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DEA-driven risk management framework for oil supply chains

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ABSTRACT

This paper develops a comprehensive risk management framework to optimise the Nigerian oil supply chain risk mitigation strategies. Given the complexities of the oil supply chain, this framework aids researchers and decision-makers in navigating innovative risk management approaches and considering the implementation of associated challenges. Data Envelopment Analysis (DEA) is initially employed to prioritise risk factors, and based on obtained results, optimal response strategies are determined. The study's findings reveal that criminality and terrorist attacks are the paramount Nigerian oil supply chain risk factors. Additionally, the research identifies practical mitigation strategies, such as risk transfer, safety planning, alternative energy carriers, improved energy efficiency, emergency rescue plans, expected shortages, and diplomatic relations. This research contributes valuable insights to both academia and industry, fostering a deeper understanding of risk dynamics in the Nigerian oil sector. The framework presented offers a powerful approach to risk management, providing a foundation for informed decision-making and strategic planning in the ever-evolving landscape of supply chain dynamics.

1. Introduction

Several factors, including geopolitical instability, supply chain disruption, price volatility, regulations, cybersecurity, and technological change, have posed uncertainty and risks in the oil (or petroleum) supply chain. Managers and policymakers continuously seek new techniques and policies to enhance risk mitigation strategies in the oil industry. Research in risk management has evolved from simple risk analysis methods to a robust and complex risk assessment in the various public and private sectors (see, e.g., Obayi and Ebrahimi [1]; Thun and Hoening [2], and Amor and Ghorbel [3]). Assessing risks across the oil supply chain remains challenging, and some scholars emphasised the lack of research in the oil industry despite the application of multiple tools and approaches [3,4]. Therefore, it is timely and crucial to undertake research on assessing risks in the oil supply chain. Many national and multinational oil companies have paid attention to minimising the risk using a combination of theories, techniques, and policies [5]. However, previous research has not sufficiently considered the oil industry's risk mitigation policies and strategies to suit the national context [3]. Very few studies observe the impact of risk on people, the environment, and business continuity in the oil supply chain, with a country-specific risk management performance evaluation framework.

The oil supply chain is a significant part of the industrialisation and sustainability of many nations. Despite a global trend toward seeking a greener energy source, there has been a steady increase in the use of oil and gas (fossil fuels) over recent years. However, global energy consumption witnessed a 4% decline in 2020 because of the COVID-19 pandemic, which contrasts 2% increase from 2000 to 2018 [6]. Today, oil and gas account for about 67% of the world's energy consumption, increasing carbon emissions from flaring, energy use, industrial processes, and methane by 5.7% (39.0 GTCO2e) in 2021 [7]. Of this, oil covers about 95% of the global transportation fuel and about 97% of the United Kingdom's transportation fuel [7]. The Nigerian oil supply chain is considered a case study for this research. Nigeria holds about 37.4 billion barrels ($5.91 \times 109\ m^3$) of proven oil reserves as of 2018, ranking Nigeria as the major oil producer in Africa. According to the Nigerian Department of Petroleum Resources, Nigeria currently operates 159 oil fields and 1481 oil wells in the coastal Niger Delta Basin of the Niger

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Delta region [8]. This Research identifies, evaluates, and ranks the risks in the Nigerian petroleum supply chain to optimise the risk mitigation strategies for decision-makers.

In this paper, we evaluate the risk factors, their causes, mitigation strategies, and challenges in implementing these strategies in the Nigerian oil supply chain. To this end, we first identify the significant risk factors through a systematic literature review and expert opinions from the Nigerian oil industry. We then evaluate the impact of these risk factors on people, the environment, and business continuity based on their severity, probability of occurrence, and detectability through expert questionnaires and interviews. This study employs a two-step approach to analyse both qualitative and quantitative data. Initially, Data Envelopment Analysis (DEA) and Failure Mode and Effect Analysis (FMEA) are applied to analyse the qualitative data. Subsequently, thematic analysis is used to study the quantitative results derived from the initial step. The main research questions addressed in this study include (i) what are the key risk factors in the Nigerian oil supply chain? (ii) how do we evaluate the identified risk factors? (iii) what are the risk mitigation strategies for the Nigerian oil supply chain? and (iv) what are the challenges of implementing these risk mitigation strategies?

The structure of this paper is as follows. Section 2 presents the related literature review. Section 3 discusses the methodology adopted for the current research. Section 4 explains the case study, presents quantitative result, and validates them using a qualitative approach. Section 5 discusses results and challenges of implementing the identified risk mitigation strategies. Finally, our paper concludes with a summary in Section 6.

2. Literature review

Supply Chain Risk Management (SCRM) plays a significant role in ensuring safe, proactive, and innovative performance [9,10]. Companies' interest in managing risk emanates from globalisation, information technology, process control, demand, supply, infrastructure, and environmental concerns [11]. Lavastre et al. [11] described SCRM as strategic and operational horizons for both short-term and long-term risk assessment. However, Baryannis et al. [12] and Senna et al. [13] affirmed that while there is no universally agreed definition of SCRM, however, there is consensus that risk identification, evaluation, mitigation, and monitoring are critical components of risk management. Guo et al. [14] suggested viewing risk factors as elements that increase the probability of disruptions. Abbasi et al. [15] categorised prevalent risks within the supply chain into four main groups: environmental, political, economic, and ethical. Choudhary et al. [16] built upon Katsaliaki et al.'s [17] review by emphasising various parameters, analytical methodologies, and attributes inherent in multi-criteria decision-making techniques for assessing supply chain risks. Emrouznejad et al. [18] presented a systematic literature review to explore various risks within supply chains and discuss strategies for their assessment and mitigation.

The oil supply chain is a complex network of infrastructures and processes that begins with crude oil exploration and ends with the distribution of petroleum products to consumers [3]. Cigolini and Rossi [19] and Fernandes et al. [20] classified the oil supply chain into three stages: the upstream, midstream, and downstream. Besides, they stressed that the upstream stage comprises crude oil exploration, production, and transportation. The midstream stage mostly focuses on transportation of crude oil and its products, and the downstream stage includes refining, transportation, storage, distribution, and retail activities. Fig. 1 shows a classification of the oil supply chain.

2.1. SCRM in the oil industry

Researchers have speculated that supply chain risk issues are similar for countries highly dependent on oil exports, yet the risks associated with supply dependence lack clarity [3]. Kumar and Barua [21] proposed a fuzzy TOPSIS method to evaluate the performance of the Indian petroleum supply chain. Their findings suggest product purity, compliance with environmental laws, and adoption of new technologies as the top three performance measurement criteria in the oil industry. Fernandes et al. [20] identified operational risks emanated from third parties, construction failure, corrosion, and ground movement in the oil supply chain. Mohamed Said et al. [22] identified the risks associated with the flow of petroleum products and applied Analytic Hierarchy Process (AHP) and Weighted Performance Measurement (WPM) to evaluate the performance of the petroleum supply chains of the Algerian state-owned oil company, NAFTAL.

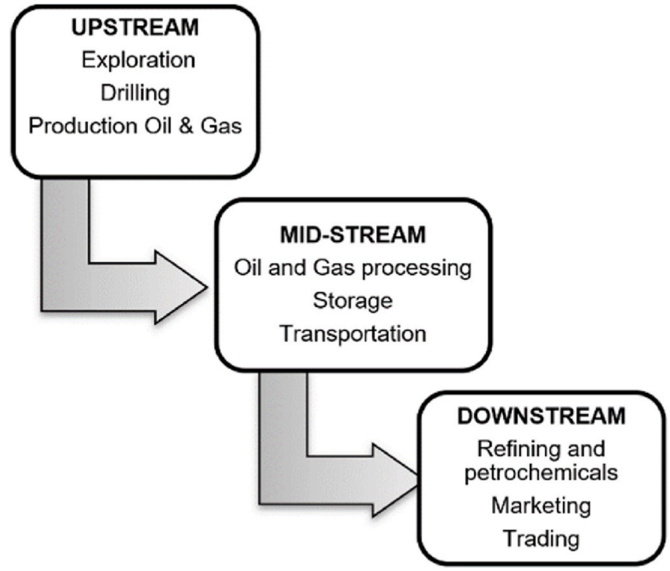

Fig. 1. Classification of the oil supply chain.

