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Supply Network Risk Mitigation-Industry 4.0 Approach

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Abstract

With the evolution of Industry 4.0, the most advanced technologies have been invented and due to rapid globalisation, supply chains (SC) have become vulnerable to various risks. Risk management performs a key role in operating SC effectively in variety of uncertain circumstances. This paper aims to reveal the adaptability of digital technologies in supply chain networks, identify and analyse the various emerging supply chain risks in the industry 4.0 environment, and develop a framework to mitigate the risk level. A systematic literature review was conducted to identify and analyse the emerging supply chain risks, and Analytical Hierarchy Process (AHP) method was used to develop a conceptual risk mitigation framework. The contribution of this study lies in the taxonomy study, and findings revealed that digitalisation of supply chain design for risk mitigation shed light on future research. Additionally, it focuses on the potential to enhance supply networks' efficiency and responsiveness.

Keywords: Supply Chain; Industry 4.0; Supply Chain Risk Management; Internet of Things,

1. Introduction

Over the past two decades, the supply chain has emerged as a critical competitive force in today's increasingly uncertain marketplace. The primary goal of supply chain management (SCM) is to effectively manage the network of suppliers, distributors, and other stakeholders involved in the flow of goods and services [1]. By doing so, SCM aims to reduce costs, minimise inefficiencies, and ultimately surpass customer expectations by providing superior service

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[2]. With the advent of the digital revolution, new opportunities have arisen to reconfigure supply chains and foster a more collaborative and interconnected value network.

Supply chain reconfiguration has become essential due to various internal and external factors. Changing customer behaviours driven by evolving preferences, expectations, and technological advancements necessitate adaptation by manufacturers to stay competitive [3].The emergence of innovative suppliers equipped with advanced technologies further emphasises the need for existing suppliers to modify their offerings to align with the industry trend. These technological advancements offer enhanced efficiency, visibility, and flexibility throughout the supply chain, leading to improved performance and better decision-making capabilities [4].

Many researches have been done in the field of SC risk management and SC design. However, only a few of these studies have focused on the impact of digital technologies on the SC design and SC risk management. In this study, the researcher has tried to move the attention towards these three streams collaborative points of view, instead of analysing the influences individually.SC designers need to have a better understanding of what technologies are required to reconfigure the SC to mitigate the risk level and improve the efficiency and responsiveness of the SC. This study aims to identify and analyse the various emerging supply chain risks in the Industry 4.0 environment and design and develop a framework to determine the factors affecting the dynamic reconfiguration of supply chain design and risk management to mitigate the risk level.

The remainder of the paper is organised as follows: section 2 covers the literature review and includes a brief description of supply chain risk management and the background on Industry 4.0. The impact of technologies on risk management and the identified gaps are also provided leading to future research work. Section 3 describes the research methodology; Section 4 illustrates the results and discussion. Then, the paper ends with section 5, which includes the overall conclusions, stressing how Industry 4.0 technologies impact the reconfiguration of supply chain design and risk mitigation.

2. Literature Review

2.1. Supply Chain Risk Management

Supply chain risk management involves identifying, assessing, and mitigating risks that can disrupt the flow of goods, services, or information within a supply chain [5]. Risks can be categorised into demand, supply, operational, financial, and external risks [6]. This process starts with risk assessments, which identify potential risks, evaluate their impact, and assess their likelihood of occurrence. Risk mitigation strategies include diversifying suppliers, creating contingency plans, establishing strong relationships, and using insurance or financial instruments [7]. Supply chain visibility is crucial for effective risk management. Real-time information about suppliers, inventory, transportation, and demand enables organisations to identify risks and respond promptly [8]. Idntfying and analysing supply chain risk factors is essential for practitioners to prioritise which risks need to be addressed [9].

Supply chain risk management is an ongoing process that requires continuous improvement. Organisations must monitor, evaluate, and update risk assessments and mitigation strategies while staying updated on emerging risks and industry best practices and building supply chain resilience is a key objective. Resilient supply chains can adapt and recover quickly from disruptions by designing flexibility, maintaining strong relationships, and investing in technologies and capabilities [10]. Technology, including advanced analytics, AI, IoT, blockchain, and cloud computing, enables real-time risk monitoring, data analysis, and collaboration, enhancing risk visibility and proactive management.

