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Evaluation of supply chain risks by fuzzy DEMATEL method: a case study of iron and steel industry in Turkey

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Abstract:

Business practices to strengthen competitiveness increase the vulnerability of supply chains to risks. Risks that can adversely affect the effectiveness and efficiency of supply chain activities are events that disrupt the flow of information, materials, money, and products. Therefore, supply chain risk management is vital for companies. It is necessary to identify the risks that threaten the supply chain and prioritize them. In addition, examining the effects of risks on each other will determine the success of supply chain risk management. This study evaluates Turkey's leading iron and steel company's supply chain risk groups and sub-risks. The fuzzy DEMATEL method was used to determine the relative importance of the risks and the effects of the risks on each other. Results show that the most critical risk group is business risks. Business risk is followed by customer risks, supplier risks, transportation risks, environmental risks, and, finally, security risks. This study provides originality by evaluating the supply chain risks from a broader perspective.

Key words:

Fuzzy DEMATEL, iron and steel industry, risk assessment, supply chain risk management.

1. Introduction

Almost every industry is exposed to increasing competitive pressure with the globalization of its business environment and markets. Companies tend to follow practices such as outsourcing, overseas manufacturing, lean manufacturing, inventory reduction, and supply chain collaboration. Although these practices strengthen companies' competitiveness, they increase the vulnerability of their supply chains to risks. In other words, companies are increasingly exposed to unexpected disruptions that affect the entire supply chain (Munir et al., 2020).

A disruption at one stage of a supply chain will affect the entire chain and negatively affect firms' different levels (Parast & Subramanian, 2021). The earthquake and the tsunami in Japan in 2011 caused an interruption in supply and demand and therefore slowed production in other countries (Tukamuhabwa et al., 2015). Recent crises such as natural disasters and epidemics have significantly interrupted supply chain activities. The COVID-19 pandemic has severely disrupted supply chains globally and locally (Pujawan & Bah, 2022). Due to the global epidemic, companies operating in different geographies but with the same supply chain have been interrupted in their production capabilities. Not only risks at

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the worldwide level, but companies may also face machine breakdowns, exchange rate fluctuation, low supplier integration, inaccurate shipment from suppliers, inaccurate shipment to customers, and order fluctuation in their daily operational processes (Dong & Cooper, 2016).

Supply chain risk management, which includes the identification, evaluation, and management of risks in supply chain processes that are critical to business performance, has become an important area in supply chain management research (Ceryno et al., 2015; Dong & Cooper, 2016; Ho et al., 2015). While previous research concentrated on supply chain risk management (Hermoso-Orzáez, & Garzón-Moreno, 2021; Ho et al., 2015; Mital et al., 2018; Zimmer et al., 2017), classification of risks (Alora & Barua, 2022; Duong et al., 2022; Kumar et al., 2020; Oke & Gopalakrishnan, 2009; Rangel et al., 2015) and assessments of risks (Ali et al., 2021; Alora & Barua, 2022; Mital et al., 2018; Zimmer et al., 2017), only a few studies (Khan et al., 2021a; Pfohl et al., 2011; Sharma & Routroy, 2016) have examined the relationships between risks. In practice, supply chain risks are generally related, but this situation is ignored in traditional risk management. It should be stressed that revealing the relationships between risks will help decision-makers determine appropriate mitigation strategies and achieve more successful risk management outcomes.

To manage various operations of an industry, there is a need to understand the links between risks (Lahane & Kant, 2021). Although the supply chain structures are generally similar, some sectoral differences exist. Therefore, it is possible to mention that not all supply chains have the same types of risks (Gurtu & Johny, 2021; Hermoso-Orzáez, & Garzón-Moreno, 2021; Srivastava & Rogers, 2021). For this reason, it would be more beneficial to focus on a particular industry to determine the causal relationships between risks more accurately. In this context, the study focuses on the supply chain risks of Turkey's iron and steel industry. The iron and steel industry is of great importance to the overall performance of the manufacturing industry in Turkey due to its high production and export potential and inputs to other sectors (Kabak et al., 2016). With this background, this study seeks answers to the following research questions:

RQ 1. What are the main risk groups in the supply chain and the sub-risks?

RQ 2. What is the relative importance of the risk groups and sub-risks?

RQ 3. What is the interrelationship between supply chain risks?

The rest of this paper is organized as follows. Section 2 discusses the main concepts of the study. The fuzzy DEMATEL method is discussed in Section 3. Section 4 introduces the results of the research. Finally, conclusions and discussions are given in Section 5.

2. Literature review

2.1. Supply chain risk management

Risk is a phenomenon that can affect the efficiency of an organization's key processes (Hopkin, 2018). A supply chain risk is damage or loss resulting from supply chain disruption. Supply chain disruption is an undesirable, abnormal triggering event that occurs somewhere in or out of the supply chain (Wagner & Bode, 2008). Ho et al. (2015) define supply chain risk as: "the probability and impact of unexpected macro and/or micro-level events that adversely affect any part of the supply chain, leading to operational, tactical or strategic level failures or irregularities."

Supply chain risk management has emerged to implement various strategies and practices to manage supply chain networks. Assessing the risks and reducing vulnerabilities (Gurtu & Johny, 2021; Oturakçı & Yıldırım, 2022; Rajesh & Ravi, 2017) will help to improve supply chain safety and performance. Finding ways to mitigate the effects of supply chain risks is critical for successfully managing supply chains in a volatile environment (Hachicha & Elmsalmi, 2014). In recent years, supply chain risk management has received more attention to overcome threats and challenges (Can Saglam et al., 2020). Generally, supply chain risk management is considered a phased process and consists of four steps: risk identification, risk assessment, risk mitigation, and risk monitoring (Ho et al., 2015). This study discusses the first two steps of supply chain risk management.

