Article history:
Received 02 July 2025
Revised 14 October 2025
Accepted 11 November 2025
Published online 01 June 2026

Journal of Resource Management and Decision Engineering

Volume 5, Issue 2, pp 1-19

Evaluating Industry 4.0–Based Technological Strategies to Reduce the Impact of Risk on Organizational Performance under Conditions of Uncertainty: (Case Study: Lavan Oil Refinery)

Farzad. Azarnavid[1], Ahmad. Jafarnejad Choqoshi[2*], Mohamadreza. Taghizadeh Yazdi[3]

[1] Department of Public Administration, Bon.C., Islamic Azad University, Bonab, Iran.
[2] Professor, Department of Operations Management and Decision Sciences, Faculty of Industrial Management and Technology, Tehran Colleges, University of Tehran, Tehran, Iran
[3] Department of Economics, CT.C., Islamic Azad University, Tehran, Iran

*** Corresponding author email address**: jafarnjd@ut.ac.ir

A r t i c l e I n f o

Article type:
Original Research

How to cite this article:
Azarnavid, F., Jafarnejad Choqoshi, A., & Taghizadeh Yazdi, M. (2026). Evaluating Industry 4.0–Based Technological Strategies to Reduce the Impact of Risk on Organizational Performance under Conditions of Uncertainty: (Case Study: Lavan Oil Refinery). *Journal of Resource Management and Decision Engineering, 5*(2), 1-14.
https://doi.org/10.61838/kman.jrmde.241

A B S T R A C T

This study aims to identify implementable strategies based on transformative Industry 4.0 technologies to eliminate or mitigate the effects of key supply chain risks and to improve organizational performance under conditions of uncertainty. Lavan Oil Refinery was selected as the case study. This topic is among the research priorities of Lavan Oil Refining Company for performance improvement. Accordingly, the research focuses on identifying financial, process-related, safety, environmental, and other factors affecting supply chain sustainability and seeks to propose solutions to reduce these risks. The study begins with a systematic literature review to identify existing risks and then employs the Intuitionistic Fuzzy Delphi method to identify and weight the refinery's key risks. In the subsequent stage, the Intuitionistic Fuzzy DEMATEL technique is used to determine causal relationships among risks and to prioritize them. The findings indicate that 29 sub-criteria across five main dimensions—financial and economic risks, environmental risks, social risks, operational risks, and geopolitical risks—have the greatest importance and impact on refinery performance. Based on these results, Industry 4.0 technologies, including smart systems, the Industrial Internet of Things, big data analytics, and process digitalization solutions, are proposed to mitigate risk impacts and are evaluated using the Hanlon method. The results demonstrate that adopting Industry 4.0 technological solutions can enhance supply chain sustainability, improve organizational performance, and reduce the effects of internal and international uncertainties. By presenting an analytical framework for managing supply chain risks in refineries, this study provides a scientific and practical decision-making tool for managers and experts in the oil industry.

Keywords: *Risk management, oil refinery, supply chain, Industry 4.0, sustainability, uncertainty*

1. Introduction

The accelerating diffusion of Industry 4.0 technologies has fundamentally reshaped the competitive logic of contemporary organizations, particularly in manufacturing and supply-chain-intensive industries. Digital technologies such as cyber–physical systems, the Internet of Things, big data analytics, artificial intelligence, blockchain, and digital twins have transformed traditional production and logistics systems into interconnected, data-driven, and adaptive networks. In this context, organizational performance is no longer determined solely by internal efficiency, but by the ability to manage complex interactions among suppliers, technologies, markets, and regulatory environments under conditions of uncertainty and volatility. Recent empirical evidence consistently demonstrates that the adoption of Industry 4.0 capabilities enhances supply chain performance, responsiveness, and resilience, while simultaneously introducing new categories of operational, financial, environmental, and cyber risks that require systematic management approaches (Fatorachian, 2021; Ivanov et al., 2019; Khan & Emon, 2025).

Supply chain risk management has therefore emerged as a central research and managerial priority in the Industry 4.0 era. Digitalization amplifies both the visibility and propagation of risks across supply networks, often referred to as the "ripple effect," where disruptions in one node rapidly cascade throughout the system (Ivanov et al., 2019). While digital technologies improve real-time monitoring, predictive analytics, and decision support, they also increase dependency on information infrastructures, data quality, and inter-organizational coordination. Studies indicate that organizations leveraging Industry 4.0 tools can better anticipate disruptions and improve recovery performance, provided that these technologies are embedded within coherent governance and risk management frameworks (Chatterjee et al., 2023; Fernando et al., 2023).

From a performance perspective, a growing body of literature confirms the positive relationship between Industry 4.0 adoption and financial, operational, and sustainability outcomes. Industry 4.0 technologies strengthen dynamic capabilities, enabling firms to sense environmental changes, seize opportunities, and reconfigure resources more effectively under uncertainty (Eslami et al., 2024; Hossain et al., 2024). Empirical studies across manufacturing sectors show that digital transformation moderates the relationship between supply chain capabilities and financial performance, particularly in volatile and turbulent environments (Eslami et al., 2024; Khan & Emon, 2025). At the same time, organizational learning and awareness play a critical role in translating technological investments into measurable performance gains, highlighting the importance of human and managerial dimensions alongside technological readiness (Haleem et al., 2023; Prashar et al., 2023).

Sustainability considerations further complicate the risk–performance nexus in Industry 4.0–enabled supply chains. Environmental, social, and governance (ESG) pressures increasingly shape organizational strategies, especially in resource-intensive industries. Research demonstrates that Industry 4.0 technologies can significantly enhance sustainable supply chain performance by supporting cleaner production, resource efficiency, circular economy practices, and transparent information flows (Belhadi et al., 2021; Rana & Jani, 2023; Sahoo & Jakhar, 2024). However, sustainability-oriented digital transformation also exposes firms to new risks, including environmental compliance failures, data privacy breaches, cyber threats, and social legitimacy challenges (Ghaithan et al., 2023; Ghaithan et al., 2021).

The integration of circular economy principles with Industry 4.0 has been identified as a particularly promising pathway for enhancing long-term sustainability performance. Digital technologies facilitate reverse logistics, remanufacturing, and green procurement by enabling traceability, lifecycle assessment, and real-time coordination across supply networks (Ghaithan et al., 2023; Sahoo & Jakhar, 2024). Nevertheless, the success of such integration depends on the organization's ability to manage trade-offs among cost, flexibility, environmental impact, and risk exposure, especially in uncertain regulatory and market contexts (Qureshi, 2023; Tsai et al., 2021).

Recent studies have also emphasized the role of information logistics and data governance as critical enablers of Industry 4.0–driven performance. Efficient information logistics ensures that accurate, timely, and relevant data are available for decision-making across organizational boundaries, thereby reducing uncertainty and enhancing coordination (Bayanati, 2024). Without robust information flows, the benefits of advanced analytics and automation remain limited, and risk management efforts may become fragmented or reactive rather than proactive.

The healthcare and service sectors provide additional insights into how Industry 4.0 technologies influence performance under extreme uncertainty, such as during the COVID-19 pandemic. Evidence from healthcare supply chains shows that digitalization improves resilience and continuity by enabling rapid reconfiguration of processes and collaborative responses to disruptions (Chatterjee et al., 2023; Tortorella et al., 2024). These findings underscore the broader applicability of Industry 4.0–based risk management frameworks beyond traditional manufacturing contexts.

Despite these advances, several research gaps remain. First, much of the existing literature examines the performance impacts of Industry 4.0 in isolation, without systematically linking technological adoption to multidimensional risk prioritization under uncertainty. Second, while multiple decision-making and analytical methods have been proposed, there is limited empirical work integrating network-based approaches such as DANP with practical prioritization tools that are accessible to managers. Third, personnel-related risks, cognitive factors, and organizational ambidexterity remain underexplored in Industry 4.0 risk management models, despite evidence that human and organizational capabilities critically shape technology outcomes (Hossain et al., 2024; Kalinichenko et al., 2023).

Advanced analytics and artificial intelligence offer new opportunities to address these challenges. Deep learning models and intelligent control systems have shown strong potential for optimizing planning, control, and risk mitigation in stochastic and uncertain manufacturing environments (Karatas et al., 2022; Paraschos et al., 2024). However, translating these sophisticated tools into actionable managerial strategies requires structured prioritization frameworks that align technological solutions with organizational risk profiles and strategic objectives.

Collaborative supply chain relationships further influence the effectiveness of Industry 4.0–based risk management. Empirical evidence indicates that digital collaboration enhances transparency, trust, and joint problem-solving among partners, thereby reducing vulnerability to disruptions and improving sustainability outcomes (Belhadi et al., 2021; Kunkel et al., 2022). Conversely, weak coordination and fragmented governance can amplify systemic risks, even in highly digitalized supply networks.

Taken together, the literature suggests that Industry 4.0 is not merely a technological upgrade, but a systemic transformation that reshapes how organizations perceive, prioritize, and manage risks while pursuing performance and sustainability objectives. Effective risk management in this context requires integrated analytical approaches that account for interdependencies among risk factors, align technological investments with strategic priorities, and support decision-making under uncertainty across multiple organizational levels (Qureshi, 2023; Rana & Jani, 2023).

Accordingly, the aim of this study is to identify, analyze, and prioritize key supply chain risks affecting organizational performance under uncertainty and to evaluate the role of Industry 4.0–based technological solutions in mitigating these risks through an integrated multi-criteria decision-making framework.