2.2. Industry 4.0 approach

Industry 4.0 has evolved from the previous industrial revolutions, marking a new era of digital transformation in manufacturing and beyond. It builds upon the advancements of the first three industrial revolutions, which introduced mechanisation, mass production, and automation. The fourth industrial revolution, Industry 4.0, incorporates digital technologies and connectivity to drive unprecedented levels of automation, data exchange, and intelligent decision-making [11].

The rapid advancement and convergence of key technologies has shaped the evolution of Industry 4.0. The Internet of Things (IoT), Artificial Intelligence (AI), Big Data and Analytics, Robotics and Automation, Cloud Computing, Cybersecurity, and Additive Manufacturing (3D Printing) form the foundation of this paradigm shift. These technologies enable the interconnection of machines, systems, and humans, creating cyber-physical systems that drive efficiency, productivity, and innovation [9] [10]. Over time, Industry 4.0 has expanded its scope beyond individual processes to encompass entire supply chains and ecosystems. The focus has shifted towards end-to-end integration, collaboration, and optimisation across all stages of production and distribution [12]. This holistic approach allows for improved visibility, agility, and responsiveness, enabling businesses to meet evolving customer demands and navigate dynamic market conditions.

Understanding the evolution of Industry 4.0 provides a context for its current state and future potential. It represents a transformative shift towards digitalisation, connectivity, and data-driven decision-making, enabling businesses to achieve new levels of efficiency, customisation, and sustainability in an increasingly interconnected world.

2.3. Impact of Industry 4.0 technologies on supply network risk mitigation.

- **Internet of Things (IoT)**

IoT technology connects physical devices and assets to the internet, enabling real-time monitoring and data collection [13]. By deploying IoT sensors across the supply network, companies can track inventory levels, monitor equipment health, and gather environmental data to identify potential risks and take proactive measures. Supply chain managers receive timely alerts and notifications from IoT sensors, allowing them to take proactive risk mitigation measures [14]. These measures can include adjusting production or transportation plans, reallocating inventory, or initiating preventive maintenance. By leveraging IoT, companies can improve risk visibility and respond swiftly to potential disruptions in the supply network [15].

- **Blockchain Technology**

Blockchain technology enhances supply chain visibility, traceability, and security. By recording transactions and data exchanges on a decentralised and immutable ledger, blockchain reduces the risk of fraud, counterfeiting, and data tampering. This technology can improve transparency and trust among supply chain partners, making it easier to identify and mitigate risks related to supplier compliance, product authenticity, and data integrity [16].

- **Big Data Analytics**

Big Data and Analytics: Big data analytics helps in identifying patterns, trends, and anomalies from large volumes of data. By analysing historical and real-time data, supply chain professionals can gain insights into potential risks, such as supplier performance issues, demand fluctuations, or quality concerns [17]. Predictive modelling techniques can forecast potential disruptions and enable proactive risk mitigation strategies, including alternative sourcing, capacity adjustments, or contingency plans [18].

- **Artificial Intelligence (AI)**

AI technologies can analyse large amounts of data and generate actionable insights. By leveraging AI-powered algorithms, companies can optimise supply chain operations, improve demand forecasting, identify potential bottlenecks, and support decision-making processes. AI can analyse various data sources, including customer demand patterns, market trends, and supply chain performance data, to identify risks and recommend appropriate actions. AI-powered forecasting models enhance demand planning accuracy, reducing the risk of stockouts or excess inventory. Additionally, AI enables real-time risk monitoring and response by detecting anomalies in production or transportation processes, triggering immediate corrective actions. With AI, companies can enhance risk assessment and decision-making, leading to improved supply network resilience [19].

