	2723	2055	1513	3132	881
	Regular order	2750	2188	4760	1580	360	881
	Reduced quantity after disruption	2750	2188	4760	0	360	881
	Emergency orders	0	0	0	0	1580	0
	Supplier selection	X (1, 3, 2) = 2750, X (2, 3, 4) = 2188,X (3, 3, 4) = 4760,X (5, 3, 3) = 360,X (6, 3, 3) = 881, E (5, 3, 3) = 1580					
P4	Demand	1071	1547	3263	2614	1215	2704
	Regular order	1071	4360	450	2860	969	2704
	Reduced quantity after disruption	1071	4360	0	2860	969	2704
	Emergency orders	0	450	0	0	0	0
	Supplier Selection	X (1, 4, 2) = 1071X (2, 4, 5) = 4360, X (4, 4, 5) = 2860, X (5, 4, 5) = 969, X (6, 4, 3) = 2704, E (2, 4, 5) = 450					
P5	Demand	2796	2997	1104	1622	1507	1914
	Regular order	2796	2997	3807	0	2340	0
	reduced quantity after disruption	2796	2997	3807	0	2340	0
	Emergency orders	0	0	0	0	0	0
	Supplier Selection	X (1, 5, 5) = 2796, X (2, 5, 5) = 2997,X (3, 5, 3) = 3807,X (5, 5, 3) = 2340					
P6	Demand	2223	2748	1232	2707	1829	1504

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(*continued*)

		T1	T2	T3	T4	T5	T6
	Regular order	3221	1750	2578	3190	0	1504
	reduced quantity after disruption	3221	1750	2578	3190	0	0
	Emergency orders	0	0	0	638	0	866
	Supplier Selection	X (1, 6, 3) = 3221, X (2, 6, 3) = 1750,X (3, 6, 5) = 2578,X (4, 6, 5) = 3190, E (4, 6, 5) = 638, E (6, 6, 5) = 866					
P7	Demand	1456	2988	732	2899	1221	963
	Regular order	2310	2134	732	2899	2184	0
	reduced quantity after disruption	2310	0	732	2899	0	0
	Emergency orders	462	1672	0	0	2184	0
	Supplier Selection	X (1, 7, 3) = 2310, X (3, 7, 4) = 732,X (4, 7, 4) = 2899 E (1, 7, 3) = 462 E (2, 7, 5) = 1672, E (5, 7, 3) = 2184					
P8	Demand	2948	2871	1815	1715	1007	1799
	Regular order	2984	4650	0	4280	0	241
	reduced quantity after disruption	2984	0	0	0	0	241
	Emergency orders	1672	1163	1815	2722	0	1558
	Supplier Selection	X (1, 8, 5) = 2984, E (4, 8, 3) = 2722, X (6, 8, 4) = 241, E (1, 8, 5) = 1672 E (2, 8, 3) = 1163 E (3, 8, 5) = 1815, E (6, 8, 5) = 1558					
P9	Demand	1221	2056	2647	3032	964	2347
	Regular order	1527	1750	4300	3080	1610	0
	reduced quantity after disruption	1527	1750	0	3080	0	0
	Emergency orders	0	0	2647	616	300	2347
	Supplier Selection	X (1, 9, 2) = 1527, X (2, 9, 5) = 1750, X (4, 9, 3) = 3080, E (3, 9, 3) = 2647, E (4, 9, 3) = 616, E (5, 9, 3) = 300,E (6, 9, 5) = 2347					
P10	Demand	1699	1797	2482	904	1882	982
	Regular order	4940	0	1942	0	1882	982
	reduced quantity after disruption	4940	0	1942	0	1882	982
	Emergency orders	0	0	0	0	0	0
	Supplier Selection	X (1, 10, 4) = 4940X (3, 10, 3) = 1942,X (5, 10, 5) = 1882,X (6, 10, 5) = 982					

