



Development of a Sustainable Outsourcing Supply Chain Framework within the Food industry

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Development of a Sustainable Outsourcing Supply Chain Framework within the Food industry

By

Somayeh Hatami

A thesis submitted in partial fulfilment of the requirements of
Sheffield Hallam University
For the degree of Doctor of Philosophy

September 2025

Declaration

I hereby declare that:

1. I have not been enrolled for another award of the University, or other academic or professional organisation, whilst undertaking my research degree.
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Abstract

Although 4PL and 5PL providers are getting more and more used to boosting the efficiency of food supply chains (FSCs), there is still no common framework for measuring their sustainability performance. The study fills in this gap by creating a set of performance indicators that consider several aspects at the same time and is specifically designed for food companies. By combining the Analytical Hierarchy Process (AHP) with a multi-objective mathematical model built in Lingo, the study measures the essential compromises between the economic, environmental, and social aspects of outsourcing.

Main findings not only point to the fact that mitigation of food wastage, health and safety accreditation as well as transport efficiency are ranked highest among sustainable logistics integration priorities, but they also show that decreases in greenhouse gas (GHG) emissions, overall costs, and lead times can be realised while simultaneously addressing social risks, reducing worker fatigue and maximising end-to-end supply chain visibility. This thesis contributes to sustainable outsourcing discourse by changing the research lens from mere 3PL execution to strategic control of 4PL and 5PL integrators, giving an indicator of where top-level logistics stand in relation to the United Nations' Sustainable Development Goals (SDGs). On the other hand, for the supply chain decision makers, the Lingo-based tool is a very powerful model for supporting optimisation of provider selection decisions, which is comparable to an extension method for achieving a trade-off among environmental performance and lead-time on one hand and social responsibility and digital transparency on the other hand.

Keywords: Sustainability, 4PL and 5PL Logistics, Food Supply Chain (FSC), Mathematical programming, AHP, GHG Emissions.

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Abbreviation

3PL	Third Party Logistics
4PL	Forth Party Logistics
5PL	Fifth Party Logistic
FSCs	Food Supply Chains
TBL	Triple Bottom Line
SSCM	Sustainable Supply Chain Management
JIT	Just-In-Time
SC	Supply Chain
VSC	Viable Supply Chain
WOS	Web of Science
MILP	Mixed-Integer Linear Programming
GA	Genetic Algorithm
PSO	Particle Swarm Optimisation
BWM	Best–Worst Method
COPRAS	Complex Proportional Assessment
CvaR	Conditional Value-at-Risk
OI	Open Innovation
BCT	Blockchain Technology
CLSC	Closed-loop Supply Chain
NSGA-II	Non-dominated Sorting Genetic Algorithm-II
MCDM	multi-criteria Decision-Making
FBWM	Fuzzy Best–Worst Method
FIS	Fuzzy Inference System
PMMs	Performance Measurement Metrics
DC	Dynamic Capability
CRMOs	Capabilities of Contract Research and Manufacturing Organisations
FAHP	Fuzzy AHP
F VIKOR	Fuzzy VlseKriterijumska Optimizacija I Kompromisno Resenje

GSCM	Green Supply Chain Management
SFBWM	Stochastic Fuzzy Best–Worst Method
AFSC	Agrifood Supply Chain
TDC	Total Distribution Cost
CZ	Customer Zones
RFSP	Robust Fuzzy Stochastic Programming
FMOP	Fuzzy Multi-Objective Programming
SSOA	Supplier Selection and Order Allocation
PCA	Principal Component Analysis
MOMILP	Multi-Objective Mixed-Integer Linear Programming
MCGP-UF	Multi-Choice Goal Programming with utility function
AHP	Analytic Hierarchy Process
MCDA	Multi-Criteria Decision Analysis
MCGP	Multi-Choice Goal Programming
R&D	Research and Development
GHG	Greenhouse Gaz
DC	Distribution centre
MSs	Manufacturing Sites
PM	Particular Matter
DB	Decibel
TSI	Traffic Stress Index
Trimf	Triangular Membership Function
MODM	Multi-Objective Decision-Making

Nomenclature

I	Set of suppliers indexed by i
J	Set of manufacturing sites indexed by j
K	Set of distribution centres indexed by k
C	Set of customers indexed by c
R	Set of raw materials indexed by r
P	Set of products indexed by p
Q	Set of quality levels indexed by q ($q = 1, 2, 3$ in which 1: low quality, 2: medium quality, and 3: high quality)
M	Set of transportation modes indexed by m
F	Set of information-sharing systems indexed by f

Parameters:

CIE_f	The establishment cost for information-sharing system f
PCR_{rqi}	The purchasing cost of RM r with quality level q from supplier i
CM_{jpq}	The cost of manufacturing product p with quality q in MS j
CD_{kp}	The operational cost of DC k for product p

FT_m	The fixed cost of utilising transportation mode m
TC_m	The unit of transportation cost for transportation mode m
CEP_{jpq}	The cost of establishing the extra capacity for product p with quality level q in MS j
CED_{kp}	The cost of establishing the extra capacity for product p in DC k
CSH_{pq}	The shortage cost for product p with quality level q
CoC	Unit buying/selling price of carbon credit
$CapS_{irq}$	The capacity of supplier i for providing raw material r with quality level q
$CapM_{jpq}$	The capacity of MS j for producing product p with quality q
$CapD_{kp}$	The capacity of DC k for dispatching product p
Dem_{cpq}	Demand of customer c for product p with quality q
ur_{rp}	The utilisation rate of raw material r in product p
SLT_{rqi}	The lead time of supplier i for RM r with quality level q
PPT_{pqj}	The processing time for manufacturing product p with quality level q in MS j
DTW_k	The required time for distributing a product in the distribution centre k
TT_m	The unit of transportation time for transportation mode m
$CCap$	The allowable capacity to emit GHG for carbon cap-and-trade policy
$DIS_{ee'}$	Distance between facility e and $e' \in \{i, j, k, c\}$
α	The predefined value for the service level of the supply chain

EIM_{pj}	The amount of GHG emissions based on the production activity for manufacturing product p in MS j
EIT_m	The amount of GHG emissions based on the transportation activity with transportation mode m
MEM_{jpq}	Maximum allowable extra capacity in MS j for product p with quality q
MED_{kp}	Maximum allowable extra capacity in DC k for product p
$SR_{mee'}$	The social risk for transportation mode m between nodes e and $e' \in \{i, j, k, c\}$
IEX_f	Percentage of information exchange in the supply chain when an information sharing system f is established
$TmaxM_j$	Maximum allowable working time for each worker in manufacturing site j
$TmaxD_k$	Maximum allowable working time for each worker in distribution centre k
NWM_j	The number of workers who worked in manufacturing site j
NWD_k	The number of workers who worked in distribution centre k
$BigM$	A large positive number

Decision Variables:

QR_{rqijm}	The quantity of RMs with quality level q shipped between nodes i and j with transportation mode m
--------------	---

QPM_{pqjkm}	The quantity of product p that is produced with level q shipped between nodes j and k with transportation mode m
QPD_{pqkcm}	The quantity of product p with quality level q that is produced and shipped between nodes k and c with transportation mode m
SH_{cpq}	The amount of shortage for product p with quality level q in node c
EXM_{jpq}	The amount of extra capacity established in MS j for product p with quality level q
EXD_{kp}	The amount of extra capacity established in DC k for product p
CS	Quantity of carbon credits sold
CP	Quantity of carbon credits purchased
VSI_f	The amount of visibility in the supply chain when ISS f is established under scenario s
MWL_j	Average working time for each worker in the manufacturing site j
DWL_k	Average working time for each worker in the distribution centre k
$ZT_{mee'}$	1 if transportation mode m is utilised between nodes e and $e' \in \{i, j, k, c\}$
ZF_f	1 if an information sharing system f is established; 0 otherwise

Chapter One

Introduction

1.1 Background

The global food market is currently going through a phase of great unpredictability. The main reasons for this are the fast growth of the world's population, the increased interconnection of economies and cultures, as well as the pressing need to take care of the environment. These three factors have led to a major change in how countries produce and distribute food. As such, the Food Supply Chain (FSC) has become a major element and basis of not only global food security but also public health and socio-economic development. Since food systems are at the foundation of human existence and social harmony, it is very likely that all those involved will be exposed to such very intricate situations as the balancing of perishable inventory and the following of stringent regulations related to safety so that the purpose of getting food from the farm to the table can be secured and sustainable (Galli & Read, 2023, p. 2).

The Triple Bottom Line (TBL) principle is fundamental to this change. Seuring & Muller (2008, p. 1701) describe the TBL as "a system by which societies fulfil their needs and improve their well-being without sacrificing the most basic human need, human rights, and the future generations' welfare." In the FSC setting, this rule acts as a guide for Sustainable Supply Chain Management (SSCM) by separating economic development from environmental damage and social exclusion. Walking down such an integrated path is not only the conservation of resources and the decrease of Greenhouse Gas (GHG) emissions but is also the reduction of food waste and the implementation of fair labour standards (Osman et al., 2023, p. 350).

Outsourcing has changed dramatically and has become almost a mandatory strategic move for businesses to find specialist help and at the same time concentrate on their main areas (TraceGains, 2023). Fourth-party logistics (4PL) and Fifth-party logistics (5PL) providers set a new trend in the logistics industry by pooling their resources and creating connected, technology-based networks (Wallenburg et al., 2011; Extensiv, 2024). 4PLs handle multiple 3PL providers, thereby breaking down operational silos and improving efficiency, while 5PLs employ technologies like blockchain and the Internet of Things (IoT) to bring about a level of transparency never seen before (Penske Logistics, 2016; Gupta & Jain, 2023). Unfortunately, the standard ways of measuring the performance of these providers are still very limited, focusing only on fast delivery and cheap costs, while the environment and social aspects have become the major components of sustainability (Houghton et al., 2016). This study aims to fill the gap by developing a sustainability-based performance measurement that is specifically designed for food supply chains and logistics outsourcing.

1.2 Problem Statement

Although the food industry is rhetorically emphasizing sustainability a lot, there is still a big gap in the actual implementation of performance measurement of outsourced operations, especially 4PL and 5PL providers, according to Kumar et al. (2023). Existing models are missing a standard, multi-dimensional set of indicators that balance economic objectives with environmental and social responsibilities (Ahi & Searcy, 2013; Taticchi et al., 2013; Shrivastava et al., 2023). In food supply chains, without proper control the problems on a larger scale can be even more intensified. For example, long-distance transport inefficiency can result in higher carbon footprints, poor coordination can lead to increased food wastage, and there may be social risks like bad labour conditions in third-party facilities (Sustainable Food Distribution and Transportation, 2024; Individual Action on Climate Change, 2025).

This gap represents a critical vulnerability. Organisations not only may they fail to follow-up with new policies such as the Farm to Fork Strategy of the European Union, but they can also lose consumer confidence forever in the global market that is becoming more ethical every day. The urgency of this problem is increased by the fact that we are not only facing climate change and resource depletion but also the fact that consumers are demanding more and more that food systems are totally transparent and ethical (UNEP, 2022; Sustainable Food System, 2025). Even though recent studies have identified sustainability as one of the main goals of performance (Kumar et al., 2023; Shrivastava et al., 2023), the set of indicators that are normally used are not specifically designed to address the unique regulatory and operational difficulties of outsourced food chains. In this way, the present research will try to fill this void by proposing a conceptual framework that combines different aspects of sustainability with precise measures of the performance of 4PL and 5PL service providers in the food sector.

1.3 Research Questions

This research addresses the following questions:

1. What is the role of the interconnectedness between the economic, environmental, and social aspects of sustainability in shaping the overall resilience and performance of the food supply chain?
2. What kind of multi-dimensional performance framework can be developed for 4PL and 5PL providers to effectively support the sustainability of the food supply chain in the face of current regulatory and environmental challenges?

1.4 Aim

The aim of this research is to develop a sustainable supply chain framework for the food industry. Moreover, develop mathematical model(s) to investigate and integrate the performance measures for outsourcing practices, with a focus on 4PL and 5PL providers.

1.5 Objectives

In order to achieve this goal, the set objectives consist of the following:

1. To carry out a review of literature on sustainable supply chain management and outsourcing performance measures in the food sector, figuring out the gaps and outcomes associated with 4PL and 5PL providers.
2. To explore the effect of the economic, environmental, and social sustainability aspects of food supply chains, giving special importance to the role of outsourcing companies in the 21st century.
3. To construct and confirm a theoretical model that combines sustainability aspects with outsourcing performance measures in food supply chains.
4. To create mathematical model(s) that capture and integrate various outsourcing results such as customer demand response, inventory management, transportation and storage costs, and just-in-time delivery, with sustainability aspects.
5. To carry out the developed model(s) using Lingo software in order to check their suitability and offer a thorough assessment by means of experimental design methods.

1.6 Significance of Research

This research is a timely and significant contribution both to the theoretical debate on Sustainable Supply Chain Management (SSCM) and to the practical governance of global food systems. The main focus of the study is high-level logistics integration, and its impact is twofold:

➤ Theoretical Significance

Academically speaking, this study addresses a major gap in the academic literature by presenting a performance measurement framework targeted at 4PL and 5PL providers. This is the area that is strongly associated with under-research in the context of sustainability. Although existing SSCM research have mainly targeted the 3PL implementation aspects of the logistics processes, this study opens up theoretically the way in which logistics integrators may strategically exert positive impacts on the sustainability results of perishable supply chains. By using economic efficiency and the Triple Bottom Line as a basis of trade-off quantification, the present research lays down the groundwork for the extension of the knowledge in the area of digitalized and outsourced logistics networks from the scholarly perspective.

➤ Practical and Socio-Economic Significance

The model proposed in this study can act as an essential decision-making support tool for various industry stakeholders namely manufacturers, retailers, and logistics integrators. It offers a thorough approach to the management of outsourcing decisions and shows that environmental protection in the form of carbon footprint reduction and food waste alleviation can go hand in hand with the achievement of task performance. Besides that, the incorporation of measures of labour

conditions and employee well-being in the study charts out the way for the reduction of social risks in the facilities that are outsourced.

➤ **Global and Regulatory Alignment**

Last but not least, one of the main values of this research is that its direction and results are very much in line with global policy frameworks. This contribution approaches the attainment of UN Sustainable Development Goal 12 (Responsible Consumption and Production) and European Union's Farm to Fork Strategy in a quantifiable manner, thus doing the work to connect the dots between policy at the highest level and operations of logistics at the local level. To sum up, the present research work strengthens the food industry's ability to withstand challenges and compete effectively, while also helping to make food supply chains meet the ethical and environmental requirements of the global market.

1.7 Outline of Research

This thesis is formatted so logically that the objective and research question are addressed systematically. The plan is outlined as follows:

- **Chapter 1:** Introduction – Provides an overview of the research, including the abstract, background, problem statement, research questions, aim, objectives, significance, and structure of the thesis.
- **Chapter 2:** Literature Review – Critically examines existing literature on sustainable supply chain management, outsourcing, and performance measurement in the food industry, focusing on 4PL and 5PL providers and identifying key gaps.

- **Chapter 3:** Methodology – Details the research design, including methods for literature review, model development, data collection, and empirical validation using expert choice and Lingo software; experimental design techniques.
- **Chapter 4:** Development, validation and Sensitivity Analysis of Sustainable Food Supply Chain Framework- Outsource performance measure perspective.
- **Chapter 5:** Results – Presents the developed conceptual and mathematical models and findings from their validation within selected food industry supply chains.
- **Chapter 6:** Discussion – Interprets the results using the sensitivity analysis.
- **Chapter 7:** Conclusion and recommendation – Summarise the key findings, contributions, limitations, and recommendations for future research.

This structure enables a logical transition from grounding the research to unpacking and explaining the results, eventually bringing us to a good overall conclusion.