2. Methods and Materials

The present study is an applied–analytical research designed to identify and evaluate Industry 4.0–based technological solutions for reducing the effects of risk on organizational performance under conditions of uncertainty. Given that the objective of the study is to analyze the causal relationships between the supply chain risks of Lavan Oil Refinery and Industry 4.0 technologies, a mixed-method research design based on a quantitative–qualitative approach was adopted. In the first step, a systematic literature review was conducted to identify financial, operational, environmental, social, and geopolitical risks associated with refinery supply chains. This review was carried out using internationally recognized scientific keywords, including Sustainability Risk Management, Oil Refinery, Sustainability Risks, Uncertainty in the Oil Industry, Environmental Risk in Oil Refinery, Social Risk in Oil Refinery, Economic Risk in Oil Refinery, Risk Management in Oil Refinery, and Oil Refinery Supply Chain Risk, and by searching reputable global databases such as Scopus, Web of Science, ScienceDirect, Springer, Wiley, MDPI, and Emerald. After identifying the existing risks, the Intuitionistic Fuzzy Delphi method was employed to determine the weight and importance of each risk based on the judgments of ten experts in oil refining and risk management. In this stage, sub-criteria that obtained at least 70% of the total importance were confirmed as the key risks of the refinery. In the next step, dependency analysis and prioritization of risks were conducted using the Intuitionistic Fuzzy DEMATEL method. This method enables the identification of causal relationships among risks and the determination of critical risks influencing organizational performance. The total relation matrix (TC) was completed by experts, and based on it, fuzzy calculations and defuzzification were performed to determine the ranking and normalization of risk impacts. In the final step, the identification and evaluation of Industry 4.0 technologies capable of reducing the effects of key risks were carried out using the Hanlon method. This stage involved evaluating technologies based on four main criteria: impact, feasibility of implementation, cost, and scheduling. The output of this phase is a set of implementable technological solutions under conditions of uncertainty to improve the performance of Lavan Oil Refinery. Through this approach, the present study provides the possibility of developing a sustainability-oriented and technology-based analytical framework for managing supply chain risks in the oil industry and can serve as a basis for strategic decision-making by organizational managers.

The DEMATEL method is one of the decision-making techniques aimed at determining relationships among criteria in complex systems while specifying the relationship matrix. The presence of uncertainty can affect these relationships. One approach that can overcome such uncertainty is the intuitionistic approach. In this step, based on experts' opinions regarding each criterion, an intuitionistic decision matrix is formed.

$$A_{(n\times n)} = \begin{bmatrix} (\mu_{11}, \nu_{11}) & \cdots & (\mu_{1j}, \nu_{1j}) \\ \vdots & \ddots & \vdots \\ (\mu_{i1}, \nu_{i1}) & \cdots & (\mu_{ij}, \nu_{ij}) \end{bmatrix}$$

To obtain the above matrix, experts' opinions must be expressed in the form of intuitionistic linguistic variables. After identifying the linguistic variables, they should be converted into intuitionistic numbers using the following table.

Table 1

Degree of influence of linguistic terms

Linguistic Term	π (Hesitation)	ν (Non-membership)	μ (Membership)
No influence	0.00	1.00	0.00
Very low influence	0.35	0.60	0.05
Low influence	0.50	0.45	0.05
High influence	0.75	0.20	0.05
Very high influence	0.90	0.10	0.00

$$N = \frac{1}{\max \sum_{j=1}^{n} a_{ij}} \times X_{(n\times n)}, 1 \le i \le n$$

To normalize the criteria, the initial matrix must first be converted into a non-fuzzy matrix. After calculating the above matrices, the fuzzy total relation matrix is obtained.

$$T = \lim_{k\to+\infty} (\widetilde{H}^1 \oplus \widetilde{H}^2 \oplus \cdots \oplus \widetilde{H}^k)$$

Each element of this matrix is a fuzzy number expressed as

$$\tilde{t}_{ij} = (l_{ij}^t, m_{ij}^t, u_{ij}^t)$$

and is calculated as follows:

$$[l_{ij}^t] = H_l(I - H_l)^{-1}$$

$$[m_{ij}^t] = H_m(I - H_m)^{-1}$$

$$[u_{ij}^t] = H_u(I - H_u)^{-1}$$

In these formulas, I denotes the identity matrix, and H_l, H_m, and H_u are $n \times n$ matrices whose elements represent the lower, middle, and upper values of the triangular fuzzy numbers of matrix H, respectively.

First, the matrix T_D must be extracted from the total criteria relation matrix T_C. Accordingly, each element of matrix T_D is calculated as follows: if each element of T_D is denoted by t_{ij}, then each t_{ij}'' is obtained from the average of each T_C^{ij}.

The indices r_i and c_j are then calculated. The index r_i represents the sum of the i-th row, and the index c_j represents the sum of the j-th column of matrix T_C with respect to the corresponding dimension. Similarly, the indices $\tilde{R}$ and $\widetilde{D}$ are calculated. The index R_i indicates the sum of the i-th row, and the index C_j indicates the sum of the j-th column of matrix T_D. For plotting and analyzing the diagram, two indices—degree of influence and influenced intensity, and direction of influence—are required, which are obtained using r_i and c_j. For each $i = j$, the following holds:

$$\widetilde{D} = (\widetilde{D}_i)_{(n\times 1)} = \left[\sum_{j=1}^{n} \widetilde{T}_{ij}\right]_{(n\times 1)}$$

$$\tilde{R} = (\tilde{R}_i)_{(1\times n)} = \left[\sum_{j=1}^{n} \widetilde{T}_{ij}\right]_{(1\times n)}$$

Here, $\widetilde{D}$ and $\tilde{R}$ are $n \times 1$ and $1 \times n$ matrices, respectively. In the next step, the importance of the indices $(\widetilde{D}_i + \tilde{R}_i)$ and the relationships among criteria $(\widetilde{D}_i - \tilde{R}_i)$ are determined. If $\widetilde{D}_i - \tilde{R}_i > 0$, the corresponding criterion is a cause; if $\widetilde{D}_i - \tilde{R}_i < 0$, the corresponding criterion is an effect.

$r_i + d_j =$ degree of influence and influenced intensity

$r_i - d_j$ = direction of influence or being influenced

Accordingly, if $r_i - d_j > 0$, the criterion is a cause, and if $r_i - d_j < 0$, the criterion is an effect. Based on the calculated values above, the indices $r_i + d_j$ and $r_i - d_j$ for criteria, as well as $\widetilde{D}_i + \tilde{R}_i$ and $\widetilde{D}_i - \tilde{R}_i$ for dimensions, are obtained.

$$\text{defuzzy} = \frac{(u-l)+(m-l)}{3} + l$$

To determine the Network Relation Map (NRM), a threshold value must be calculated. Using this approach, minor relationships can be disregarded, and a meaningful network of relationships can be drawn. Only relationships whose values in matrices T_C and T_D are greater than the threshold value are displayed in the NRM. To calculate the threshold value of relationships, it is sufficient to use expert judgment or the mean values for each T_C^{ij} (in matrix T_C) and also the mean values of matrix T_D (for drawing the dimensional relationship map). After determining the threshold intensity, all values smaller than the threshold are set to zero, meaning that the corresponding causal relationship is not considered. The matrix T_D is then normalized by calculating the sum of each row of matrix T_D with respect to the relevant dimension, dividing each element of the row by the sum of that row, and finally transposing the row and column positions.

$$T_D^{\alpha} = \left[\frac{t_{ij}^{(D)}}{d_i}\right]$$

Matrix T_C is normalized as follows: in this step, the sum of each row T_C^{ij} is calculated with respect to the corresponding dimension, and then in each T_C^{ij}, each element is divided by the sum of the elements of its corresponding row. For example, if each T_C^{α} consists of a set of $T_C^{(\alpha ij)}$, then $T_C^{(\alpha 11)}$ is obtained from the normalization of T_C^{11}. By transposing matrix T_C^{α}, the unweighted supermatrix is obtained.

At this stage, matrix T_D^{α} is multiplied by matrix W, such that each $t_D^{(\alpha ij)}$ is multiplied by its corresponding W_{ij}. The weighted supermatrix is then raised to successive powers (odd numbers) until all values in each row converge.

$$\lim_{Z\to\infty}(W^{(\alpha l)})^Z, \lim_{Z\to\infty}(W^{(\alpha m)})^Z, \lim_{Z\to\infty}(W^{(\alpha u)})^Z$$

The Hanlon technique is a quantitative and systematic method for prioritization in decision-making and planning, through which important and actionable problems can be identified. This technique consists of four main components: (1) the size or magnitude of the problem (0–10), (2) seriousness or severity of consequences with sub-criteria including urgency, severity of consequences, and economic and human impacts (0–20), (3) effectiveness of possible actions (0–10), and (4) feasibility of implementing actions based on five criteria (0–5). The final score is calculated based on a specified formula.

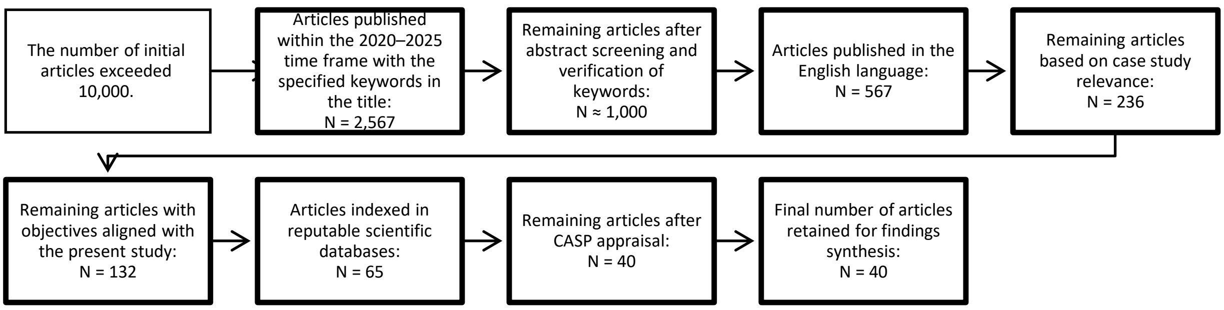
$$\text{DBPR} = \frac{A + BC}{3} D$$

3. Findings and Results

In the figure below, the results of article inclusion based on the entry criteria are presented.