Appendix A7. Emergency supplier selection and order allocation to manage disaster caused demand fluctuations and capacity disruptions (Disruption Scenario III)

		T1	T2	T3	T4	T5	T6
P1	Demand	2581	896	3155	1673	1307	3029
	Demand during disasters	2581	1079	3338	1856	1490	3212
	Regular order	2581	1561	2490	4000	0	2009
	reduced quantity after disruption	2581	1561	2490	0	0	2009
	Emergency orders	0	0	366	3594	0	955
	Supplier Selection	X (1, 1, 3) = 2581 X (2, 1, 5) = 1561X (3, 1, 3) = 2490 E (3, 1, 3) = 366, X (6, 1, 3) = 2009, E (4, 1, 3) = 3594 E (6, 1, 3) = 955					
P2	Demand	2689	2923	1330	1014	1732	2632
	Demand during disasters	2689	3106	1513	1197	1914	2814
	Regular order	3042	2570	2388	0	4320	0
	reduced quantity after disruption	3042	0	2388	0	4320	0
	Emergency orders	1854	899	322	0	408	0
	Supplier Selection	X (1, 2, 5) = 3042 X (3, 2, 4) = 2388 X (5, 2, 4) = 4320 E (1, 2, 5) = 1854, E (2, 2, 3) = 899, E (3, 2, 5) = 322 E (5, 2, 5) = 408					
P3	Demand	2215	2723	2055	1513	3132	881
	Demand during disasters	2215	2906	2238	1695	3314	1064
	Regular order	2750	2188	4760	1580	360	881
	reduced quantity after disruption	2750	2188	4760	0	360	881
	Emergency orders	183	0	0	0	2310	0
	Supplier Selection	X (1, 3, 2) = 2750, X (2, 3, 4) = 2188 X (3, 3, 4) = 4760,X (5, 3, 3) = 360,X (6, 3, 3) = 881,E (1, 3, 2) = 183,E (5, 3, 3) = 2310					
P4	Demand	1071	1547	3263	2614	1215	2704
	Demand during disasters	1071	1730	3446	2797	1398	2887
	Regular order	1071	4360	450	2860	969	2704
	reduced quantity after disruption	1071	4360	0	2860	969	2704
	Emergency orders	0	816	0	549	0	0
	Supplier Selection	X (1, 4, 2) = 1071,X (2, 4, 5) = 4360,X (4, 4, 5) = 2860,X (5, 4, 5) = 969,X (6, 4, 3) = 2704,E (2, 4, 5) = 816,E (4, 4, 5) = 549					
P5	Demand	2796	2997	1104	1622	1507	1914
	Demand during disasters	2796	3180	1287	1805	1690	2097
	Regular order	2796	2997	3807	0	2340	0
	reduced quantity after disruption	2796	2997	3807	0	2340	0
	Emergency orders	0	183	264	0	468	0
	Supplier Selection	X (1, 5, 5) = 2796, X (2, 5, 5) = 2997,X (3, 5, 3) = 3807,X (5, 5, 3) = 2340,E (2, 5, 5) = 183,E (3, 5, 3) = 264,E (5, 5, 3) = 468					
P6	Demand	2223	2748	1232	2707	1829	1504
	Demand during disasters	2223	2931	1414	2890	2012	1687
	Regular order	3221	1750	2578	3190	0	1504
	reduced quantity after disruption	3221	1750	2578	3190	0	0
	Emergency orders	0	183	0	638	0	1597
	Supplier Selection	X (1, 6, 3) = 3221X (2, 6, 3) = 1750,X (3, 6, 5) = 2578,X (4, 6, 5) = 3190,E (2, 6, 3) = 183,E (4, 6, 5) = 638,E (6, 6, 5) = 1597					
P7	Demand	1456	2988	732	2899	1221	963
	Demand during disasters	1456	3171	914	3082	1404	1146
	Regular order	2310	2134	732	2899	2184	0
	reduced quantity after disruption	2310	0	732	2899	0	0
	Emergency orders	462	2220	0	0	2550	0
	Supplier Selection	X (1, 7, 3) = 2310, X (3, 7, 4) = 732,X (4, 7, 4) = 2899,E (1, 7, 3) = 462,E (2, 7, 5) = 2220,E (5, 7, 3) = 2550					
P8	Demand	2948	2871	1815	1715	1007	1799
	Demand during disasters	2948	3054	1998	1898	1190	1982