1.8 Conclusion

This first chapter is setting the stage for the whole thesis by emphasising the critical need for a sustainable supply chain model that still aligns with the outsourcing practices in the food industry. It is anticipated that this research will not only fill the gaps in the performance measurement of 4PL and 5PL providers but also enrich the conceptual and operational framework of SSCM. The intended research questions, aim, and objectives collectively map out the course to the new model's development and validation, while the importance undoubtedly highlights the potential benefits of its usage in the spheres of education, industry, and global sustainability goals. It is reasonable to expect, in response to the feedback, the following chapters will track the development of this issue in a structured manner and therefore make a major contribution to the debate on sustainable outsourcing in the food sector.

Chapter Two

Literature Review

2.1- Supply Chain in the 21st century

The scope of supply chain (SC) management studies has changed a lot over time. One of the main factors that caused these changes is technology, but social and environmental changes, as well as some international issues like the COVID-19 pandemic, have had an effect on supply chain management too (Ivanov 2022). In summary, this process includes the following:

- Early 21st century: In the early 21st century, the main focus was on operational efficiency and cost reduction. Traditional approaches like Just-In-Time (JIT) inventory management and lean manufacturing were introduced to reduce waste and increase productivity. These methods primarily focused on optimising internal processes and collaborating with nearby suppliers (Green Jr et al. 2014).

- 2010s: As we entered the 2010s, the concepts of sustainability and resilience gained more serious attention. Environmental issues, such as climate change and the consumption of natural resources, have become more significant. Research moved towards developing green and sustainable supply chains that were not only efficient but also environmentally friendly (Ivanov and Dolgui 2021; Mehrjerdi and Shafiee 2021).

- Post-COVID-19 pandemic: The COVID-19 pandemic was a turning point in supply chain research. The global crisis highlighted the need for supply chains to be highly resilient in order to withstand major and unexpected shocks. During this period, new models such as the Viable Supply Chain (VSC) emerged, integrating the three key concepts of agility, resilience, and sustainability (Ivanov 2022; Rostami et al. 2023).

The supply chain has changed a lot over time, their concerns have shifted from primarily taking up in the early 2000s, efficiency and cost-saving to providing a resilience and sustainability mainly during the last decade and the post-COVID-19 era. It is predicted that over the next few years, supply chains will reap substantial benefits from the utilisation of cutting-edge technologies. These changes imply that corporations, if they wish to not only overcome today's challenges but also ensure that their supply chains remain viable in the future, need to introduce ingenious and flexible approaches in supply chain management.

Overall, it is observed that the trend in supply chain articles has been increasing over the past 10 years, reaching a peak in 2022. According to the outputs of the Web of Science (WOS) article database, as shown in Figure 2.1, the number of articles in 2022 is more than double the number of articles in this field in 2015.

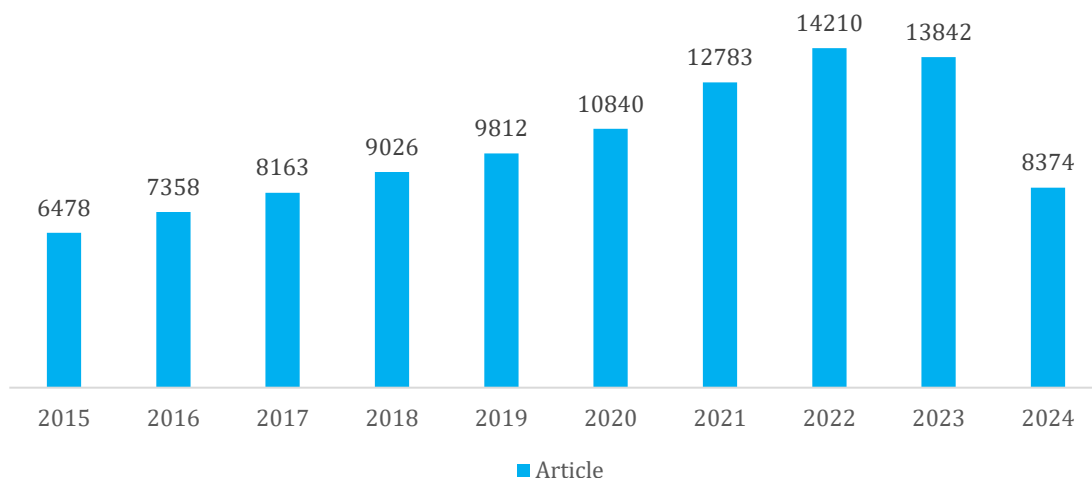


Figure 2. 1: The Number of supply chain articles in the last ten years.

Source: Author's own work using WOS data

Additionally, in Figure 2.2, it can be observed that China and the United States hold the largest share in publishing articles in this field. The top ten countries in this domain are shown in Figure 2.2.

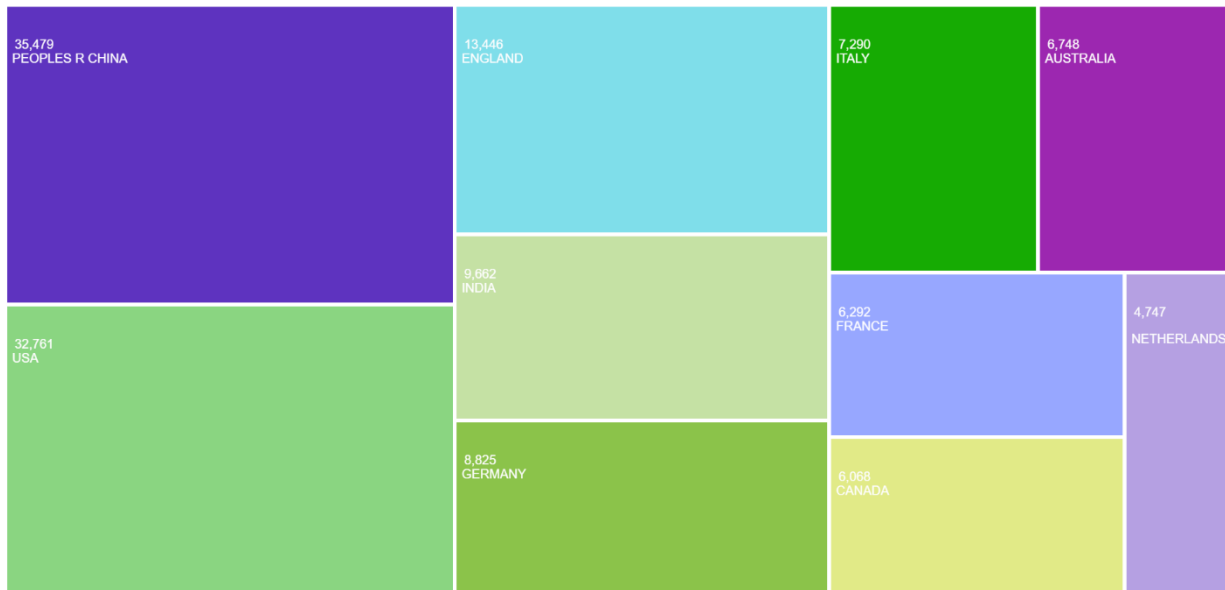


Figure 2. 2: Number of supply chain articles in different countries.
Source: Author's own work using WOS data

Overall, in line with the topic of this study, the Food Supply Chain will be examined and analysed in the next section.

2.2 Food supply chain (especially differences between FSC and other manufacturing SC)

The food supply chain is a system that encompasses all the actions and processes that bring food from the point of origin up to the final consumer. In this chain, the roles of production, processing, packaging, storage, shipping, distribution, and sale are involved. The significance of the food supply chain is in guaranteeing the quality, security, and sustainability of food for the consumers (Bigliardi et al. 2023).

Effective management of this chain can result in the minimisation of food waste, the maximisation of the use of resources, and the assurance of the availability of healthy and nutritious foods. Furthermore, at a time of crisis like a pandemic or a disaster, the correct operation of a food supply chain is a way to avoid the occurrence of food shortages and price rises. (Joshi, Singh, and Sharma 2023).

Establishing a reverse supply chain process in the food supply chain (FSC) is important. The reverse supply chain in the food supply chain refers to the process of returning food products from consumers to producers or processors for recycling, reuse, or optimal disposal. This chain's importance lies in its ability to reduce waste of food, manage resources more effectively, and protect the environment. The reverse supply chain, by recycling the food materials that are still usable and disposing of the rest properly, can be a great helper in reducing pollution and in the efficient use of natural resources (Rahbari, Khamseh, and Mohammadi 2023). Moreover, this chain is very instrumental in getting the rotten or the non-edible food products back to the production system, which indicates the raising of quality and safety of the final food products. Hence, the reverse supply chain can become a major player in the creation of a sustainable and efficient food supply chain (Cruz and Ignacio 2024).

As of August 8, 2024, a total of 20,653 articles with the keyword “Food Supply Chain” are available in the WOS article database. Figure 2.3 shows the trend of articles in this field, with the peak observed during the years 2022-2023.

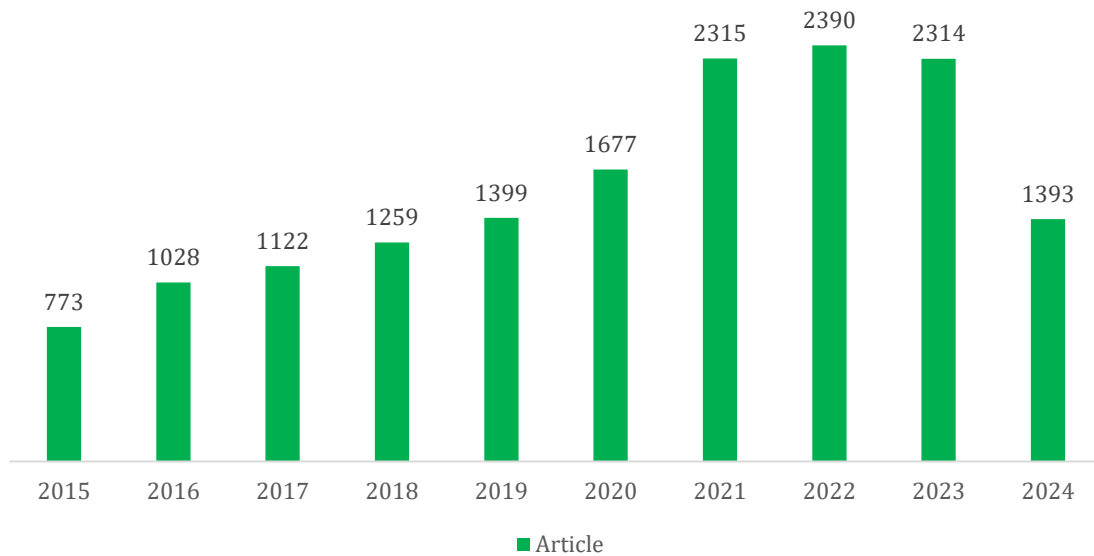


Figure 2. 1: Number of FSC articles in the last ten years.
Source: Author's own work using WOS data

Additionally, the countries with the highest number of published articles in this field are shown in Figure 2.4 The United States has the highest number of published articles in this area.

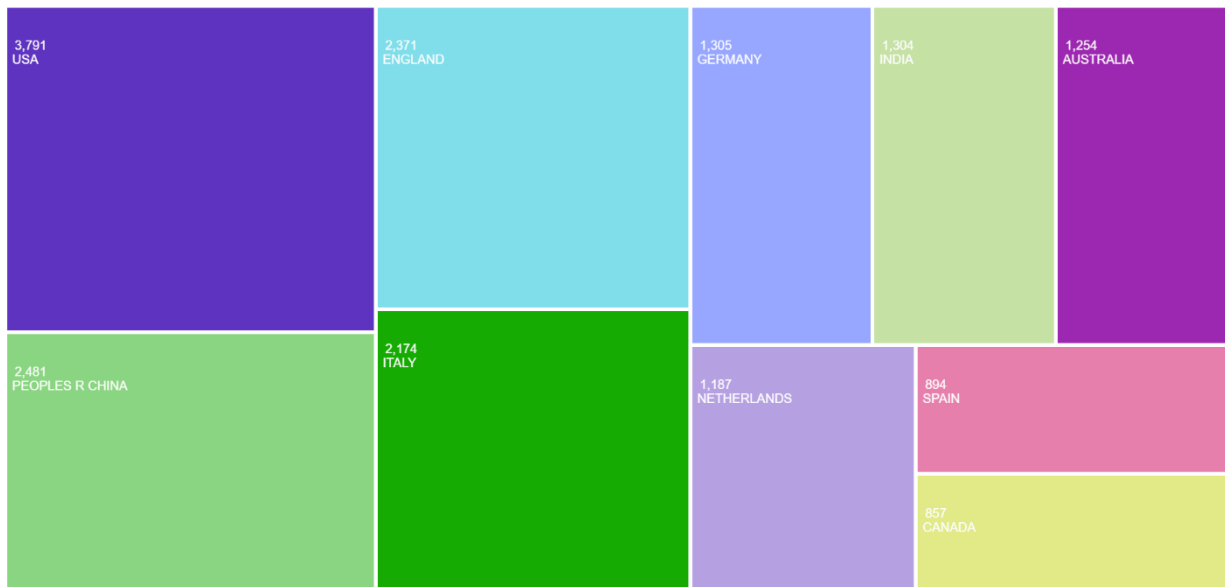


Figure 2. 2: Number of FSC articles in different countries. Source:
Author's own work using WOS data

Food supply chains were the subject of numerous studies. For example, (Mogale, Kumar, and Tiwari 2020) concentrated on the development of a green food supply chain network with attention given to post-harvest risks and losses. The objective was to use mathematical models to design a sustainable and efficient network that could reduce environmental impacts and manage post-harvest losses. The objective's functions were to minimise the total supply chain costs, decrease the losses that occur after harvest, and extend environmental sustainability. The optimisation model put forward made use of Mixed-Integer Linear Programming (MILP) to find solutions to the optimisation problems that involve uncertainties and various kinds of risks. Their findings revealed that employing the MILP method led to a great reduction in costs and post-harvest losses, while the environmental sustainability of the supply chain was improved. The new model was able to offer the risk management and the network efficiency improvement, among other, practical strategies.

(Jouzdani and Govindan 2021) have produced a sustainable perishable food supply chain network, mainly concentrating on dairy products. They developed a multi-objective mathematical programming model which aims to minimise costs, energy consumption, and traffic congestion in the supply chain. In their research, they accounted for uncertainty in product perishability, which was modelled by a Weibull random variable. Their results suggest that focusing primarily on the economic aspect of very perishable products might lead to raising the environmental impact of the supply chain by as much as 120%, while in high-traffic road networks, social impacts could rise by up to 51%. However, a 15% compromise in the economic aspect could improve the sustainability of the supply chain network design by up to 150%. The study also showed that road congestion and uncertainty in product perishability are critical factors that can differently affect the operations and design of supply chains.

(Fikry, Gheith, and Eltawil 2021) developed a mathematical model to optimise the agricultural food supply chain, considering crop rotation decisions and related industrial decisions. They produced an idea of a multi-objective optimisation model that used mathematical programming to pick the best crop rotation schedules for a small area to satisfy the demand. The functions of objectives were to use profit as a measure, lower the impact on the environment, and raise the sustainability of the supply chain. This research pointed out that the multi-objective optimisation model developed was highly effective in optimising crop rotation schedules to meet the necessary demand. The outcomes reflected that the employment of this model enabled one to accomplish the objectives of profitability, emission of environmental impacts, and sustainability of the agricultural food supply chain. Moreover, the model was also effective in linking industrial decisions with production and distribution.