2.2. Supply chain risks identification

The first step of the supply chain risk management is identifying risk types. It is essential to understand the firm's internal and external dynamics to evaluate the potential for supply chain disruptions (Sreedevi et al., 2021; Srivastava & Rogers, 2021). At this step, managers focus on recognizing and clearly defining all risks. Thus, decision-makers become conscious of the events that cause uncertainty (Hallikas et al., 2004). Resources such as literature review, brainstorming, expert opinions, and examination of past events can be used to identify risks. In addition to qualitative methods, quantitative methods are also used to identify potential supply chain risks (Ho et al., 2015).

With the literature review and expert opinions, it is possible to talk about the existence of more than a hundred risks affecting businesses (Venkatesh et al., 2015). To provide an overview, the supply chain risk classifications that different researchers included in their studies are shown in Table 1.

In some studies, risks are classified into two basic categories: internal risks and external risks. While internal risks are related to the activities in the supply chain processes, external risks consist of macro risks outside the supply chain and not under the control of the enterprise. Some other studies classify supply chain risks into three categories: internal risks, external risks within the supply chain, and risks outside the supply chain.

Table 1. Supply chain risks.

Authors	Risk types
(Jüttner et al., 2003)	Environmental, network-related, organizational risks
(Chopra & Sodhi, 2004)	Disruptions, delays, information systems, forecast, intellectual property, procurement, receivables, inventory, and capacity risks
(Christopher & Peck, 2004)	Internal risks: process and control risk, risks outside the firm but within the supply chain network: demand and supply risks, risks outside the supply chain: environmental risks
(Manuj & Mentzer, 2008)	Supply, operational, demand, security, macro, political, competitive, and resource risks
(Wagner & Bode, 2008)	Demand-side, supply-side, legal and regulatory, infrastructure, and catastrophic risks
(Trkman & McCormack, 2009)	Endogenous (internal) risks: market and technology turbulence, Exogenous (external) risks; discrete events (e.g., terrorist attacks, contagious diseases, workers' strikes, and continuous events (e.g., inflation rate, consumer price index changes)
(Kumar et al., 2010)	Internal operational risks: demand, production and distribution, supply risks, External operational risks: terrorist attacks, natural disasters, exchange rate fluctuation
(Tummala & Schoenherr, 2011)	Demand, delay, disruption, inventory, manufacturing (process) interruption, capacity, supply, system, sovereign, and transportation risks
(Samvedi et al., 2013)	Supply, process, demand, and environmental risks
(Punniyamoorthy et al., 2013)	Supply, manufacturing, demand, logistics, and environmental risks
(Ho et al., 2015)	Macro risks, Micro risks: demand, manufacturing, supply, and infrastructure risks (information systems, transportation, and financial risks)
(Rangel et al., 2015)	Planning: strategic, inertia, informational, capacity, and demand risks, Source: supply, financial and relational risks, Make: operational and disruption risks, Delivery: customer risk, Returns: legal risk, Other: environmental and cultural risks
(Prakash et al., 2017)	Supply, demand, control, process, and environmental risks
(Shahbaz et al., 2019)	Supply, process, demand, logistics, collaboration, financial, and environmental risks
(Chu et al., 2020)	Political, environmental, financial, supply and demand, logistics, system, and operational risks
(Ali et al., 2021)	Natural, human-made, system accidents, and financial
(Hermoso-Orzáez, & Garzón-Moreno, 2021)	Operational, direct process to the product/service, suppliers, security, and labor rights
(Lahane & Kant, 2021)	Operational and technological risks, product recovery risks, supply risks, demand risks, environmental risks, economic risks, social risks
(Parast & Subramanian, 2021)	Supply risks, demand risks, process risks, and environmental risks
(Srivastava & Rogers, 2021)	Operational, infrastructure, legal, economic, supplier, forecasting, transportation, and labor
(Duong et al., 2022)	External risk, time risk, supply risk, operational risk, and demand risk
(Oturakçı & Yıldırım, 2022)	Supply, manufacturing, demand, financial, macro, transportation, and information risks

When the research on supply chain risks is reviewed, it has been observed that there is no universal classification. Classifications differ by industry or scope. As the content of this research is enormous, the number of risks was kept as wide as possible. Accordingly, environmental, safety, customer, supplier, transportation, and business risk groups were used in this article.

2.3. Supply chain risks assessment

Risk assessment is the second step of supply chain risk management. It is a critical step as the risk assessment affects the managerial decisions such as risk prioritization and resource allocation to mitigate risks (Sodhi & Tang, 2012; Hallikas et al., 2004). There is a need to assess and prioritize risks to identify appropriate management actions for the risks at the focal business and supply chain levels. Since it will not be possible to take measures at the same level for all supply chain risks, it is necessary to determine each risk's impact and rank them. Due to the reasons like budget, resources, time, labor constraints, etc., it is not possible to attach the same importance to all risks. Hence, it is a need to handle the risks with a proper approach (Oturakçı & Yıldırım, 2022). Ranking the risks helps managers focus on the risks that need immediate attention and choose the appropriate mitigation strategies. Various methods used in risk assessment are shown in Table 2.

A literature review for this study showed that the DEMATEL method is employed in some risk studies. However, to our best knowledge, there is no study using the DEMATEL to assess supply chain risks in the iron and steel industry. The DEMATEL method is accepted as one of the best tools for evaluating the importance and causal relationships among evaluation criteria (Hsu et al., 2013).

Table 2. Risk assessment methods.