Figure 1

Article Selection Flowchart



A total of 37 sub-risks were identified. Based on a thematic approach in the final step of a meta-synthesis (i.e., synthesis of findings), sub-themes were categorized into main themes and labeled accordingly. Therefore, consistent with a sustainability perspective under conditions of uncertainty, five main risks were formed by integrating the sub-risks. The integration process and the main and sub-risks of Lavan Oil Refinery, based on a sustainability approach under conditions of uncertainty, are specified and presented in the table below.

Table 2

Risks of Lavan Oil Refinery Based on a Sustainability Approach Under Conditions of Uncertainty

Sub-risk	Main risk category
Fluctuations in global crude oil and petroleum product prices	Financial and economic risks
Supply–demand imbalance	Financial and economic risks
Market volatility and market conditions	Financial and economic risks
Increased operating and maintenance costs	Financial and economic risks
Investment shortages and project budget constraints	Financial and economic risks
Exchange-rate volatility and domestic inflation	Financial and economic risks
Financial penalties due to non-compliance with environmental standards	Financial and economic risks
Changes in government taxation	Financial and economic risks
Oil leakage and soil/sea pollution	Environmental risks
Pollution and greenhouse gas emissions (CO_2, SOx, NOx)	Environmental risks
Non-compliance with environmental standards	Environmental risks
Inefficient management of industrial waste and wastewater	Environmental risks
Natural disasters (earthquakes, storms, floods, etc.)	Environmental risks
Environmental incidents and biological contamination (fire, explosion, chemical leaks)	Environmental risks
Occupational safety and employee health	Social risks
Dissatisfaction and protests of the local community	Social risks
Health impacts on residents and local/indigenous populations	Social risks
Employee dissatisfaction and strikes	Social risks
Insufficient employee environmental training and awareness	Social risks
Discrimination and inequity in hiring or compensation	Social risks
Failure of critical equipment and disruption of drilling and production	Operational risks
Weaknesses in preventive maintenance planning and execution	Operational risks
Refinery explosions (pipelines, tanks, etc.)	Operational risks
Human error and shortage of specialized/skilled workforce	Operational risks
Untimely access to spare parts and equipment	Operational risks
Inefficient transportation and logistics	Operational risks
Disruptions in technologies and smart systems	Operational risks
Dependence on foreign technologies (weakness of domestic technologies)	Operational risks
International sanctions and export restrictions	Geopolitical risks
Government performance	Geopolitical risks
International policies	Geopolitical risks
Political instability in the world and the Persian Gulf region	Geopolitical risks
Changes in global energy laws and policies	Geopolitical risks
Terrorist attacks on refineries and oil tankers	Geopolitical risks
International tensions and risk of military conflict	Geopolitical risks
Security and cyber risks	Geopolitical risks
Changes in domestic laws and policies and the need for compliance	Geopolitical risks

In this section, based on the opinions of 10 experts, the indicators are evaluated using the Intuitionistic Fuzzy Delphi method. First, the weight of each expert is determined. Accordingly, based on each expert's work experience, education, and organizational position, a score representing the expert's importance is assigned according to the scale in Table 3-1. The importance of Expert 1 is "Important (I)," whose intuitionistic fuzzy spectrum is (0.75, 0.20, 0.05). The weight calculation is as follows.

$$\lambda_1 = \frac{\left(0.75+0.05\left(\frac{0.75}{0.75+0.2}\right)\right)}{\left(0.75+0.05\left(\frac{0.75}{0.75+0.2}\right)\right)+\left(0.75+0.05\left(\frac{0.75}{0.75+0.2}\right)\right)+\left(0.75+0.05\left(\frac{0.75}{0.75+0.2}\right)\right)+\left(0.75+0.05\left(\frac{0.75}{0.75+0.2}\right)\right)+\left(0.5+0.1\left(\frac{0.5}{0.5+0.4}\right)\right)+\left(0.5+0.1\left(\frac{0.5}{0.5+0.4}\right)\right)+\left(0.75+0.05\left(\frac{0.75}{0.75+0.2}\right)\right)+\left(0.5+0.1\left(\frac{0.5}{0.5+0.4}\right)\right)+\left(0.9+0.05\left(\frac{0.975}{0.9+0.05}\right)\right)+\left(0.9+0.05\left(\frac{0.975}{0.9+0.05}\right)\right)} = 0.1051$$

Subsequently, a questionnaire was administered to the 10 experts to score each indicator. This phase was conducted for the final confirmation of criteria. Similar calculations were performed for the remaining criteria. Based on the experts' opinions, criteria that achieved at least 70% of the total importance were confirmed; therefore, the threshold value was set at 0.70. The results indicate that 7 criteria were eliminated and 29 criteria were confirmed.

Table 3

Intuitionistic Fuzzy Delphi Results

Criterion	Sub-criterion	Intuitionistic fuzzy score	Defuzzified score	Status
Financial and economic risks	Fluctuations in global crude oil and petroleum product prices	(0.824, 0.114, 0.061)	0.855	Confirmed
Financial and economic risks	Supply–demand imbalance	(0.795, 0.137, 0.069)	0.829	Confirmed
Financial and economic risks	Market volatility and market conditions	(0.519, 0.385, 0.096)	0.567	Rejected
Financial and economic risks	Increased operating and maintenance costs	(0.783, 0.141, 0.076)	0.821	Confirmed
Financial and economic risks	Investment shortages and project budget constraints	(0.738, 0.181, 0.081)	0.779	Confirmed
Financial and economic risks	Exchange-rate volatility and domestic inflation	(0.657, 0.253, 0.091)	0.702	Confirmed
Financial and economic risks	Financial penalties due to non-compliance with environmental standards	(0.551, 0.346, 0.103)	0.602	Rejected
Financial and economic risks	Changes in government taxation	(0.655, 0.276, 0.069)	0.690	Rejected
Environmental risks	Oil leakage and soil/sea pollution	(0.740, 0.189, 0.072)	0.775	Confirmed
Environmental risks	Pollution and greenhouse gas emissions	(0.721, 0.196, 0.084)	0.762	Confirmed
Environmental risks	Non-compliance with environmental standards	(0.795, 0.137, 0.069)	0.829	Confirmed
Environmental risks	Inefficient management of industrial waste and wastewater	(0.812, 0.120, 0.068)	0.846	Confirmed
Environmental risks	Natural disasters	(0.286, 0.582, 0.132)	0.352	Rejected
Environmental risks	Environmental incidents and biological contamination	(0.383, 0.500, 0.117)	0.441	Rejected
Social risks	Occupational safety and employee health	(0.743, 0.189, 0.068)	0.777	Confirmed
Social risks	Dissatisfaction and protests of the local community	(0.732, 0.197, 0.071)	0.768	Confirmed
Social risks	Health impacts on residents and local/indigenous populations	(0.782, 0.137, 0.081)	0.823	Confirmed
Social risks	Employee dissatisfaction and strikes	(0.760, 0.161, 0.079)	0.800	Confirmed
Social risks	Insufficient employee environmental training and awareness	(0.772, 0.161, 0.068)	0.806	Confirmed
Social risks	Discrimination and inequity in hiring or compensation	(0.529, 0.377, 0.094)	0.576	Rejected
Operational risks	Failure of critical equipment and disruption of drilling and production	(0.678, 0.245, 0.077)	0.716	Confirmed
Operational risks	Weaknesses in preventive maintenance planning and execution	(0.747, 0.174, 0.078)	0.787	Confirmed
Operational risks	Refinery explosions	(0.414, 0.468, 0.117)	0.473	Rejected
Operational risks	Human error and shortage of specialized/skilled workforce	(0.700, 0.218, 0.081)	0.741	Confirmed
Operational risks	Untimely access to spare parts and equipment	(0.722, 0.196, 0.082)	0.763	Confirmed
Operational risks	Inefficient transportation and logistics	(0.696, 0.218, 0.086)	0.739	Confirmed
Operational risks	Disruptions in technologies and smart systems	(0.771, 0.163, 0.066)	0.804	Confirmed
Operational risks	Dependence on foreign technologies	(0.832, 0.105, 0.062)	0.864	Confirmed
Geopolitical risks	International sanctions and export restrictions	(0.839, 0.100, 0.061)	0.870	Confirmed
Geopolitical risks	Government performance	(0.549, 0.361, 0.090)	0.594	Rejected
Geopolitical risks	International policies	(0.791, 0.138, 0.071)	0.827	Confirmed
Geopolitical risks	Political instability in the world and the Persian Gulf region	(0.734, 0.183, 0.082)	0.775	Confirmed
Geopolitical risks	Changes in global energy laws and policies	(0.700, 0.215, 0.085)	0.742	Confirmed
Geopolitical risks	Terrorist attacks on refineries and oil tankers	(0.751, 0.177, 0.072)	0.787	Confirmed
Geopolitical risks	International tensions and risk of military conflict	(0.756, 0.167, 0.077)	0.795	Confirmed
Geopolitical risks	Security and cyber risks	(0.738, 0.193, 0.069)	0.773	Confirmed
Geopolitical risks	Changes in domestic laws and policies and the need for compliance	(0.795, 0.137, 0.069)	0.829	Confirmed

Based on the Intuitionistic Fuzzy Delphi results, 29 sub-criteria across five main dimensions were finally confirmed.