(Abbasian, Sazvar, and Mohammadisiahroudi 2023) examined the design of a sustainable and resilient supply chain network for the perishable food industry using hybrid optimisation methods. The aim was to create a network through multi-objective optimisation techniques that were able to reduce costs and carbon emissions, as well as raise the network's resilience against interferences. In their mathematical model, they defined objectives such as total supply chain costs should be minimised, CO₂ emissions should be reduced and supply chain resilience against disruptions should be improved. To manage the optimisation model, a hybrid method consisting of Particle Swarm Optimisation (PSO) and Genetic Algorithm (GA) was utilised. This approach was adopted due to the fact that it allows for the effective and speedy optimisations by leveraging the advantages of the two algorithms. Their results showed that the use of the hybrid model significantly reduced costs and CO₂ emissions while improving network resilience. Additionally, the proposed model

provided effective strategies for inventory and transportation management under uncertainty and improved network efficiency.

(Arabsheybani and Khasmeh 2023) created a strong and flexible supply chain network for the food sector. They built a strong multi-objective mathematical model, where the objective functions were the maximization of profit and the maximization of the total resilience score. They assigned weights to the resilience factors through the AHP-MOORA hybrid method and then they used the ε -constraint method to find a solution to the model. Eventually, a sensitivity analysis was performed to follow the interplay between optimisation and resilience under different robust parameter settings and to observe the changes in demand and the advantages of considering resilience.

The paper of (Mahroof et al. 2024) is a detailed study of Industry 5.0 drones that investigates the potential such devices have to improve the precision and safety of the pesticide application process in agriculture. The primary goal of this research was to identify the main factors that affected the decision-making of the stakeholders in relation to the adoption of such clean and efficient technologies. The research conducted by means of surveys and statistical methods aimed at the level of adoption of Industry 5.0 drone technology by the different stakeholders in emerging markets. It regraded human-machine collaboration as a way to make pesticide application better and safer and thus lowering the risks that were associated with it. The main thrust was on the direct food supply chain, especially the stage of agricultural production. Their case study in emerging economies analysed the adoption of Industry 5.0 drones. The findings showed that factors such as reducing plant diseases and improving forecasting precision had more influence on adoption decisions than pollution reduction.

(Found et al. 2024) investigated the robustness of the food supply chain against serious disturbances. Their research looked at the ability of the food supply network to withstand considerable interruptions, mainly focusing on the effects of the COVID-19 pandemic on the supply chains. The intention was to find strategies and areas of potential to increase the resilience against future health crises of a global nature. They have done a review of the literature on management and business studies concerning the food supply chain during the COVID-19 pandemic (December 2019 to December 2021) as their methodology. Their study identified the problems and immediate responses required during large-scale disruptions, focusing on the direct food supply chain. Their findings provided strategies for building resilience, including diversifying supply sources, improving digital tracking, and enhancing coordination between supply chain partners. The objective functions included risk reduction, maintaining supply continuity, and ensuring the safety and quality of food.

(Shekarabi, Vali-Siar, and Mozdgir 2024) studied the development of a food supply chain network resilient to pandemics using a mathematical model. The aim was to build a supply chain that would be able to handle the ripple and random effects of the disruptions. They employed a hybrid robust-stochastic optimisation method, supported by mathematical modelling to locate the warehouses and manage the inventory under uncertainty and disruptions. The functions of the objectives involved cost minimisation, supply chain resilience promotion, and customer service level enhancement. The outcome of their research indicated that the application of hybrid robust-stochastic optimisation models might be a great way to prepare food supply chains against pandemic interruptions. The optimal network design resulted in lower total costs and higher service levels. Additionally, the proposed model was able to identify optimal warehouse locations under uncertainty and enhance inventory management.

(Fathi, Zamanian, and Khosravi 2024) proposed a mathematical model for designing a sustainable food supply chain that could reduce environmental impacts and increase efficiency. In the first step, they evaluated suppliers and transfer hubs using the BWM and COPRAS hybrid method. Then they presented a multi-objective mixed-integer linear programming model that optimises the three dimensions of the sustainable supply chain: economic, social, and environmental. In the economic dimension, the total costs, including transportation, construction, maintenance, and decommissioning of transformers and distribution sites, transformer capacity changes, and production costs, were minimised. In the social dimension, the number of jobs created per unit was maximised. In the environmental dimension, water consumption and carbon dioxide emissions were reduced. Additionally, a fourth objective function was provided to minimise product delivery time in addition to the three sustainability dimensions. The proposed mathematical programming model was solved using the LP-metric method, and the necessary comparisons between the results were made. The findings showed that the developed model performed well.

Lotfi et al. (2024) detailed the use of a data-driven robust optimisation tool for the design of an environmentally friendly supply chain network that considers the application of blockchain technologies. Their model's objective function combines the expected value, maximum cost, and CVaR cost. Their study results indicate that the merged application of OI and BCT provides the SC system with a better overall performance. Sensitivity analysis was carried out to explore the impacts of the reduction coefficient, DDRO coefficient, agility rate, demand variations, and problem size.

(Gholipour et al. 2024) developed a multi-objective closed-loop supply chain (CLSC) for pomegranates. Their research mentions that the competitive environment in the world market is the reason that many countries are seeking better ways to solve their problems. Food waste is the

main cause of global food insecurity. Not only that but ignoring the pomegranate waste process, for example, the separating of the peel from other parts, and overlooking the cost of using artificial intelligence to fight pests in orchards and the cost of maintaining processed products are the missing pieces of the puzzle in previous research. Their research identifies the use of artificial intelligence technology in the supply chain as well as the employment of reverse logistics, i.e., waste recycling, as the main differences from other studies. This paper proposes a CLSC design for pomegranates. The logistics network that is connected is a multi-period design and thus, covers producers, distribution centres, customers, factories, recycling centres (compost centres), and the final consumer of compost (compost markets). Through reverse logistics, wasted pomegranates are turned into recycled products such as ethanol which is a fuel for cars and renewable energy, and a kind of compost which is processed as an organic fertilizer. The model presented is to cut down on the costs of the supply chain, lower supply risks, and raise the income of farmers and the public and non-profit agricultural sectors in Iran. The findings indicate that the higher the maximum supply risk, the total costs and risks increase, conversely, network responsiveness decreases. Moreover, the increment of disruption periods results in the growth of total costs and network risks, thus, at first, responsiveness gets higher but later it reduces. Additionally, an increase in disruption periods leads to higher total costs and network risks, initially increasing but then reducing responsiveness.

(Gholian-Jouybari et al. 2024) came up with a deep metaheuristic method, which is used for the sustainable design of a closed-loop agri-food supply chain network. They provided a mixed-integer linear programming model to represent a supply chain network design in the coconut industry under sustainable conditions. The objective of this research is to deal with multi-objective closed-loop supply chain problem, where product transfers are both forward and reverse. The model is

aimed at controlling the net present value of the total costs for some specific planning horizons, along with keeping track of environmental pollution and job opportunities in the network. Due to the NP-hard character of the network, the solution method is a combination of newly introduced metaheuristics that are used to solve the network efficiently. To achieve this purpose, several (six) multi-objective optimisers and three hybrid algorithms were utilised. Among them, the multi-objective artificial rabbit optimiser was created and employed for the first time in this paper. Fifteen real tests were used to check the model's closeness to the actual situation. The findings obtained from distance plots and the Friedman statistical test indicate that the assignees can tackle the problem to any extent. Even so, the Non-dominated Sorting Genetic Algorithm-II (NSGA-II) demonstrated superior performance in the practical experiments as judged by the outcome of the statistical tests and the newly introduced multi-criteria decision-making framework (MCDM).

In Table 2.1, a summary of FSC studies is shown.

Table 2. 1: Summary of FSC field studies

Study	Supply chain		Sustainability			Resilience	Methodology	Case Study
	Directly	Reverse	Economic	Social	Environmental			
Mogale et al, 2020	✓		✓		✓		MILP-Particle swarm	Wheat
Jouzdani & Govindan, 2021	✓		✓	✓	✓		Mathematical model	Dairy Food
Fikry et al, 2021	✓		✓	✓	✓		Mathematical model	---
Abbasian et al, 2023	✓	✓	✓		✓	✓	Mathematical model – PSO – GA	Dairy Food
Arabsheyanbani & Khasmeh, 2023	✓	✓	✓			✓	Mathematical model-Robust Optimisation	Flavor industry
Mahroof et al, 2024	✓			✓	✓		Statistical review	Emerging economies
Found et al, 2024	✓					✓	Systematic review	Food industry of the whole world
Shekarabi et al, 2024	✓					✓	Mathematical model-Stochastic Robust Optimisation	---
Fathi et al, 2024	✓		✓	✓	✓	✓	BWM - COPRAS - Mathematical	---

						cal model - LP-metric	
Lotfi et al, 2024	✓		✓		✓	DDRP – LP metric	---
Gholipour et al, 2024	✓	✓	✓		✓	Goal Programmi ng	Pomegra nate
Gholian-Jouybari et al, 2024	✓	✓			✓	Metaheuris tics	Coconut

2.2.1 Differences between food supply chains (FSCs) and other industrial or manufacturing supply chains

Due to the different basic structures between food supply chains (FSCs) and other industrial or manufacturing supply chains, it is very important to recognise the unique features of FSCs. These features have a significant contribution to the performance, control, and endurance of the supply chain, and they require the creation of policies and decision-making models that reflect the unique characteristics of FSCs. Some of the key features of food supply chains have been identified and summarized from various sources in the following text. (Belamkar et al. 2023; Ciccullo et al. 2021; Corallo et al. 2024; Davis, Downs, and Gephart 2021; Desiderio et al. 2022; Fikry, Gheith, and Eltawil 2021; Found et al. 2024; Gholian-Jouybari et al. 2024; Kaur et al. 2022; Leong, Wong, and Wong 2022; Y. Li, Rakesh, and Reddy 2016; Rao and Sujatha 2023; Sahu et al. 2023):

- **High perishability:** Food products have a short shelf life and are susceptible to spoilage, quality deterioration, and safety risks. This increases the importance of precise timing, temperature control, and transportation processes.

- **Need for temperature control:** Many food items require cold chain logistics, and adherence to temperature standards from production to final delivery is essential to maintain quality and safety.
- **High product variety:** FSCs deal with a wide range of items, from seasonal raw materials to processed foods. This diversity increases complexity in planning, warehousing, and distribution.
- **Sensitivity to hygiene and safety:** Issues such as contamination, foodborne diseases, and health regulations place significant pressure on FSC management and raise operational risks.
- **Strong dependency on environmental and climatic conditions:** Primary production in FSCs is directly affected by variables like rainfall, temperature, and drought, leading to supply fluctuations and shifts in production patterns.
- **Key role of small-scale actors (e.g., farmers):** Unlike many industrial supply chains, FSCs rely heavily on small and vulnerable producers, who face limitations in terms of financial resources, technology, and resilience.
- **High volume of waste and need for reverse logistics:** Significant amounts of waste occur throughout production, distribution, and consumption, increasing the need for reverse supply chains for recycling, reuse, or proper disposal.
- **High consumer sensitivity to quality and safety:** Consumer decisions in FSCs are highly influenced by perceived quality, healthiness, freshness, and product origin, creating strong market pressure on companies.

- **Complex interaction between regulation and market forces:** FSCs are subject to strict regulations in areas like public health, safety standards, imports/exports, and pricing, all which shape supply chain decisions.
- **High importance of traceability and information transparency:** To ensure safety, authenticity, and risk control, end-to-end traceability from farm to fork is essential, increasingly supported by technologies like blockchain.
- **Sharp demand fluctuations:** Food consumption patterns vary due to events, seasons, advertising, and crises, which reduces predictability and complicates inventory and supply management.
- **Complexity in harvest and distribution timing:** The optimal time for harvesting agricultural products is often narrow, and any delay in harvest or delivery can lead to quality loss or total spoilage.
- **Seasonality of production:** Many food products are seasonal, while demand persists year-round. This creates a need for long-term storage or imports to fill gaps.
- **Role of culture and consumption preferences:** Food consumption patterns are shaped by culture, religion, habits, and regional preferences, affecting product design, packaging, and market segmentation.
- **Need for international coordination in supply chains:** With the globalization of FSCs, supply and distribution often span multiple countries, requiring complex coordination across regulations, standards, and operational procedures.

- **Media pressure and crisis responsiveness:** FSCs are highly exposed to public scrutiny and media attention. Any contamination or scandal can quickly erode consumer trust and necessitate fast crisis response.
- **Dependence on efficient and safe transportation infrastructure:** Maintaining product freshness and safety requires reliable transportation systems, particularly in rural or remote areas.
- **Low product valuation at source:** Often, the economic value of products is very low at the initial stages (e.g., on the farm) but increases significantly through processing and retail. This imbalance poses livelihood challenges for primary producers.
- **Complexity of contamination traceability:** In the event of food contamination, pinpointing the exact source within a complex, multi-stage supply chain is difficult and requires advanced information systems.
- **Critical role of trust in supply chain relationships:** Given the direct implications for consumer health and safety, maintaining trust among all chain actors (e.g., farmers, wholesalers, retailers, and consumers) is essential for FSC integrity.

The food supply chain (FSC) differs fundamentally from traditional supply chains due to the unique nature of its products. First and foremost, perishability, the need for precise temperature control, and time sensitivity are significantly more critical in FSCs compared to industrial supply chains, where products are generally stable and suitable for long-term storage (Chandan, John, and Potdar 2023; Corallo et al. 2024; Joshi, Singh, and Sharma 2023; Leong, Wong, and Wong 2022). Whereas traditional supply chains prioritize engineering quality and technical specifications, hygiene and safety form the core of decision-making in FSCs (Found et al. 2024; Yadav et al.

2022). Small-scale activities and farmers are usually part of food supply chains that are less formalized, where they are more exposed to risks and need more support and coordination, whereas in the case of traditional supply chains, these are generally controlled by large, well-organised businesses. The unpredictability of FSCs is caused by the combination of seasonality in production, sharp changes in demand, and reliance on climatic conditions; while industrial supply chains, are mostly run through exact planning and steady production lines. (Ahumada and Villalobos 2009; Belhadi et al. 2024; Chandan, John, and Potdar 2023; Found et al. 2024; Sahu et al. 2023). Nowadays, the food supply chain needs to be fast, traceable, and partly refrigerated if it is transported through the standard supply chain, which in turn needs to have delivery and logistics flexibility. Furthermore, public opinion, media pressure, and brand reputation are factors that have a substantially larger influence on the food industry compared to traditional supply chains. First of all, food supply chains (FSCs) are deeply affected by health risks, food safety problems, and complicated legal requirements, and the latter have a significant impact on managerial complexity..(Ciccullo et al. 2021; Mogale, Kumar, and Tiwari 2020; Sahu et al. 2023; Yadav et al. 2022; Zeynali et al. 2025). Table 2.2 presents a comparative overview of the key differences between traditional supply chains and FSCs.

Table 2. 2: Differences between FSC features and traditional supply chains.

Feature	Food Supply Chain (FSC)	Traditional Supply Chain
Type of product	Perishable, sensitive to temperature and time	Durable, with longer shelf life
Primary actors	Small-scale producers and farmers	Factories and industrial companies
Hygiene and safety	Highly critical and central to decision-making	Important but less critical
Logistics management	Requires fast, cold, and traceable transportation	Standard and more flexible transportation
Demand fluctuations	High and seasonal	More predictable and stable
Climatic risk	High (dependent on weather and environmental conditions)	Low or not directly affected
Public/media scrutiny	High sensitivity, influenced by scandals	Less subject to public attention
Traceability and transparency	Essential to ensure safety and authenticity	Important but often limited to quality control
Regulatory standards	Multi-layered, complex, and international	Typically, fixed, and industrialized
End goal	Ensuring consumer health, freshness, and trust	Ensuring quality, performance, and efficiency

2.3. Importance of sustainability in SC (including all criteria and sub criteria) according to the model

In this section, first deals with the trends of articles about sustainable supply chains, after that gives an overview of the related supply chain literature by various industries and different approaches. The scope of this part is to find the main indicators and sub-indicators of the supply chain sustainability.