Methods	Authors
AHP	(Hermoso-Orzáez, & Garzón-Moreno, 2021)
AHP- Fuzzy TOPSIS	(Alora & Barua, 2022)
ANP- Improved grey relational analysis	(Hashemi et al., 2015)
AHP- Fuzzy DEMATEL	(Mzougui et al., 2020)
Bayesian networks	(Lockamy III & McCormack, 2009)
Fuzzy set theory- multi-objective mathematical programming	(Ji & Zhu, 2012; Kumar et al., 2004)
Fuzzy-AHP	(Samvedi et al., 2013)
Fuzzy-DEMATEL	(Khan et al., 2021b)
Fuzzy-BWM	(Khan et al., 2021a)
Fuzzy inference system-Bow-Tie analysis	(Aqlan & Lam, 2015)
DEMATEL -ANP	(Tarei et al., 2018)
Newsvendor model	(Cheong & Song, 2013)
Hybrid Petri-nets	(Khilwani et al., 2011)
PF-AHP&PF-VIKOR	(Lahane & Kant, 2021)
SEM-Fuzzy AHP	(Oturakçı & Yıldırım, 2022)
Simulation	(Durowoju et al., 2012)

3. Methodology

The fuzzy DEMATEL method and its methodological steps are explained in this section.

3.1. Fuzzy DEMATEL method

DEMATEL (Decision Making Trial and Evaluation Laboratory) is one of the multi-criteria decision-making methods that helps to evaluate human judgments numerically. A better understanding of the causal relationship allows for planning and solving the problems by dividing the relevant factors into cause-effect groups. Also, there are no sample size limitations with the DEMATEL method (Govindan & Chaudhuri, 2016).

The main handicap in risk analysis is the subjectivity of the inputs obtained from the experts. Therefore, it is possible to use fuzzy or gray theories to minimize this subjectivity (Samvedi et al., 2013). Using fuzzy logic, experts can make inferences about the problems they encounter under uncertainty and quantitatively define the bilateral relations they evaluate with verbal expressions (Lin & Wu, 2008). Therefore, the DEMATEL method combining it with fuzzy theory is used in this study.

The steps of the fuzzy DEMATEL method are given below (Baykasoğlu et al., 2013):

Step 1: Constructing the fuzzy direct relationship matrix.

The relationships between the criteria are determined using the pairwise comparisons in Table 3. Here, a matrix is created with the answers obtained from each participant. The symbol $\tilde{z}_{ij}$ indicates the degree to which the i factor affects the j factor. In the formula $\tilde{Z}^k=[\tilde{z}_{ij}^k]$ k refers to each participant and should be $1 \leq k \leq p$ $\tilde{Z}^1$, $\tilde{Z}^2$, $\tilde{Z}^3 \ldots \tilde{Z}^p$, participants show separate matrices of answers. If the number of participants is more than one, $\tilde{Z}=[\tilde{z}_{ij}]$ matrix is formed by calculating the arithmetic averages over the answers given to calculate the direct relationship matrix.

Table 3. The fuzzy linguistic scale.

Linguistic variables	Triangular Fuzzy Numbers
No influence (No)	(0, 0, 0.25)
Very low influence (VL)	(0, 0.25, 0.50)
Low influence (L)	(0.25, 0.50, 0.75)
High influence (H)	(0.50, 0.75, 1)
Very high influence (VH)	(0.75, 1, 1)

$$\tilde{Z} = \frac{\tilde{z}^1 + \tilde{z}^2 + \cdots + \tilde{z}^p}{p} \tag{1}$$

$$\tilde{Z} = \begin{bmatrix} 0 & \tilde{z}_{12} & \cdots & \tilde{z}_{1n} \\ \tilde{z}_{21} & 0 & \cdots & \tilde{z}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{z}_{n1} & \tilde{z}_{n2} & \cdots & 0 \end{bmatrix} \tag{2}$$

Step 2: Calculating the normalized fuzzy direct relationship matrix

The 'u' value, the last of the triangular numbers, is used to create this matrix. The 'r' value obtained with the help of Equation (3) is divided by each value in the fuzzy direct relationship matrix.

$$\tilde{X} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{n1} & \tilde{x}_{n2} & \cdots & \tilde{x}_{nn} \end{bmatrix} \quad \tilde{x}_{ij} = \frac{\tilde{z}_{ij}}{r} = \left(\frac{\ell_{ij}}{r}, \frac{m_{ij}}{r}, \frac{u_{ij}}{r}\right) r = max_{1\le i\le n}\left(\sum_{j=1}^{n} u_{ij}\right) \tag{3}$$

Step 3: Calculating the fuzzy total relationship matrix.

In the normalized fuzzy direct relationship matrix, each triangular number group is divided into separate matrices, and using Equation (5) are combined into a single matrix to form a fuzzy total relationship matrix.

$$X_\ell = \begin{bmatrix} 0 & \ell'_{12} & \cdots & \ell'_{1n} \\ \ell'_{21} & 0 & \cdots & \ell'_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \ell'_{n1} & \ell'_{n2} & \cdots & 0 \end{bmatrix}, \quad X_m = \begin{bmatrix} 0 & m'_{12} & \cdots & m'_{1n} \\ m'_{21} & 0 & \cdots & m'_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ m'_{n1} & m'_{n2} & \cdots & 0 \end{bmatrix}, \quad X_u = \begin{bmatrix} 0 & u'_{12} & \cdots & u'_{1n} \\ u'_{21} & 0 & \cdots & u'_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ u'_{n1} & u'_{n2} & \cdots & 0 \end{bmatrix} \tag{4}$$

$$[\ell''_{ij}] = X_\ell(I - X_\ell)^{-1}$$
$$[m''_{ij}] = X_m(I - X_m)^{-1}$$
$$[u''_{ij}] = X_u(I - X_u)^{-1}$$
$$\tilde{T} = \begin{bmatrix} \tilde{t}_{11} & \tilde{t}_{12} & \cdots & \tilde{t}_{1n} \\ \tilde{t}_{21} & \tilde{t}_{22} & \cdots & \tilde{t}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{t}_{n1} & \tilde{t}_{n2} & \cdots & \tilde{t}_{nn} \end{bmatrix} \tag{5}$$
$$\tilde{t}_{ij} = (\ell''_{ij}, m''_{ij}, u''_{ij})$$

Step 4: Defuzzification.