Agu and Omolade [23] used the Participatory Development Strategy Approach (PDSA) to collect opinions from 1260 stakeholders across the six Africa's Oil Exporting Countries (AOECs) to examine their views on economic revival post-COVID-19. Their findings suggest that rebuilding AOECs post-COVID-19 requires a mixture of government and private sector involvement. Lochner and Dieckhöner [24] inferred that political instability is a significant source of risk in high conflict areas such as Libya. Villada and Olaya [25] proposed a simulation approach to address the complexity of the oil and gas supply chain. Their findings showed that the oil price elasticity, demand fluctuations, regulations, political stability of oil exporter countries, external environmental factors, and technical issues are the main factors causing this complexity. Oliveira et al. [26] presented a decomposition framework based on Lagrangean decomposition for tackling multi-product, multi-period, and supply investment planning problems through network design and discrete capacity expansion under demand uncertainties. Their study considered logistic cost, demand forecasting, and inventory policies as the key determinants for optimising the profitability of petroleum supply chains. In analysing the Iranian crude oil supply chain, Fazli et al. [27] applied DEMATEL-ANP to classify oil supply chain risks into five groups; (a) demand-side risks such as market dynamics, transportation challenges, and competition, (b) supply-side risks such as exploration, drilling, production, and quality issues, (c) regulation risks such as governmental policies, international actions, (d) infrastructure risks such as machine failure and information security, and (e) disaster risks such as the risk of natural disasters, terrorist activities, and social-political instability.

van Moerkerk and Crijns-Graus [28] analysed external oil supply risks for the five largest oil-importing regions/countries, including European Union (EU), the United States, Japan, China, and India. Their study suggested that risk significantly increases if must-have climate change policies are not implemented. Nsikan et al. [29] surveyed 284 supply chain executives from 38 oil and gas marketing and logistics firms in Nigeria's downstream petroleum industry to identify disruption drivers and mitigation strategies. They concluded that top five disruption drivers are poor quality of the supply chain information, third-party logistics outsourcing, inadequate critical storage infrastructure, inaccurate product demand forecasts, and poor inventory visibility. The study also identified flexible supply chains, collaborative outsourcing, efficient management of petroleum products inventory management, and supply chain relationship coordination as top mitigating strategies. Obasanjo et al. [30] suggested risk mitigation strategies in the petroleum refinery operations, including the regulation of tankers operations, governmental actions to reduce insecurity in Nigeria, and the formulation of more profitable modes of transportation. Yanting and Liyun [31] reckoned that major risks in the petroleum industry involve economic losses and environmental pollution, originating from the high-risk nature of petroleum operations. Last but not least, Capolei et al. [32] reviewed various risk measures in the petroleum industry and identified conditional value at risk and the worst-case scenario as effective measures to reduce risk.

In the Gulf of Mexico's outer continental shelf region (GOMR), Lavasani et al. [33] analysed leakage through permanently abandoned oil and natural gas wells in drilling companies by utilising Fuzzy Fault Tree Analysis (FFTA). Cheliyan and Bhattacharyya [34] conducted a risk assessment using Event Tree Analysis (ETA) to identify the failure of leakage detection as the leading cause of equipment fires in offshore installations. Similarly, uncertainties resulting from leaks in subsea pipelines pose severe threats to humans, the environment, infrastructure, and corporate reputation. In that regard, Li et al. [35] conducted a dynamic risk assessment of subsea oil pipeline leaks to resolve catholic protection failure, design and construction effect flaws, attachment ageing, insufficient buried depth of the pipeline, and oil theft as leading causes of subsea pipeline failures. Considering the distribution of petroleum products, dynamic uncertainty such as transport tariff regimes imposed by regulators is a pivotal factor [3]. Potočnik et al. [36] showed that errors in demand forecasts could pose risks to demadistribution of petroleum products. Further, Pelletier and Wortmann [37] considered tariff policies, demand volatility, and production levels as considerable risk factors in petroleum product distribution. Risk factors directly impacting people are significant challenges in the distribution of oil and gas in both developing and underdeveloped countries. For instance, in Nigeria, distribution companies encounter pipeline sabotage, oil theft under an unstable political environment, and frequent explosions (accidents) of road tankers carrying petroleum products [3]. Vidmar and Perkovič [38] demonstrated that risks in distributing petroleum products through tankers result in collisions, groundings, fires/explosions, and structural failures.

2.2. DEA literature

DEA is a mathematical programming technique used to measure relative efficiency of a set of decision-making units (DMUs). The history of DEA dates back to Debreu [39] and Farrell [40], who introduced the basic frontier production model that measures efficiency with multiple inputs and single outputs. Charnes et al. [41] extended the DEA model to multiple inputs, multiple outputs. DEA models and their application have been widely developed and applied across varying fields [42,43]. DEA has recently gained much attention from researchers and practitioners for analysing and ranking risks in the supply chain; however, its application in the oil industry remains scarce. For instance, Sueyoshi [44] proposed a stochastic DEA model for restructuring strategies of the Japanese petroleum industry to express the link between the stochastic DEA and actual decision-making for future planning.

Sadjadi et al. [45] proposed a DEA model incorporating the robust counterpart of super-efficiency DEA to deal with the shortcomings related to the probability distribution for inputs and outputs. Their model was used for ranking petroleum companies in Iran to support decision-making. Al-Najjar and Al-Jaybajy [46] employed DEA to measure the relative efficiency of petroleum refineries in Iraq from 2009 to 2010. Cosme Bezerra et al. [47] reviewed the application of DEA in the petroleum industry to assess the efficiency of conflicting variables for planning and decision-making. The authors emphasised that DEA is a powerful tool in evaluating oil refinery efficiency, environmental efficiency, and the efficiency of environmental management practices. Their recommendations show that DEA is effective in petroleum industry engineering, exploration and exploitation, automation, and environmental analysis.

Yousefi et al. [43] presented an integrated robust DEA-FMEA approach to evaluate and prioritise Health, Safety, and Environment (HSE) risks in manufacturing industries to overcome the setback of the traditional Risk Priority Number (RPN) scoring method. Tavana et al. [48] applied a network DEA for the Malmquist Productivity Index (MPI) to examine the productivity change within Iran's oil and gas supply chain. Sharahi et al. [49] measured the relative efficiency of various Iranian gas supply chain stages including production, transmission, and distribution using Network DEA over a five-year time period. Nasri et al. [50] proposed a hybrid approach to assess suppliers' performance in the Iranian petroleum industry. This novel method combines fuzzy DEMATEL, analytic network process, DEA, and Anderson-Peterson methods. Their study aimed to find and rank sustainable suppliers, considering the environmental effects, social impact and business performance. Dalei and Joshi [51] undertook a two-stage performance evaluation of seven Indian oil refineries. In the first stage, they applied a VRS-DEA model to measure the performance of oil refineries. In the second stage, they used the Ordinary Least Square (OLS) regression, random effect Generalized Least Square (GLS) regression and Tobit regression models to study the impact of external factors on operational efficiency. Hatami-Marbini et al. [52] developed a DEA-based framework to measure the efficiency and productivity of 25 countries with high refining capacity over the period 2000–2018 under data uncertainty. CO_2 emissions were identified as an undesirable output to ensure environmental efficiency and productivity analysis. Their result shows that the price of robustness varies based on technologies when assessing productivity in the global oil market, and the US oil industry has the highest productivity growth in all cases, confirming its efforts for the rapid rise in oil extraction and production at low costs.

In summary, early indications suggest that applying DEA in the oil and petroleum industry for performance evaluation is productive and beneficial. Thus, the current research focuses on applying DEA to assess, rank and prioritise the significant risk factors in the petroleum industry supply chain for effective decision and policy making. This research seeks to apply DEA in the oil industry risk evaluation, which is complex due to the presence of numerous factors and their interdependencies.