The WEB of Science article database has been used to examine the research trends in this field. By searching for "Sustainable Supply Chain" (on August 8, 2024), a total of 24,149 articles identified. Overall, the trend of sustainable supply chain research has experienced a significant upward trajectory since 2015. As seen in Figure 2.5, the trend of articles in the field of the Sustainable Supply Chain has been increasing, and it is expected to continue this upward trend through the end of 2024.

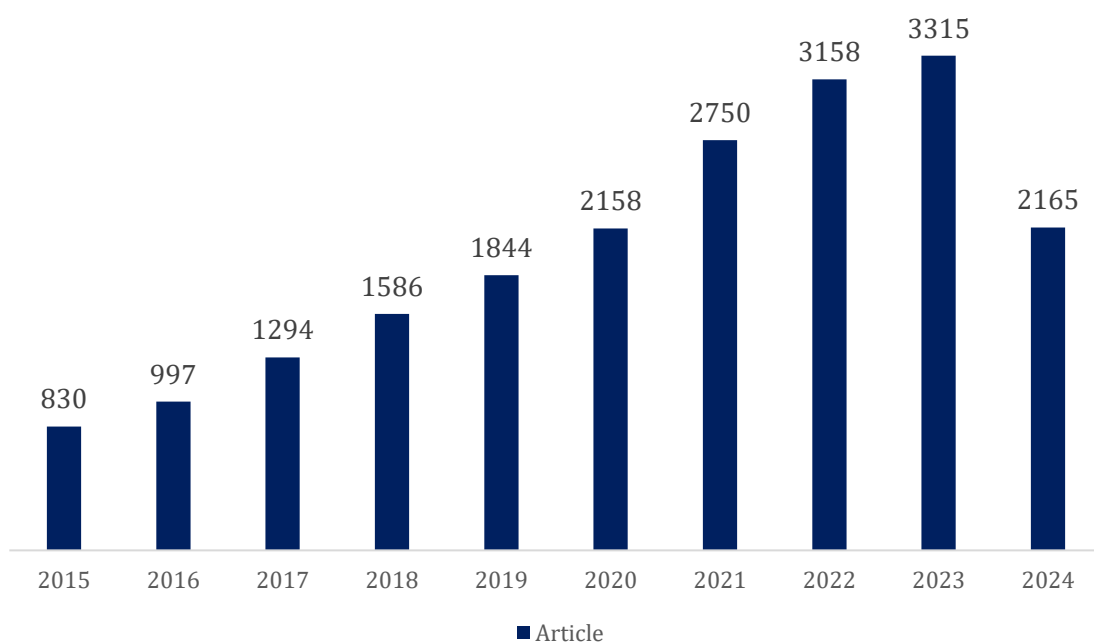


Figure 2. 3: Number of SSC articles in the last ten years

Additionally, in Figure 2.6, it can be seen that most articles in this field have been published by China, the United States, and the United Kingdom. The top ten countries in this field and the number of their articles are shown in the figure below.



Figure 2. 4: Number of SSC articles in different countries

After this, articles regarding the Sustainable Supply Chain (SSC) topic have been analysed subjecting the key indicators that define this field of study to identification and investigation based on the articles. For example, (Zimmer, Fröhling, and Schultmann 2016) conducted a review study to evaluate sustainable suppliers. They analysed various articles in this field from different aspects such as solution methods, evaluation indicators, and the prominent countries in this domain. Additionally, (Fallahpour et al. 2017) unveiled a decision support system to aid in choosing suppliers who are sustainable. Their research is based on a supply chain of the textile industry. The key indicators that reflect suppliers' evaluation in this field have been specified as the source to evaluate suppliers in the sustainable supply chain context. In another study, (Durmić et al. 2020) evaluated sustainable suppliers using combined MCDM approaches, where the evaluation indicators were identified in three dimensions of sustainability.

(Alavi, Tavana, and Mina 2021) evaluated and selected sustainable suppliers considering circular economy dimensions using a combined FBWM and FIS method. (Sazvar et al. 2022) evaluated

pharmaceutical suppliers based on sustainability and resilience criteria during the COVID-19 pandemic. They identified a total of 13 sustainability evaluation indicators, with social indicators holding the most weight and importance. Furthermore, (Rostami et al. 2023) evaluated medical equipment suppliers according to viable supply chain criteria, one of which was sustainability. They considered eight indicators for the sustainability dimension, with the environmental component being the most prominent. (Nayeri et al. 2023) evaluated suppliers and allocated orders to them under uncertainty conditions, considering sustainability and resilience criteria. They used sustainability indicators in supplier evaluation and the objective functions of their mathematical optimisation model. (Shao, Barnes, and Wu 2023) proposed a two-stage framework for evaluating sustainable suppliers and assigning orders to them, with evaluation indicators selected in the three dimensions of sustainability. (Hailiang et al. 2023) defined a structure based on the Best-Worst Method for evaluating sustainable suppliers, defining 21 indicators overall for evaluating suppliers within the sustainability structure and dimensions.

Table 2.3 provides a summary of sustainability indicators in the supply chain from various studies.

Table 2. 3: Sustainability indicators in the supply chain

Study	Sustainability Indicators		
	Economic	Social	Environmental
Zimmer et al, 2016	Management and Organisation: Strategy and organisation	Internal social practices: Social commitment	Environmental practices: Environmental commitment
	Internal management Supplier management Compliance	Social management	Environmental management Environmental capabilities
	Financial performance: Cost Financial situation	Social performance: Child and forced labour.	Environmental performance: Material

		Occupational health and safety Wages and working hours. Training of employees Employment relationship Discrimination and diversity Freedom of association	Energy Emissions Water Waste Environmental product performance
	Capabilities: Quality Production and logistics Technology Service Communication	External social practices: Stakeholder involvement Society	
	External perception: Public disclosure Reputation and market structure Certificates and labelling		
	Cost: Material cost Freight cost After sales service cost	Workers' Rights: Workers' contract Employment insurance Employment compensation Standard working hours Overtime pays	Environmental Management System: ISO-14001 certification Environmental performance evaluation Eco-labelling Environment-friendly raw materials
Fallahpour et al, 2017	Quality: Rejection rate of the product Capability of handling abnormal quality Process for internal quality audit of material	Health and Safety at Work: Health Insurance at Work Training for Safety at Work Providing Appropriate Equipment at Work	Green product: Green certification Reuse Green packaging Air emissions Wastewater Hazardous wastes
	Delivery & Service: Lead time flexibility. After sales service	Supportive Activities: Discrimination Growth at Work	Green warehousing Inventory of non-hazardous substances

	Time to solve the complaint.	Wages	Inventory of substitute material
	On-time delivery	Attention to Religious and Cultural Issues at Work	Warehouse management
	Flexibility: Flexibility in giving discount. Flexibility of delivery time Flexibility in ordering		Eco-design: Recycle of products when design. re-Manufacturing of products when design Reduction of the use of hazardous materials when design
			Green Transportation: Using a modern eco-efficient transportation fleet Using green fuels with low sulfuric content
Durmić et al, 2020			Green Technology: Materials used in the supplied components Capability of R&D Ability to alter process and product for reducing
	Cost/price	Reputation	Ecological image
	Quality	Safety at work	Recycling
	Flexibility	Workers' rights	Pollution control
	Productivity	Local community influence	Environmental management system
	Financial capacity	Employee training	Ecological products
	Partnerships	Respect for rights and policies	
	Eco-innovation	Release of information	
Alavi et al, 2021	Cost	Human rights	Attention to energy consumption in production and recycling products

	Quality	Product responsibility	Attention to air pollution in production and recycling products
	On-time delivery	Occupational health and safety management system	Producing products using recyclable raw materials
	Reputation	Information disclosure	Utilizing clean and green technology in production and recycling products
	Flexibility	Social commitment	Employing eco-friendly materials for packaging and products
	Technological capacity	Ethical issues	Respecting environmental regulations and standards
	R&D	Employment practices	Waste management
	Responsiveness	Social management	Environmental management system
	Financial capability	Attention to child and forced labour problem	Managing returned products
	Productivity		Reverse logistics
	Service efficiency		
	Risk		
Sazvar et al, 2022	Ability	Trust	Resource consumption
	Quality	Workers' contract	Eco-friendly
	Cost	Labour insurance	Pollution control
		Standard working hours	
		Speed in payment of salaries	
		career progression	
Rostami et al, 2023		Wage	
	Cost	Job safety and labour health	Greenhouse gas emission
		Job opportunities	Waste management
		Employment insurance	Pollution control
			Energy and resource consumption

Nayeri et al, 2023	Cost	Links between paid work and social benefits	GHG emission
		Job safety	Re-use
		Workers' contract	Waste Management
			Energy consumption
Shao et al, 2023	Quality	Labour safety and healthy	Resource and energy consumption
	Delivery	Staff training	Eco-design
	Service	Social responsibility	Environmental management system
	Technology capability		
Hailiang et al, 2023	Delivery reliability	Influence on the local community	Control on pollution
	Supply capacity	Staff training	Environmental management system
	Service	Health and safety	Environmental competencies
	Flexibility	Adherence to law and policy	Green involvement
	Price	Disclosure of information	Energy conservation
	Quality	Stakeholder rights	Environmental cost
	Relationship condition	Employee rights	
		Forced child labour	

2.4. Outsourcing companies (3PLs, 4PLs, 5PLs) and a clear comparison (table) between these companies, supported by references.

This section addresses the indicators and metrics used to evaluate outsourcing companies. In general, Gunasekaran et al. (2015) explored this topic in their article. They described outsourcing as the handing over of a particular job or a series of functions in a company to another company or a different organisational unit. Therefore, companies hire external suppliers to perform some of their functions, thereby freeing themselves to concentrate on core competencies, cut down on costs, acquire more agility, and so on, streamline their work. Moreover, the practice of outsourcing has mainly evolved as a cost-cutting measure, but by the 1990s it became a strategy to concentrate

on the strengths of the company. Later, in the 2000s, its development was towards "transformational outsourcing" that was going to be a competitive advantage created through the business model reforms (Dubey, Gunasekaran, and Childe 2015). Typically, in the outsourcing process, decisions are divided into tactical and strategic levels. Each level comprises several types of task delegation to external suppliers, which are further broken down based on the amount of responsibility handed over and the closeness of the activity to the organisation's strategy. As per the model implemented by Sanders et al. (2007), the outsourcing decisions can be categorized into four major groups: Out-tasking, Co-managed Services, Managed Services, and Full Outsourcing. This categorization assists the decision leaders in pinpointing the degree of their participation as well as control over the activities that are outsourced and thus, making the right evaluation frameworks as per the task's importance and risk level. Table 2.4 depicts these groups along with the decision levels and descriptions (Sanders et al. 2007).

Table 2. 4: Classification of outsourcing types

Category	Decision Level	Description
Out-tasking	Tactical	Delegation of a specific, low-risk task
Co-managed Services	Tactical	Delegation of broader tasks with retained customer control
Managed Services	Strategic	Delegation of design, implementation, and management to the supplier
Full Outsourcing	Strategic	Complete delegation of responsibility for an activity or process to the supplier

Decisions regarding strategic outsourcing are connected to the activities and procedures that are essential for the survival and competitiveness of the organisation overall. At such a level, the organisation not only hands over the implementation but also the creation, administration, and the

organisation's strategic direction of a certain function or process to the external supplier. Consequently, performance measurement metrics (PMMs) at the strategic level must encompass both financial and non-financial aspects, including the ones that can be measured (such as profitability and service quality) and the ones that cannot (such as trust, innovation, and organisational learning capability). These metrics are utilised in the stages of pre-, during, and post-outsourcing to verify that the outsourcing scheme is correctly aligned with the organisation's strategic objectives and that the agency's risks are being managed effectively. Strategic-level performance metrics are presented in Table 2.5.

Table 2. 5: Performance evaluation indicators at the strategic level

Phase	Indicator Type	Tangible	Intangible	References
Pre-outsourcing	Financial	Supply chain costs, ROI, ROE, profitability	Financial strength, R&D	(Holcomb and Hitt 2007; S. Li, Murat, and Huang 2009; Nam, Chaudhury, and Rao 1995)
Pre-outsourcing	Non-financial	Quality, flexibility, external expertise	Trust, relationships, tacit knowledge	(Huang and Keskar 2007; Kshetri 2007)
During outsourcing	Financial	Sales, cost reduction, profitability	Financial strength	(Arya, Mittendorf, and Sappington 2008; Ellram and Billington 2001; Lim and Tan 2010)
During outsourcing	Non-financial	Service quality, IT infrastructure	Innovation, knowledge management, trust	(Aksin and Masini 2008; Barthélemy 2003; Kotabe, Mol, and Murray 2008)
Post-outsourcing	Financial	Efficiency, switching cost	Contract complexity	(Barthélemy and Quélin 2006; Jiang, Frazier, and Prater 2006)
Post-outsourcing	Non-financial	Reliability, quality control	Satisfaction, reputation, communication coherence	(Elmuti 2003; Weidenbaum 2005)

Tactical outsourcing decisions are generally about the operations and activities that support the organisation's daily activities, which are necessary for the organisation's survival but not directly related to the achievement of sustainable competitive advantage. These decisions are often aimed at cutting costs, increasing the effectiveness of the organisation, and raising the pace and the accuracy of the execution of work. At this stage, the performance measurement metrics (PMMs) concentrate more on the measurable aspects of the organisation's activities such as operating costs, response time, service quality, and inventory levels. Nevertheless, collaboration, employee motivation, and the communication between organisations, although not measurable, are also very

important. These are the indicators that present the performance of the supplier and the outsourcing efficiency to decision-makers at the stages of the selection phase, contract execution, and post-implementation evaluation. The relevant tactical-level performance metrics are presented in Table 2.6.

Table 2. 6: Performance evaluation indicators at the tactical level

Phase	Indicator Type	Tangible	Intangible	References
Pre-outsourcing	Financial	Production cost, distribution, inventory	Hidden cost, innovation	(Araz and Ozkarahan 2007; Lee and Choi 2011)
Pre-outsourcing	Non-financial	Delivery rate, technology level	Trust, intellectual capital, cultural development	(Han, Lee, and Seo 2008; Tjader, Shang, and Vargas 2010)
During outsourcing	Financial	Poor quality cost, component defects	Motivation productivity	(Raiborn, Butler, and Massoud 2009; K.-J. Wang and Chen 2009)
During outsourcing	Non-financial	Process control, cycle time	Collaboration, team skills	(Currie, Michell, and Abanisque 2008)
Post-outsourcing	Financial	ROI, efficiency, transfer cost	Customer control	(Mao, Lee, and Deng 2008; Tate and van der Valk 2008)
Post-outsourcing	Non-financial	Project quality, satisfaction	Learning, coherence	(Han, Lee, and Seo 2008; Tarakci, Tang, and Teyarachakul 2009)

The performance of outsourcing companies has been the topic of various studies. Hsiao et al. (2010) suggested a decision-making system for offloading what varies from line to level of logistics operations in the agri-food supply chain industry. In their work, authors combine findings from a literature review, several case studies, and an exploratory survey to produce a model that

accounts for the rationale behind the outsourcing and the in-house retention of certain logistics activities. These activities are defined across four levels:

- 1) Basic operational level, such as transportation and warehousing,
- 2) Value-added level, such as packaging and labelling,
- 3) Planning and control level, such as inventory and transport management,
- 4) Strategic decision-making level, such as network design.