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		T1	T2	T3	T4	T5	T6
	Regular order	2984	4650	0	4280	0	241
	reduced quantity after disruption	2984	0	0	0	0	241
	Emergency orders	1672	1346	1998	3088	0	1741
	Supplier Selection	X (1, 8, 5) = 2984, X (6, 8, 4) = 241, E (1, 8, 5) = 1672, E (2, 8, 3) = 1346, E (3, 8, 5) = 1998,E (4, 8, 3) = 3088,E (6, 8, 5) = 1741					
P9	Demand	1221	2056	2647	3032	964	2347
	Demand during disasters	1221	2239	2830	3214	1147	2530
	Regular order	1527	1750	4300	3080	1610	0
	reduced quantity after disruption	1527	1750	0	3080	0	0
	Emergency orders	0	350	2663	616	665	2530
	Supplier Selection	X (1, 9, 2) = 1527 X (2, 9, 5) = 1750X (4, 9, 3) = 3080, E (2, 9, 5) = 350,E (3, 9, 3) = 2663,E (4, 9, 3) = 616,E (5, 9, 3) = 665,E (6, 9, 5) = 2530					
P10	Demand	1699	1797	2482	904	1882	982
	Demand during disasters	1699	1980	2665	1087	2065	1165
	Regular order	4940	0	1942	0	1882	982
	reduced order quantity after disruption	4940	0	1942	0	1882	982
	Emergency orders	0	0	0	732	0	183
	Supplier Selection	X (1, 10, 4) = 4940,X (3, 10, 3) = 1942,X (5, 10, 5) = 1882,X (6, 10, 5) = 982,E (4, 10, 5) = 732,E (6, 10, 5) = 183					

Appendix A8. Emergency supplier selection and order allocation to manage disaster caused demand fluctuations and capacity disruptions (Disruption Scenario IV)