3. Research methodology

The current study adopts both qualitative and quantitative methods to collect data and evaluate risks across a three-echelon Nigerian oil supply chain, including the supply, production, and distribution stages. Some Nigerian oil supply chain researchers, such as Nsikan et al. [29], assessed the oil petroleum supply chain's downstream sector (i.e., distribution). However, the current research attempts to evaluate the overall Nigerian oil supply chain risks to provide a wide range of decision-making and mitigation strategies. The present study scrutinises literature on global oil supply chain risks and incorporates the opinions of Nigerian oil industry practitioners to identify 28 significant risk factors associated with the oil supply chain (See Table 1). Besides the inputs provided by participants for risk identification, potential risk factors are obtained from relevant literature on Nigerian and global petroleum supply chain risks (see e.g., Fazli et al. [27]; Yeeles and Akporiaye [53]; Nsikan et al. [29]; Kumar and Barua [54]).

Table 1
Identified risk factors in the Nigerian oil supply chain.

DMUs	Description	Source	Author
R01	Market risk	LR[a]	Fazli et al. [27]
R02	Transportation risk	LR	Fazli et al. [27], Briggs [55], Li et al. [56], Vidmar and Perkovič [38]
R03	Transportation mode	LR	Pelletier and Wortmann [37], Vidmar and Perkovič [38], Zhou et al. [57],
R04	Socio-political instability	LR	Yeeles and Akporiaye [53], Fazli et al. [27]
R05	Inventory control risk	LR	Nsikan et al. [29], Oliveira et al. [26]
R06	Logistic risk	LR	Oliveira et al. [26], Oliveira and Hamacher [26]
R07	International action risk	LR	Fazli et al. [27]
R08	Environmental risk	LR	Yanting and Liyun [31]
R09	Exploration and drilling risk	LR	Aven and Zio [58], Fazli et al. [27], Yeeles and Akporiaye [53]
R10	Crude oil reserve risk	PI[b]	N/A
R11	Explosions risk	LR	Zhou et al. [57], Pelletier and Wortmann [37], Vidmar and Perkovič [38], Srivastava and Gupta [4]
R12	Host community risk	LR	Yeeles and Akporiaye [53]
R13	Machinery risk	LR	Fazli et al. [27], Won et al. (2013)
R14	Information technology risk	LR	Nsikan et al. [29], Lavastre et al. [11], Srivastava and Gupta [4], Sa'idi et al. [59]
R15	Design and construction failure	LR	Li et al. [35], Shi et al. [60], Lu et al. [61]
R16	Energy consumption risk	LR	Zhao and Chen [62]
R17	Criminality and terrorist attacks on an oil facility	LR	Jüttner [63], Fattouh [64], Doukas et al. [65], Fazli et al. [27]
R18	Storage penalisation	LR	Lababidi et al. [66], Husain et al. [67]
R19	Natural disaster	LR	Aydin et al. [68], Blome and Schoenherr [69]
R20	Permanently abandon oil well	LR	Fazli et al. [27]
R21	Risk of competition	LR	Fazli et al. [27]
R22	Government decision-related risk	LR	Fazli et al. [27]
R23	Import dependent risk	LR	Wagner and Bode [70]
R24	Quality risk	LR	Fazli et al. [27]
R25	Toxic circulation risk	LR	Zhou et al. [57]
R26	Kidnapping of personnel	PI	N/A
R27	Labour union strike action	PI	N/A
R28	Unskilled labour	PI	N/A

[a] LR: Literature Review.
[b] PI: Participant Inputs.

3.1. Inputs and outputs variables

In this study, a DEA model with multiple inputs and outputs (see Tables 2 and 3) is applied to evaluate and prioritise the identified risk factors. The input and output variables are identified and verified by experts during the pilot study for further risk evaluation. The inputs are based upon indicators used in FMEA, including the severity of risk, probability of occurrence, and risk detection. FMEA is functional across multi-disciplinary organisations to recognise failure modes, assess risk, and prioritise appropriate corrective actions [71]. Traditionally, FMEA is assessed using the Risk Priority Number (RPN), calculated as "RPN=S × O × D″ where S is the severity of the failure, O is the probability of occurrence, and D is the detectability of the failure.

In most cases, failure ranking with a higher RPN value is critical and requires more attention [71]. The current study considers the RPN indicators as the input variables of the DEA model, evaluated by experts using the scoring pattern in Table 2. Chin et al. [72] assumed that scoring risk factors to determine the RPN applies to any organisation involved in risk ranking, which is a view supported by Yousefi et al. [43], Chin et al. [72], and Subriadi and Najwa [73]. The key advantage of FEMA-RPN is its effectiveness as a powerful risk assessment tool, allowing a team of practitioners to assigna numeric value to each failure mode that helps quantify the likelihood of occurrence, the likelihood of detection, and the severity of impact [74,75]. FMEA-RPN also includes other advantages, notably through the incorporation of expert evaluation, which enhances the depth and accuracy of the information conveyed [76].

The output variables—people, the environment, and business continuity—are the significant indicators in the oil supply chain most impacted by threats. Maslow and Herzberg both articulated that the primary aim of any organisation, irrespective of its nature, should be to address fundamental human needs for a meaningful existence [77]. Similarly, EIA [78] suggested that *"although petroleum products make life easier, finding, producing, and moving crude oil may negatively affect the environment"*, making the environment an essential indicator in the petroleum supply chain. Furthermore, these output variables align with Hafeez et al. [79] and Shafiq et al. [80]'s studies on Total Quality Management (TQM), showing that people, the environment, and operations play a vital role in ensuring the continuity of business performance. Business continuity supports the organisation's resilience in responding quickly to interruptions. Effective business continuity management saves money, time, and the company's reputation [81]. Table 4 gives the definitions of input and output variables.

The data collection methods include questionnaire surveys and interviews with participants, including supply chain managers, petroleum engineers, risk managers, and top management of the Nigerian oil industry, all of whom have more than seven years of experience. The questionnaire derived from risk factors from the above-mentioned literature, is pre-tested using feedback from three Nigerian oil supply

Table 2
Scoring RPN (input) factors.

Rating	Inputs		
	Severity	Occurrence	Detection
9	Very high risk	High >1 in 10	Very remote
7	High risk	High >2 in 25	Remote detection
5	Moderately	Moderate: occasional failure	Moderate detection
3	Low risk	Low occurrence	High detection
1	Very low risk	Relatively low	Very high detection

Table 3
Scoring impact (output) factors.

Rating	Outputs		
	Impact on people	Impact on environment	Impact on business continuity
9	Very high	Very high	Very high
7	High	High	High
5	Moderate	Moderate	Moderate
3	Little	Little	Little
1	Very little	Very little	Very little

Table 4
Description of inputs and outputs variables.

Inputs		
Variables		Definitions
Input 1	Severity of risk	Describing the potential damage levels arising from uncertainties related to a particular hazard. Severity ranges from catastrophic (severe and widespread consequences) to negligible (minimal impact).
Input 2	Probability of occurrence	Indicating the likelihood of a risk occurring, often categorised from very unlikely to very likely.
Input 3	Probability of detecting risk	Measuring the likelihood of detecting a failure before it causes harm. Risk detection ensures that potential threats or actual failures are recognised in advance, enabling timely corrective action to prevent organisational impacts.
Outputs Variables		**Definitions**
Output 1	Impact on people	The risks associated with the petroleum supply chain can potentially affect stakeholders, shareholders, or the general population, either directly or indirectly.
Output 2	Impact on the Environment	The environmental impact of risks within the oil industry encompasses the geographical areas that may be affected, including both living organisms and the non-living components within those areas.
Output 3	Impact on Business Continuity	The potential effect of risks associated with the petroleum supply chain could disrupt normal operations and continuity of business activities.

chain experts, including one academic at the University of Petroleum in Nigeria and two professionals with extensive industry experience in the Nigerian oil supply chain. These experts have practical knowledge and experience in the Nigerian oil supply chain. Through the questionnaire survey and semi-structured interviews, experts and academics were tasked with assessing the severity, probability, and detectability of each risk presented in Table 1, utilising a Likert scale ranging from 1 to 9, as detailed in Tables 2 and 3. For instance, experts and academics are prompted to evaluate the severity, occurrence probability, and detection likelihood of “market risk”, assigning ratings on a scale from 1 to 9. Regarding the outputs, participants are requested to measure the impact of each risk on people, the environment, and business continuity, employing a scale ranging from 1 to 9 as outlined in Table 3. Here, 9, 7, 5, 3 and 1 indicate “Very High”, “High”, “Moderate”, “Little”, and “Very Little”, respectively.