Different defuzzification methods are mentioned in the literature. In this study, the defuzzification method of CFCS (Converting Data into Crisp Values) proposed by Opricovic & Tzeng (2003) is used. Thus, triangular fuzzy numbers are converted to more net numbers.

$$R = \max_j u_{ij},\ L = \min_j \ell_{ij} \text{ and } \Delta = R - L \tag{6}$$

$$x_{\ell j} = (\ell_{ij} - L)/\Delta \tag{7}$$

$$x_{mj} = (m_{ij} - L)/\Delta \tag{8}$$

$$x_{uj} = (u_{ij} - L)/\Delta \tag{9}$$

$$x_j^{ls} = x_{mj}/(1 + x_{mj} - x_{\ell j}) \tag{10}$$

$$x_j^{rs} = x_{uj}/(1 + x_{uj} - x_{mj}) \tag{11}$$

$$x_j^{crisp} = [x_j^{ls}(1 - x_j^{ls}) + x_j^{rs} x_j^{rs}]/[1 - x_j^{ls} + x_j^{rs}] \tag{12}$$

$$\tilde{f}_{ij}^{crisp} = L + x_j^{crisp}\Delta \tag{13}$$

$$\tilde{T}^{def} = \begin{bmatrix} \tilde{t}_{11}{}^{def} & \tilde{t}_{12}{}^{def} & \cdots & \tilde{t}_{1n}{}^{def} \\ \tilde{t}_{21}{}^{def} & \tilde{t}_{22}{}^{def} & \cdots & \tilde{t}_{2n}{}^{def} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{t}_{n1}{}^{def} & \tilde{t}_{n2}{}^{def} & \cdots & \tilde{t}_{nn}{}^{def} \end{bmatrix} \tag{14}$$
$$\tilde{t}_{ij}{}^{def} = (\ell''_{ij}, m''_{ij}, u''_{ij})^{def}$$

Step 5: Identifying cause and effect groups.

The "$\tilde{D}^{def}$" matrix is obtained by taking the sum of rows of defuzzified $\tilde{T}^{def}$ total relation matrix. The matrix "$\tilde{R}^{def}$" is obtained by transposing the matrix formed by the sum of the total relationship matrix columns, $\tilde{D}_i^{def}$ shows the effects i. factor on other factors, $\tilde{R}_i^{def}$ shows the sum of the direct and indirect effects on factor i. $\tilde{D}_i^{def}$+$\tilde{R}_i^{def}$ shows the importance of the element of i in the whole system, and $\tilde{D}_i^{def}-\tilde{R}_i^{def}$ shows the net effect of i criteria. If $\tilde{D}_i^{def}-\tilde{R}_i^{def}$ is positive, it means it is a cause, and if negative, it is an effect.

Step 6: Calculating the threshold value and obtaining a cause and effect diagram.

In the $\tilde{T}^{def}$ total relationship matrix, a threshold value is determined to eliminate criteria with a relatively low degree of influence. An expert can determine this threshold value, or it can be obtained by summing the values in the total relationship matrix and averaging them. To easily understand the relations between the criteria and their positions relative to each other, an impact-relationship graph can be created that $\tilde{D}_i^{def}+\tilde{R}_i^{def}$ is placed on the horizontal axis and $\tilde{D}_i^{def}-\tilde{R}_i^{def}$ on the vertical axis.

4. A case study on the iron and steel industry in Turkey

Supply chain risks and their impact levels may differ depending on the industry characteristics of businesses. The iron and steel industry is of great importance for the overall performance of the manufacturing industry in Turkey due to its high rate of production and export potential and provision of inputs to other sectors (Kabak et al., 2016). In 2019, the Turkish Steel Industry ranked 8th in the world and 2nd among steel producers in Europe after Germany (Iron Steel Sector Report, 2020). Due to its connection with many industries, disruptions in the iron and steel industry, directly and indirectly, affect other sectors. The iron and steel company chosen for this study is among the top 30 companies in Turkey's Top 500 Industrial Enterprises. It has a corporate risk policy to identify and manage risks to increase its competitive advantage by reducing losses. The company's senior management has adopted the vision of developing a practical risk management approach throughout the company and its suppliers.

A comprehensive literature review was made to identify main supply chain risks and sub-risks in this case study. This review resulted in a large number of supply chain risks. Some of these risks were eliminated based on the opinions of two academicians in the field of operations and supply chain management. Experts' views at the executive level in the production, purchasing, and marketing departments were taken to determine the risks specific to the company's supply chain. This process resulted in six risk groups and 58 risk types (Table 4).

Table 4. Identified supply chain risk group and sub-risks.

Risk Groups	Risks
Environmental Risks (R1)	E1: PPolitical uncertainty E2: PExchange rate E3: PRaw material price fluctuation E4: PBureaucracy E5: PEconomic crisis E6: PCompetition changes E7: PEnergy supply E8: PRegulatory
Security Risks (R2)	SC1: PNatural disaster SC2: PTerrorism SC3: POccupational disease SC4: PWar SC5: PCyberattack SC7: POccupational accident
Customer Risks (R3)	C1: PInsufficient information about customer orders or demand C2: POrder cancellation C3: PCustomers' desire to expedite orders C4: PCustomers unable to make payments on time C5: PDemand uncertainty C6: PIncorrect information about customer orders or demand
Supplier Risks (R4)	S1: PSupplier inability to deliver materials on time S2: PSupplier inability to provide material in desired quantity S3: PSupplier inability to provide materials of desired quality S4: PSupplier bankruptcy S5: PSupplier inability to respond to different types of material demand S6: PInability to select the right supplier S7: PFailure to share order information correctly with the supplier S8: PInability to fully share order information with the supplier S9: PInsufficient storage and handling S10: PLack of supplier capacity
Transportation Risks (R5)	T1: PIncrease in transportation costs T2: PDelays due to railway capacity T3: PPort strikes T4: PDelays due to port capacity T5: PHigh transportation costs
Business Risks (R6)	B1: PInsufficient or excess capacity B2: PInformation infrastructure breakdown B3: PInability to find qualified employees B4: PInsufficient or excess inventory