		T1	T2	T3	T4	T5	T6
P1	Regular Demand	2581	896	3155	1673	1307	3029
	Demand during disaster	2581	1128	3387	1905	1539	3261
	Regular orders	2581	1561	2490	4000	0	2009
	Reduced orders after disruptions	2581	1561	2490	0	0	2009
	Emergency orders	0	0	464	3741	0	955
	Supplier Selection	X (1, 1, 3) = 2581,X (2, 1, 5) = 1561,X (3, 1, 3) = 2490,X (6, 1, 3) = 2009,E (3, 1, 3) = 464,E (4, 1, 3) = 3741,E (6, 1, 3) = 955					
P2	Regular Demand	2689	2923	1330	1014	1732	2632
	Demand during disaster	2689	3156	1563	1246	1964	2864
	Regular orders	3042	2570	2388	0	4320	0
	Reduced orders after disruptions	3042	0	0	0	0	0
	Emergency orders	1854	949	2809	0	1964	2864
	Supplier Selection	X (1, 2, 5) = 3042, E (1, 2, 5) = 1854,E (2, 2, 3) = 949,E (3, 2, 5) = 2809,E (5, 2, 5) = 1964,E (6, 2, 5) = 2864					
P3	Regular Demand	2215	2723	2055	1513	3132	881
	Demand during disaster	2215	2956	2287	1745	3364	1113
	Regular orders	2750	2188	4760	1580	360	881
	Reduced orders after disruptions	2750	0	0	0	360	881
	Emergency orders	0	2841	3612	0	3236	0
	Supplier Selection	X (1, 3, 2) = 2750, X (5, 3, 3) = 360, X (6, 3, 3) = 881, E (2, 3, 3) = 2841, E (3, 3, 5) = 3612, E (5, 3, 3) = 3236					
P4	Regular Demand	1071	1547	3263	2614	1215	2704
	Demand during disaster	1071	1779	3495	2846	1447	2937
	Regular orders	1071	4360	450	2860	969	2704
	Reduced orders after disruptions	1071	4360	0	2860	969	2704
	Emergency orders	0	872	42	572	0	125
	Supplier Selection	X (1, 4, 2) = 1071, X (2, 4, 5) = 4360,X (4, 4, 5) = 2860,X (5, 4, 5) = 969,X (6, 4, 3) = 2704,E (2, 4, 5) = 872,E (3, 4, 5) = 42, E (4, 4, 5) = 572, E (6, 4, 3) = 125					
P5	Regular Demand	2796	2997	1104	1622	1507	1914
	Demand during disaster	2796	3230	1337	1854	1739	2146
	Regular orders	2796	2997	3807	0	2340	0
	Reduced orders after disruptions	2796	2997	3807	0	2340	0
	Emergency orders	0	233	461	0	468	0
	Supplier Selection	X (1, 5, 5) = 2796, X (2, 5, 5) = 2997, X (3, 5, 3) = 3807, X (5, 5, 3) = 2340, E (2, 5, 5) = 233, E (5, 5, 3) = 468					
P6	Regular Demand	2223	2748	1232	2707	1829	1504
	Demand during disaster	2223	2980	1464	2939	2061	1737
	Regular orders	3221	1750	2578	3190	0	1504
	Reduced orders after disruptions	3221	1750	2578	3190	0	0
	Emergency orders	0	290	0	638	0	1737
	Supplier Selection	X (1,6,3) = 3221, X (2, 6, 3) = 1750, X (3, 6, 5) = 2578, E (3, 5, 3) = 461, E (2, 6, 3) = 290, X (4, 6, 5) = 3190, E (4, 6, 5) = 638, E (6, 6, 5) = 1737					
P7	Regular Demand	1456	2988	732	2899	1221	963
	Demand during disaster	1456	3220	964	3131	1453	1195
	Regular orders	2310	2134	732	2899	2184	0
	Reduced orders after disruptions	2310	0	0	0	0	0
	Emergency orders	462	2868	0	3131	2648	0
	Supplier Selection	X (1, 7, 3) = 2310, E (1, 7, 3) = 462, E (2, 7, 5) = 2868, E (4, 7, 3) = 3131, E (5, 7, 3) = 2648					
P8	Regular Demand	2948	2871	1815	1715	1007	1799
	Demand during disaster	2948	3104	2047	1947	1239	2031
	Regular orders	2984	4650	0	4280	0	241
	Reduced orders after disruptions	2984	0	0	0	0	0
	Emergency orders	1672	1396	2047	3186	0	2031
	Supplier Selection	X (1, 8, 5) = 2984, E (1, 8, 5) = 1672, E (2, 8, 3) = 1396,E (3, 8, 5) = 2047, E (4, 8, 3) = 3186, E (6, 8, 5) = 2031					
P9	Regular Demand	1221	2056	2647	3032	964	2347

(*continued on next page*)

(*continued*)

		T1	T2	T3	T4	T5	T6
	Demand during disaster	1221	2289	2879	3264	1197	2579
	Regular orders	1527	1750	4300	3080	1610	0
	Reduced orders after disruptions	1527	1750	0	3080	0	0
	Emergency orders	0	350	2762	616	765	2579
	Supplier Selection	X (1, 9, 2) = 1527, X (2, 9, 5) = 1750, X (4, 9, 3) = 3080, E (2, 9, 5) = 350, E (3, 9, 3) = 2762, E (4, 9, 3) = 616, E (5, 9, 3) = 765, E (6, 9, 5) = 2579					
P10	Regular Demand	1699	1797	2482	904	1882	982
	Demand during disaster	1699	2030	2714	1137	2114	1214
	Regular orders	4940	0	1942	0	1882	982
	Reduced orders after disruptions	4940	0	1942	0	1882	982
	Emergency orders	0	0	0	930	0	232
	Supplier Selection	X (1, 10, 4) = 4940, X (3, 10, 3) = 1942, X (5, 10, 5) = 1882, X (6, 10, 5) = 982, E (4, 10, 5) = 930, E (6, 10, 5) = 232, E (6, 10, 5) = 232					