3.2. DEA and thematic analysis

In DEA, DMUs include a diverse range of entities such as schools, banks, hospitals, oil industries, and organisational sectors. In this study, the risk factors are considered as the DMUs. The DEA model ranks all DMUs on a single scale, allowing for the identification of the best-performing DMUs that serve as benchmarks for those with inferior performance [82]. The mathematical details of the DEA model are provided in Appendix 1. Various DEA models, including extensions, can enhance risk management in the oil supply chain [83]. This research focuses on the input-oriented DEA model under Constant Returns to Scale (CRS). This choice aligns with the situation of our case study where increasing input variables often leads to proportional output increases. Input orientation is preferred because it allows for controlling input variables, aiding decision-makers in mitigating critical risks to achieve evaluation objectives.

This study proposes a DEA-based approach to rank and prioritise the risk factors. The proposed approach enhances the traditional DEA model by incorporating FMEA-RPN indicators as inputs of risk factors (DMUs) impacting people, the environment, and business continuity. The input and output data for the DEA model have been collected from the Nigerian oil supply chain operators comprising public and private petroleum companies operating in Nigeria. The data has been collected in two steps; (i) a questionnaire survey is set to gather judgmental data used to collect the DEA variables for risk assessment, and (ii) semi-structured interviews are conducted to validate the findings and explore the risk mitigation strategies using thematic analysis.

In brief, the first stage of this case study is to identify the potential risk factors in the Nigerian oil supply chain. Secondly, Nigerian oil supply chain experts allocate input and output values through a survey questionnaire.[1] The results from the DEA-based model help us rank and prioritise the significant risk factors in the Nigerian oil supply chain and, thereby facilitating decisions on mitigation actions. Notably, the management team should pay more attention to the risks with higher input values because they negatively impact the supply chain performance.

The next step involves using semi-structured interviews to validate the questionnaire findings and further assess the challenges of implementing the proposed mitigation strategies. The interview data is analysed using thematic analysis, which is the process of identifying patterns and relationships extracted from qualitative data. One of the advantages of thematic analysis is that it is more of a method than a methodology, as it is not tied to any epistemological perspective, making it flexible [84]. This work adopts the six discrete stages of the thematic analysis model proposed by Braun and Clarke [84], which includes familiarising ourselves with the dataset, generating initial codes, searching for themes, reviewing themes, defining and naming themes, and producing the report. The current study proposes ten interviews with ten participants. However, eight participants successfully attend and complete the interview process to validate the quantitative findings and identify the causes and impacts of risk, including mitigation strategies and the challenges of implementing these strategies.

4. Case study

The oil industry supply chain is a main contributor to the Nigerian economy while it faces various risks such as shortages of refined petroleum products, crude oil theft, and poor national transportation of these products [29]. A total of 28 risk factors, reported in Table 1, is identified from the supply, production, and distribution stages of the Nigerian oil supply chain. Two hundred seventy-two (272) potential respondents receive the link to the questionnaire. Fifty-five respondents complete and submit the questionnaire, resulting in a response rate of 20.22%. The questionnaires are distributed online from January 2020 to April 2021 during the COVID-19 pandemic. The online questionnaire link is shared via emails and various social media platforms such as WhatsApp, Facebook Messenger, LinkedIn, and Instagram.

The risk management framework is a standard guideline outlining processes for effective risk management to enhance system performance. Fig. 2 presents the steps proposed in our paper to manage the oil supply chain risks.

The first step is to identify potential risk factors. Recognising these factors is vital for enhancing the risk management plan. Many researchers, including Fazli et al. [27] and Yousefi et al. [43], support this process of risk identification. The risk evaluation that constitutes the second step capture the important events related to identified risk factors, including their causes, likelihood, and impact. These parameters can be assessed using various measurement scales (such as Likert scale) by industry experts with substantial experience. In the third step, literature review, historical data, and expert opinions are some method for identifying risk mitigation strategies. Finally, continuous monitoring,

[1] The questionnaire can be found in https://forms.office.com/Pages/ResponsePage.aspx?id=48B4T1DS3027HBXTFFaXzAxBZ2NagyJIrY9iaB2VGAlUOE5YSFVIRFpRTUUwRjRYQ0s2SkhKSVBPNi4u.

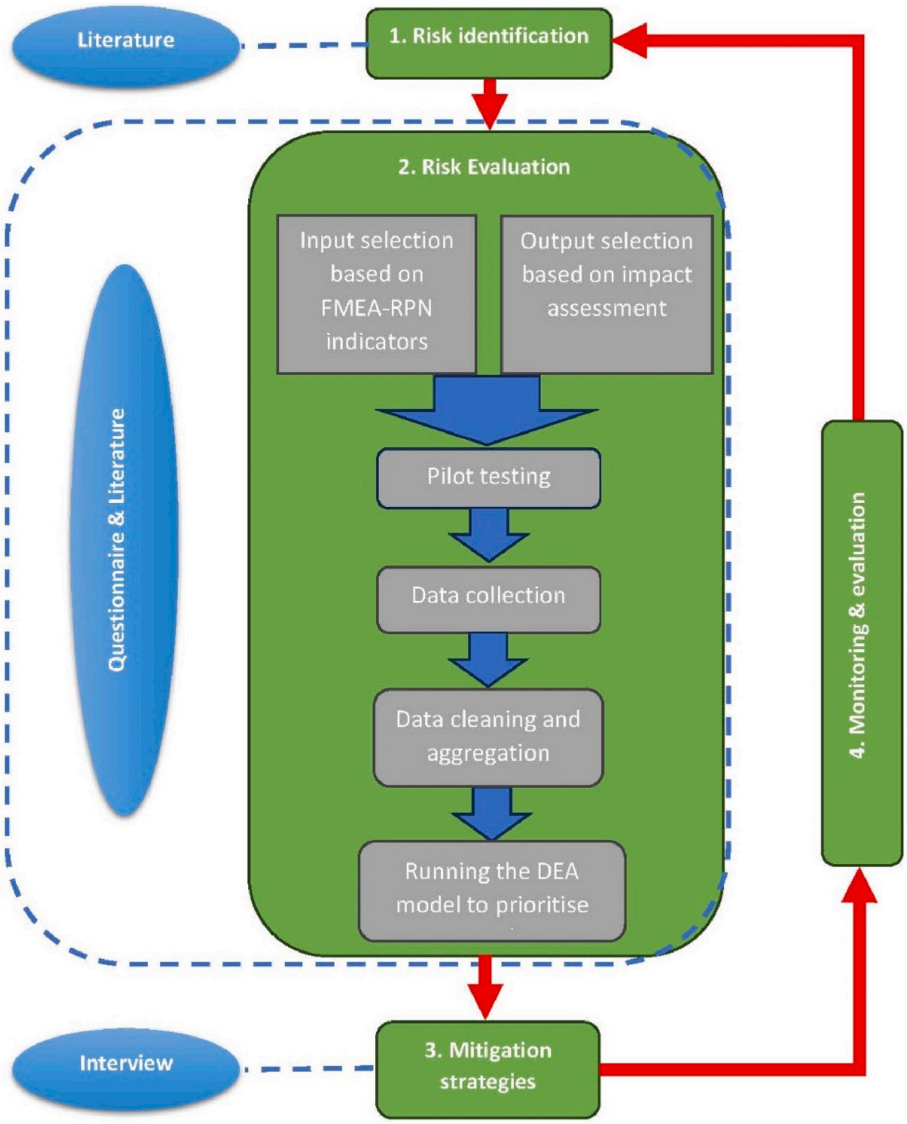

Fig. 2. Risk management steps for the Nigerian oil supply chain.

evaluation and reporting of risks are vital for organisational performance, ensuring that controls are effective and efficient at all stages of the risk management process.