Table 4

Finally Confirmed Factors

Criterion	Sub-criterion	Symbol	Intuitionistic fuzzy score	Defuzzified score	Status
Financial and economic risks	Fluctuations in global crude oil and petroleum product prices	A1	(0.824, 0.114, 0.061)	0.855	Confirmed
Financial and economic risks	Supply–demand imbalance	A2	(0.795, 0.137, 0.069)	0.829	Confirmed
Financial and economic risks	Increased operating and maintenance costs	A3	(0.783, 0.141, 0.076)	0.821	Confirmed
Financial and economic risks	Investment shortages and project budget constraints	A4	(0.738, 0.181, 0.081)	0.779	Confirmed
Financial and economic risks	Exchange-rate volatility and domestic inflation	A5	(0.657, 0.253, 0.091)	0.702	Confirmed
Environmental risks	Oil leakage and soil/sea pollution	B1	(0.740, 0.189, 0.072)	0.775	Confirmed
Environmental risks	Pollution and greenhouse gas emissions	B2	(0.721, 0.196, 0.084)	0.762	Confirmed
Environmental risks	Non-compliance with environmental standards	B3	(0.795, 0.137, 0.069)	0.829	Confirmed
Environmental risks	Inefficient management of industrial waste and wastewater	B4	(0.812, 0.120, 0.068)	0.846	Confirmed
Social risks	Occupational safety and employee health	C1	(0.743, 0.189, 0.068)	0.777	Confirmed
Social risks	Dissatisfaction and protests of the local community	C2	(0.732, 0.197, 0.071)	0.768	Confirmed
Social risks	Health impacts on residents and local/indigenous populations	C3	(0.782, 0.137, 0.081)	0.823	Confirmed
Social risks	Employee dissatisfaction and strikes	C4	(0.760, 0.161, 0.079)	0.800	Confirmed
Social risks	Insufficient employee environmental training and awareness	C5	(0.772, 0.161, 0.068)	0.806	Confirmed
Operational risks	Failure of critical equipment and disruption of drilling and production	D1	(0.678, 0.245, 0.077)	0.716	Confirmed
Operational risks	Weaknesses in preventive maintenance planning and execution	D2	(0.747, 0.174, 0.078)	0.787	Confirmed
Operational risks	Human error and shortage of specialized/skilled workforce	D3	(0.700, 0.218, 0.081)	0.741	Confirmed
Operational risks	Untimely access to spare parts and equipment	D4	(0.722, 0.196, 0.082)	0.763	Confirmed
Operational risks	Inefficient transportation and logistics	D5	(0.696, 0.218, 0.086)	0.739	Confirmed
Operational risks	Disruptions in technologies and smart systems	D6	(0.771, 0.163, 0.066)	0.804	Confirmed
Operational risks	Dependence on foreign technologies	D7	(0.832, 0.105, 0.062)	0.864	Confirmed
Geopolitical risks	International sanctions and export restrictions	E1	(0.839, 0.100, 0.061)	0.870	Confirmed
Geopolitical risks	International policies	E2	(0.791, 0.138, 0.071)	0.827	Confirmed
Geopolitical risks	Political instability in the world and the Persian Gulf region	E3	(0.734, 0.183, 0.082)	0.775	Confirmed
Geopolitical risks	Changes in global energy laws and policies	E4	(0.700, 0.215, 0.085)	0.742	Confirmed
Geopolitical risks	Terrorist attacks on refineries and oil tankers	E5	(0.751, 0.177, 0.072)	0.787	Confirmed
Geopolitical risks	International tensions and risk of military conflict	E6	(0.756, 0.167, 0.077)	0.795	Confirmed
Geopolitical risks	Security and cyber risks	E7	(0.738, 0.193, 0.069)	0.773	Confirmed
Geopolitical risks	Changes in domestic laws and policies and the need for compliance	E8	(0.795, 0.137, 0.069)	0.829	Confirmed

In this section, using a 0–4 scale, the opinions of 10 experts were collected regarding the pairwise influence comparisons among the 29 sub-criteria of the study.

$$\mu = 1 - ((1-0.9)^{0.1051} \times (1-0.75)^{0.1051} \times (1-0.5)^{0.1051} \times (1-0.75)^{0.1051} \times (1-0.5)^{0.074} \times (1-0.75)^{0.074} \times (1-0.5)^{0.1051} \times (1-0.5)^{0.074} \times (1-0.75)^{0.1262} \times (1-0.5)^{0.1262}) = 0.682$$

$$\nu = ((0.1)^{0.1051} \times (0.2)^{0.1051} \times (0.45)^{0.1051} \times (0.2)^{0.1051} \times (0.45)^{0.074} \times (0.2)^{0.074} \times (0.45)^{0.1051} \times (0.45)^{0.074} \times (0.2)^{0.1262} \times (0.45)^{0.1262}) = 0.275$$

$$\pi = 1 - 0.682 - 0.275 = 0.042$$

Next, the intuitionistic fuzzy number is converted into a crisp value as follows:

$$\text{Crisp} = \frac{(0.682 - 0.275 + 1)}{2} = 0.703$$

Table 5

Normalized Matrix

	A1	A2	A3	A4	A5	…	E4	E5	E6	E7	E8
A1	0.000	0.043	0.044	0.044	0.038	…	0.023	0.018	0.020	0.010	0.013
A2	0.024	0.000	0.019	0.024	0.006	…	0.022	0.010	0.018	0.006	0.003
A3	0.017	0.019	0.000	0.027	0.030	…	0.019	0.017	0.023	0.024	0.031
A4	0.030	0.019	0.037	0.000	0.026	…	0.028	0.027	0.030	0.027	0.036
A5	0.018	0.024	0.047	0.043	0.000	…	0.029	0.024	0.032	0.027	0.027
B1	0.014	0.011	0.018	0.028	0.017	…	0.012	0.037	0.022	0.033	0.041
B2	0.013	0.013	0.018	0.026	0.016	…	0.000	0.037	0.023	0.025	0.043
B3	0.013	0.005	0.022	0.042	0.022	…	0.026	0.030	0.029	0.029	0.043
B4	0.011	0.012	0.024	0.033	0.033	…	0.022	0.030	0.028	0.019	0.039
C1	0.000	0.016	0.031	0.040	0.030	…	0.030	0.045	0.034	0.038	0.035
C2	0.025	0.025	0.021	0.030	0.021	…	0.023	0.039	0.034	0.030	0.040
C3	0.000	0.011	0.027	0.028	0.021	…	0.022	0.033	0.021	0.019	0.042
C4	0.018	0.021	0.035	0.036	0.038	…	0.017	0.032	0.031	0.031	0.025
C5	0.011	0.000	0.026	0.029	0.021	…	0.022	0.036	0.025	0.021	0.030
D1	0.023	0.032	0.039	0.032	0.019	…	0.023	0.044	0.036	0.034	0.028
D2	0.014	0.022	0.027	0.032	0.021	…	0.028	0.031	0.026	0.024	0.022
D3	0.030	0.023	0.030	0.033	0.028	…	0.018	0.043	0.030	0.030	0.029
D4	0.022	0.017	0.032	0.038	0.038	…	0.024	0.019	0.030	0.030	0.019
D5	0.023	0.019	0.032	0.027	0.034	…	0.023	0.024	0.018	0.026	0.026
D6	0.023	0.030	0.030	0.028	0.038	…	0.017	0.031	0.017	0.024	0.017
D7	0.019	0.026	0.028	0.035	0.032	…	0.024	0.032	0.027	0.028	0.028
E1	0.040	0.029	0.034	0.044	0.048	…	0.044	0.026	0.042	0.020	0.028
E2	0.037	0.027	0.026	0.025	0.034	…	0.034	0.019	0.041	0.017	0.017
E3	0.041	0.027	0.027	0.029	0.033	…	0.043	0.021	0.051	0.019	0.025
E4	0.031	0.019	0.017	0.022	0.035	…	0.000	0.024	0.031	0.017	0.030
E5	0.008	0.008	0.030	0.027	0.029	…	0.022	0.000	0.039	0.030	0.027
E6	0.031	0.020	0.020	0.036	0.035	…	0.032	0.040	0.000	0.027	0.028
E7	0.010	0.029	0.023	0.030	0.021	…	0.017	0.026	0.035	0.000	0.026
E8	0.021	0.018	0.030	0.030	0.025	…	0.023	0.031	0.026	0.024	0.000

Table 6

Total Relation Matrix (TC)