Credit author statement

Harpreet Kaur developed the proposed model as well as the numerical case. She solved the proposed OR based model in LINGO and prepared the revised paper considering the reviewers comments. She also drafted the paper. Surya Prakash Singh provided the initial research idea of the proposed work using Multi-criteria decision making tools for supplier selection and order allocation under disruption and risk. He also assisted on improving the paper based on reviewer's comments.

Overall, the paper was discussed and prepared by these above two authors where several round of discussion happened over phone.

References

Altay, N., Gunasekaran, A., Dubey, R., Childe, S.J., 2018. Agility and resilience as antecedents of supply chain performance under moderating effects of organizational culture within the humanitarian setting: a dynamic capability view. Prod. Plann. Contr. 29 (14), 1158–1174.

Ardito, L., Petruzzelli, A.M., Panniello, U., Garavelli, A.C., 2019. Towards industry 4.0: mapping digital technologies for supply chain management-marketing integration. Bus. Process Manag. J. 25 (2), 323–346.

Barata, J., Rupino Da Cunha, P., Stal, J., 2018. Mobile supply chain management in the industry 4.0 era: an annotated bibliography and guide for future research. J. Enterprise Inf. Manag. 31 (1), 173–192.

Barreto, L., Amaral, A., Pereira, T., 2017. Industry 4.0 implications in logistics: an overview. Procedia Manufacturing 13, 1245–1252.

Barroso, A.P., Machado, V.H., Barros, A.R., Machado, V.C., 2010. Toward a resilient supply chain with supply disturbances. In: 2010 IEEE International Conference on Industrial Engineering and Engineering Management. IEEE, pp. 245–249.

Bhutta, K.S., Huq, F., 2002. Supplier selection problem: a comparison of the total cost of ownership and analytic hierarchy process approaches. Supply Chain Manag.: Int. J. 7 (3), 126–135.

Brettel, M., Friederichsen, N., Keller, M., Rosenberg, M., 2014. How virtualization, decentralization and network building change the manufacturing landscape: an industry 4.0 perspective. International journal of mechanical, industrial science and engineering 8 (1), 37–44.

Cavalcantea, I.M., Frazzon, E.M., Forcellinia, F.A., Ivanov, D., 2019. A supervised machine learning approach to data-driven simulation of resilient supplier selection in digital manufacturing. Int. J. Inf. Manag. 49, 86–97.

Chopra, S., Sodhi, M.S., 2004. Supply-chain breakdown. MIT Sloan Manag. Rev. 46 (1), 53–61.

Colicchia, C., Dallari, F., Melacini, M., 2010. Increasing supply chain resilience in a global sourcing context. Prod. Plann. Contr. 21 (7), 680–694.

Dolgui, A., Ivanov, D., Sokolov, B., 2018. Ripple effect in the supply chain: an analysis and recent literature. Int. J. Prod. Res. 56 (1-2), 414–430.

Duarte, S., Cruz-Machado, V., 2017. An investigation of lean and green supply chain in the industry 4.0. In: Proceedings of the 2017 International Symposium on Industrial Engineering and Operations Management (IEOM).

Dubey, R., Gunasekaran, A., Childe, S.J., 2015. The design of a responsive sustainable supply chain network under uncertainty. Int. J. Adv. Manuf. Technol. 80 (1-4), 427–445.