The results indicate that three main factors play a key role in outsourcing decisions:

- Asset Specificity: The more specialized the asset required for an activity, the more likely the company is to retain its in-house.
- Core Closeness: The closer an activity is to the company's mission or competitive advantage, the less likely it is to be outsourced.
- Supply Chain Complexity: The more complex the supply chain (in terms of product variety, distribution channels, or international customers), the higher the tendency to outsource.

In addition to these, two other factors were examined which, although statistically weaker, still influenced decision-making:

- Performance Measuring Uncertainty: When it is difficult to evaluate supplier performance, companies prefer to keep the activity internal.
- Logistics Strategy: Companies focused on cost reduction tend to outsource more, while those prioritizing quality or flexibility are less likely to do so.

Outsourcing companies' assessment has been investigated in numerous studies. Zhang et al. (2013) outlined a research project that focused on the examination of the capabilities of contract research and manufacturing organisations (CRMOs) in the pharmaceutical industry through an evaluation study. Relying on the Dynamic Capability (DC) theory, the article argues that pharmaceutical companies need to move from merely checking the operational performance of the suppliers to evaluating their strategic capabilities in order to have stable, strategic partnerships. In this research, the multinational company PharmCo is evaluating four CRMOs from China and India by using the three main dimensions of dynamic capability as criteria.

(Kalinzi 2016) conducted an empirical study on the impact of outsourcing logistics services on supply chain performance at Mukwano Company in Uganda. Through the implementation of surveys and interviews, the study revealed that strategic and well-controlled outsourcing has a positive impact on the efficiency of the supply chain. However, the first moves based only on money-related issues will not entail the rise of the performance. In this study, the evaluation metrics for outsourcing companies are classified into three categories: financial, technical, and strategic. Financial indicators are those things that may include a reduction in transportation costs, savings in the cost of administration, and a lower amount of idle or delay costs, all of which are the direct reflection of economic efficiency. Technical indicators are features that may be cargo safety, delivery time, and the accuracy of order fulfilment, the process of supplier operational effectiveness. Moreover, strategic indicators, for instance, alignment with organisational goals, grasping customer needs, and being the first to act at challenging times, are the reflection of the relationship between the company and the use of outsourced services to help the company achieve its objectives. The results showed that among financial, technical, and strategic indicators, the former was the most important in the weighting of Mukwano's outsourcing decisions; however,

only the performance of the supply chain improved if it was efficient and properly controlled by the management of the company.(C.-N. Wang et al. 2021) proposed a hybrid decision-making model for selecting third-party logistics (3PL) companies, incorporating supply chain sustainability dimensions. Their model is based on two advanced MCDM techniques: Fuzzy AHP (FAHP) and Fuzzy VIKOR and evaluates outsourcing companies across multiple sustainability dimensions. (Stekelorum et al., 2021) explored green supply chain management (GSCM) practices in 3PL firms. Using cluster analysis, the study categorized logistics service providers into four GSCM clusters based on the type and extent of their environmental actions. Cluster one highlights working closely with suppliers to come up with environmentally friendly packaging designs. Clusters two and three, respectively, deal with the first one to make use of reverse logistics, investment recovery, and customer collaboration; the third one being committed to green warehousing, sustainable distribution strategies, and customer-centred green services. Meanwhile, cluster four, the most inclusive, dealt with the various internal and external GSCM practices as well as environmental management by top management. This categorization allows firms to recognise their place within the greening process and plan more eco-friendly development strategies.(Nayeri et al. 2023) developed a multi-stage model for evaluating and selecting suppliers in a responsive supply chain. The model focuses on assessing suppliers across three dimensions: sustainability, resilience, and responsiveness. In the first stage, a novel method called Stochastic Fuzzy Best–Worst Method (SFBWM) is used to handle both subjective and event-based uncertainty. Supplier scores are then calculated, and in the second stage, a multi-objective model is formulated for order allocation. (Tavakoli et al. 2023) proposed an innovative integrated model for evaluating and selecting sustainable and resilient suppliers, taking customer preferences into account. The authors used multiple criteria decision making (MCDM) techniques in uncertain

settings to discover and prioritize the main criteria within four aspects: economic, social, environmental, and resilience. Some of the main features that were mentioned are cost, quality, delivery time, trust, technological capability, labour safety, social responsibility, and recovery capacity in crisis. The results of the weighting indicate that after cost and quality, customers still focus on the responsiveness, collaboration, and the reduction of the operational risk. This model gives support to the decision-makers as it helps them to select those suppliers who are not only efficient but also sustainable, adaptive, and socially and environmentally friendly. (Zeynali et al., 2025) introduced a multi-stage, data-driven decision-making model to pick recycling partners in a reverse corn supply chain. The paper deals with the assessment of third-party recycling firms as representatives of an outsourcing model in waste management of the agricultural sector utilizing the parameters of sustainability, resilience, and agility. (Tajally et al., 2025) came up with a data-driven hybrid model for the evaluation of raw material suppliers. The primary objective is to identify the most sustainable suppliers in the automotive sector, focusing on two main areas: the circular economy and supplier viability.

Table 2.7 summarizes the identified evaluation criteria and their definitions extracted from these studies.

Table 2. 7: Evaluation indicators for outsourcing companies

Study	Indicator Title	Definition	Case Study
Hsiao et al., 2010	Asset Specificity	Specificity of equipment, skills, or investments for logistics tasks. Higher specificity reduces outsourcing likelihood.	Food Supply Chain
	Core Closeness	Closeness of task to core business or competitive advantage. The closer it is, the less likely to outsource.	

	Supply Chain Complexity	Complexity from product variety, uncertain demand, and customer/channel diversity increases outsourcing.	
	Performance Measuring Uncertainty	Difficulty in measuring and monitoring performance leads to keeping tasks in-house.	
	Logistics Strategy	Cost-reduction oriented companies prefer outsourcing; quality- or flexibility-driven firms outsource less.	
Zhang et al., 2013	Processes	Includes project delivery quality, communication, and cost estimation.	Pharmaceutical Industry
	Positions	Financial strength, human capital, service diversity, and geographical scope of outsourcing firm.	
	Paths	Past collaboration experience, project value, R&D or production domain, and duration of relationship.	
Kalinzi, 2016	Financial Indicators	Measures cost savings such as in transport, admin, and delay.	
	Technical Indicators	Measures service reliability, safety, and timeliness.	
	Strategic Indicators	Measures alignment with strategic goals like responsiveness and flexibility.	
Wang et al., 2021	Logistics Cost	Total outsourcing cost including transport, warehousing, pricing, and operations.	Logistics Company
	Financial Stability	Supplier's financial status, service continuity, and operation updates.	
	IT and R&D Systems	Tech innovation capacity, data security, tracking.	
	Network Management	Network scope, market coverage, partnerships.	
	Service Quality	Service monitoring and continuous improvement.	
	Delivery Reliability and Time	On-time delivery, responsiveness, delivery accuracy.	
	Flexibility and Responsiveness	Ability to adapt to demand changes and professional service.	
	Environmental Pollution	Volume of carbon, noise, and pollutants.	
	Environmental Regulations	Compliance with environmental laws and waste handling.	
	Green Operations	Green supply chain, packaging, and storage practices.	

	Health and Safety	Workplace safety and prevention efforts.	
	Voice of Customer	Customer feedback on service and products.	
	Reputation	Supplier's reputation and work experience.	
	Operational Risk	Process errors, human error, security/legal risks.	
	Financial Risk	Liquidity risk, financial resource risks.	
Stekelorum et al., 2021	Top Management Commitment	Top management commitment to GSCM.	Logistics Companies
	Cross-functional Collaboration	Cross-functional environmental collaboration.	
	Environmental Performance Measurement	Environmental performance tracking and audits.	
	Green IT	Use of green information technologies.	
	Customer Cooperation	Collaboration with customers for cleaner products.	
	Green Packaging	Use of recyclable or biodegradable packaging.	
Nayeri et al., 2023	Cost	Cost of purchasing from supplier.	Medical Equipment
	Quality	Quality of received raw materials.	
	Delivery Time	Time required to deliver materials.	
	Service	Post-purchase support and services.	
	GHG Emission	Efforts to reduce greenhouse gas emissions.	
	Energy Consumption	Energy efficiency and optimisation.	
	Occupational Safety	Workplace safety practices.	
	Inventory Buffer	Maintaining extra inventory for crisis.	
	Agility	Ability to rapidly respond to changes.	
	Cooperation	Level of collaboration with supply chain actors.	
Tavakoli et al., 2023	Cost	Total purchase cost.	Online Retail
	Delivery	Delivery speed and accuracy.	
	Quality	Compliance of product with standards.	
	Service	After-sale service level.	
	Trust	Trust in supplier's reliability.	
	Technology Capability	Technological advancement capability.	
	Environmental Competencies	Environmental policy adherence.	
	Risk Reduction	Reducing operational risks.	

Rezaei Zeynali et al., 2025	Responsiveness	Ability to quickly meet changing demands.	Food Supply Chain
	Backup Supplier	Alternative supplier arrangements.	
	Recycling Cost	Total waste collection and recycling cost.	
	Financial Power	Investment power and liquidity.	
	Quality Management System	Quality control systems in place.	
	Cooperation Willingness	Willingness for long-term transparent cooperation.	
	Resource Consumption	Usage and wastage of natural resources.	
	Pollution and Waste	Pollution and waste production in process.	
	Job Creation	Social impact through job creation.	
	Future Technology Development	Investment in green and future technologies.	
Tajally et al., 2025	GHG Emissions	Amount of greenhouse gas emitted.	Home Appliances
	Green Warehouse	Green standards in warehouse management.	
	Green Image	Company's perceived green image.	
	Job Opportunities	Employment generation.	
	Lead Time Flexibility	Flexibility in procurement timing.	
	Reliability	Consistency in delivery and product quality.	
	Manufacturing Flexibility	Production process changeability.	
	Responsiveness	Speed in responding to demand changes.	
	Cyber Security	Cybersecurity strength.	
	Smart Factory	Use of smart production systems.	

Based on the reviewed studies, it can be concluded that the evaluation of outsourcing companies in the food supply chain, across different levels (from operational tasks to strategic decision-making), requires consideration of a multi-dimensional set of indicators. Among these, sustainability metrics play a prominent role, but other aspects such as agility, resilience, digitalization, and financial performance also carry varying degrees of importance at different levels.

At the operational and execution level (e.g., transportation and packaging), indicators such as cost, delivery time, service quality, energy consumption, waste management, and environmental efficiency are prioritized. Third-party logistics providers (3PLs) operating at this level should be able to provide services that are not only precise and cost-effective but also in line with environmental compliance. Besides that, pollution prevention, eco-friendly packaging, and energy efficiency are some essential aspects upon which their selection depends (C.-N. Wang et al. 2021).

When it comes to planning and middle management, aspects like reactivity, adaptability of capabilities, cooperation among stakeholders and being able to overcome interruptions become more significant. The extent to which a firm can carry out operations through the use of safety stock, divert distribution, employ environmentally friendly technologies, and establish efficient customer communication are the major factors at this stage (Nayeri et al. 2023).

More weight is given to social and institutional sustainability aspects when decisions are made at the level of strategy and executive management. Such features comprise the pledge to human rights at work, safety at the workplace, clean energy and green innovation investment, as well as being open about the performance of the environment and society, all of which are instrumental in picking outsourcing partners for the extended period (Tajally et al. 2025; Tavakoli et al. 2023).

In summary, the food supply chain outsourcing firms need to handle a bundle of measurable and qualitative indicators that correspond with the extent of their functioning. Environmental sustainability, operational resilience, responsiveness, digital capability, and social responsibility are the main dimensions decision-makers have to consider. Actually, in the food sector, where there is the danger of the perishability of food, diseases caused by food

and rigid regulations, these indicators turn out to be very helpful in guaranteeing the efficiency and the perpetuation of the supply chain.

2.5. What are the available sustainability models in the LR but critically identify pros and cons of these models to find out research gap

This section goes through a number of research papers on the supply chains of the agrifood sector and breaks down the objectives used in each work to find out and assess the gaps that exist in this field of study. A few researchers have made contributions to this field. For example, (Patidar and Agrawal 2020) targeted to pattern a suitable mathematical model for the agrifood supply chain (AFSC) in India, presenting two models to mitigate such issues as distribution costs that are high and post-harvest losses. The first model (M1) centres around minimizing the total distribution cost (TDC) whereby the cost components are hub establishment, the transportation both from farms to hubs and from hubs to customer zones (CZ), and inventory holding. The second model (M2) deals with the perishability of products and features disposal costs for spoiled items. Consequently, from an economic point of view, the function of both these models is to eliminate transportation, hub construction, and inventory of supply chain as the main sources of costs. Meanwhile, the model does not have a prominent environmental goal, it still can be regarded as a tool in pollution reduction, most likely through more efficient management of perishables and avoidance of waste. In terms of social aspects, the model also elevates public welfare by facilitating the supply of fresher products. The research revealed that the perishability-aware model (M2) was superior to M1 in that it was able to achieve a total cost reduction of 3.16%. This work represents a structured mathematical approach for agricultural supply chains in developing countries like India.

(Mehrbanfar, Bozorgi-Amiri, and Nasiri 2020) devised a multi-product, multi-echelon, sustainable agricultural supply chain network under uncertainty that involves greenhouses, farmlands, processing plants, and farmer markets. Their model is a three-objective function one: from the economic point of view, it minimises the total network cost including cultivation, transportation, construction, and production expansion; from the environmental point of view, besides reducing carbon emissions from production, transportation, and infrastructure, it also names the water efficiency; and from the social point of view, it increases employment through the production unit's expansion. The model of the supply chain includes uncertainty in such factors as the rate of employment, product decay, tomato Brix index, water use, and ideal yield, and the solution is given by fuzzy logic and the augmented ε -constraint method. On a case study in Hamedan Province (Iran), the model demonstrated that it could increase productive capacity of the agricultural land, reduce water consumption by as much as 65%, promote the quality of processed products, and raise employment. (Saurabh and Dey 2021) explored the adoption of blockchain technology in agricultural supply chains, focusing on the grape-wine chain in India. First, they wanted to find out which would be the main factors that would affect the stakeholders' decision to accept the modern technologies and then design a modular blockchain architecture that would be traceable for a sustainable supply chain. They found these factors by implementing conjoint analysis: removal of intermediaries, traceability, price, trust, regulatory compliance, and coordination/control. The first three factors are from the economic aspect, "elimination of intermediaries" leading to cost reduction, "pricing" allowing the producer to get a larger share, and "traceability" for the increasing of efficiency. The rest of the factors, namely trust, regulatory compliance, and coordination/control are now added to the social dimension, with each of them representing the features of the community namely transparency, trust, and collaborative

management, respectively. Additionally, by incorporating technologies like IoT, cloud computing, machine learning, and sensors, the model addresses aspects such as resource control, emission reduction, and input optimisation, which reflect the environmental dimension. Thus, this study contributes to the development of a sustainable, transparent, and inclusive agrifood supply chain enabled by blockchain-based architecture and informed technology adoption analysis.

The main thrust of the study (Rana, Tricase, and De Cesare 2021) is associated with the discussing the application of the blockchain technology in supply chains in agriculture, with a focus on sustainability. The authors of the paper set as the principal task to explore the possible benefits, challenges, and future research directions of the implementation of blockchain technology in food supply chain to achieve better traceability, transparency, and sustainability. Through a comprehensive review of literature from 2010 to 2020, the research identified blockchain as a potential tool to achieve supply chain sustainability by ensuring that information is shared more openly, traceability of resources is conducted more efficiently, and forgery is reduced. On the economic side, blockchain can be the source of saving and efficiency increase in the supply chain by cutting information exchange costs, removing the middlemen, and allowing smart contracts (for example, agricultural insurance) to be used. Within the environmental aspect of the sustainability diamond, blockchain technology has been utilised in initiatives including product carbon footprint tracking, the fight against illegal fishing, and the facilitation of recycling in the circular economy. As for the social aspect, one of the main benefits of the transparent and unalterable data recording is its potential to be a barrier against labour rights violations, a support resource for smallholders, and an enabler of public trust in food brands. The research also refers to blockchain combined with other tech such as IoT, sensors, and AI for creating the next level and eco-friendly traceability systems in agricultural supply chains.