- **Robotics and Automation**

Robotics and automation technologies play a pivotal role in enhancing operational efficiency and reducing human error within the supply network. By automating repetitive tasks, such as order picking and packaging, these technologies minimise the risk of errors and delays while improving accuracy and speed. They also help address labor shortages and disruptions by reducing reliance on manual labor. Additionally, robotics and automation optimise supply chain processes, streamlining warehouse operations, inventory management, and order fulfilment. They contribute to workplace safety by handling hazardous tasks, and reducing the risk of accidents and injuries. Overall, these technologies enhance operational resilience, mitigate supply network risks, and improve efficiency and safety [20].

- **Cloud Computing**

Cloud computing leverages cloud-based platforms to enable real-time data sharing, collaboration, and access to information across the supply network [21]. By centralising data storage and providing scalable computing resources, cloud computing facilitates rapid and efficient analysis of supply chain data. This improves coordination and communication among supply chain partners, enabling better risk assessment and response. Additionally, cloud-based analytics and applications allow for faster deployment of risk management solutions and decision support tools. Overall, cloud computing enhances supply chain visibility, enables efficient data analysis, and supports effective risk mitigation strategies in the supply network [22].

These Industry 4.0 technologies can work together to enable end-to-end supply chain visibility, enhance risk assessment and mitigation, and improve overall supply network resilience. By leveraging these technologies effectively, companies can proactively identify and address risks, ultimately minimising the impact of disruptions on their supply networks.

2.4. Gaps leading to future research

According to the literature review, many of research articles discussed supply chain design, risk, and digitalisation. However, there are fewer research papers concerning executing and adapting digitalisation in the context of supply chains. Several research gaps can be identified in the process of digitalisation of the supply chains [23].

Deficiency of development frameworks that provide the directions for Digital Supply Chain (DSC) adoption in the supply chain with clear guidelines. The development framework would assist the managers in getting a clear idea about which stage and wherein the supply chain implements the DSC and lack of tools and technologies that aid in identifying the issues in the SC in the digital environment. DSC requires advanced tools and technologies in the digitalisation environment, such as Big Data created from Sensor Technology and IoT. The third gap, however, as there are several difficulties in the execution of digitalisation into the supply chain from both technological and managerial perspectives. Industry 4.0 is yet in the initial phase, and studies are required to explore the development and application of the Industry 4.0 tools and solve the existing issues. Moreover, blockchain technology is still in the early stages, and would be more applicable in the future SCs [24]. Many articles identified the important areas of SC risk management, and little attention was received from the quantitative analysis. It can be considered as a future research opportunity. When considering the dynamic behaviour of SC, the motivating research path would be to implement dynamic systems theory with the mathematical programming method [25].

3. Research Methodology

3.1. Systematic literature review

The purpose of a literature review is to evaluate existing knowledge and identify research gaps. Systematic Literature Network Analysis (SLNA) is a valuable method for studying emerging fields. This study adapted the systematic literature review approach to gather relevant literature on Supply Chain Risk Management (SCRM) in the digital era. Keywords and topics were used to identify journals and articles for analysis. This approach ensures clear judgment and traceability [26].

This study adheres to the five steps of a systematic literature review (SLR) proposed by Denyer and Tranfield, [27].The steps are question formulation, locating studies, study selection and evaluation, analysis, and synthesis and finally, reporting and using the results. To locate the relevant research, the researcher used various databases, including Web of Science, Scopus, and ProQuest. This approach helps to reduce the risk of missing any important research or publication bias. After identifying the keywords, the researcher designed search strings with appropriate terms to achieve the best results. The search strings were constructed using the keywords Supply network, risk mitigation, Industry 4.0, and digital technologies. This confirmed that the search results would include the desired keywords in either the title, abstract, or keywords of the research papers.

Figure 1 displays the developed framework based on the identified literature gaps to mitigate the supply chain risks using industry 4.0 technologies.