	A1	A2	A3	A4	A5	…	E4	E5	E6	E7	E8
A1	0.061	0.102	0.125	0.134	0.118	…	0.092	0.102	0.105	0.081	0.094
A2	0.070	0.046	0.082	0.094	0.070	…	0.075	0.076	0.083	0.062	0.066
A3	0.083	0.086	0.094	0.132	0.122	…	0.098	0.116	0.119	0.107	0.125
A4	0.118	0.109	0.162	0.142	0.151	…	0.133	0.160	0.159	0.138	0.163
A5	0.105	0.110	0.166	0.177	0.121	…	0.130	0.151	0.156	0.134	0.149
B1	0.089	0.086	0.125	0.148	0.123	…	0.101	0.151	0.132	0.129	0.151
B2	0.083	0.084	0.118	0.139	0.115	…	0.085	0.143	0.126	0.115	0.146
B3	0.094	0.086	0.135	0.169	0.134	…	0.122	0.151	0.146	0.130	0.159
B4	0.087	0.088	0.132	0.155	0.139	…	0.113	0.146	0.140	0.116	0.149
C1	0.087	0.101	0.151	0.175	0.150	…	0.131	0.174	0.159	0.146	0.159
C2	0.105	0.105	0.134	0.158	0.134	…	0.119	0.159	0.151	0.131	0.156
C3	0.076	0.085	0.133	0.147	0.126	…	0.110	0.146	0.131	0.115	0.151
C4	0.098	0.101	0.148	0.163	0.150	…	0.112	0.151	0.147	0.132	0.140
C5	0.083	0.072	0.127	0.143	0.122	…	0.107	0.144	0.130	0.112	0.134
D1	0.117	0.125	0.170	0.181	0.151	…	0.134	0.184	0.172	0.152	0.163
D2	0.094	0.101	0.138	0.157	0.133	…	0.122	0.150	0.141	0.125	0.136
D3	0.110	0.105	0.145	0.162	0.142	…	0.115	0.164	0.148	0.132	0.146
D4	0.099	0.095	0.141	0.160	0.145	…	0.116	0.134	0.141	0.126	0.129
D5	0.096	0.092	0.134	0.142	0.135	…	0.109	0.132	0.124	0.117	0.130
D6	0.094	0.100	0.130	0.140	0.136	…	0.101	0.136	0.120	0.113	0.118

D7	0.096	0.103	0.135	0.155	0.138	…	0.114	0.144	0.137	0.122	0.135
E1	0.131	0.120	0.161	0.186	0.174	…	0.151	0.159	0.173	0.132	0.155
E2	0.106	0.096	0.121	0.133	0.129	…	0.115	0.119	0.139	0.100	0.112
E3	0.113	0.099	0.127	0.140	0.133	…	0.127	0.124	0.153	0.106	0.124
E4	0.099	0.088	0.112	0.129	0.129	…	0.081	0.124	0.130	0.101	0.124
E5	0.089	0.088	0.143	0.154	0.142	…	0.117	0.122	0.156	0.132	0.143
E6	0.109	0.099	0.130	0.158	0.144	…	0.125	0.155	0.115	0.123	0.138
E7	0.085	0.103	0.127	0.147	0.124	…	0.105	0.137	0.142	0.094	0.132
E8	0.097	0.094	0.137	0.151	0.132	…	0.113	0.146	0.137	0.120	0.112

The values of D and R are computed for each criterion. The index D_i represents the sum of the i-th row, and the index R_i represents the sum of the i-th column of the T_c matrix, with respect to the relevant dimension.

Table 7

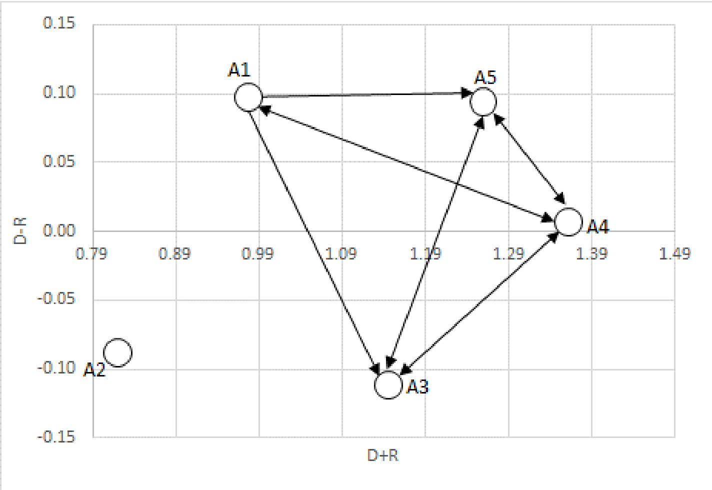
Causal Relationship Pattern of Criteria

Criterion	Sub-criterion	Symbol	Di	Ri	Di+Ri	Di−Ri	Criterion type
Financial and economic risks	Fluctuations in global crude oil and petroleum product prices	A1	0.540	0.437	0.978	0.103	Cause
Financial and economic risks	Supply–demand imbalance	A2	0.363	0.453	0.816	-0.090	Effect
Financial and economic risks	Increased operating and maintenance costs	A3	0.517	0.630	1.146	-0.113	Effect
Financial and economic risks	Investment shortages and project budget constraints	A4	0.683	0.679	1.362	0.004	Cause
Financial and economic risks	Exchange-rate volatility and domestic inflation	A5	0.679	0.582	1.261	0.097	Cause
Environmental risks	Oil leakage and soil/sea pollution	B1	0.568	0.547	1.115	0.021	Cause
Environmental risks	Pollution and greenhouse gas emissions	B2	0.520	0.558	1.077	-0.038	Effect
Environmental risks	Non-compliance with environmental standards	B3	0.574	0.561	1.134	0.013	Cause
Environmental risks	Inefficient management of industrial waste and wastewater	B4	0.548	0.544	1.092	0.004	Cause
Social risks	Occupational safety and employee health	C1	0.761	0.724	1.485	0.037	Cause
Social risks	Dissatisfaction and protests of the local community	C2	0.714	0.735	1.450	-0.021	Effect
Social risks	Health impacts on residents and local/indigenous populations	C3	0.672	0.677	1.349	-0.005	Effect
Social risks	Employee dissatisfaction and strikes	C4	0.709	0.737	1.446	-0.027	Effect
Social risks	Insufficient employee environmental training and awareness	C5	0.643	0.627	1.271	0.016	Cause
Operational risks	Failure of critical equipment and disruption of drilling and production	D1	1.268	1.230	2.498	0.038	Cause
Operational risks	Weaknesses in preventive maintenance planning and execution	D2	1.058	1.112	2.170	-0.054	Effect
Operational risks	Human error and shortage of specialized/skilled workforce	D3	1.058	1.102	2.161	-0.044	Effect
Operational risks	Untimely access to spare parts and equipment	D4	1.028	1.005	2.033	0.023	Cause
Operational risks	Inefficient transportation and logistics	D5	0.967	0.933	1.899	0.034	Cause
Operational risks	Disruptions in technologies and smart systems	D6	0.926	0.927	1.854	-0.001	Neutral
Operational risks	Dependence on foreign technologies	D7	1.000	0.995	1.995	0.005	Neutral
Geopolitical risks	International sanctions and export restrictions	E1	1.249	1.208	2.457	0.040	Cause
Geopolitical risks	International policies	E2	0.959	1.040	2.000	-0.081	Effect
Geopolitical risks	Political instability in the world and the Persian Gulf region	E3	1.031	1.003	2.034	0.027	Cause
Geopolitical risks	Changes in global energy laws and policies	E4	0.956	0.935	1.890	0.021	Cause
Geopolitical risks	Terrorist attacks on refineries and oil tankers	E5	1.075	1.085	2.160	-0.010	Effect
Geopolitical risks	International tensions and risk of military conflict	E6	1.101	1.144	2.245	-0.043	Effect
Geopolitical risks	Security and cyber risks	E7	0.981	0.909	1.890	0.073	Cause
Geopolitical risks	Changes in domestic laws and policies and the need for compliance	E8	1.012	1.040	2.052	-0.027	Effect

Based on the $d + r$ and $d - r$ values, the cause–effect diagram of the criteria is plotted. Among the sub-criteria of financial and economic risks, three risks—fluctuations in global crude oil and petroleum product prices (A1), investment shortages and project budget constraints (A4), and exchange-rate volatility and domestic inflation (A5)—are the most influential risks. The risk of increased operating and maintenance costs (A3) is the most affected (i.e., the most influence-receiving) risk, and it is influenced by these three risks. Although the supply–demand imbalance risk (A2) has an effect (receiver) nature, its degree of influence reception is negligible; therefore, the impacts of other risks on this risk are not considered.

Figure 2

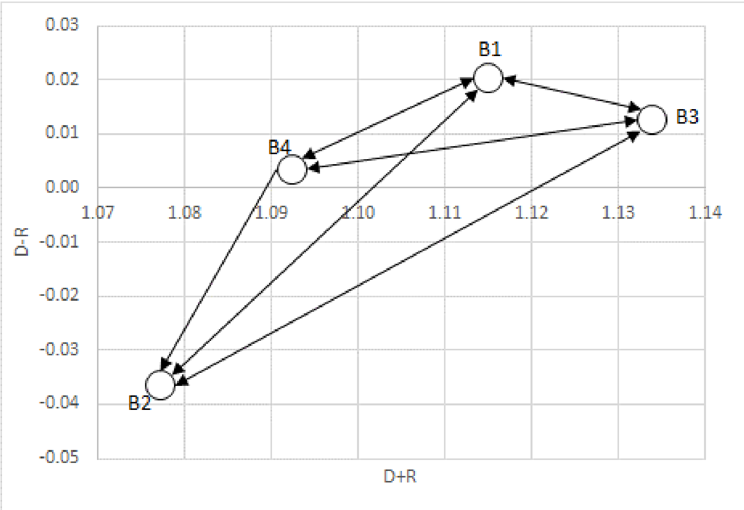
Causal diagram of the sub-criteria of financial and economic risks



Among the sub-criteria of environmental risks, the risk of pollution and greenhouse gas emissions (B2) is the most affected risk, such that the other three risks in this set—oil leakage and soil/sea pollution (B1), non-compliance with environmental standards (B3), and inefficient management of industrial waste and wastewater (B4)—affect this risk. The three risks B1, B3, and B4 also exert mutual influence on one another.