(De et al. 2022) developed research to build an eco-friendly supply chain optimisation model for the Norwegian salmon supply chain, as a case study. The authors came up with a multi-level, multi-period mixed-integer linear programming (MILP) model that merges strategic and operational decision-making. The main idea of the model is the efficient use of the transport, processing, inventories, and waste prevention as well as carbon emissions abatement. For the economic dimension, the goal function of the model is to minimise the total supply chain costs that include transportation, fuel, inventory holding, processing, and waste management. In the environmental dimension, the model integrates carbon emission limits as a result of product transportation across the stakeholder area. The primary focus has been on cutting down the use of fuel through the selection of the most suitable transportation modes (e.g., a change from land to sea transportation). Though not having any explicit social objective function, such a model still aggregates to overall sustainability through waste reduction and supply network optimisation. The model has been designed in each of the N1 and N2 forms, which stand for the upstream and downstream parts of the supply chain, respectively. Sensitivity experiments with demand and transport scenarios revealed that shipping by sea could lead to a substantial drop of both costs and carbon emissions. The research provides a feasible cost–carbon trade-off model which can be used for the food supply chain planning that is sustainable.

Research by Joshi, Singh, and Sharma (2023) was carried out with the objective of identifying the factors that would lead to the adoption and implementation of sustainable practices in the agricultural food supply chain (A-FSC) in India. The study focused on the attitudes, the issues farmers faced, and the incentives they and other supply chain stakeholders in the Uttarakhand region considered. Five factors were the major determinants of the farmers' decision to adopt the practice of sustainable agriculture. The findings have been established through a combination of

literature review and the outcomes of 1,100 semi-structured interviews conducted with supply chain actors. The authors, with this study, do not seem to be sketching a mathematical model or objective functions in the traditional manner, but, at the same time, they are barely touching upon the main pillars of sustainability implicitly. The economic aspect of the paper is when it talks about increasing productivity, cutting down on post-harvest losses, and helping local economic growth become better. On the social side, it mentions the empowerment of farmers, their education, the provision of extension services, and the improvement of labour rights and working conditions. In the environmental dimension, the study mentions the implementation of the environmental discourse in farming operations, cutting down on greenhouse gas emissions, and the use of clean technologies. The paper is, in fact, putting forward a conceptual framework that is very much reliant on the context for the successful development of sustainable agriculture in the third world countries.

(Belamkar et al. 2023) designed a study to create a multi-objective optimisation model for the apple supply chain to improve a sustainability perspective under the uncertainty scenario. They worked with a mixed-integer linear programming (MILP) model with type-2 fuzzy data and introduced three objective functions. The first objective in the economic dimension is to maximise the total profit of the supply chain, which should include, along with the product sales revenues, the emission reduction bonuses, and the operational costs subtracted. The environmental dimension is represented by the second objective of the model, which is to minimise total costs, mainly the penalties caused by the exceeding of greenhouse gas emission limits. The third objective, however, is directly aimed at minimizing the sum of carbon dioxide emissions in transportation routes between supply and distribution centres. The model is verified with actual data from the apple supply chain in Himachal Pradesh, India, and implemented multi-objective

decision-making methods like fuzzy Tchebycheff are used to solve the problem. The paper demonstrates that the design of farm supply chains in a volatile environment needs a remarkably close adjustment of the economic profitability and the environmental impacts, mostly in transportation.

(Rahbari, Khamseh, and Mohammadi 2023) have done a study to come up with an improved model and optimise the same for a sustainable supply chain of processed agricultural products (canned foods) with the aspect of uncertainty in focus. The newly introduced model is a multi-objective, multi-product, multi-period location-inventory-routing problem with the main emphasis on the vehicle fleet having different characteristics. This model involves the decision-making process for both the higher-level (location, allocation) and lower-level (production, inventory, transportation) types of operations simultaneously. The first objective function in the economic aspect attempts to lower the total supply chain costs to the greatest extent possible. The costs included are production, transportation, warehousing, raw material procurement, and facility establishment. The fourth objective in the social aspect is to encourage the utilization of labour resources to the maximum extent possible in the supply chain network. The paper integrates a carbon cap-and-trade system with the purpose of cutting carbon emissions from manufacturing and transportation activities in the community. The second objective of the model is to cut the level of dissatisfaction among customers by alleviating the shortage of products and increasing satisfaction, which can also be ranked within the economic and social spheres. In order to treat parameter uncertainty, a Robust Fuzzy Stochastic Programming (RFSP) model is formulated and then the Torabi-Hassini (TH) algorithm is implemented to solve the model. The case study of the canned food industry in Iran pointed to an increase in the confidence level making the problem more intricate with worse

objective values. The sensitivity analysis showed that export price alongside raw material costs have a significant impact on where the model goes.

(Fathi, Zamanian, and Khosravi 2024) went on to design a multi-stage mathematical model for network design of sustainable agricultural supply chain. They combined multi-criteria decision-making (MCDM) methods and mathematical programming to an optimal design of a network that included raw material suppliers, processing sites, and final distributors. The decisions about the selection of suppliers, locations of conversion plants, and distribution centres in this model were carried out using Delphi, Best–Worst Method (BWM), and COPRAS. After that, a hybrid multi-objective optimisation model was drawn up for supply chain design. The authors dealt with four objective functions, allowing for three main aspects of environmental, social, and economic sustainability: In the economic dimension, the first objective minimises total costs, including transportation, construction, maintenance, capacity modification of sites, and production.

- In the environmental dimension, the second objective minimises environmental impacts such as CO₂ and NO_x emissions from transportation and internal operations, as well as water consumption during production, construction, and maintenance.
- In the social dimension, the third objective seeks to maximise job opportunities (both permanent and temporary) created by building, operating, or expanding the sites.
- The fourth objective aims to enhance supply chain agility and resilience by minimizing product delivery time to customers.

The model was implemented in a case study for the "Delpazir" food company and solved and analysed using the LP-Metric method.

Gharye Mirzaei et al. (2024) ventured to conceive and optimise the agricultural supply chain amid environmental and monetary unpredictability, using a date-palm-related case study. They built a mixed-integer linear programming (MILP) model to achieve the goal of maximizing the supply chain profit in such a new world where demand, price, production costs, and harvest volumes are climate change and economic fluctuations affected variables. The proposed model includes five supply chain levels: farmers, sorting centres, distribution centres, processing industries, recycling industries, and markets. They chose a scenario-based robust optimisation method to deal with uncertainties. They used PSO, WOA, and their hybrid as metaheuristic algorithms to solve the model. In the economic aspect, the maximization of total profit is the goal of the objective function, which is calculated as the sum of the revenues from the sale of products and by-products less the transportation, production, inventory, and facility construction costs. On the one hand, environmental waste is considered in an implicit way through waste collection, waste segregation, and recycling without any explicit environmental objective. The social aspect had no explicit objective either, and social impacts were dealt with by job creation through new processing centres and auxiliary industries. The model was tested on the implementation of the date supply chain in Iran with sensitivity analysis, therefore the applicability of the model in complex real-world scenarios for decision improvement is demonstrated.

Gholian-Jouybari et al. (2024) carried out research for the creation of an Environmentally Closed-Loop Agri-Food Supply Chain network in the case of the coconut industry. Their work translated into a mixed-integer linear programming (MILP) model with the multiple objectives which were implemented to oversee the supply chain as well as the return flows.

- In the economic dimension, the first objective (OBJ1) minimises the net present value of total costs, including transportation, construction, maintenance, procurement, and inventory.
- In the environmental dimension, the second objective (OBJ2) aims to minimise environmental pollution caused by facility construction, production, recycling, and transportation.
- In the social dimension, the third objective (OBJ3) focuses on maximizing job opportunities, both permanent and temporary, across the supply chain network.

The authors applied six multi-objective metaheuristic algorithms and three hybrid versions, including NSGA-II and MOARO, to solve the model. Numerical experiments and sensitivity analysis were conducted to evaluate algorithm performance and provide policy recommendations for improving sustainability in agricultural supply chains.

(Ye, Song, and Song 2024) collaborated to make the decisions of supplier selection and distribution ordering more efficient in the supply chain of the food industry. They came up with a combined Delphi, Fuzzy Analytic Hierarchy Process (FAHP), and Fuzzy Multi-Objective Programming (FMOP) framework as a vehicle for a comprehensive, pure data-driven, and one that could easily solve social, economic, and environmental issues simultaneously. Their suggested model went on to define five objective functions: minimizing purchase cost, maximizing quality, minimizing delivery delays, lowering carbon emissions, and maximizing the reliability of suppliers in the occurrence of disruptions. Initially, the Delphi method and a literature review were used to identify and finalize the evaluation criteria. The weights of the criteria were first set using FAHP, and FMOP was used to find the solution of the order allocation model. An application of the model

in a food production enterprise in China demonstrated that the approach could lead to a better selection of the supply chain by including sustainability and risk factors, besides achieving a higher quality, on-time delivery, and environmental compliance in purchasing activities.

(Islam, Amin, and Wardley 2024) came up with comprehensive research to address the Supplier Selection and Order Allocation (SSOA) problem in the red meat supply chain in Canada. They constructed a three-stage framework. Firstly, they employed an ensemble-LSTM deep learning network, which takes advantage of product correlation to provide an accurate demand forecast for the future. Next, they merged Principal Component Analysis (PCA) and trapezoidal fuzzy numbers to assign weights for qualitative supplier evaluation indicators. Finally, a multi-objective mixed-integer linear programming (MOMILP) model was applied for the best decision in supplier selection and order allocation.

The proposed model clearly incorporates all three main sustainability dimensions:

- In the economic dimension, one objective function minimises total costs, including procurement, storage, transportation, and fixed costs.
- In the environmental dimension, another objective aims to reduce carbon emissions resulting from the procurement process, particularly in supplier selection and transportation route planning.
- In the social dimension, criteria such as compliance with health standards, brand reputation, workplace safety, and preparedness for biological hazards address social sustainability.

The model was implemented with real data from the red meat industry in Ontario, Canada, and demonstrated that incorporating deep learning for demand forecasting leads to improved decisions in order allocation and supplier selection.

(Ardra and Barua 2024) conducted a study to develop a comprehensive framework for selecting sustainable suppliers in the circular supply chain of fresh fruits and vegetables for Indian supermarkets. The study followed three phases:

- First, key supplier selection indicators were identified through literature review and expert opinions.
- Second, these indicators were weighted using the Best–Worst Method (BWM).
- Finally, the suppliers were ranked using fuzzy TOPSIS based on the defined indicators.

The research highlighted the circular economy concept and the associated indicators such as resource optimisation, reverse logistics, and operational sustainability capabilities. Resource optimisation and circular competencies obtained the highest weight among the seven main criteria, thus indicating these as the most important criteria. Among sub-indicators, product return systems, circular operational capabilities, and reverse logistics were the most highly ranked. The findings indicate that a sustainable circular supply chain in the perishable goods sector can be achieved by focusing on return capabilities, knowledge and technology management, and supplier service quality. This model can help the decision-makers to choose suppliers who are more likely to contribute to the sustainability of the food supply chain, especially in the developing countries.

Zeynali et al. (2025) have done the research to develop a multi-stage decision-making model based on machine learning to enable the configuration of a sustainable, resilient, and agile reverse supply

chain for the agricultural sector, with a focus on recycling corn waste by third-party companies. The first stage was the performance evaluation of recycling suppliers through the application of the CatBoost algorithm, with the input being the sustainability, resilience, and agility indicators. After that, the authors have developed a multi-objective mathematical model for the reverse logistics network design, which has the following objective functions: In the economic dimension, the first objective aims to maximise the total profit of the network, accounting for costs and revenues from compost and energy sales.

- In the environmental and social dimensions, the second objective minimises greenhouse gas emissions from transportation and maximises job opportunities created through collection centre establishment.
- In the agility dimension, the third objective maximises the service level to compost and energy demand points.
- In the combined dimension of sustainability, resilience, and agility, the fourth objective seeks to maximise the total score of selected recycling companies based on all three categories of indicators.

The model was developed under uncertainty using fuzzy programming and SARIMA time-series algorithms and solved using the H-GRMCGP heuristic method.

A summary of the objective functions of these studies, aligned with different sustainability dimensions in the supply chain, is provided in Table 2.8

Table 2. 8: Summary of the research literature review

Study	Objective		
	Economic	Social	Environmental
Mehrbanfar et al, 2020	Minimise total network cost	Maximise employment	Reduce greenhouse gas emissions
Patidar and Agrawal, 2020	Reduce total supply chain cost	---	---
Rana et al, 2021	Reduce information exchange costs, eliminate intermediaries, and enable smart contracts	---	---
De et al, 2022	Minimise total supply chain cost	---	Carbon emission constraints from inter-stakeholder transport
Belamkar et al, 2023	Maximise total profit	---	Minimise total CO ₂ emissions in transport routes
Rahbari et al, 2023	Minimise total supply chain cost	Maximise job opportunities in the supply chain network	Reduce environmental impacts from production and transport
Fathi et al, 2023	Minimise total cost including transport, construction, maintenance, capacity adjustment, and production	Maximise job opportunities (fixed and variable) resulting from site construction, operation, or expansion	Minimise environmental impacts including CO ₂ and NO _x emissions, and water consumption in production, construction, and maintenance
Joshi et al, 2023	Increase productivity, reduce post-harvest losses, support local economic growth	Empower farmers, education, extension, improve labour rights and working conditions	Integrate environmental concerns in farming, reduce greenhouse gases, promote clean technologies
Gharye Mirzaei et al, 2024	Maximise total profit	---	---
Gholian-Jouybari et al, 2024	Minimise net present value of total costs including transport, construction, maintenance, purchase, and inventory	Maximise fixed and variable job opportunities in the supply chain network	Minimise environmental pollution from facility construction, production, recycling, and transport
Ye et al, 2024	Minimise procurement cost	---	Reduce carbon emissions

Islam et al, 2024	Minimise total cost	---	Reduce carbon emissions
Ardra and Barua, 2024	Minimise total cost	---	---
Rezaei Zeynali et al. (2025)	Maximise total profit of the network considering costs and revenues from compost and energy sales	Maximise opportunities from job collection centre establishment	Minimise greenhouse gas emissions from transport

2.6 Research Gap and Conclusion

While the surge in publications identified in this review confirms that Sustainable Supply Chain Management (SSCM) is a mature field of study, a critical synthesis of the current literature reveals two significant structural omissions:

2.6.1. The Imbalance of the Triple Bottom Line (TBL)

Despite the theoretical importance of the "Triple Bottom Line," current Food Supply Chain (FSC) models exhibit a disproportionate focus on economic and environmental variables. As evidenced by Table 2.8, most researchers prioritize cost-minimisation or CO₂ reduction, treating the social dimension as a secondary factor. Labor rights, community impact, and social equity are frequently omitted from mathematical models because they are traditionally difficult to quantify. However, in the context of the food industry which relies heavily on small-scale farmers and vulnerable labour this omission leads to a fragmented understanding of sustainability. Without integrating social indicators, FSC models remain operationally efficient but ethically unverified, failing to meet the requirements of modern corporate social responsibility.