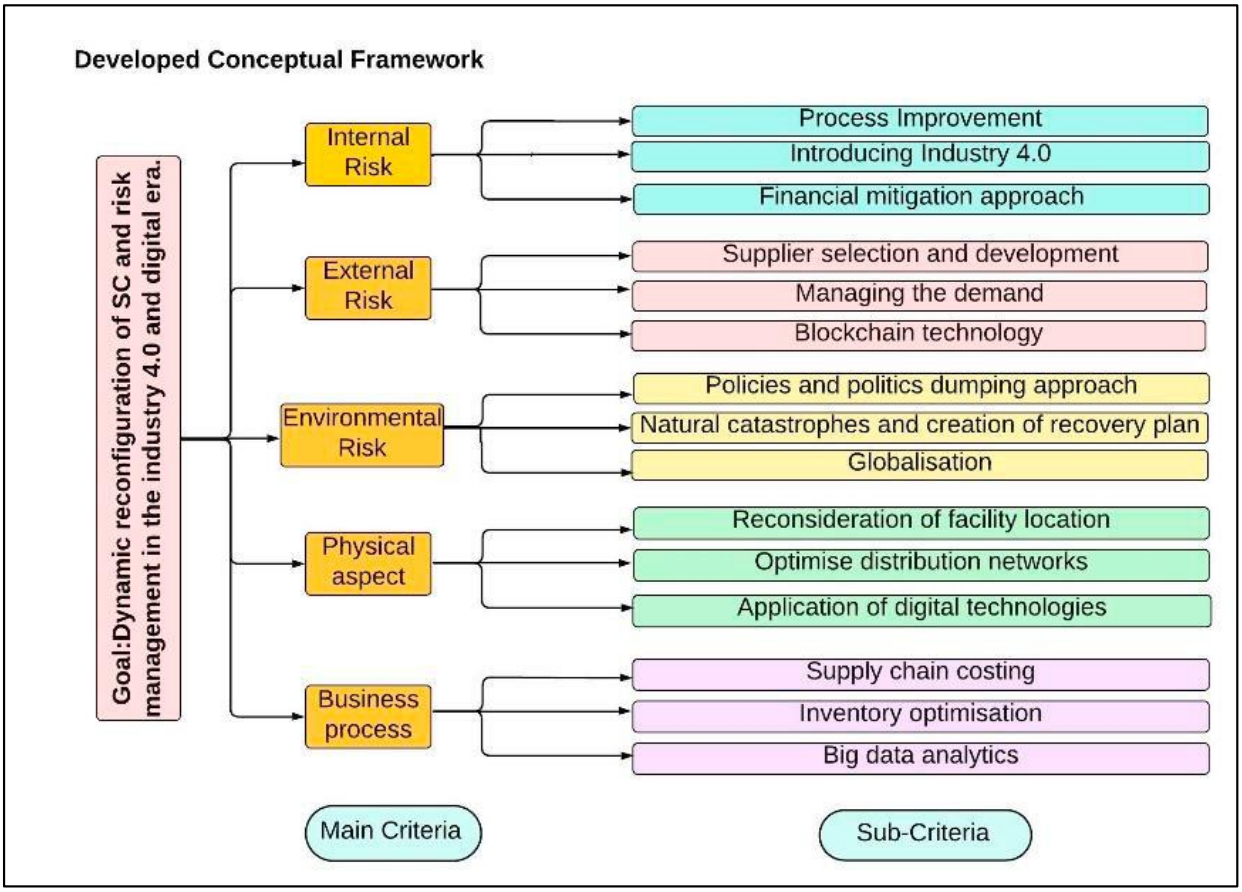

Fig. 1. The developed conceptual framework for supply network risk mitigation- I4.0 approach.

3.2. Research Questionnaire

The conceptual model of supply network risk mitigation-Industry 4.0 approach is developed using the relevant literature and then a questionnaire to carry out a pairwise comparison between the criteria and sub-criteria within the proposed framework based on the opinion of the industrial and academic experts. The questionnaire consists of a series of questions related to the fact that respondents respond to it or among the available answers to choose the most relevant answer [28].