(Table 4 continues on next page)

(Table 4 continues on next page)

Risk Groups	Risks
Business Risks (R6)	B5: PCompany's inability to meet demand changes B6: PCompany's inability to respond to different types of material demand B7: PMachine failure /production disruption B8: PLabor absenteeism B9: PHigh unit production cost B10: PCapacity cost B11: PManagement of labor strikes and union processes B12: PInability to deliver orders on time B13: PHigh labor turnover B14: PPoorly designed process B15: PInsufficient process improvements B16: PInability to retain qualified employee B17: PSecurity of critical information B18: PBusiness continuity disruption B19: PEnvironmental pollution B20: PInternal transportation and semi-finished product/ finished product stocking B21: PCorporate communications B22: PFailure to make appropriate investments

Then, the experts made pairwise comparisons with linguistic expressions to determine the relationships between the six risk groups. The same linguistic comparison procedure was also performed for the sub-risks. Finally, risk groups and sub-risks were analyzed with the fuzzy DEMATEL method, and the results were evaluated.

After obtaining the pairwise comparison data on the risk groups, the following fuzzy DEMATEL methodology steps were followed.

Step 1: Establish the fuzzy direct relation matrix.

In Table 5, the binary linguistic comparisons of expert 1 about the risk groups are shown as an example. For this purpose, expert 1 used the linguistic expressions given in Table 3.

Table 5. Linguistic assessment of risk groups of the expert 1.

	R1	R2	R3	R4	R5	R6
R1	-	L	H	L	H	VL
R2	L	-	L	L	H	VL
R3	No	VL	-	L	No	H
R4	VL	No	L	-	L	H
R5	VL	No	H	L	-	H
R6	L	L	VH	H	H	-

The linguistic expressions obtained from the experts were converted into fuzzy triangular numbers. The fuzzy direct relationship matrix in Table 6 was obtained by taking the arithmetic average of the experts' assessments.

Step 2: Calculate the normalized fuzzy direct relation matrix (Table 7).

Step 3: Calculate the total relation matrix (Table 8).

Step 4: Defuzzification.

CFCS (Converting Data into Crisp Values) defuzzification method proposed by Opricovic & Tzeng (6), (7), (8), (9), (10), (11), (12), (13), and (14) triangular numbers were converted into crisp values, and defuzzified total relation matrix was created (Table 9).

Step 5: Identify cause and effect groups.

$\tilde{D}^{def}$ and $\tilde{R}^{def}$ values, which give the row and column sums of the defuzzified total relation matrix, are calculated, and the importance level of risk groups, the cause-and-effect risk clusters are formed.

Step 6: Calculate the threshold value and draw the cause and effect diagram.

This study calculates the threshold value by taking the average values in the defuzzified fuzzy total relationship matrix, 0.440. In Table 9, threshold values and higher values are marked in bold.

4.1. Findings

Considering the analysis results of the risk groups in the study, the risk groups were divided into two clusters, as seen in Figure 1 and Table 10. These are the cause cluster with the positive $\tilde{D}_i^{def}-\tilde{R}_i^{def}$ value and effect cluster with the negative $\tilde{D}_i^{def}-\tilde{R}_i^{def}$ value.

Considering the $\tilde{D}_i^{def}+\tilde{R}_i^{def}$ values, which show the degree of prominence of the criteria, it is seen that the highest valued risk group is business risks (R6) (5.945). This risk is followed by customer risks (R3) (5.529), supplier risks (R4) (5.211), transportation risks (R5) (5.206), environmental risks (R1) (5.077), and finally, security risks (R2) (4.716). Looking at the $\tilde{D}_i^{def}-\tilde{R}_i^{def}$ values, the cause-and-effect clusters of risks emerge. R1 with the highest positive $\tilde{D}_i^{def}-\tilde{R}_i^{def}$ value (0.830) possesses the most substantial effect on others, while R3 with the smallest negative value (−0.996) is the most influenced risk group.

Table 6. Fuzzy direct relation matrix.

	R1			R2			R3			R4			R5			R6		
R1	0.000	0.000	0.000	0.333	0.583	0.833	0.375	0.625	0.875	0.417	0.667	0.917	0.458	0.708	0.958	0.375	0.625	0.792
R2	0.250	0.458	0.708	0.000	0.000	0.000	0.417	0.667	0.875	0.333	0.583	0.792	0.292	0.542	0.792	0.417	0.667	0.833
R3	0.208	0.375	0.625	0.125	0.292	0.542	0.000	0.000	0.000	0.208	0.375	0.625	0.292	0.458	0.708	0.417	0.667	0.875
R4	0.125	0.292	0.542	0.125	0.292	0.542	0.417	0.667	0.875	0.000	0.000	0.000	0.333	0.542	0.792	0.417	0.667	0.917
R5	0.125	0.292	0.542	0.042	0.125	0.375	0.625	0.875	1.000	0.375	0.667	0.833	0.000	0.000	0.000	0.542	0.792	0.958
R6	0.375	0.583	0.750	0.333	0.542	0.750	0.667	0.917	1.000	0.417	0.667	0.917	0.292	0.500	0.708	0.000	0.000	0.000

Table 7. Normalized fuzzy direct relation matrix.