4.1. Key findings

The raw data from the survey questionnaire, collected using the measurements illustrated in Tables 2 and 3, provide scores from experts' opinions for relevant inputs and outputs. The datasets are aggregated by averaging participant responses (scores) obtained from individual input and output scores. Table 5 presents the descriptive statistics of the input and output data.

Table 5
Descriptive statistics of input and output data.

Data	Min	Mean	Median	Sd.	Max
Input 1	5.13	6.04	5.84	0.63	7.38
Input 2	3.76	5.02	5.46	0.87	7.08
Input 3	1.00	1.50	1.31	0.62	3.10
Output 1	1.00	2.50	2.71	0.89	4.75
Output 2	1.00	3.19	3.02	1.30	4.84
Output 3	1.00	2.21	2.41	0.61	3.22

The performance scores of DMUs vary between 0 and 1. Given the measured scores from the DEA model, we classify the risk factors (DMUs) in the Nigerian oil supply chain into three groups; (i) highly performed DMUs with a score of 1 (green colour in Table 6), (ii) moderately performed DMUs with a score ranging from 0.65 to 0.99 (amber colour in Table 6), and (iii) low-performance DMUs with a score ranging from 0 to 0.649 (red colour in Table 6). Table 6 shows that 8 of the 28 risk factors, including international action risk (R07), crude oil reserve (R10), information technology risk (R14), energy consumption risk (R16), storage penalisation (R18), permanently abandoned oil wells (R20), government decision risk (R22), and the risk of competition (R21) have a performance score of 1. Resultantly, 29% of all DMUs exhibit significantly high performance in their risk management strategies, while 71% show varying performance scores. The findings also show that 15 of the 28 DMUs have a moderate performance score ranging from 0.65 to 0.99 (see Table 6). This category of DMUs requires some effort to significantly improve their performance in risk management strategies. Lastly, criminality and terrorist attacks (R17), explosions risk (R11), logistic risk (R06), and environmental risk (R08) have significantly low-performance scores ranging from 0 to 0.65. The last column on the right-hand side of Table 6 also shows the priority (rank) of each DMU, where a lower rank signifies high priority, while a higher

Table 6
Performance distribution for risk mitigation in the Nigerian oil supply chain.

DMUs	Description	Performance Score	Priority (Rank)
R01	Market risk	0.963	19
R02	Transportation risk	0.699	6
R03	Transportation mode	0.743	7
R04	Socio-political instability	0.747	8
R05	Inventory control risk	0.978	20
R06	Logistics risk	0.570	3
R07	International action risk	1	21
R08	Environmental risk	0.642	4
R09	Exploration and drilling risk	0.749	9
R10	Crude oil reserve risk	1	21
R11	Explosions risk	0.2801	2
R12	Host community risk	0.689	5
R13	Machinery risk	0.898	16
R14	Information technology risk	1	21
R15	Design and construction failure	0.859	15
R16	Energy consumption risk	1	21
R17	Criminality and terrorist attacks on oil facilities	0.270	1
R18	Storage penalisation	1	21
R19	Natural disaster	0.835	14
R20	Permanently abandon oil wells	1	21
R21	Risk of competition	1	21
R22	Government decision-related risk	1	21
R23	Import dependent risk	0.821	13
R24	Quality risk	0.759	10
R25	Toxic circulation risk	0.9549	18
R26	Kidnapping of personnel	0.9512	17
R27	Labour union strike	0.8104	12
R28	Unskilled labour force	0.7915	11

Significantly low-performance risk factors	*Moderate-performance risk factors*	*High-performance risk factors*

rank represents lower priority. For instance, the risk factor of criminality and terrorist attacks on oil facilities is ranked first, indicating high priority.

We observe that significantly low-performance DMUs negatively impact the output variables and are ranked with the highest priority due to their high input values and low output values, implying improper resources allocation. Therefore, the management and policymakers can mitigate these inefficiencies by using the targeted projections to determine the effort needed for a crucial risk factor to achieve an acceptable performance. We undertake sensitivity analysis by observing input reductions for significantly low-performance DMUs (Table 7). The percentage of shortfall signifies the need to reduce input resources. The findings identify four significantly low-performed risk factors that decision-makers must address to ensure an efficient operation. Table 7 shows improvement strategies by focusing on input variables. For example, criminality and terrorist attacks (R17) is the most significant factor that requires the most management attention, with a staggering 72.91% reduction needed to gain significantly high or acceptable performance.

4.2. Validation of results

The qualitative survey is used to validate the findings and recommendations for the mitigation strategies and to cope with the implementation challenges. The thematic analysis method is applied to analyse the interview data. We first familiarise ourselves with the data to enable data preparation. A list of priori codes derived from the research aim, objectives, and the research case is provided to obtain trends. The codes include years of experience, designation, causes of critical risk, mitigation strategies, and challenges of implementing risk mitigation strategies. As mentioned, we approached ten experts from the Nigerian oil industry to help identify and classify the risk management-specific criteria. These experts are selected based on their knowledge of the field but are not personally known to the research team (to keep the

Table 7
Mitigation strategies for low-performance risk factors.

DMUs	Description	Score	Rank	Severity shortfall (%)	Occurrence shortfall (%)	Detection shortfall (%)
R06	Logistics	0.57	3	−42.97	−46.34	−42.97
R08	Environmental	0.64	4	−35.81	−44	−35.81
R11	Explosions	0.28	2	−71.94	−73.05	−71.94
R17	Criminal and terrorist attacks	0.27	1	−72.91	−72.91	−79.84

objectivity in data responses). The expert selection is made through snowball sampling, targeting senior personnel with over seven years of experience across the Nigerian oil supply chain stages including supply, production, and distribution. These expert-specific job titles include petroleum supply chain manager, petroleum risk manager, senior management personnel, and academic experts with publications in this area. The semi-structured interview questions are provided for use during the interview. Out of the ten experts, eight participants respond to the interview questions. The themes are determined by the frequency of code occurrence in the transcribed data, where the number of instances influences its significance. There are four thematic question areas upon which these interviews are based.

Question 1. "*The current research identified criminality and terrorist attacks risk, explosions risk, logistics risk, and environmental risk as the most significant risk factors in the Nigerian oil supply chain. What is your opinion on this finding?"* Nearly 80% of the respondents were in complete agreement with our findings, including criminality and terrorist attacks risk (0.27), explosions risk (0.28), logistics risk (0.57), and environmental risk (0.64).

Question 2. "*What are the major causes of the significant risk factors in the Nigerian oil supply chain?*" Once again, more than 80% of the respondents suggest the major causes of risk factors as follows: a lack of early warning information on the likelihood of occurrence, insufficient physical security around facilities, poor awareness of national and regional security situations, and poor governance, training and adherence to safety. Also, approximately 50% of responses emphasise the lack of advanced security technologies such as drones and CCTV, poor collaboration and communication between stakeholders, and diversified modes of transportation as exacerbating these risk factors.

Question 3. "*What are the mitigation strategies for the risk in the Nigerian oil supply chain?*" The expert responses to this question reveal significant divergence. Only 50% of respondents propose the top mitigation strategies: establishing an active emergency response plan (including rapid forces) to reduce external terrorist risks, and ensuring effective collaboration with stakeholders through insurance, acceptance, and risk transfer for main internal risks.