3.3. The Analytic Hierarchy Process (AHP)

The analytic hierarchy process (AHP) is one of the most widely used methods in Multiple Attribute Decision-Making (MADM) problems, which was proposed in 1980 by Thomas L. Saaty [29]. AHP (Analytic Hierarchy Process) software is utilised to implement a multi-criteria decision-making approach for mitigating supply chain risks using Industry 4.0 technologies. AHP is one of the Multi-Criteria Decision Making tools that can be used to identify the priorities of the criteria, sub-criteria, and the solutions that should be used. AHP is unique because it utilises pairwise comparisons to rank alternatives. This approach is associated with the consistency ratio, and it enhances the reliability of the decision making process. The AHP software enabled to conduct pairwise comparisons of the identified criteria and technologies. It guided through a structured process of evaluating the relative importance or preference of each criterion and the relative performance or suitability of each technology for each criterion. Based on the pairwise comparisons, the AHP software calculated the priorities for each criterion and technology. These weights represent their relative importance in the decision-making process. Once the weights are assigned, the software can help analyse and generate a comprehensive ranking of the different sub-criteria for mitigating supply chain risks. This ranking considered the weights of the criteria and the performance of the technologies [30].

By using AHP software for multi-criteria decision-making, supply chain managers can effectively evaluate and prioritise the criteria for mitigating supply chain risks. The software streamlines the decision-making process, provides a structured framework for considering multiple criteria, and supports the identification of the most suitable technologies based on their performance in risk mitigation. The scale for these pairwise comparisons is introduced based on a standard evaluation scheme, as shown in Table 1, which enables the decision-makers to express preference or importance between each pair of elements with respect to the main goal or higher criterion by incorporating their experience and knowledge [29].

Table 1. The scale of Relative Importance

Intensity of Importance	Definition	Explanation
1	Equally important	Two activities contribute equally to the objective
3	Moderate Importance	Experience and judgment slightly favour one activity over another
5	Strong Importance	Experience and judgment strongly favour one activity over another
7	Very strong Importance	An activity is strongly favoured, and its dominance demonstrated in practice
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgments	When compromise is needed

Figure 2, shows the implementation of the proposed framework within AHP, which consists of the goal, criteria and sub-criteria. This allows the pairwise comparison to be carried out and synthesise performance, including measuring the inconsistency ratio among participants' opinions.

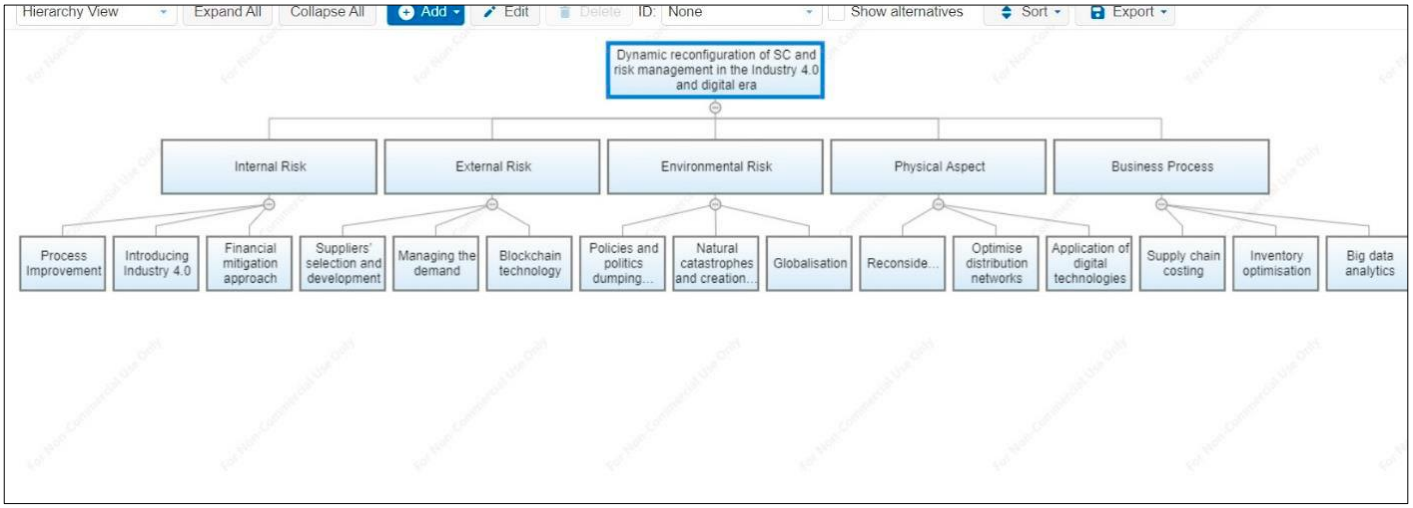

Fig. 2. The developed conceptual framework implementation within the AHP software.