	R1			R2			R3			R4			R5			R6		
R1	0.000	0.000	0.000	0.076	0.133	0.190	0.086	0.143	0.200	0.095	0.152	0.210	0.105	0.162	0.219	0.086	0.143	0.181
R2	0.057	0.105	0.162	0.000	0.000	0.000	0.095	0.152	0.200	0.076	0.133	0.181	0.067	0.124	0.181	0.095	0.152	0.190
R3	0.048	0.086	0.143	0.029	0.067	0.124	0.000	0.000	0.000	0.048	0.086	0.143	0.067	0.105	0.162	0.095	0.152	0.200
R4	0.029	0.067	0.124	0.029	0.067	0.124	0.095	0.152	0.200	0.000	0.000	0.000	0.076	0.124	0.181	0.095	0.152	0.210
R5	0.029	0.067	0.124	0.010	0.029	0.086	0.143	0.200	0.229	0.086	0.152	0.190	0.000	0.000	0.000	0.124	0.181	0.219
R6	0.086	0.133	0.171	0.076	0.124	0.171	0.152	0.210	0.229	0.095	0.152	0.210	0.067	0.114	0.162	0.000	0.000	0.000

Table 8. Total relation fuzzy matrix.

	R1			R2			R3			R4			R5			R6		
R1	0.034	0.163	1.028	0.099	0.265	1.145	0.154	0.414	1.595	0.140	0.361	1.448	0.145	0.353	1.418	0.144	0.388	1.518
R2	0.085	0.245	1.093	0.026	0.136	0.913	0.153	0.397	1.491	0.116	0.326	1.334	0.106	0.305	1.299	0.144	0.373	1.424
R3	0.069	0.196	0.953	0.048	0.169	0.904	0.052	0.207	1.149	0.081	0.242	1.151	0.095	0.246	1.133	0.130	0.319	1.264
R4	0.054	0.191	0.993	0.049	0.178	0.955	0.144	0.360	1.392	0.038	0.177	1.092	0.107	0.275	1.212	0.135	0.338	1.343
R5	0.059	0.203	0.998	0.036	0.157	0.931	0.195	0.418	1.419	0.123	0.326	1.258	0.042	0.180	1.064	0.168	0.380	1.357
R6	0.115	0.279	1.122	0.101	0.256	1.082	0.212	0.460	1.542	0.140	0.356	1.382	0.115	0.313	1.313	0.067	0.260	1.295

Table 9. The total relation matrix defuzzified with CFCS.

	R1	R2	R3	R4	R5	C6	$\tilde{D}_i^{def}$	$\tilde{D}_i^{def}+\tilde{R}_i^{def}$	$\tilde{D}_i^{def}-\tilde{R}_i^{def}$
R1	0.313	0.415	**0.595**	0.537	0.527	0.566	2.953	5.077	0.830
R2	0.390	0.270	**0.569**	**0.492**	**0.471**	**0.542**	2.734	4.716	0.752
R3	0.327	0.296	0.369	0.398	0.399	**0.477**	2.267	5.529	–0.996
R4	0.330	0.312	**0.528**	0.336	0.435	**0.504**	2.445	5.211	–0.321
R5	0.340	0.291	**0.577**	**0.480**	0.333	**0.539**	2.560	5.206	–0.085
R6	0.423	0.398	**0.625**	**0.523**	**0.480**	0.434	2.883	5.945	–0.179
$\tilde{R}_i^{def}$	2.123	1.982	3.262	2.766	2.645	3.062			

The fuzzy DEMATEL steps applied for the risk groups were also carried out for the sub-risks, and a clustered values table was prepared to show $\tilde{D}_i^{def}+\tilde{R}_i^{def}$, $\tilde{D}_i^{def}-\tilde{R}_i^{def}$ of the criteria and sorted according to these values.

When the environmental risks in Table 11 are examined, it can be seen that the most important environmental risk with the highest $\tilde{D}_i^{def}+\tilde{R}_i^{def}$ value is the risks related to the economy (E5) (4.667). This risk is followed by E2 (4.172), E1 (4.135), E6 (3.833). However, when the $\tilde{D}_i^{def}-\tilde{R}_i^{def}$ values are examined, it is seen that E1 is the risk that most affects other risks with a value of 0.833. This risk was followed by E2 (0.383). Among the risks most influenced by the risks in this class, E6 (−0.845) took first place, while E3 (−0.429) took second place.

Looking at all interactions in the security risks in Table 12, it can be seen that war is the highest risk with $\tilde{D}_i^{def}+\tilde{R}_i^{def}$ value 4.443 (SC4). Then, SC2 (4.383), SC5 (4.229), SC6 (4.048), SC7 (3.588), SC1 (2.791), and SC3 (2.622) follow as well. Considering the $\tilde{D}_i^{def}-\tilde{R}_i^{def}$ values, SC1 (1.030) is the risk most affects other risks, and SC6 (−0.076) is the most influenced risk.

Among the customer risks in Table 13, the risk of C1 (2.792) was determined as the most important risk. This risk was followed by C6 (2.537) and C2 (2.446). Again, while C1 (0.505) had the strongest effect on other risks, C4 (−0.511) was the most influenced risk.

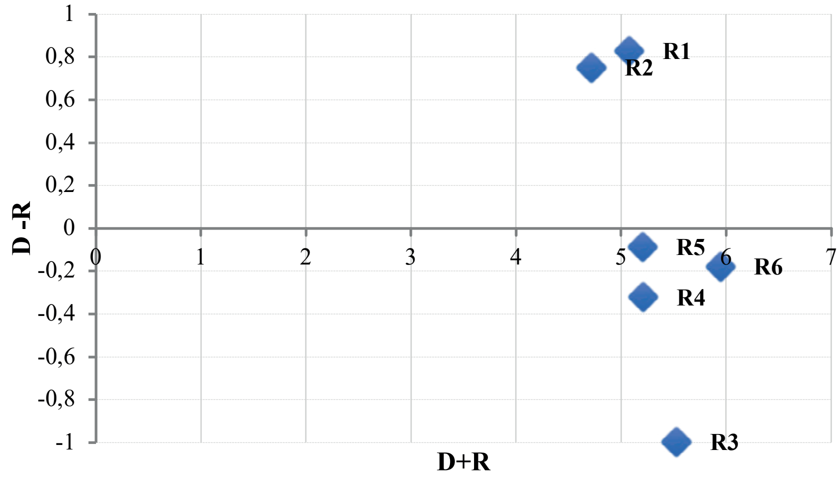

Figure 1. The casual diagram of supply chain risks.