Dubey, R., Gunasekaran, A., Childe, S.J., Fosso Wamba, S., Roubaud, D., Foropon, C., 2019. Empirical investigation of data analytics capability and organizational flexibility as complements to supply chain resilience. Int. J. Prod. Res. 1–19. https://doi.org/10.1080/00207543.2019.1582820.

Dubey, R., Gunasekaran, A., Childe, S.J., Papadopoulos, T., Blome, C., Luo, Z., 2017. Antecedents of resilient supply chains: an empirical study. IEEE Trans. Eng. Manag. (99), 1–12.

Fawcett, S.E., Wallin, C., Allred, C., Fawcett, A.M., Magnan, G.M., 2011. Information technology as an enabler of supply chain collaboration: a dynamic-capabilities perspective. J. Supply Chain Manag. 47 (1), 38–59.

Gamage, D.D., Rupasinghe, T.D., 2017. Supply chain collaboration for sustainable Industry 4.0: a case study from the apparel industry. In: International Research Symposium on Pure and Applied Sciences, 2017 Faculty of Science. University of Kelaniya, Sri Lanka.

Ghadimi, P., Wang, C., Lim, M.K., Heavey, C., 2019. Intelligent sustainable supplier selection using multi-agent technology: theory and application for industry 4.0 supply chains. Comput. Ind. Eng. 127, 588–600.

Gnimpieba, Z.D.R., Nait-Sidi-Moh, A., Durand, D., Fortin, J., 2015. Using Internet of Things technologies for a collaborative supply chain: application to tracking of pallets and containers. Procedia Computer Science 56, 550–557.

Gupta, V., He, B., Sethi, S.P., 2015. Contingent sourcing under supply disruption and competition. Int. J. Prod. Res. 53 (10), 3006–3027.

Haldar, A., Ray, A., Banerjee, D., Ghosh, S., 2012. A hybrid MCDM model for resilient supplier selection. Int. J. Manag. Sci. Eng. Manag. 7 (4), 284–292.

Haldar, A., Ray, A., Banerjee, D., Ghosh, S., 2014. Resilient supplier selection under a fuzzy environment. Int. J. Manag. Sci. Eng. Manag. 9 (2), 147–156.

Hofmann, E., Rüsch, M., 2017. Industry 4.0 and the current status as well as future prospects on logistics. Comput. Ind. 89, 23–34.

Hosseini, S., Ivanov, D., Dolgui, A., 2019a. Review of quantitative methods for supply chain resilience analysis. Transport. Res. Part E 125, 285–307.

Hosseini, S., Al Khaled, A., 2019. A hybrid ensemble and AHP approach for resilient supplier selection. J. Intell. Manuf. 30 (1), 207–228.

Hosseini, S., Barker, K., 2016. A Bayesian network model for resilience-based supplier selection. Int. J. Prod. Econ. 180, 68–87.

Hosseini, S., Ivanov, D., 2019. A new resilience measure for supply networks with the ripple effect considerations: a Bayesian network approach. Ann. Oper. Res. 1–27.

Hosseini, S., Ivanov, D., Dolgui, A., 2019c. Ripple effect modelling of supplier disruption: integrated Markov chain and dynamic Bayesian network approach. Int. J. Prod. Res. 1–20.

Hosseini, S., Morshedlou, N., Ivanov, D., Sarder, M.D., Barker, K., Al Khaled, A., 2019b. Resilient supplier selection and optimal order allocation under disruption risks. Int. J. Prod. Econ. 213, 124–137.

Hwang, C.L., Yoon, K., 1981. Methods for multiple attribute decision making. In: Multiple Attribute Decision Making. Springer, Berlin, Heidelberg, pp. 58–191.

Ivanov, D., Dolgui, A., 2018. Low-Certainty-Need (LCN) Supply Chains: a new perspective in managing disruption risks and resilience. Int. J. Prod. Res. https://doi.org/10.1080/00207543.2018.1521025.