4. Results and discussion

Data analysis is an essential and critical aspect of research as it involves various processes such as examining, categorising, charting, and recombining collected data. This section will explore different approaches to conducting data analysis on a global scale.

4.1. The relative importance of the criteria and sub-criteria of the proposed framework

According to the results presented in Figure 3, it is evident that the physical aspect holds a relative importance of 27.25% compared to other criteria in the proposed framework. Furthermore, the sub-criteria with the highest significance is the application of digital technologies, accounting for 9.07%.

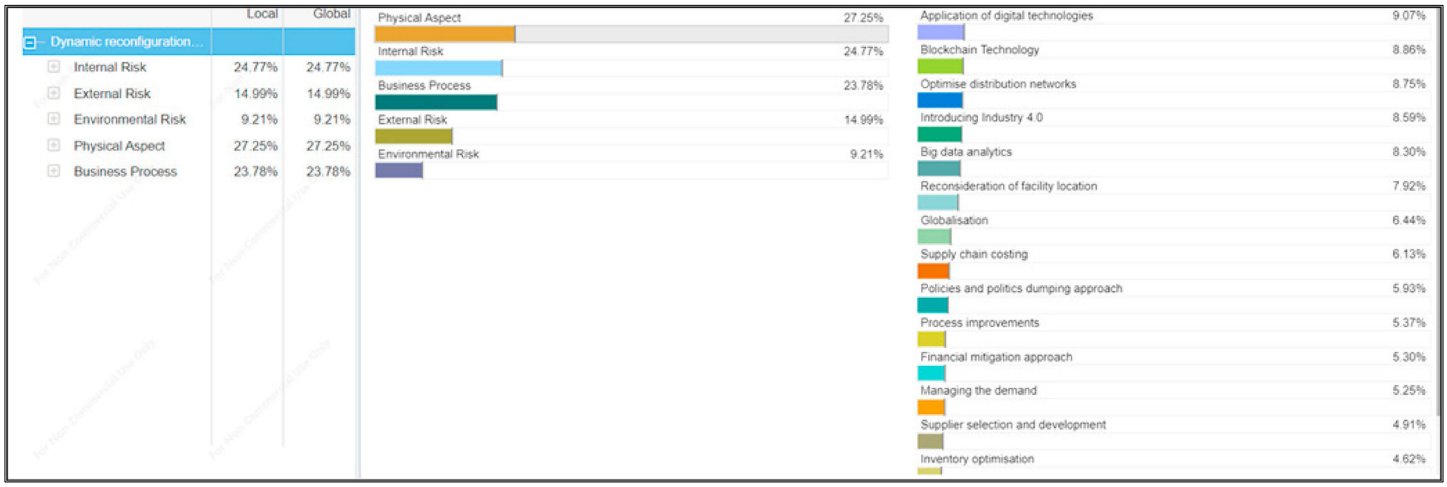

Fig. 3. The relative importance of the criteria and sub-criteria of the proposed framework

4.2. Sensitivity Analysis

Sensitivity analysis in AHP examines how changes in input values or weights impact the final priority rankings, assessing decision-making stability and robustness. By varying inputs within a specified range, it reveals the sensitivity of rankings to these changes. This analysis enables informed decision-making based on factors' varying degrees of influence. Identifying critical criteria or alternatives affecting outcomes and understanding associated uncertainties and risks are benefits of sensitivity analysis in AHP[30].