Question 4. "*What are the significant challenges in implementing risk mitigation strategies in the Nigerian oil supply chain?"* Drawing on their in-depth knowledge, the experts identify the absence of qualified risk management personnel as a major challenge. In addition, companies face hurdles in establishing a supportive top-down organisational risk management culture, understanding of the perceived benefits of effective risk management, gaining access to new technologies, meeting a short-time demand requirements, and ensuring adequate communication amongst stakeholders. However, the lack of perceived benefits from effective risk management and short-term demand requirements receive less support as significant challenges in implementing mitigation strategies.

5. Discussions and challenges of implementing mitigation strategies

With globalisation and the increased need for supply chain sustainability, organisations seek to develop sustainable strategies to improve performance. Managing risk in the supply chain is one of the ways to enhance the supply chain performance. The discussions in this section aim to develop a SCRM framework for the oil supply chain, which can be applied to other organisations. The framework analyses the causes and mitigation strategies for significant risk factors in the Nigerian oil supply chain. This study identifies 28 risk factors associated with the Nigerian oil supply chain through literature and expert opinion. The results from the performance ranking are categorised into three groups: significantly low-performance risk factors, moderate-performance risk factors, and significantly high-performance risk factors. The significantly low-performance risk factors are presented (see Table 7) with a score ranging from 0 to 0.65, requiring substantial corrective action and urgent attention.

Criminality and the terrorist attacks on Nigerian oil facilities are the lowest-performing risk factor (DMU) and require urgent treatment in selecting and applying risk mitigation strategies. Understanding the nature and causes of risks can help assess, anticipate and mitigate them. For instance, during the interview, an expert reveals that most of the challenges stem from criminal activities sabotaging pipeline transmission lines. The expert further suggests that criminal attacks persist because of the sector's importance to Nigerian economic development and the often remote location of critical infrastructure. The interviews also reveal that government policies leading to unemployment, unfavourable economic situations, a lack of all-stakeholder inclusion, and selfish interests by powerful individuals are the major cause of criminal and terrorist activities. For example, on October 6, 2022, Nigerian security officials discovered an illegal 4-km pipeline from the Forcados export terminal, with the capacity to export 250,000 barrels of crude oil per day, connected to the seaand undetected for years (NNPC 2022). Such illegal channels for transporting crude oil impact the Nigerian economy. Similarly, theft has caused daily production capacity to drop from 2 million barrels to about 1.6 million barrels per day in 2021 and 2022, forcing oil companies to contend with high operational costs. These findings are consistent with the Global Trade Review [85].

Upon reviewing the causes of these attacks, the experts assume that criminal attacks are not always targeted at people but are often intended to destroy infrastructure where millions of barrels of crude oil are produced and stored. For example, in 2016, criminal and terrorist attacks on the Nigerian oil and gas pipeline caused a 36% deficit in production [86]. The experts also listed disagreements between key stakeholders and the federal government as a cause of risk. They described a case on August 17, 2021, when Niger Delta militants attacked the oil and gas envoy in response to the presidential enactment of a petroleum bill. Similarly, in May and June 2009, Chevron oil company in Nigeria reported an attack on an oil pipeline caused by the 'Movement for the Emancipation of the Niger Delta' (MEND), which led to a loss of about 10,000 barrels of oil. Although the infrastructure was not severely affected, the spillage could casue environmental pollution. Other risk impacts include civil unrest and less attraction for foreign investment. Some of these risk impacts are also listed in Imhonopi and Urim [87].

Explosions risk (Risk 11) records a significantly low-performance score, which is unacceptable and necessitates critical examination and exploration. According to expert opinion, explosions in the Nigerian oil supply chain are persistent and unavoidable. Most explosions result from hydrogen, gasoline/petrol, ethanol, and other gases from fossil fuels mixing with air to ignite. Other causes of explosions are accidents during the transportation of petroleum products on the road and in storage facilities (depots, drilling sites, and distribution stations). Evidence from historical data also shows countless explosion incidents, which highlight the significance of explosions risk, as noted by experts. The historical data indicates that explosions risk poses a very high severity probability of occurrence and has low-risk detection. These findings align with the expert's opinions, helping to triangulate the empirical results. In addition, the participantsemphasise the impact of oil industry-related explosions leading to death, injury, infrastructural damage and reputational harm. The experts further state that the primary causes of the explosions risk include maintenance issues and improper use of appliances. Leakages from worn-out gas lines, defective equipment, violations of codes and safety standards, and faulty manufacturing procedures cause explosions in the Nigerian oil supply chain. The experts also suggest that human factors are among the leading causes of accidents in the oil supply chain due to unprofessional behaviours and the lack of adherence to safety rules.

Regarding mechanical factors, the participants blame the influx of fake spare parts in the Nigerian market, which cause the failure of most tankers on the highway. In addition, the participants emphasise the poor state of road infrastructure, social menace, defective equipment, employee fatigue, inexperienced workers, and insufficient maintenance as contributing factors to tanker accidents and highway explosions. However, the experts recommend that moving petroleum products by rail, routine equipment maintenance, and adherence to ethical procedures could eliminate the causes of explosions. In addition, the experts suggest the most suitable mitigation strategies for the explosions risk include emergency response to salvage, environmental response, crisis communication, insurance, and acceptance. The above evidence explains why the explosions risk (R11) recorded a low-performance score.

Logistics risk (R06) is also among the significantly low-performance risk factors. High-performance logistics activities can improve areas such as production rate, cost of production, inventory control, effective use of warehouse space, and customer and supplier satisfaction. In this vein, Griffis et al. [88] believed that performance measurement of logistics operations across the supply chain is key to attaining a competitive advantage. However, logistics activities in the Nigerian oil industry are flexible, complex, and more vulnerable compared to other sectors [89]. Logistics activities in the oil industry manage the relationship between the upstream and downstream relative to suppliers and customers to engineer value at the lowest possible cost [90]. The logistics network described by Ejiro et al. [90] and Ikeogu et al. [89] is complex and faces with many uncertainties; these findings are reflected in his research, where logistics risk (R06) is the third most significant risk factor. This is evidenced by its high severity and probability of occurrence, significantly impacting people, the environment, and business continuity.

The interviews with experts uncover that the logistics failure in Nigeria is systemic and chronic, requiring immediate attention. The participants emphasise total reliance on the import of refined petroleum products as the main reason for the petroleum logistics bottleneck. Other reasons include sabotage, bureaucratic interests, poor forecasting technology, and human error. Regarding mitigation strategies for logistics risk, the experts highlight the domestic refining of petroleum products as the top priority. Domestic refining of petroleum products has many advantages, including employment opportunities, improved distribution of refined petroleum products, and reduced costs associated with importing refined petroleum products, thereby creating economic advantage. However, the experts also mention adequate forecasting, alternative transportation modes, training, and stakeholder collaboration as potential prevention strategies. This is in line with Nsikan et al. [29], who proposed using integrated technology to enhance supply chain activities such as forecasting, handling, and distribution could help reduce the cause of logistics risk.

Oyedeji [91] reported that Nigeria spent 37.9 billion dollars to import refined petroleum products, contributing to a total import value of $220.2 billion between 2015 and 2019. Despite having a total refining capacity of 446 Mbd in 2018, the industry operates far below capacity. If the four refineries owned by the Nigerian National Petroleum Cooperation (NNPC) worked at total capacity, they could refine over 66 Mbd of petroleum products. However, Nigeria imports over 80% of its domestically consumed petroleum. The participants also note that logistics risks significantly impact people, including product scarcity, price volatility, and adulteration. However, other researchers believe that importing petroleum products poses a significant challenge to supply chain efficiency. For instance, in 2022, subsidies for importing refined petroleum products were expected to rise (to 3 trillion Nairas), causing a heavy burden on the Nigerian economy. Oyedeji [91] recommended the rehabilitation of local Nigerian refineries to reduce reliance on importation. The National Bureau of Statistics (NBS) assumes that stopping the importation of refined petroleum products would reduce Nigeria's negative trade balance by 44%.