Figure 3

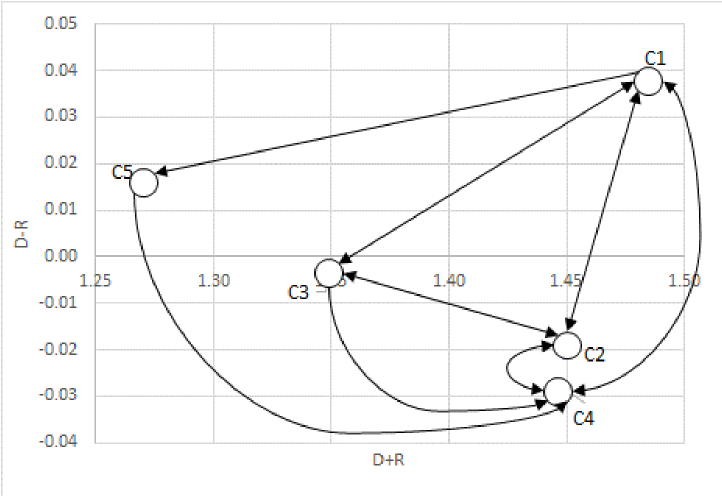
Causal diagram of the sub-criteria of environmental risks



Among the sub-criteria of social risks, the risk of occupational safety and employee health (C1) is the most influential risk and affects all four other risks, namely dissatisfaction and protests of the local community (C2), health impacts on residents and local/indigenous populations (C3), employee dissatisfaction and strikes (C4), and insufficient employee environmental training and awareness (C5). Risk C4 is also the most affected risk, meaning that all risks influence this risk.

Figure 4

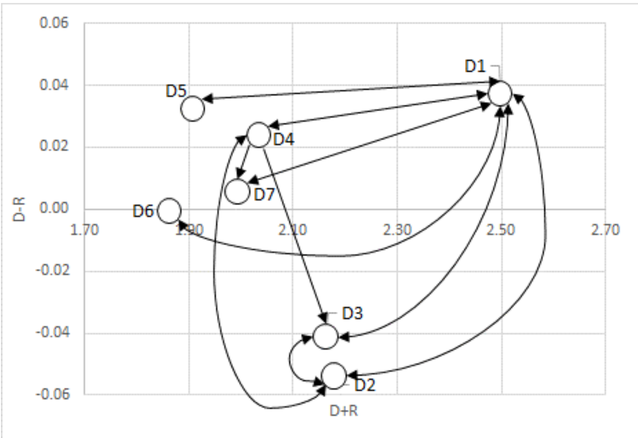
Causal diagram of the sub-criteria of social risks



Among the sub-criteria of operational risks, the risks of failure of critical equipment and disruption of drilling and production (D1), untimely access to spare parts and equipment (D4), and inefficient transportation and logistics (D5) have a causal and influential nature. Risk D1 is the most influential and affects all other risks; it is also influenced by all risks, indicating that it has the highest level of interconnection with the other risks. The two risks of disruptions in technologies and smart systems (D6) and dependence on foreign technologies (D7) have a neutral nature, meaning that their influence exerted and influence received are negligible and approximately equal.

Figure 5

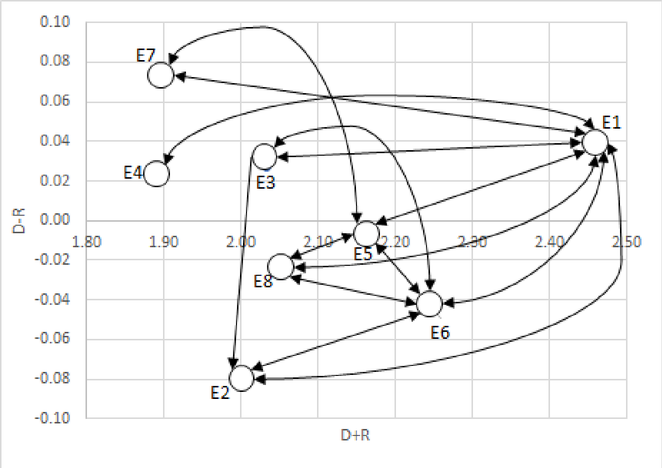
Causal diagram of the sub-criteria of operational risks



Among the sub-criteria of geopolitical risks, the risk of international sanctions and export restrictions (E1) is the most influential risk; it affects the other seven risks in this set and is also influenced by these seven risks, thereby exhibiting the strongest interconnectedness with the other risks. Although the risk of international tensions and the risk of military conflict (E6) has an effect (receiver) nature, it influences all risks except changes in global energy laws and policies (E4) and security and cyber risks (E7).

Figure 6

Causal diagram of the sub-criteria of geopolitical risks



Accordingly, pollution and greenhouse gas emissions ranked first with a weight of 0.0511, non-compliance with environmental standards ranked second with a weight of 0.0504, and oil leakage and soil/sea pollution ranked third with a weight of 0.0499.

Table 8

Relative and Final Weights of the Factors

Main risk	Sub-risk	Symbol	Weight	Rank
Financial and economic risks	Fluctuations in global crude oil and petroleum product prices	A1	0.0284	18
Financial and economic risks	Supply–demand imbalance	A2	0.0283	19
Financial and economic risks	Increased operating and maintenance costs	A3	0.0401	9
Financial and economic risks	Investment shortages and project budget constraints	A4	0.0453	5
Financial and economic risks	Exchange-rate volatility and domestic inflation	A5	0.0397	10
Environmental risks	Oil leakage and soil/sea pollution	B1	0.0499	3
Environmental risks	Pollution and greenhouse gas emissions	B2	0.0511	1
Environmental risks	Non-compliance with environmental standards	B3	0.0504	2
Environmental risks	Inefficient management of industrial waste and wastewater	B4	0.0493	4
Social risks	Occupational safety and employee health	C1	0.0429	8
Social risks	Dissatisfaction and protests of the local community	C2	0.0433	6
Social risks	Health impacts on residents and local/indigenous populations	C3	0.0393	11
Social risks	Employee dissatisfaction and strikes	C4	0.0431	7
Social risks	Insufficient employee environmental training and awareness	C5	0.0362	13
Operational risks	Failure of critical equipment and disruption of drilling and production	D1	0.0362	12
Operational risks	Weaknesses in preventive maintenance planning and execution	D2	0.0334	14
Operational risks	Human error and shortage of specialized/skilled workforce	D3	0.0334	15
Operational risks	Untimely access to spare parts and equipment	D4	0.0296	17
Operational risks	Inefficient transportation and logistics	D5	0.0278	20
Operational risks	Disruptions in technologies and smart systems	D6	0.0277	21
Operational risks	Dependence on foreign technologies	D7	0.0297	16
Geopolitical risks	International sanctions and export restrictions	E1	0.0273	22
Geopolitical risks	International policies	E2	0.0232	26
Geopolitical risks	Political instability in the world and the Persian Gulf region	E3	0.0224	27
Geopolitical risks	Changes in global energy laws and policies	E4	0.0210	29
Geopolitical risks	Terrorist attacks on refineries and oil tankers	E5	0.0267	23
Geopolitical risks	International tensions and the risk of military conflict	E6	0.0259	24
Geopolitical risks	Security and cyber risks	E7	0.0224	28
Geopolitical risks	Changes in domestic laws and policies and the need for compliance	E8	0.0258	25

In order to assess the priority of the risks identified in the previous sections and to compare and align the results with the DANP multi-criteria decision-making approach, the Hanlon method was employed as one of the well-established prioritization techniques in the fields of risk management and industrial health. Accordingly, based on Equation (17), the final Hanlon value for each risk was calculated and is presented in Table 8. After computing the final Basic Priority Rating (BPR) index for the 29 risks identified at Lavan Oil Refinery using the Hanlon method, the results indicated that risks associated with the environmental domain possess the highest level of importance. In this method, four components—risk magnitude, severity of consequences, effectiveness of control measures, and feasibility of intervention—were scored by experts and incorporated into the final Hanlon equation. According to the methodological guidelines, the interpretation of the BPR index is as follows: when the BPR value equals zero, no direct action or operational planning is required; when the BPR value is less than 20, corrective actions should be planned over the long term; when the BPR value falls between 20 and 60, medium-term planning and managerial attention are required; and finally, when the BPR value exceeds 60, immediate, annual, or biennial actions for risk control become absolutely necessary. The computational results of this study showed that the risks of "pollution and greenhouse gas emissions," "non-compliance with environmental standards," "oil leakage and soil/sea pollution," and "inefficient management of industrial waste and wastewater," with BPR values greater than 60, have the highest managerial priority and require the formulation and implementation of immediate control programs. This finding indicates that environmental issues constitute the core challenges of Lavan Oil Refinery, and any negligence in this domain may lead to irreversible damage to the environment, human health, and the waters of the Persian Gulf. Moreover, the implementation of Industry 4.0–based advanced technologies—such as intelligent pollutant monitoring systems, Internet of Things sensors for immediate leak detection, digital twins for simulating pollutant dispersion, and artificial intelligence algorithms for predicting critical conditions—can play a significant role in the rapid and sustainable mitigation of the consequences of these risks. At the next level, risks with BPR values between 40 and 58, such as "investment shortages and budget constraints," "local community dissatisfaction," "employee strikes," "occupational safety and employee health," and certain economic and equipment-related risks, require medium-term planning and evolutionary actions. These risks are often rooted in human, organizational, or economic factors, and their proper management helps prevent secondary environmental consequences and production disruptions. Industry 4.0 technologies can also play an important role in this area, particularly in predictive maintenance, improvement of employees' working conditions, and enhancement of interactions with local stakeholders. In contrast, a group of risks exhibited BPR values below 20 or even equal to zero. These risks—such as "international policies," "macro-level technological disruptions and cybersecurity," "global supply fluctuations," and "changes in regional macro-policies"—are largely dependent on external factors and lie beyond the direct control of refinery management. Therefore, the effectiveness of technology-based corrective actions in this domain is limited, and their operational necessity is assessed as low. Under such conditions, it is recommended that these risks be addressed primarily at the strategic and macro-level energy policy-making arena of the country. Notably, the results obtained from the Hanlon method are fully aligned with those derived from the DANP decision-making method used in the previous stage. In the DANP analysis, environmental risks were also identified as the most influential cluster affecting organizational performance. This consistency confirms the validity and robustness of the research findings and reinforces the necessity of investing in digital transformation technologies for risk management at Lavan Oil Refinery. In other words, the convergence of two independent decision-making methods demonstrates that adopting Industry 4.0–based technological solutions is not merely an optional choice, but rather a strategic imperative for sustaining performance and reducing operational uncertainties at this refinery.