Table 10. The rank of main risk groups.

Rank	Risks	$\tilde{D}_i^{def}+\tilde{R}_i^{def}$	Rank	Risks	$\tilde{D}_i^{def}-\tilde{R}_i^{def}$	Cluster
1	R6	5.945	1	R1	0.830	Cause Cluster
2	R3	5.529	2	R2	0.752	
3	R4	5.211	3	R5	–0.085	Effect Cluster
4	R5	5.206	4	R6	–0.179	
5	R1	5.077	5	R4	–0.321	
6	R2	4.716	6	R3	–0.996	

Table 11. Environmental risks.

Rank	Risks	$\tilde{D}_i^{def}+\tilde{R}_i^{def}$	Rank	Risks	$\tilde{D}_i^{def}-\tilde{R}_i^{def}$	Cluster
1	E5	4.667	1	E1	0.833	Cause Cluster
2	E2	4.172	2	E2	0.383	
3	E1	4.135	3	E8	0.230	
4	E6	3.833	4	E4	0.025	
5	E3	3.745	5	E5	–0.012	Effect Cluster
6	E4	3.425	6	E7	–0.185	
7	E7	3.391	7	E3	–0.429	
8	E8	3.186	8	E6	–0.845	

Table 12. The rank of security risks.

Rank	Risks	$\tilde{D}_i^{def}+\tilde{R}_i^{def}$	Rank	Risks	$\tilde{D}_i^{def}-\tilde{R}_i^{def}$	Cluster
1	SC4	4.443	1	SC1	1.030	Cause Cluster
2	SC2	4.383	2	SC2	0.356	
3	SC5	4.229	3	SC4	0.147	
4	SC6	4.048	4	SC5	–0.076	Effect Cluster
5	SC7	3.588	5	SC3	–0.212	
6	SC1	2.791	6	SC7	–0.585	
7	SC3	2.622	7	SC6	–0.658	

As seen in Table 14, S1 with $Didef+Ridef$ value of 7.940 is the first, and S2 (7.864) is the second most important risk in the supplier risks group. S8, with a value of 0.898, is the most affected, and S3 (−0.864) has emerged as the most influenced risk.

Among the transportation risks, T5 (8.840) was the most critical risk, while T2 took the last place in the order of importance. While T3 was the most affected transportation risk, T5 (−1.701) was the most influenced risk (Table 15).

Table 13. The rank of customer risks.

Rank	Risks	$\tilde{D}_i^{def}+\tilde{R}_i^{def}$	Rank	Risks	$\tilde{D}_i^{def}-\tilde{R}_i^{def}$	Cluster
1	C1	2.792	1	C1	0.505	Cause Cluster
2	C6	2.537	2	C6	0.368	
3	C2	2.446	3	C3	0.170	
4	C5	2.036	4	C2	–0.220	Effect Cluster
5	C3	1.979	5	C5	–0.312	
6	C4	1.748	6	C4	–0.511	

Table 14. The rank of supplier risks.

Rank	Risks	$\tilde{D}_i^{def}+\tilde{R}_i^{def}$	Rank	Risks	$\tilde{D}_i^{def}-\tilde{R}_i^{def}$	Cluster
1	S1	7.940	1	S8	0.898	Cause Cluster
2	S2	7.864	2	S7	0.805	
3	S5	7.344	3	S10	0.641	
4	S6	7.339	4	S6	0.384	
5	S3	7.098	5	S4	0.035	
6	S4	6.601	6	S5	–0.433	Effect Cluster
7	S8	6.443	7	S1	–0.445	
8	S7	6.397	8	S2	–0.494	
9	S10	6.380	9	S9	–0.526	
10	S9	5.758	10	S3	–0.864	

Table 15. The rank of transportations risks.

Rank	Risks	$\tilde{D}_i^{def}+\tilde{R}_i^{def}$	Rank	Risks	$\tilde{D}_i^{def}-\tilde{R}_i^{def}$	Cluster
1	T5	8.840	1	T3	0.960	Cause Cluster
2	T1	8.699	2	T4	0.913	
3	T3	7.478	3	T2	0.864	
4	T4	7.428	4	T1	–1.037	Effect Cluster
5	T2	6.803	5	T5	–1.701	

Table 16. The rank of business risks.

Rank	Risks	$\tilde{D}_i^{def}+\tilde{R}_i^{def}$	Rank	Risks	$\tilde{D}_i^{def}-\tilde{R}_i^{def}$	Cluster
1	B6	5.094	1	B11	0.995	Cause Cluster
2	B15	5.068	2	B16	0.960	
3	B14	5.008	3	B21	0.762	
4	B5	4.923	4	B8	0.683	
5	B22	4.618	5	B17	0.555	
6	B10	4.568	6	B2	0.487	
7	B1	4.567	7	B7	0.339	
8	B4	4.507	8	B3	0.278	
9	B12	4.503	9	B15	0.256	
10	B18	4.464	10	B13	0.222	
11	B3	4.360	11	B14	0.081	
12	B9	4.325	12	B22	–0.005	Effect Cluster
13	B16	4.197	13	B19	–0.189	
14	B8	4.160	14	B10	–0.262	
15	B7	4.151	15	B1	–0.317	
16	B20	4.140	16	B18	–0.415	
17	B13	4.075	17	B6	–0.466	
18	B21	3.903	18	B20	–0.567	
19	B11	3.854	19	B4	–0.692	
20	B2	3.606	20	B5	–0.698	
21	B17	3.024	21	B9	–0.861	
22	B19	2.864	22	B12	–1.145	

Finally, when we look at the business risks in Table 15, according to the value, B6 (5.094) is in the first place, while B15 (5.068) is the second. and B14 (5.008) is the third most significant risk. According to values, B11 (0.995), one of the most affected business risks, is first, while B16 (0.960) is second. B12 (−1.145) ranks first in the influenced business risk, and B9 (−0.861) ranks second.