Environmental risk (R08) is also a significantly lowperformance factor among the selected risk factors. Environmental efficiency continues to generate concern in today's globalised world. Environmental sustainability not only refers to effectively managing natural resources but also considers the entire world, including climate change, which is the major hindrance to ecological sustainability. The oil industry is a significant source of Nigerian government revenue and, at the same time, a source of environmental concern. However, most of the environmental sustainability concerns in the oil industry are linked to supply chain operations [53]. The current empirical findings show that environmental risk significantly impacts the stakeholders, particularly the people, the environment, and business continuity. Also, the interviews validate that environmental risk is a significant factor and needs to be addressed on a priority basis. The participants highlighted some causes of environmental risk, including oil production, petroleum-related transportation activities, criminality leading to oil spillage, and the lack of collaboration with all stakeholders, most notably the host communities. The negligence of effective environmental management harms the Nigerian oil supply chain, leading to reputational damage from not meeting international environmental standards, especially when decommissioning petroleum illegal refineries in the Niger Delta area. The environmental impact of petroleum activities in Nigeria also relates to public health issues, disruption of wildlife, climate change, and land degradation.

Environmental issues in the Nigerian oil industry have been a cause of concern since the discovery of oil in the Niger Delta region of Nigeria. Most environmental issues relate to unregulated oil production activities, and the inefficiency of petroleum product transportation modes [92,93]. This evidence justifies the experts' opinions that environmental risk is a crucial risk factor needing urgent attention in the Nigerian oil supply chain.

The general risk mitigation strategies are proposed by analysing the mitigation strategies of individual risk factors, as suggested by experts' opinions. Most participants recommend emergency response, effective crisis communication, insurance, avoidance, acceptance, and transfer as the most prioritised mitigation strategies. Emergency response is a systematic response to an unexpected risk occurrence, aiming to mitigate the event's impact on people, the environment, and business continuity. Effective communication involves creating a risk response plan to protect the reputation of all stakeholders across the petroleum supply chain. Insurance transfers risk from one organisation to another. Avoidance of risk means taking action to withdraw from a risk situation. One challenge pointed out by the participants is the inconsistency in responding to crisis incidents, which hinders a proper evaluation before the evidence is corrupted. The participants insist that insurance could be more effective if the response team go to the crisis site on time to evaluate the damage before any intrusion. Finally, risk transfer seeks to share the benefit and burden of losses from a risk event with another party. The participants reveal that transfer is common in distributing petroleum products, which helps major oil companies reduce their risks.

Effective government regulation on oil production is necessary to reduce illegal activities, which are a major cause of environmental pollution in the Nigerian Niger Delta area. The participants also recommend shifting transportation from road to rail to reduce road congestion and environmental pollution caused by petroleum road tankers accidents. Other significant mitigation strategies identified by the participants are the application of security technology and collaboration with all stakeholders to enforce environmental regulations.

Effective stakeholder collaboration plays a significant role in improving information flow to address perceived dissatisfaction. The participants state that collaboration and proactive communication can prevent crisis escalation, especially when necessary compensation is paid to victims. The participants also acknowledge that collaboration with the host community fosters inclusion. Without such commitment, perceived grievances can lead to a crisis. Government policies are another significant prevention strategy for the Nigerian oil supply chain risk. The participants point out that poor government policies are a major source of disturbance in the Niger Delta area of Nigeria. They insist that government policies also affect the supply chain by necessitating the import of about 80% of domestic consumption of refined

Table 8
Risk mitigation strategies for the Nigerian oil supply chain.

Mitigation strategies	Related risks
Rational government policy	Logistics (R06), Environmental (R08), and Criminal and terrorist attacks (R17)
Training and equipment maintenance	Environmental (R08), Explosions (R11), and Logistics (R06)
Alternative transport mode	Environmental (R08), Explosions (R11), and Logistics (R06)
Technology and physical security	Criminal and terrorist attacks (R17), Environmental (R08), Explosions (R11), and Logistics (R06)
Active emergency response and communication plan	Criminal and terrorist attacks (R17), Environmental (R08), Explosions (R11), and Logistics (R06)
Effective collaboration with all stakeholders	Criminal and terrorist attacks (R17), Environmental (R08), Explosions (R11), and Logistics (R06)
Insurance	Criminal and terrorist attacks (R17), Environmental (R08), Explosions (R11), and Logistics (R06)
Acceptance	Criminal and terrorist attacks (R17), Explosions (R11), and Logistics (R06)
Transfer	Criminal and terrorist attacks (R17), Environmental (R08), Explosions (R11), and Logistics (R06)
Avoidance	Logistics (R06) and Environmental (R08)

petroleum products. Encouraging domestic refining of petroleum products could reduce logistics bottlenecks. Training and equipment maintenance are other important mitigation strategies. The perceived non-importance of unpaid training and the poor maintenance culture of petroleum supply chain equipment are major challenges to effective risk management practices. In most cases, employees attend training for the associated allowances.

These findings are consistent with Fazli et al. [27], who analysed the Iranian crude oil supply chain risks. However, in the petroleum refinery operations, Obasanjo et al. [30] suggested mitigation strategies, including regulating tanker operations, reducing insecurity, and subsequently formulating or rehabilitating another profitable mode of transportation in Nigeria. Table 8 shows an overview of the mitigation strategies for the significant risk factors in the Nigerian oil supply chain.

The expert selects the prevention and mitigation strategies based on their experience in the Nigerian oil supply chain. Among the identified mitigation strategies, effective collaboration with stakeholders, rational government policy, and enhancement of security technology are prioritised. These mitigation strategies are applied to the related risk factors (see Table 8) due to their consistency in the literature review and frequency in the experts' opinions. Therefore, risk managers and policymakers could consider these risk mitigation strategies.

The current research identifies potential challenges to implementing the proposed risk management framework in the Nigerian petroleum industry. The proactive decision-making nature of risk management in a complex entity such as the oil supply chain requires strong leadership, commitment to allocating resources, timely reporting of events, and real-time data collection. Any lack of these characteristics could allow risks to disrupt the supply chain.

Within the context of the Nigerian oil supply chain, there are significant challenges in implementing risk mitigation strategies, including a lack of perceived benefit from risk management, lack of a supportive organisational risk culture, limited access to new technology, inadequate communication, absence of qualified risk management personnel, and constraints related to time horizon. Our findings align with the study of Zoufa and Ochieng [94], who suggested that all risk management personnel must understand the fundamental project requirements, including planning, organisation, motivation, direction, and control, while maintaining a proactive stance to implement risk management strategies. The lack of perceived benefit of risk management is an issue of irresponsibility and needs continuous awareness during team meetings. Also, the inclusion of risk protocol in the organisational culture enhances awareness of risk management within the Nigerian oil supply chain. Another significant challenge in implementing risk mitigation strategies is the time horizon, where the response time to risks often falls below acceptable best practices. Bureaucratic issues in approving resources for risk management exacerbate time delays and, perpetuating a cycle of deteriorating situations. Therefore, managers and policymakers should provide prompt access to necessary resources through streamlined and routine procedures.

One effective approach to reducing bureaucratic delays in the approval of funds or resources is to foster a cooperative relationship between the government and associated bodies at all levels of the supply chain. This can help minimise bureaucratic hurdles, as suggested by van Thuyet et al. [95]. In addition, managers in the Nigerian oil supply chain should undergo training on regulations governing risk management practices and project approval. Based on an organisational risk culture, there is a need to incorporate a 'corporate risk culture' to give room for a collective ability to identify and evaluate risk issues. Incorporating risk culture can also help policymakers overcome the immediate threats, as discussed by Pan et al. [96].

The lack of a risk culture leads to risk illiteracy, unplanned risk management strategies, and insufficient risk management maturity. Given risk literacy, an interviewee describes that "*most senior employees in the Nigerian oil supply chain do not have sufficient knowledge of risk management procedures and strategies, which imposes uncertainty in making strategic decisions in their department*". This demonstrates the need for managers and decision-makers to continually educate and train employees. For unplanned risk mitigation strategies and risk management maturity, most frameworks lack pre-planned set of actions to address both short-term and long-term risk management plans. To achieve risk management excellence, we must consider risk management as a serious and regular organisational activity and strategy, thus aligning business practices with the associated risk management processes.