Table 9

Results of the Hanlon Method

Risks	DANP rank	A score	B Urgency	B Severity	B Economic	B Human	B Sum	C score	P	E	A (PEARL)	R	L	D Sum	BPR raw	BPR
Fluctuations in global crude oil and petroleum product prices	18	4	2	2	3	1	8	4	0	0	0	0	0	0	0	0
Supply–demand imbalance	19	4	1	2	2	2	7	4	0	0	0	0	0	0	0	0
Increased operating and maintenance costs	9	7	3	4	5	2	14	7	1	1	1	1	1	5	140	46.7
Investment shortages and project budget constraints	5	9	3	5	5	4	17	9	1	1	1	1	1	5	175	58.3
Exchange-rate volatility and domestic inflation	10	7	3	4	5	2	14	7	1	1	1	1	1	5	140	46.7
Oil leakage and soil/sea pollution	3	10	5	5	4	5	19	10	1	1	1	1	1	5	195	65
Pollution and greenhouse gas emissions	1	10	5	5	4	5	19	10	1	1	1	1	1	5	195	65
Non-compliance with environmental standards	2	10	5	5	4	5	19	10	1	1	1	1	1	5	195	65
Inefficient management of industrial waste and wastewater	4	9	5	5	4	5	19	9	1	1	1	1	1	5	185	61.7
Occupational safety and employee health	8	8	3	4	3	5	15	7	1	1	1	1	1	5	150	50
Local community dissatisfaction and protests	6	8	3	4	4	5	16	7	1	1	1	1	1	5	155	51.7
Health of residents and local populations	11	6	3	3	2	5	13	5	1	1	1	1	1	5	120	40
Employee dissatisfaction and strikes	7	8	3	4	4	5	16	7	1	1	1	1	1	5	155	51.7
Insufficient environmental training and awareness of employees	13	6	2	3	2	4	11	5	1	0	0	0	1	2	44	14.7
Failure of critical equipment and production shutdown	12	6	4	2	4	2	12	6	1	1	1	1	1	5	120	40

Weakness in preventive maintenance planning	14	5	3	2	3	3	11	5	1	0	0	0	1	2	42	14
Human error and shortage of skilled workforce	15	5	3	2	3	2	10	5	1	0	0	0	0	1	20	6.7
Untimely access to spare parts and equipment	17	4	3	2	3	1	9	5	0	0	0	0	0	0	0	0
Inefficient transportation and logistics	20	3	2	1	2	1	6	4	0	0	0	0	0	0	0	0
Disruptions in technologies and smart systems	21	3	2	1	2	1	6	4	0	0	0	0	0	0	0	0
Dependence on foreign technologies	16	5	3	2	3	1	9	5	0	0	0	0	0	0	0	0
International sanctions and export restrictions	22	2	1	2	1	1	5	2	0	0	0	0	1	1	9	3
International policies	26	1	0	1	0	1	2	2	0	0	0	0	0	0	0	0
Political instability in the Persian Gulf region	27	1	0	0	0	1	1	2	0	0	0	0	0	0	0	0
Changes in global energy laws and policies	29	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0
Terrorist attacks on refineries and oil tankers	23	2	1	1	1	1	4	2	0	0	0	0	1	1	8	2.7
International tensions and risk of military conflict	24	2	1	1	1	1	4	2	0	0	0	0	1	1	8	2.7
Security and cyber risks	28	0	0	0	0	1	1	2	0	0	0	0	0	0	0	0
Changes in domestic laws and policies and compliance requirements	25	1	1	1	1	0	3	2	0	0	0	0	0	0	0	0

4. Discussion and Conclusion

The findings of this study provide robust empirical evidence that, under conditions of uncertainty, environmental risks constitute the most critical determinants of organizational performance in Industry 4.0–enabled supply chains. The integrated application of DANP and the Hanlon prioritization method revealed a clear convergence: risks related to environmental pollution, non-compliance with environmental standards, oil leakage, and inefficient waste and wastewater management exhibit the highest causal influence and managerial priority. This result underscores that, in capital-intensive and environmentally sensitive industries, sustainability-related risks are no longer peripheral concerns but core drivers of operational continuity and performance degradation. This observation is strongly aligned with prior studies demonstrating that Industry 4.0 technologies amplify both the visibility and consequences of environmental risks, making their proactive management indispensable for sustainable performance (Belhadi et al., 2021; Ghaithan et al., 2023).

The dominance of environmental risks in the causal structure is theoretically consistent with the dynamic capabilities perspective, which emphasizes the role of sensing and responding to external environmental pressures. Industry 4.0 technologies enhance organizations' ability to detect emissions, leaks, and regulatory deviations in real time; however, when these technologies are insufficiently deployed or poorly integrated, the resulting risks rapidly propagate across the supply chain and undermine performance (Eslami et al., 2024; Fatorachian, 2021). The high DANP weights and Hanlon BPR scores assigned to environmental risks in this study therefore reflect not only their inherent severity but also their strong interdependencies with other risk categories, including operational disruptions, social legitimacy, and financial penalties.

The results further indicate that environmental risks act as primary "cause" factors within the risk network, exerting significant influence on operational and social risks. This finding corroborates earlier research suggesting that environmental incidents often trigger cascading effects, such as production shutdowns, community dissatisfaction, reputational damage, and increased regulatory scrutiny (Ivanov et al., 2019; Tsai et al., 2021). The causal role of environmental risks identified through DANP reinforces the argument that sustainability-oriented risk management must be embedded at the strategic level rather than treated as a compliance-driven function.

From a technological standpoint, the study demonstrates that Industry 4.0 solutions are particularly effective in mitigating high-priority environmental risks. Technologies such as IoT-based monitoring systems, real-time data analytics, and digital twins directly address the dominant risk drivers identified in this research. Prior empirical studies support this interpretation by showing that advanced sensing, analytics, and automation significantly reduce emissions, improve waste management, and enhance regulatory compliance when systematically implemented (Bayanati, 2024; Sahoo & Jakhar, 2024). The alignment between the study's findings and the literature suggests that investments in environmental digitalization yield disproportionate performance benefits relative to other risk domains.

Beyond environmental risks, the study reveals a second tier of risks—primarily social and economic in nature—that require medium-term managerial attention. Risks such as employee dissatisfaction, occupational safety and health, local community protests, and investment constraints exhibited moderate BPR values and mixed causal characteristics. These results highlight the socio-technical nature of Industry 4.0 transformation, where technological upgrades interact closely with human and organizational factors. Previous research emphasizes that the success of Industry 4.0 initiatives depends heavily on organizational learning, leadership, and workforce readiness, particularly in managing human-centered risks (Hossain et al., 2024; Prashar et al., 2023). The findings of this study extend this perspective by demonstrating that social risks are not merely consequences of technological change but active components of the risk network influencing performance outcomes.

Operational risks, including equipment failure, maintenance deficiencies, and logistics inefficiencies, occupied an intermediate position in the prioritization results. While some operational risks exhibited strong causal influence, others were classified as neutral, indicating balanced levels of influence and dependence. This nuanced pattern aligns with earlier studies showing that Industry 4.0 adoption improves operational resilience and predictive maintenance capabilities, thereby reducing the relative severity of traditional operational risks (Kamble et al., 2020; Paraschos et al., 2024). However, the persistence of certain operational risks in the priority structure suggests that technological solutions alone are insufficient without complementary process redesign and managerial coordination.

Geopolitical and macro-level risks, such as international sanctions, global policy shifts, and regional political instability, consistently received the lowest priority scores and were largely categorized as uncontrollable or external. This result is theoretically consistent with the boundary conditions of organizational risk management, as these risks lie beyond the direct influence of firm-level technological interventions. Prior studies similarly note that while digital technologies enhance adaptability, they cannot fully offset exogenous shocks rooted in geopolitical dynamics (Khan & Emon, 2025; Kunkel et al., 2022). The findings therefore support a differentiated risk management approach, where firm-level Industry 4.0 investments are complemented by higher-level policy and institutional strategies for managing external uncertainty.