2.6.2 The "Black Box" of Outsourcing in FSC Sustainability

Furthermore, there is a distinct disconnect between supply chain theory and practical execution. Although 21st-century food chains are increasingly reliant on outsourcing partners (3PL, 4PL, and 5PL) for specialized tasks like cold-chain management and reverse logistics, these actors are largely treated as "black boxes" in existing research. Current models often assume sustainability is a centralized responsibility of the focal firm, overlooking the fact that a chain is only as sustainable as its outsourced links. There is a scarcity of research that critically assesses how third-party contractors are audited for sustainability particularly regarding their social performance and resilience during global disruptions.

2.6.3 Conclusion

In summary, the literature lacks an integrated framework that evaluates the viability of outsourcing contractors through a balanced TBL lens. This study addresses these gaps by moving beyond the binary "cost-vs-environment" trade-off. Instead, it proposes a more inclusive assessment model that incorporates social sustainability and contractor accountability, thereby providing a more resilient and socially responsible roadmap for the future of food supply chain management.

The present research attempts to answer two main questions that have not been sufficiently discussed due to these gaps. Firstly, by considering the three pillars of sustainability, that is, the economic, environmental, and social aspects, this research decides to measure the sustainability of the food supply chain, thus, moving to a more integrated concept of sustainability. Secondly, besides that, the research deeply focuses on the assessment of the outsourcing organisations that are working in FSCs and mainly concentrating on how their activities set either the barrier or the way to the achievement of sustainability goals. Thus, it helps to close an important gap in the

literature while at the same time it lays the ground for more open, stable, and socially responsible supply chain planning in the food industry.

Chapter Three

Research Methodology

3.1 Introduction

In this chapter, the methodological framework of this research is presented in which the philosophical bases, research design, data collection methods, and analytical procedures selected to approach the core research questions are discussed in great detail. The aim of the chapter is to give a rationale for the research process selected and to show the instruments used that secure a consistent and trustworthy investigation of that problem. The following sections reveal how this research develops a mathematical model to integrate sustainability within outsourcing performance measures in the Food supply chain.

3.2 Research Philosophy

This research is positioned in a pragmatist paradigm. Pragmatism ontologically sees reality as a combination of both objective (numerical supply chain data) and subjective (expert perceptions of sustainability) components. This is in line with the aim of the study to address a real-life problem, how to incorporate sustainability in outsourcing as widely as possible, using the most effective means. The research takes a multi-positional stance epistemologically: on one hand, it employs positivism when it deals with mathematical optimisation, on the other hand, it utilizes interpretivism in grasping the varied supply chain professionals' experiences through semi-structured interviews. This philosophical orientation supports a mixed-methods approach as the best and most logical way of dealing with the intricacies of the food supply chain (Saunders et al., 2019).

3.3 Research approach

Quantitative, qualitative, and mixed methods are the three major research methodologies used in this research. Quantitative research pertains to the collection of numerical data and statistical analysis; thus, the goal is to test the hypothesis, find out regularities, and provide generalisable findings. Besides, qualitative research, which is mainly based on interviews or observational data, deals with the description of deeper meanings, behaviours, and experiences. Such data is often structured in the form of a textual or a narrative (Bryman, 2016). Mixed methods, as the name suggests, bring both quantitative and qualitative approaches together in one study, which, in turn, results in the use of the strengths of each method to come up with an ever-more comprehensive understanding of the research problem (Creswell & Plano Clark, 2008).

A mixed methods approach was used in the research. Such an approach is especially valuable because it enables the researcher to avoid the sole usage of one method. On the one hand, quantitative methods provide a wide spectrum of trends or describe patterns. On the other hand, qualitative methods deliver detailed information about the viewpoints of persons or complex issues mastered. Merging these methods effectively provides a scope that includes both the representation of numerous trends and the exploration of the deep reasoning or the experience of writing them (Teddlie & Tashakkori, 2009).

Mixed methods research is typically conducted according to one of three different designs. In the convergent design, quantitative and qualitative data are gathered simultaneously and then integrated to have a broader and deeper understanding of the research question in its totality. Explanatory sequential design, after the quantitative data collection process, qualitative research is conducted to provide a thorough explanation and no way by which numerical findings are treated

as the basis for further discoveries. On the other hand, exploratory sequential design uses qualitative data to determine the hypotheses, or measurement tools and then tests them quantitatively (Johnson & Onwuegbuzie, 2004).

A completely quantitative method alone would overlook the organisational sustainability barriers in the food sector and at the same time, completely qualitative method would miss out on the mathematical exactness needed in multi-criteria optimisation. This research, by adopting an exploratory sequential design, initially acknowledges expert opinions to spot criteria that subsequently supply the empirical weightings for the MCGP-UF model.

This study uses both methods and through this approach, it leverages the inclusion of more quantitative data and in-depth qualitative insights, thus ensuring a balanced and high-quality investigation of the research objectives.

3.4 Data Collection Methodology

The empirical focus of this research is sustainability in the food industry, particularly looking at sustainability criteria and performance measures of outsourcing. In order to have a full grasp of this multi-faceted phenomenon, the study depends on a mixed-methods approach, which gives researchers an opportunity to find confirming and disconfirming evidence for their interpretations to increase credibility and trustworthiness of the findings (Bell, Bryman, & Harley, 2018).

3.4.1 Primary and secondary data

The study uses both primary and secondary data sources. Secondary data were taken from academic literature, case studies, and industry reports after a thorough investigation. Such a literature review was instrumental in pinpointing the gaps in existing knowledge and aligning the

research with the wider academic setting (Snyder, 2019). Primary data, which is the main focus of the research, were gathered directly from the participants by means of structured questionnaires and semi-structured interviews. Employing both methods enables the researchers to capture not only statistical patterns but also profound qualitative perspectives, thereby communicating a more compelling story through the results (Creswell & Creswell, 2018).

3.4.2 Quantitative Phase: Survey Design and Distribution

A comprehensive questionnaire was carefully developed to assess sustainability criteria from environmental, social, and economic perspectives and was distributed through SurveyMonkey. Purposive sampling was the method of choice to identify a sample of 100 supply chain professionals and academic experts who have in-depth practical and theoretical knowledge of the food sector (Etikan, Musa, & Alkassim, 2016). SurveyMonkey was chosen with a view to carrying out a survey because it offers excellent features for managing respondents and generating live reports, thereby making the data collection process more orderly (Dillman, Smyth, & Christian, 2014). With a Likert scale, participants were able to indicate the importance level of different criteria, which gave the necessary numerical data for the later AHP analysis.

3.4.3 Qualitative Phase: Semi-structured Interviews

Along with the questionnaire, semi-structured interviews were held with 50 supply chain professionals and sustainability experts. This approach was selected due to its flexibility feature, which allows the researcher to have a list of predetermined topics for reference and at the same time to be open for asking questions based on the unexpected new ideas that arise from the conversation (Kvale & Brinkmann, 2015). Such interviews greatly helped in unveiling the tacit outsourcing performance indicators that are usually overlooked by the strict quantitative tools. The

main subject was still the difficulties of aligning sustainability objectives with outsourcing operations strategies, thus revealing the detailed "how" and "why" of the present industry practices.

3.4.4 Optimisation Data and Software

For the optimisation analysis, hypothetical data were generated and used in the LINGO software. This method was adopted to allow the Multi-Choice Goal Programming with Utility Function (MCGP-UF) model to be applicable in various supply chain scenarios even when real-world proprietary data might not be available. These sets of data including cost, carbon footprint, and lead times were not randomly selected. Instead, they were deliberately created following industry standards and best practices so that the model stays realistic and practitioners can relate to it easily (Chang, 2013).

3.4.5 Ethical Considerations and Participant Selection

All participants were selected because the experts in sustainability as well as supply chain management that they had been identified as based on the nature of the prior work documented on them for the domain of expertise. Those who participated were properly informed of the study's scope and purpose, and this was one of the key factors in ensuring ethical integrity. In line with established research ethics, consent was sought from participants after being suitably briefed about the study, and reliable arrangements were put in place to uphold the anonymity and confidentiality of all the respondents (Bryman, 2016).

3.5. Analysis methods

For the analysis of AHP (Analytic Hierarchy Process), the conceptual model, researcher applied a very popular tool in this field, namely the Expert Choice software, which is one of the most well-known among the applications in MCDA (Multi-Criteria Decision Analysis). Saaty (2008) said

Expert Choice can be instrumental in deconstructing a problem into sequential parts and then saying goodbye to weeks or even months of meetings for the stakeholders, who then concentrate on compressing the relative importance of the criteria and their judgments. Through the use of paired comparisons and the calculation of priority vectors, Expert Choice brings along a structured method, which can be described as the most effective way to make good decisions from a pool of other alternatives (Vargas, 2010).

Talking about the mathematics modelling and optimisation software, I would like to emphasise that I used LINGO software, which is very well-suited for linear, nonlinear, and integer programming problems of various degrees of complexity. LINGO for the translation of complicated decision problems involving multiple targets or limitations to mathematical models can be efficiently optimised. The LINGO can be used to define the decision variables for which the most suitable solution can be solved to maximise the desired outcome or minimise it, depending on the problem structure (Schrage, 2006).

In this study, the fuzzy inference system (FIS) will be used to analyse the social risk of transportation. The Mamdani Inference System has been used for fuzzy inference. This method was chosen due to its transparency in reasoning, high interpretability, and widespread application in decision-making problems. All the process is summarised in the following diagram:

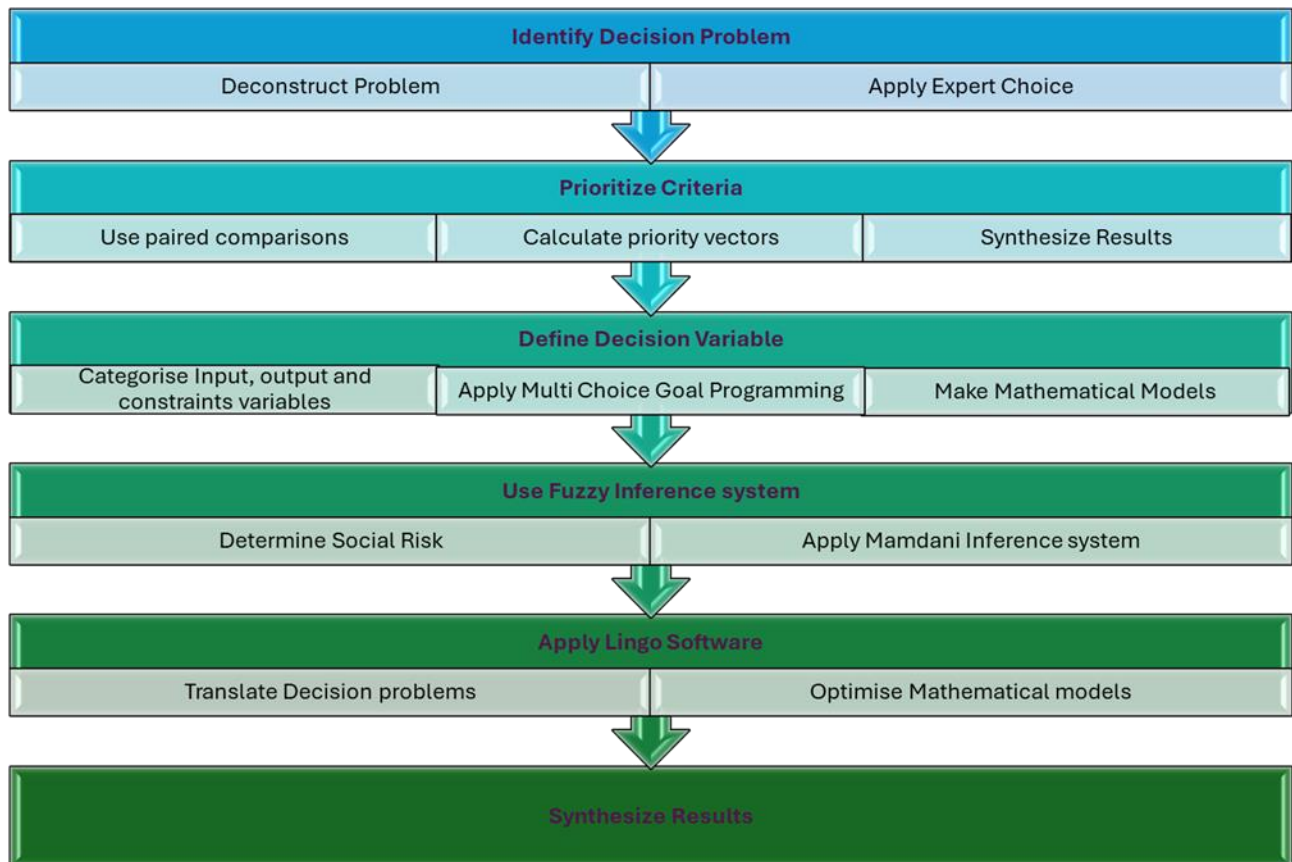


Figure 3. 1: Analysis Methods Diagram

The summary of each method is explained in the following sub-sections.

3.5.1. AHP

The Analytic Hierarchy Process (AHP) is an instrument for multiple decision-making criteria that was designed to determine the weights of criteria and sub-criteria and rank of the alternatives. This technique, invented by Thomas Saaty, is the basis of how to get weights for criteria, sub-criteria, as well as the research options that are part of the decision-making processes (Saaty, 1980; Saaty, 1990).

The Analytic Hierarchy Process (AHP) is applicable in circumstances where decision-making involves complicated preferences such as the number of alternatives and the number of characteristics. The criterion may comprise both quantitative and qualitative properties. This method basically utilises pairwise comparisons. The decision-maker starts the process by forming a decision hierarchy tree. The components to be compared and alternatives that compete to be appraised along the decision-making process from this tree (Saaty, 1980). Then, pairwise comparisons are made to measure the extent to which each of the factors is more valuable in terms of the options (Saaty,1990). The AHP approach engages in the synthesis of the pairwise comparison matrices one way is to choose the optimal option (Saaty, 1980).

AHP is used in group decision-making to keep the merits of group decision-making but without the drawbacks such as narrowness, cost, and speed. AHP permits various opinions to be expressed and at the same time, it helps in the development of a methodical and cohesive process for achieving consensus among the group (Vargas, 1990; Forman & Peniwati, 1998).

3.5.2 Semi-structured interview

Semi-structured interviews are a qualitative research method that is said to consist of the two polar elements of structured and unstructured interviews. That is, the method of analysis where the openness of unstructured interviews can be accommodated to the degree of structure found in structured interviews (Galletta,2013). This method is specifically helpful in social sciences and other fields that aim to understand research participants' perspectives in an in-depth manner (Bryman,2016).

The semi-structured format separates a list of predetermined questions or themes that go along with the research objectives from free-form interview interaction, which, however, can be used at the discretion of the interviewee in this case.

On the one hand, like structured interviews, it lets the interviewer stick to the pre-decided list, on the other hand, it allows the interviewer to abandon the list in situations where the respondent wants to bring up unforeseen issues or encourages the interviewer to probe into more interesting issues (Kvale & Brinkmann, 2015). The procedure then painstakingly begins with preparations, where researchers craft open-ended questions which draw out lengthy answers which, besides the ethical consideration of informed consent and confidentiality, also come to the attention of the researchers too (Creswell, 2018).

During the interview, the researcher starts with initial questions to know better and establish rapport and move steadily to the main issues by engaging the respondent with open-ended questions like "What do you mean by that?" to generate explanations. With the open-ended nature of the conversation, the interviewee's unique perspective and experience is accommodated and hence permitting the developing of the newly discovered insights (Silverman, 2020).

3.5.3. Fuzzy Inference System (FIS)

In this system, seven input variables are considered, each representing a social indicator related to transportation. Each of these variables is categorised into three levels: low, medium, and high. Based on these inputs, the social risk level of transportation is determined on a ten-point scale ranging from 0.1 to 1.0, where lower values indicate lower social risk, and higher values represent greater social risk.