Concerning inadequate communication, the flow of information is even critical, particularly in the case of a global supply chain, and the oil industry is no exception. It should be noted that communication is even more critical in remote locations. Management must invest in the latest communication equipment to improve performance. This was highlighted by the Nigerian National Emergency Management Agency (NEMA) on June 15, 2013 which suggested that the Nigerian incident communication and response rate is often slowed by bureaucratic processes. Our research confirms that the situation has not changed over the past decade. As a result, our findings urgently call on managers and policymakers to address the challenges of implementing a risk management framework in the Nigerian oil supply chain.

Access to technology is also crucial in managing risks in the Nigerian oil supply chain. In this regard, Ngowi [97] considered the inability of developing countries to adopt and adapt to established best practices in harnessing the latest technologies. Implementing best practice techniques in the Nigerian oil supply chain would increase the tracking of criminality activities, logistics failures, explosions, and environmental pollution.

6. Conclusion and final remarks

Risk management is a fundamental element of organisational processes and can be integrated into the organisational culture. This research aims to develop a risk management framework to analyse the Nigerian oil supply chain using different analytical tools. First, a literature review and input from Nigerian oil industry experts are used to define the research variables (risk factors, inputs and outputs). Second, a structured survey questionnaire is conducted to systematically collect data from experts. Third, DEA-FMEA is applied to assess the risks, and then thematic analysis is used to analyse the qualitative data collected from interviews to validate the quantitative findings. The main research findings suggest that criminality and terrorist attacks (R17), explosions risk (R11), logistic risk (R06), and environmental risk (R08) are the significant risk factors in the Nigerian oil supply chain. As a result of this research, the risk mitigation strategies identified for the Nigerian oil supply chain include effective collaboration with all stakeholders, training, adherence to safety procedures, adoption of physical and security technology, rational government policy, and regular equipment maintenance. However, the critical mitigation strategies are emergency response and communication plans, insurance transfer, acceptance, and alternative energy sources. The challenges of implementing the proposed risk management framework are a deficiency of qualified personnel, supportive organisational risk culture, lack of perceived benefit of risk management, lack of access to new technologies, inadequate communication, and time horizon. To the best of our knowledge, this research is the first to assess risks across the Nigerian oil supply chain, emphasising the impact of risk on people, the environment, and business continuity. This research makes a significant methodological contribution by integrating DEA and FMEA-RPN to establish a reliable risk prioritisation model. The experts' contributions, along with the research variables for assessing the performance of risk factors in this study, could stimulate more careful and critical risk management decision-making. The DEA analysis also guides the expected projection for a risk factor to achieve an acceptable level of risk mitigation. The results provide critical information on risk trends in the Nigerian oil supply chain.

The result of this research raises several vital questions relative to policy-making and risk-management processes. The need to enhance the risk management strategies in the Nigerian oil supply chain is evidenced by these research findings. Effective collaboration with stakeholders could improve supply chain resilience and risk management. In addition, diversification of suppliers such as reduction in dependency on imported refined petroleum products, developing contingency planning to address potential disruptions, adopting modern risk management technologies, ensuring regulatory compliance, and providing continous training are all strategies that could enhance the performance of the Nigerian oil supply chain risk management.

The paper is limited by its sample size, potentially affecting the generalisability of findings, and by its reliance on expert opinions, which could introduce biases. The proposed framework, however, can be applied to other sectors for risk assessment using similar variables, allowing for cross-validation of the method. For future research directions, the proposed approach could be extended with fuzzy sets theory [98] to better deal with uncertainties that arise from linguistic judgments and experts' opinions.

Declaration of competing interest

The authors declare that they have no known competing personal relationships and financial interests that could have influenced this study.

CRediT authorship contribution statement

Adel Hatami-Marbini: Writing – review & editing, Supervision, Methodology, Conceptualization. **John Otu Asu:** Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Khalid Hafeez:** Supervision, Conceptualization. **Pegah Khoshnevis:** Methodology, Validation, Writing – review & editing.

Data availability

The data that has been used is confidential.

Appendix 1

The two basic DEA models commonly used in real-world applications are the CCR model introduced by Charnes, Cooper and Rhodes [41] on the assumption of constant returns to scale (CRS) and the BCC model developed by Banker, Charnes and Cooper [99] under the assumption of a variable returns to scale (VRS). Assume that there is a set of n DMUs; $DMU_1, DMU_2, \ldots, DMU_n$ where each DMU uses m inputs, $x_{1j}, x_{2j}, \ldots, x_{mj,}$ to produce s outputs $y_{1j}, y_{2j}, \ldots, y_{sj}$. Let DMU_o be evaluated using the following model under the assumption of CRS [41]:

$$eff_o = \max_{v,u} \frac{\sum_{r=1}^{s} u_r y_{ro}}{\sum_{i=1}^{m} v_i x_{io}}$$

$$\text{s.t. } \frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \leq 1, \quad j = 1, \ldots, n,$$

$$u_r, v_i \geq 0, \quad r = 1, \ldots, s; \; i = 1, \ldots, m, \tag{1}$$

where u_r and v_i are the weights associated with the r^{th} output and i^{th} input, respectively. Model (1) is a linear fractional program which can be transformed into the following linear program [100]:

$$eff_o = \max_{v,u} \sum_{r=1}^{s} u_r y_{ro}$$

$$\text{s.t. } \sum_{i=1}^{m} v_i x_{io} = 1$$

$$\sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} v_i x_{ij} \leq 0, \quad j = 1, \ldots, n,$$

$$u_r, v_i \geq 0, \quad r = 1, \ldots, s; \; i = 1, \ldots, m, \tag{2}$$

where eff_o is the relative efficiency of DMU_o, and $eff_o^* = 1$ indicates an *efficient* DMU; otherwise, it is considered *inefficient*. The CCR model (2) is called the input-oriented model whose aim is to minimise input levels of the DMU under evaluation while keeping its output levels constant. Commonly, the dual form of a classic envelopment form in the DEA literature is known as the envelopment form. The following dual of model (2) can be formulated as follows:

$$\min_{\lambda,e} e_o$$
$$\text{s.t.} \sum_{j=1}^{n} \lambda_j x_{ij} \le e_o x_{io}, \quad i = 1, \dots, m,$$
$$\sum_{j=1}^{n} \lambda_j y_{rj} \ge y_{ro}, \quad r = 1, \dots, s, \tag{3}$$
$$\lambda_j \ge 0, \quad j = 1, \dots, n.$$

Given e_o^*, the following linear program model can be solved to identify the possible input excesses (s_i^-) and output shortfalls (s_r^+):

$$\max_{\lambda,s^-,s^+} \omega = \sum_{i=1}^{m} s_i^- + \sum_{r=1}^{s} s_r^+$$
$$\text{s.t.} \sum_{j=1}^{n} \lambda_j x_{ij} + s_i^- = e_o x_{io}, \quad i = 1, \dots, m,$$
$$\sum_{j=1}^{n} \lambda_j y_{rj} - s_r^+ = y_{ro} \quad r = 1, \dots, s \tag{4}$$
$$\lambda_j, s_i^-, s_r^+ \ge 0, \quad j = 1, \dots, n; i = 1, \dots, ; , r = 1, \dots, s$$

Note that the current research seeks to advise on improving the performance of the significantly low-performed DMUs. Hence, we define a reference set as $E_o = \left\{j, \lambda_j^* > 0\right\}$, $j \in \{1, \dots, n\}$. An optimal improvement can be obtained as follows:

$$e_o^* x_{io} = \sum_{j \in E_o} \lambda_j^* x_{ij} + s_i^{-*}$$
$$y_o = \sum_{j \in E_o} \lambda_j^* y_{rj} - s_r^{+*} \tag{5}$$

The relationship expressed above suggests that the efficiency of DMU_o can be improved by reducing the input levels radially by the ratio e_o^* and omitting the input excesses s_i^{-*}. Likewise, efficiency can be obtained if the output levels are increased by the output shortfalls in s_r^{+*}.

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