A key contribution of this study lies in demonstrating the methodological convergence between DANP and the Hanlon method. The consistency of results across these two independent approaches enhances the robustness and credibility of the findings. While DANP captures the structural interdependencies and causal relationships among risks, the Hanlon method translates these insights into actionable managerial priorities. This methodological alignment addresses a recognized gap in the literature, where advanced analytical models often lack practical decision-making relevance (Qureshi, 2023; Rana & Jani, 2023). By integrating these methods, the study provides a comprehensive framework that bridges analytical rigor and managerial applicability.

Overall, the discussion highlights that Industry 4.0–based risk management is most effective when it prioritizes environmental sustainability, acknowledges socio-technical interdependencies, and differentiates between controllable and uncontrollable risks. The findings reinforce the view that digital transformation is not a purely technological endeavor but a strategic process that reshapes risk structures, performance drivers, and sustainability outcomes across the supply chain (Belhadi et al., 2021; Haleem et al., 2023).

The limitations of this study should be acknowledged. First, the empirical analysis was conducted within a single industrial context, which may limit the generalizability of the findings to other sectors or geographical regions. Second, expert judgment played a central role in both DANP and the Hanlon method, introducing the possibility of subjective bias despite the use of structured and validated procedures. Third, the study adopted a cross-sectional design, which restricts the ability to capture dynamic changes in risk priorities over time as Industry 4.0 adoption matures.

Future research is encouraged to extend this work in several directions. Longitudinal studies could examine how risk structures and priorities evolve as organizations deepen their Industry 4.0 capabilities. Comparative studies across industries and countries would further enhance external validity and reveal contextual moderators. In addition, future research could integrate quantitative performance data with expert-based decision models and explore the role of advanced artificial intelligence techniques in automating and refining risk prioritization under uncertainty.

From a practical perspective, the findings offer several actionable insights for managers. Organizations should prioritize environmental digitalization initiatives as a core element of their Industry 4.0 strategies and allocate resources accordingly. Medium-priority social and operational risks require coordinated interventions that combine technological tools with human resource development and stakeholder engagement. Finally, managers should distinguish between risks that can be mitigated through firm-level actions and those that require strategic alignment with policymakers and industry associations, thereby ensuring a balanced and resilient approach to performance management under uncertainty.

Authors' Contributions

Authors contributed equally to this article.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

Acknowledgments

We would like to express our gratitude to all individuals helped us to do the project.

Declaration of Interest

The authors report no conflict of interest.

Funding

According to the authors, this article has no financial support.

Ethics Considerations

In this research, ethical standards including obtaining informed consent, ensuring privacy and confidentiality were considered.

References

Bayanati, M. (2024). Examining Dimensions, Components, and Key Performance Indicators of Information Logistics in Industry 4.0. In *Information Logistics for Organizational Empowerment and Effective Supply Chain Management* (pp. 27-39). IGI Global. https://www.igi-global.com/chapter/examining-dimensions-components-and-key-performance-indicators-of-information-logistics-in-industry-40/334821

Belhadi, A., Kamble, S. S., Gunasekaran, A., & Mani, V. (2021). Analyzing the Mediating Role of Organizational Ambidexterity and Digital Business Transformation on Industry 4.0 Capabilities and Sustainable Supply Chain Performance. *Supply Chain Management an International*

Journal, *27*(6), 696-711. https://doi.org/10.1108/scm-04-2021-0152

Chatterjee, S., Chaudhuri, R., Gupta, S., Kumar Mangla, S., & Kamble, S. (2023). Examining the influence of industry 4.0 in healthcare supply chain performance: Moderating role of environmental dynamism. *Journal of Cleaner Production*, *427*, 139195. https://doi.org/10.1016/j.jclepro.2023.139195

Eslami, M. H., Jafari, H., Achtenhagen, L., Carlbäck, J., & Wong, A. (2024). Financial performance and supply chain dynamic capabilities: the Moderating Role of Industry 4.0 technologies. *International Journal of Production Research*, *62*(22), 8092-8109. https://doi.org/10.1080/00207543.2021.1966850

Fatorachian, H. (2021). Impact of Industry 4.0 on supply chain performance. *Production Planning & Control*, *32*(1), 63-81. https://doi.org/10.1080/09537287.2020.1712487

Fernando, Y., Tseng, M. L., Wahyuni, I. S., & Jabbour, A. B. (2023). Cyber supply chain risk management and performance in industry 4.0 era: information system security practices in Malaysia. *Journal of Industrial and Production Engineering*, *40*(2), 102-116. https://doi.org/10.1080/21681015.2022.2116495

Ghaithan, A. M., Alshammakhi, Y., Mohammed, A., & Mazher, K. M. (2023). Integrated Impact of Circular Economy, Industry 4.0, and Lean Manufacturing on Sustainability Performance of Manufacturing Firms. *International journal of environmental research and public health*, *20*(6), 5119. https://doi.org/10.3390/ijerph20065119

Ghaithan, A. M., Khan, M. A., Mohammed, A., & Hadidi, L. A. (2021). Impact of Industry 4.0 and Lean Manufacturing on the Sustainability Performance of Plastic and Petrochemical Organizations in Saudi Arabia. *Sustainability*, *13*(20), 11252. https://doi.org/10.3390/su132011252

Haleem, A., Javaid, M., Singh, R. P., Suman, R., & Khan, S. (2023). Management 4.0: Concept, applications and advancements. *Sustainable Operations and Computers*, *4*, 10-21. https://doi.org/10.1016/j.susoc.2022.10.002

Hossain, M. I., Kumar, J., Islam, M. T., & Valeri, M. (2024). The interplay among paradoxical leadership, industry 4.0 technologies, organisational ambidexterity, strategic flexibility and corporate sustainable performance in manufacturing SMEs of Malaysia. *European Business Review*, *36*(5), 639-669. https://doi.org/10.1108/EBR-04-2023-0109

Ivanov, D., Dolgui, A., & Sokolov, B. (2019). The impact of digital technology and industry 4.0 on the ripple effect and supply chain risk analytics. *International Journal of Production Research*, *57*(3), 829-846. https://doi.org/10.1080/00207543.2018.1488086

Kalinichenko, L. L., Melnyk, L. H., Matsenko, O. M., Dehtyarova, I. B., & Doroshenko, H. O. (2023). *Personnel risk management based on the cognitive approach in the context of industry 4.0*. Primedia eLaunch. https://doi.org/10.46299/ISG.2023.MONO.ECON.1.3.1

Kamble, S. S., Gunasekaran, A., Ghadge, A., & Raut, R. (2020). A performance measurement system for industry 4.0 enabled smart manufacturing system in SMMEs-A review and empirical investigation. *International Journal of Production Economics*, *229*, 107853. https://doi.org/10.1016/j.ijpe.2020.107853

Karatas, M., Eriskin, L., Deveci, M., Pamucar, D., & Garg, H. (2022). Big Data for Healthcare Industry 4.0: Applications, challenges and future perspectives. *Expert Systems with Applications*, *200*, 116912.

Khan, T., & Emon, M. M. H. (2025). Supply chain performance in the age of Industry 4.0: evidence from manufacturing sector. *Brazilian Journal of Operations & Production Management*, *22*(1), 2434-2434. https://doi.org/10.14488/BJOPM.2434.2025

Kunkel, S., Matthess, M., Xue, B., & Beier, G. (2022). Industry 4.0 in sustainable supply chain collaboration: Insights from an interview study with international buying firms and Chinese supplie rs in the electronics industry. *Resources, Conservation and Recycling*, *182*, 106274. https://doi.org/10.1016/j.resconrec.2022.106274

Paraschos, P. D., Gasteratos, A. C., & Koulouriotis, D. E. (2024). Deep learning model for optimizing control and planning in stochastic manufacturing environments. *Expert Systems with Applications*, *257*, 125075. https://doi.org/10.1016/j.eswa.2024.125075

Prashar, A., Tortorella, G. L., & Sreedharan, V. R. (2023). Role of organizational learning on industry 4.0 awareness and adoption for business performance improvement. *Ieee Transactions on Engineering Management*, *71*, 4904-4917. https://doi.org/10.1109/TEM.2023.3235660

Qureshi, K. M. (2023). Sustainable Manufacturing Supply Chain Performance Enhancement Through Technology Utilization and Process Innovation in Industry 4.0: A SEM-PLS Approach. *Sustainability*, *15*(21), 15388. https://doi.org/10.3390/su152115388

Rana, J. A., & Jani, S. Y. (2023). Enhancing sustainable supply chain performance by adopting sustainable lean six sigma-Industry 4.0 practices. *Management of Environmental Quality: An International Journal*, *34*(4), 1198-1221. https://doi.org/10.1108/MEQ-04-2022-0122

Sahoo, S., & Jakhar, S. K. (2024). Industry 4.0 deployment for circular economy performance-Understanding the role of green procurement and remanufacturing activities. *Business Strategy and the Environment*, *33*(2), 1144-1160. https://doi.org/10.1002/bse.3542

Tortorella, G. L., Prashar, A., Antony, J., Fogliatto, F. s., Gonzalez, v., & Godinho Filho, M. (2024). Industry 4.0 adoption for healthcare supply chain performance during COVID-19 pandemic in Brazil and India: the mediating role of resilience abilities development. *Oper Manag Res*, *17*, 389-405. https://doi.org/10.1007/s12063-023-00366-z

Tsai, F. M., Bui, T.-D., Tseng, M.-L., Ali, M. H., Lim, M. K., & Chiu, A. S. F. (2021). Sustainable supply chain management trends in world regions: A data-driven analysis. *Resources, Conservation and Recycling*, *167*, 105421. https://doi.org/10.1016/j.resconrec.2021.105421