5. Conclusions and discussions

Identifying and assessing risks in supply chains is very important to eliminate or reduce the consequences of risks. It would be insufficient to address the risks in a supply chain one by one and assess their individual effects. Evaluating each risk individually and with other risks enables managers to obtain more accurate and meaningful results. This study aims to determine the supply chain risk groups and sub-risks of a leading company operating in Turkey's iron and steel industry and examine the causal relationships between the risks. For this purpose, the pairwise comparison data about the risks obtained from the experts in the company's purchasing, production, and marketing departments were analyzed with the fuzzy DEMATEL method.

Results show that the most crucial risk group is the business risks. This is followed by customer risks, supplier risks, transportation risks, environmental risks, and, finally, security risks. Business risks, also called operational risks, arise in a company's internal product development, manufacturing, and distribution operations (Deloitte, 2012). Companies invest in programs such as Total Quality Management (TQM), Lean Manufacturing, and Six Sigma to improve their quality and capabilities. However, these programs reduce the tolerance of faults and increase the negative effect of any problems (Punniyamoorthy et al., 2013). Therefore, it is not surprising that business risk is first in the study. Also, it can be said that business operations take the most part for a greater supply chain performance (Duong et al., 2022). The results showed that the environmental risk is the most influential of the other risks. This risk group has a low probability of occurring but a high impact. Therefore, risks in this category drastically cause many disruptions in the supply chain (Alora & Barua, 2022). Kumar et al. (2010) evaluated environmental risks as interaction risks and stated that the supply chain environment emerges from interaction with physical, social, legal, operational, economic, and political factors.

Similarly, Samvedi et al. (2013) stated that environmental risks could affect a single level or organization or the entire supply chain. In our study, customer risk is most affected by the other risk groups. One of the supply chain management purposes is to achieve customer satisfaction by meeting customer needs and expectations. Therefore, any disruption at any stage of the supply chain will directly or indirectly affect customer satisfaction.

When the results of environmental risks are examined, it is observed that economic risk is the most critical risk. Similarly, Kumar et al. (2020) assessed various risks affecting demand for the Indian automotive sector. They found that companies are most affected by economic risks than other risks. Political uncertainty affects the other environmental risks the most. This could be because those political uncertainties in Turkey harm the economy. Political tensions can also affect companies within the country and, therefore, supply chain partners in other countries (Mostafa et al., 2021). Environmental risk analysis also indicated that competition risk is the most affected environmental risk type.

Regarding the security risks, it has been seen that the two most crucial security risks are terrorism and war risk. A current example of war risk is the Ukraine-Russia war. Ukraine exports components such as iron ores, ferro-silico manganese, and pig iron that are input to the European steel industry. Due to the war, there is a potential for supply chain disruption in the European iron and steel industry (World Bank, 2022). A natural disaster is a risk that triggers other environmental risks. Chopra & Sodhi (2004) stated that natural disasters, which they consider one of the unpredictable and rare disruptions, interrupt the physical flow in the supply chain.

When the importance of customer risks is assessed, insufficient information about customer orders/ demand and incorrect information about customer orders/ demand come first and second, respectively. The analysis emphasizes the importance of demand-side risks since the lack of demand information is the most influential on other types of customer risks. To reduce the demand-side supply chain risks, decision-makers should identify the factors that increase the demand risks and make appropriate process improvements to reduce them.

Regarding the supplier risks, the most important is that the company's suppliers cannot deliver the materials in the desired time and quantity. In the literature, some authors (e.g., Kumar et al., 2010; Punniyamoorthy et al., 2013) indicated that supplier-related risks would negatively affect the ability of the focal firm to meet customer demand (both in terms of quantity and quality) at the anticipated costs and at the desired time. Therefore, it would be beneficial for company managers to develop reactive and proactive action plans against supplier-related risks.

Among the transportation risks, high transportation costs and an increase in transportation costs take the first and second places in the company. Experts consider transportation costs as an essential risk that threatens the company. As disruptions in transportation operations prevent the timely supply of materials, it can disrupt the company's production activities (Paul et al., 2020). So, transportation is seen as one of the critical risks (Schoen et al., 2018). Transport mode, which depends on the final products' characteristics, is a strategic variable that increases supply chain performance (Oliveira et al., 2017). Maritime transportation is very important in this company. Therefore, port strikes were found to have the most effect on other transportation risks. On the other hand, it was determined that high transportation costs were influenced by the other transportation risks the most. According to this finding, it can be said that the company should reduce other transportation risks to reduce high transportation costs.

Regarding the business risks, the first risk is the inability to respond to different types of material demand. The second risk is insufficient process improvements. And the third risk is poorly designed processes. These results indicate that there are deficiencies in the company's own internal operational processes. For this reason, the managers should identify inefficient business processes and make necessary process improvements. The most affected business risk is that orders cannot be delivered on time, proving that internal problems are reflected on the customer.

This study is comprehensive as it includes many supply chain risks. The case study presented sets an example for practitioners and researchers to identify supply chain risks and assess the impact on each other. However, the lack of evaluation of experts from other companies in the iron and steel industry limits the generalization of the research findings. Similar studies in different sectors can be conducted to enrich the field of supply chain risk management. In addition, studies that include risk mitigation strategies, which is the third stage of supply chain risk management, will provide significant benefits to academicians and managers working in supply chain risk management. Finally, this study only used the fuzzy DEMATEL method. In the future, hybrid techniques may be used for model creation.

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