Ivanov, D., 2018. Structural Dynamics and Resilience in Supply Chain Risk Management. Springer, New York. ISBN 978-3-319-69304-0.

Ivanov, D., Sokolov, B., 2012. Structure dynamics control approach to supply chain planning and adaptation. Int. J. Prod. Res. 50 (21), 6133–6149.

Ivanov, D., Dolgui, A., Sokolov, B. (Eds.), 2019a. Handbook of Ripple Effects in the Supply Chain. Springer, New York. ISBN 978-3-030-14301-5.

Ivanov, D., Dolgui, A., Sokolov, B., 2018. The impact of digital technology and Industry 4.0 on the ripple effect and supply chain risk analytics. Int. J. Prod. Res. 1–18.

Ivanov, D., Dolgui, A., Sokolov, B., Werner, F., Ivanova, M., 2016. A dynamic model and an algorithm for short-term supply chain scheduling in the smart factory Industry 4.0. Int. J. Prod. Res. 54 (2), 386–402.

Ivanov, D., Dolgui, A., Sokolov, B., 2019b. The impact of digital technology and industry 4.0 on the ripple effect and supply chain risk analytics. Int. J. Prod. Res. 57 (3), 829–846.

Ivanov, D., Sokolov, B., Dolgui, A., 2014. The Ripple effect in supply chains: trade-off 'efficiency-flexibility-resilience' in disruption management. Int. J. Prod. Res. 52 (7), 2154–2172.

Kamalahmadi, M., Mellat-Parast, M., 2016. Developing a resilient supply chain through supplier flexibility and reliability assessment. Int. J. Prod. Res. 54 (1), 302–321.

Khajavi, S.H., Partanen, J., Holmström, J., 2014. Additive manufacturing in the spare parts supply chain. Comput. Ind. 65 (1), 50–63.

Khalili, S.M., Jolai, F., Torabi, S.A., 2017. Integrated production–distribution planning in two-echelon systems: a resilience view. Int. J. Prod. Res. 55 (4), 1040–1064.

Kim, Y., Chen, Y.S., Linderman, K., 2015. Supply network disruption and resilience: a network structural perspective. J. Oper. Manag. 33, 43–59.

Lee, S.H., 2017. A fuzzy multi-objective programming approach for determination of resilient supply portfolio under supply failure risks. J. Purch. Supply Manag. 23 (3), 211–220.

Lovell, C.K., Pastor, J.T., 1999. Radial DEA models without inputs or without outputs. Eur. J. Oper. Res. 118 (1), 46–51.

Mohr, S., Khan, O., 2015. 3D printing and its disruptive impacts on supply chains of the future. Technology Innovation Management Review 5 (11), 20.

Müller, J.M., 2019. Business model innovation in small-and medium-sized enterprises: strategies for Industry 4.0 providers and users. J. Manuf. Technol. Manag.

Opricovic, S., Tzeng, G.H., 2004. Compromise solution by MCDM methods: a comparative analysis of VIKOR and TOPSIS. Eur. J. Oper. Res. 156 (2), 445–455.

Panetto, H., Iung, B., Ivanov, D., Weichhart, G., Wang, X., 2019. Challenges for the cyber-physical manufacturing enterprises of the future. Annu. Rev. Contr. 47, 200–213.

Parkouhi, S.V., Ghadikolaei, A.S., 2017. A resilience approach for supplier selection: using fuzzy analytic network process and grey VIKOR techniques. J. Clean. Prod. 161, 431–451.

Parkouhi, S.V., Ghadikolaei, A.S., Lajimi, H.F., 2019. Resilient supplier selection and segmentation in grey environment. J. Clean. Prod. 207, 1123–1137.

Parmar, D., Wu, T., Callarman, T., Fowler, J., Wolfe, P., 2010. A clustering algorithm for supplier base management. Int. J. Prod. Res. 48 (13), 3803–3821.