In this work, the dynamic sensitivity built in AHP was applied to dynamically change the priorities of the main criteria to determine how these changes affect the priorities of the lower sub-criteria. Therefore, the impact of changing the priority of the five main criteria “Internal Risk, External Risk, Environmental Risk, Physical Aspect and Business Process” on overall results has been investigated.

Figure 4, presents the priorities of the five main criteria and als the ranking of the associated sub-criteria, this represents the main scenario. However, in the scenario shown in Figure5, the priority of "Physical Aspect" was reduced to the third position (from 27.25% to 21.51%), all the sub-criteria remained unchanged in their priorities, with only minor alterations in the percentage of alternatives. This indicates that the model demonstrates consistency, allowing for the prioritisation of objectives over alternatives to evaluate the sensitivity of objectives in relation to alternatives.

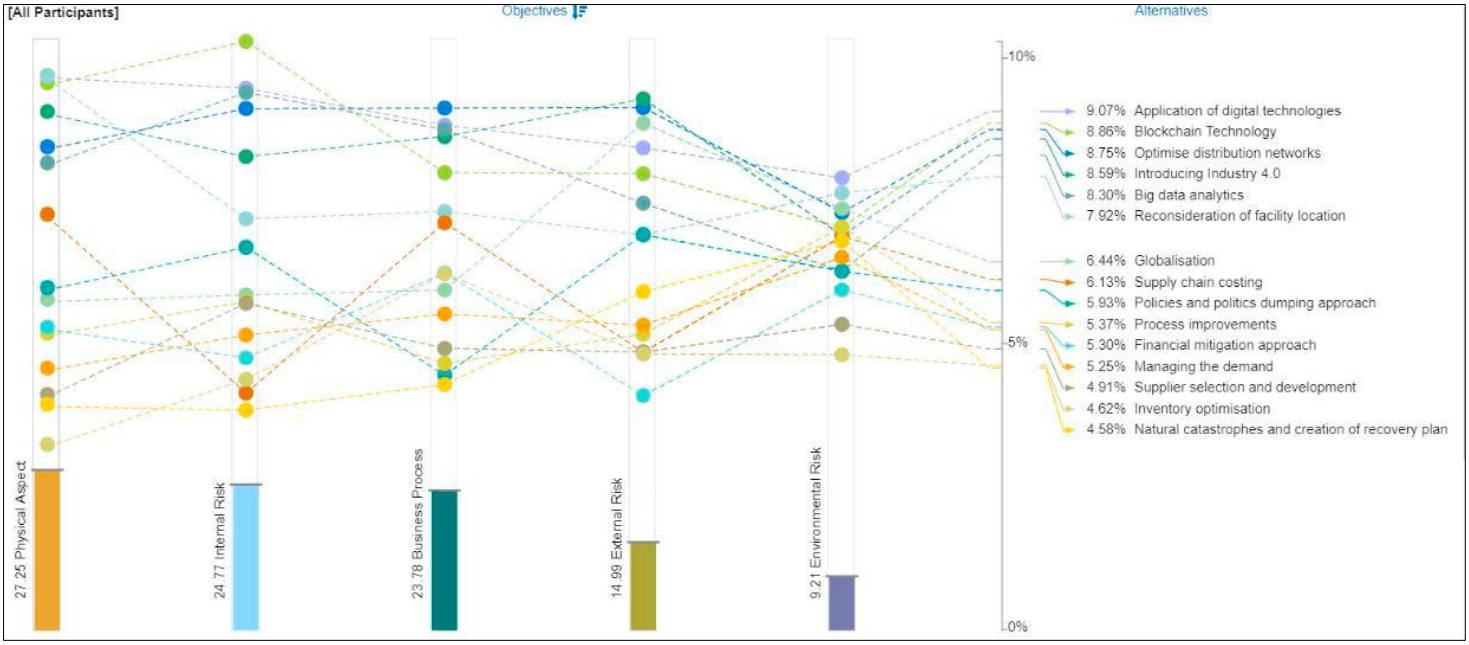

Fig. 4. The performance analysis of all participants

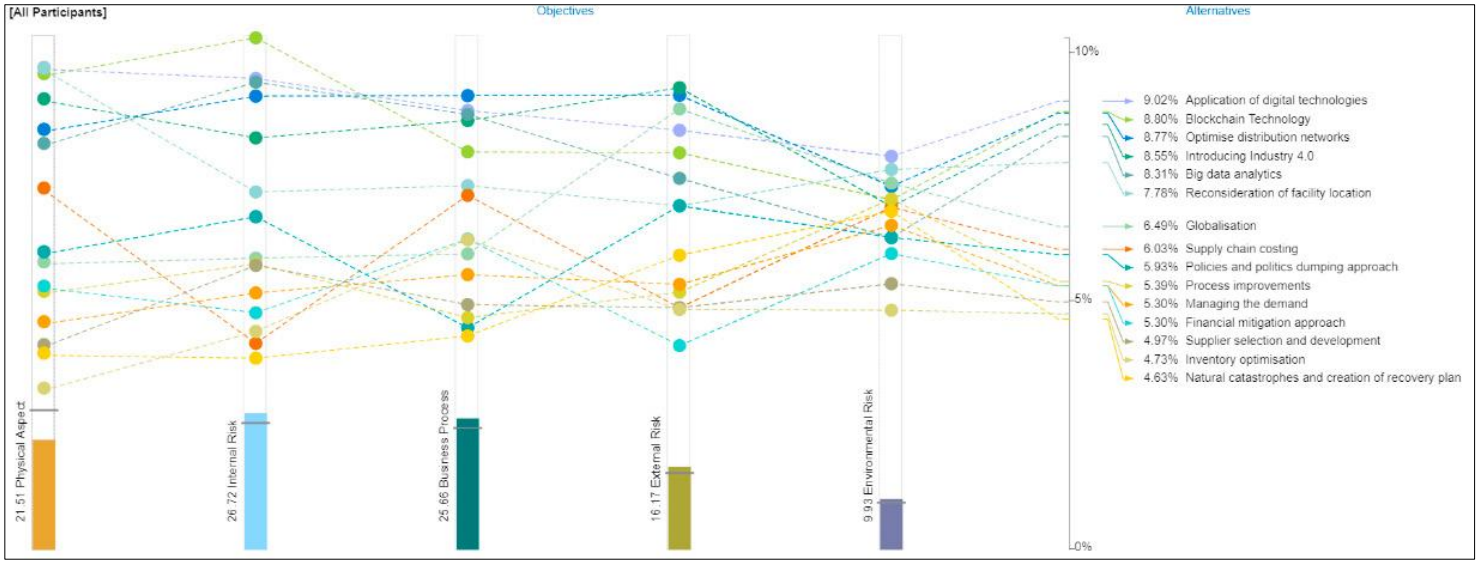

Fig. 5. A scenario of sensitivity analysis.

5. Conclusion

In summary, this study has discussed the relationship between digital technologies and Industry 4.0 with SC risk management and SC reconfiguration, while identifying gaps that suggest future research avenues. Leveraging Industry 4.0 technologies offers significant benefits, such as enhanced visibility, data-driven decision-making, proactive risk monitoring, and optimised supply chain processes. Furthermore, this study emphasises the opportunities for SC designers to enhance supply chain design through the use of digital technologies and Industry 4.0. These advancements enable SC reconfiguration, leading to improved efficiency and responsiveness. Furthermore, understanding the impact of dynamic supply chain reconfiguration on risk management is vital for maintaining an effective supply chain and providing superior customer service.From the theoretical perspective, this paper identified the types of risk involved

in the supply chain that should be mitigated. From the practical point of view, we applied the AHP tool to prioritise the criteria and sub criteria involved in order to react and mitigate the risk involved the supply chain.

Overall, the study highlights the potential of digital technologies and Industry 4.0 in SC risk management and SC reconfiguration, while also suggesting areas for further research. By leveraging these advancements, organisations can strengthen their supply chains, optimise operations, and effectively manage risks, ultimately ensuring smooth operations and customer satisfaction.

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