Parreño-Marchante, A., Alvarez-Melcon, A., Trebar, M., Filippin, P., 2014. Advanced traceability system in aquaculture supply chain. J. Food Eng. 122, 99–109.

Prajogo, D., Sohal, A., 2013. Supply chain professionals: a study of competencies, use of technologies, and future challenges. Int. J. Oper. Prod. Manag. 33 (11/12), 1532–1554.

Roszkowska, E., 2011. Multi-criteria decision making models by applying the TOPSIS method to crisp and interval data. Multiple Criteria Decision Making/University of Economics in Katowice 6, 200–230.

Sahebjamnia, N., Torabi, S.A., Mansouri, S.A., 2015. Integrated business continuity and disaster recovery planning: towards organizational resilience. Eur. J. Oper. Res. 242 (1), 261–273.

Sawik, T., 2013. Selection of resilient supply portfolio under disruption risks. Omega 41 (2), 259–269.

Schlüter, F., Sprenger, P., Spyridakos, A., Vryzidis, L., 2016. Migration framework for decentralized and proactive risk identification in a Steel Supply Chain via Industry 4.0 technologies. In: Conference Proceedings of the 5th International Symposium and 27th National Conference on Operational Research, pp. 85–91. Athens.

Schmitt, A.J., Singh, M., 2012. A quantitative analysis of disruption risk in a multi-echelon supply chain. Int. J. Prod. Econ. 139 (1), 22–32.

Schröder, M., Indorf, M., Kersten, W., 2014. Industry 4.0 and its impact on supply chain risk management. In: Proceedings of the 14th International Conference "Reliability and Statistics in Transportation and Communication, pp. 114–125.

Sheffi, Y., 2001. Supply chain management under the threat of international terrorism. Int. J. Logist. Manag. 12 (2), 1–11.

Sheffi, Y., 2015. Preparing for disruptions through early detection. MIT Sloan Manag. Rev. 57 (1), 31.

Sheffi, Y., Rice Jr., J.B., 2005. A supply chain view of the resilient enterprise. MIT Sloan Manag. Rev. 47 (1), 41.

Skipper, J.B., Hanna, J.B., 2009. Minimizing supply chain disruption risk through enhanced flexibility. Int. J. Phys. Distrib. Logist. Manag. 39 (5), 404–427.

Stentoft, J., Rajkumar, C., 2018. Does supply chain innovation pay off? Innovation and Supply Chain Management: Relationship, Collaboration and Strategies 237–256.

Tierney, K.J., 2007. Businesses and disasters: vulnerability, impacts, and recovery. In: Handbook of Disaster Research. Springer, New York, NY, pp. 275–296.

Tjahjono, B., Esplugues, C., Ares, E., Pelaez, G., 2017. What does industry 4.0 mean to supply chain? Procedia Manufacturing 13, 1175–1182.

Tomlin, B., 2006. On the value of mitigation and contingency strategies for managing supply chain disruption risks. Manag. Sci. 52 (5), 639–657.

Torabi, S.A., Baghersad, M., Mansouri, S.A., 2015. Resilient supplier selection and order allocation under operational and disruption risks. Transport. Res. E Logist. Transport. Rev. 79, 22–48.

Wu, T., Blackhurst, J., O'grady, P., 2007. Methodology for supply chain disruption analysis. Int. J. Prod. Res. 45 (7), 1665–1682.

Wunnava, S., 2011. Application of Protection Motivation Theory to Study the Factors that Influence Disaster Recovery Planning: an Empirical Investigation. Louisiana Tech University.

Yu, H., Zeng, A.Z., Zhao, L., 2009. Single or dual sourcing: decision-making in the presence of supply chain disruption risks. Omega 37 (4), 788–800.

Zhu, S.X., 2013. Dynamic replenishment, production, and pricing decisions, in the face of supply disruption and random price-sensitive demand. Int. J. Prod. Econ. 146 (2), 612–619.