As mentioned in the Analysis method section above, the Mamdani Inference System has been used for fuzzy inference. This method was chosen due to its transparency in reasoning, high interpretability, and widespread application in decision-making problems. Additionally, the centroid method has been applied for defuzzification of output values, which determines the final social risk of transportation based on the combination of membership functions.

Following the outlined steps, the proposed approach has been implemented using Python programming language, and the desired outputs have been generated accordingly.

3.5.4. Multi-Choice Goal Programming

Multi-Choice Goal Programming with Utility Function (MCGP-UF) is a decision-making approach that was originally introduced by Ching-Ter Chang as a new extension of the traditional Multi-Choice Goal Programming (MCGP). With the help of the utility functions, MCGP-UF renders a more adaptable modelling approach to the situation, thus the decision-makers can capture their preferences more contentedly, even with the multi-objective problems that are complex, and they may also differ in priority. Rather than merely static aspiration levels in the original MCGP, MCGP-UF empowers the decision-makers to modify the aspiration levels as needed for each of the goals, and this way the resultant hierarchy becomes clear if the objectives are ranked based on the importance attributed to them by the decision-makers (Chang, 2013; Chang & Tsai, 2009).

In MCGP-UF, utility functions consist of the idea of satisfaction or desirability that is associated with the achievement of some specific levels of each goal. This is especially important when it is possible that one goal has both lower and upper acceptable bounds. For the illustration, a goal that lies within an optimal range such as, how to reduce costs by 10% to 20% can be mathematically represented by a utility function, making satisfaction levels vary within this range instead of

following rigid rules. This approach provides the flexibility to "slide" the achievement of the goal within the acceptable bounds, which finally resulted in more adaptable and realistic decisions (Chang, 2013; Chang & Wu, 2014).

The capability of the model to deal with several levels of aspiration, which is very attractive, is what makes MCGP-UF a toady in balancing opposing goals on the one hand while maximising utility globally on the other hand. In the characteristic areas, for example, resource allocation, supply chain management, and policy planning, the method proves to be practical where decision-makers face numerous tasks contemporaneously that must be optimised (Chang, 2013; Chang & Tsai, 2009).

3.6 Conclusion

These tools, Expert Choice for the conceptual AHP model and LINGO for the mathematical part are complementing each other; one is used for the structure with the use of fuzzy sets and another for the real formulation. Combining, these instruments will help to find a satisfactory solution that is plausible at the conceptual stage and accepted at the operational level. This hybrid method also guarantees that the qualitative as well as the quantitative factors in decision-making are dealt with effectively.

Chapter Four

Development, validation, and Sensitivity Analysis of Sustainable Food Supply Chain Framework- Outsource performance measure perspective.

4.1 Introduction

A conceptual framework is an analysis tool that picturizes the variables and the possible outcomes of the research that you expect to find. The advent of sustainability in business is directly linked to the assessment of outsourcing performance. Indeed, traditional performance metrics in outsourcing like cost savings, quality, and delivery time, do not exclude the socio-environmental aspects. Research shows that the decision to outsource is a powerful source of sustainability, e.g. the supply chain's carbon footprint and labour conditions, which are not the case if the sustainability is not considered with performance assessments. The companies are increasingly including environmental sustainability criteria for suppliers in their outsourced operations, through supplier codes of conduct and public social and environmental reporting. Nowadays, sustainability is regarded as an inseparable part of the outsourcing performance assessment, which means that supplier assessment should be combined with the overall sustainability objectives of the company and the whole food supply chain must follow the expected ethical and eco-friendly criteria.

4.2 Proposed Conceptual Framework

The following sections discuss the elements of the proposed framework in detail, as displayed in Figure 4.1.

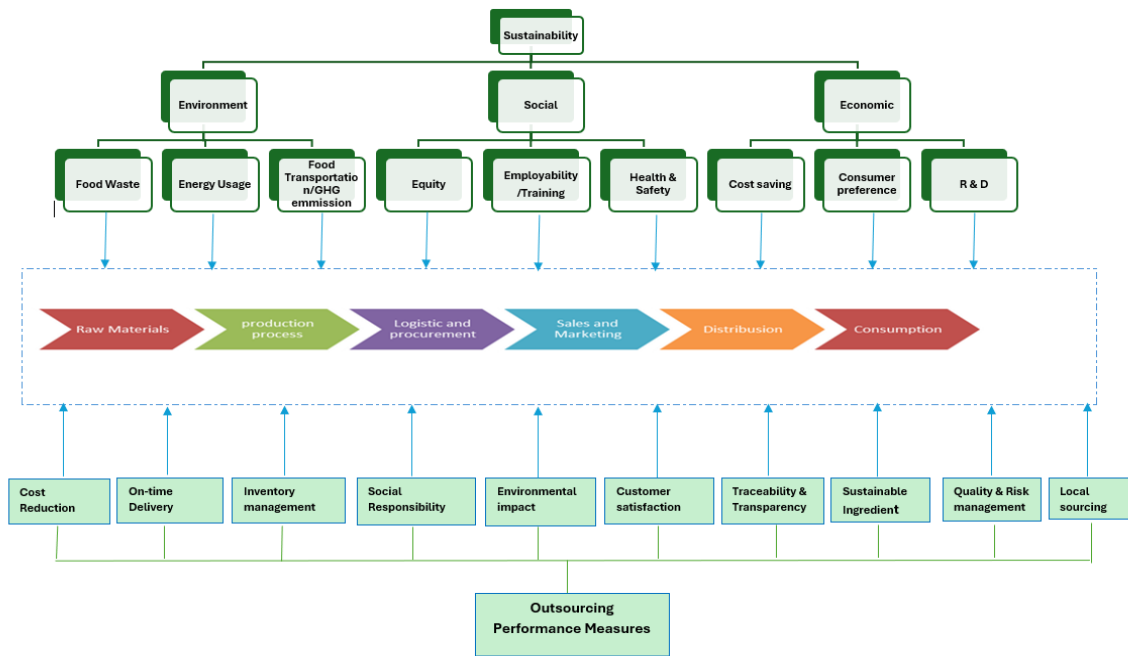


Figure 4. 1: Elements of the proposed framework

The framework follows a top-down deductive logic integrated with bottom-up empirical validation. Level 1 defines the strategic intent; Level 2 adopts the Triple Bottom Line (TBL) as the theoretical anchor; Level 3 identifies the operational constructs synthesized from literature; and Level 4 presents the performance measures validated through industry interviews.

4.2.1 Framework Development and Structural Logic

To address the complexity of outsourcing in the food supply chain, a multi-level framework was developed. The process of development involved a two-stage approach:

1. Literature Synthesis: High-level constructs (Levels 1–3) were derived from a thematic analysis of existing sustainability and supply chain literature.

2. Empirical Validation: Specific performance measures (Level 4) were refined and ranked based on semi-structured interviews with 50 industry professionals.

The framework is organized into four hierarchical levels to bridge the gap between abstract sustainability goals and concrete operational performance. Table 4.1 provides a transparent "referencing trail," justifying the inclusion of each construct and explaining the analytical role of each level.

Table4. 2: Synthesis of Framework Hierarchy and Theoretical Origins

Level	Construct / Dimension	Key Source(s)	Justification for Inclusion in Framework
1 (Goal)	Sustainability in FSC	Bennett et al. (2019); OECD (2025)	To ensure long-term food security and resilience against environmental/socio-economic shocks.
2 (Main Criteria)	Economic Pillar	Ageron et al. (2011); Du et al. (2020)	Beyond profit, ensures long-term viability and stakeholder welfare across fragmented global networks.
2 (Main Criteria)	Environmental Pillar	Govindan (2017); Kumar et al. (2022)	Addresses the critical juncture of resource depletion and the need for eco-friendly distribution strategies.
2 (Main Criteria)	Social Pillar	Mamun (2021); Govindan (2017)	Focuses on the moral influences of food production and the welfare of workers/local communities.
3 (Sub criteria)	Cost Saving	Herrero et al. (2023); Kalfas et al. (2024)	Directs resource allocation and technological acquisition to enhance operational productivity.
3 (Sub Criteria)	Food Waste	Slorach et al. (2019); Gkoutani et al. (2021)	A primary contributor to environmental damage; reducing waste is a core necessity for circularity.
3 (Sub Criteria)	Energy Usage	Yontar & Ersöz (2020); Rosen (2021)	Connects all stages of the FSC; essential for evaluating the total environmental footprint.
3 (Sub Criteria)	Equity & Fairness	Toussaint et al. (2020); Khokhar et al. (2020)	Ensures stakeholders enjoy equal opportunities and promotes long-term societal well-being.
3 (Sub Criteria)	Health & Safety	Zheng (2016); Acedo et al. (2024)	Addresses public health concerns and trade worries exacerbated by the globalization of food trade.

4 (Performance measure)	Cost Reduction	Jain et al. (2020); Tian et al. (2021)	Fundamental for operational efficiency and strategic flexibility in outsourcing.
4 (Performance measure)	On-Time Delivery	Wattanukul et al. (2018); Kresnanto et al. (2021)	Vital for fresh/perishable food to prevent rot and maintain consumer safety.
4 (Performance measure)	Inventory Management	Kaipia & Tanskanen (2003); Li et al. (2014)	Balances shelf-life constraints with demand variability to reduce waste.
4 (Performance measure)	Social Responsibility	Hartmann (2011); Mani & Gunasekaran (2021)	Addresses ethical labor practices and societal impact across the global network.
4 (Performance measure)	Environmental Impact	Govindan (2017); Stefanelli & Jabbour (2021)	Integrates green perspectives into outsourcing decisions and supplier selection.
4 (Performance measure)	Traceability & Transparency	Regattieri et al. (2007); Mishra et al. (2018)	Enables precise tracking of product history to mitigate food safety risks.
4 (Performance measure	Customer Satisfaction	Nayan & Hassan (2020); Rahman & Urmi (2020)	Measures the complete service experience, impacting brand equity and loyalty.
4 (Performance measure	Sustainable Ingredient	Açar et al. (2019); Issa et al. (2024)	Ensures responsible sourcing from the inception of the supply chain lifecycle.
4 (Performance measure)	Quality & Risk Mgmt	Liu & Guo (2018); Aung & Chang (2013)	Protects against food fraud and maintains compliance with global safety standards.
4 (Performance measure)	Local Sourcing	Jarzębowski et al. (2020); Kiss et al. (2020)	Reduces food miles/GHG emissions and supports regional economic resilience.

Level one-Goal

4.3 Sustainability in Food Supply Chain

Sustainability in the food industry focuses on balancing environmental protection, social responsibility, and economic viability. This balance is essential for ensuring long-term food security and meeting the needs of both current and future generations, especially given the industry's wide-ranging impact on land use, packaging, and emissions.

Besides, ensuring sustainability in the food supply chain is necessary to guarantee food security in the long run. The twisted global food system is facing several problems such as climate change, resource depletion, population growth, and supply chain vulnerabilities that occur specifically (Bennett et al., 2019; World Resources Institute, 2023). It is possible for the industry to contribute to food security by employing the sustainable agricultural practices like for instance regenerative agriculture, water-efficient irrigation, crop diversification, and adopting energy-saving transportation. Such measures will not only help if adopted but also make it strong and resilient in a way that both environmental and socio-economic shocks can be absorbed (Godfray et al., 2010; Kummu 2020). Particularly when a changing climate and challenges to natural resources, such as extreme changes in weather patterns and resources ceasing to be available, have the potential to become more frequent in the future and what is worse, to destroy the conventional methods of food production and distribution (Wheeler and von Braun, 2013; OECD, 2025; Fanzo et al., 2021). By focusing on sustainability, the food systems are also becoming more resistant to risk through the means of tracing the products, the waste reduction, and the diversified strategies of sourcing (Zurek et al., 2022). Such methods, besides delivering on environmental objectives, are also the basis of enhanced supply chain performance and risk mitigation.

The implementation of more resource-efficient activities in businesses is also necessary for these companies to be able to comply with the regulations that are getting tighter and stricter. Governments across the globe are enforcing stricter environmental and social policies, such as, for instance, emission standards, obligatory ESG reporting, and sustainable procurement rules. Amongst such companies, those that introduce practices, which are environment-friendly at an earlier stage, are better adapted to meet the changes in the restrictions owing to the fact that they are agile (Springmann et al., 2018; OECD, 2025). Failing to implement such measures can also harm the companies and may attract illegal consequences, divestment by the investors, or the loss of the company's reputation (Eccles et al., 2014; Schilling & Chiang, 2011).

Moreover, companies which align with sustainability issues often find themselves in an advantageous position over their competition for a long time. The studies indicate that companies that incorporate sustainability into their core strategy are better placed to attract green consumers, retain employees, and get access to sustainable investment capital (Clark et al., 2015; Porter & Kramer, 2011). Therefore, we see that sustainability is not only of a legal compliance nature but also of strategic business essence.

It is research about sustainability in the food sector that deals with new measures which are responsive to the call for lessening the negative effects on the natural environment and in addition, contribute to the improvement of social issues as well as to the progress of the economy through the entire supply chain.

Level Two: Main-Criteria

4.3.1. Economic

Economic sustainability is a highly important requirement in the food supply chain, especially for outsourcing companies involved in the highly sophisticated global network. These companies have to deal with a complex network of stakeholders covering different countries and continents, each with their own crops, food products, and often fragmented supply chains (Kumar et al., 2022). Considering profit maximisation without keeping in mind the long-term economic impacts can lead to bad situations like resource depletion, market imbalances, and as a result, the chain of supply will become unstable. That is why businesses outside have to take a broad view, meaning that they should be totally in compliance with the principles of economic sustainability and not only see them as core business strategies or practices. (Ageron et al., 2011). Supply chain integration involves informed decisions about the sources, production, and distribution, which should be made on the one hand with the idea of economy in mind, and on the other hand with social welfare in the perspective of all stakeholders involved, namely from farmers and suppliers to consumers and the environment (Du et al., 2020). Supply chain integration creates the opportunity to collaborate with both suppliers and customers, which is critical for the success of supply chains (Ali et al., 2021).

In order to boost the economic sustainability, outsourcing companies ought to be focused on creating sustainable and thus resilient supply chains capable of quickly adapting to external disruptions and ever-changing market conditions (Tundys & Wiśniewski, 2023).

In this research, cost saving, customer preference, and R&D will be applied as a practice of economic sustainability at level two of the proposed framework.

4.3.2. Environmental

The increasing globalisation and the fact that more and more people are becoming a part of a global society have made the sustainability of food supply chains an issue of primary importance. In order to comply with the environmental go-green awareness all the way, the only solution we have is a complete rethinking of how food is grown, processed, distributed, and finally used by putting into practice some eco-friendly strategies in each section of the supply chain (Govindan, 2017). The complex inter-organisational nature of the food supply chains where various stakeholders are involved in this interconnection has led to a lot of food wastage in these channels and, thus, put into focus the necessity of those in charge to search for a better pathway to reach the worthy goal, that of handling stakeholders' positions in a integration of sustainable development and environmental protection in the food sector (Kumar et al., 2022). In 2050, if the world population is to be 9.1 billion, we would need three planets' worth of resources if current lifestyles are pursued (Canto et al., 2021). The issue of the sustainability of our food systems needs to be dealt with not only because a few years down the line the world may be faced with difficult choices and major trade-offs related to food quality and food security, but also because the world is at a critical juncture of history-find itself in a dangerous place or a more hopeful one (Béné et al., 2019). At the same time, coping with the ecological footprint and ensuring the continuous existence of the earth has become a matter of grave importance and thus efforts like the reduction of non-renewable energy use, encouraging the use of renewable energy resources, and being conscious of pollution sources that come through waste and human activities while at the same time controlling through the use of technology that helps in due course manner, are very vital (Sousa et al., 2024)

To sum up, the merging of green sustainable practices with the food supply chain is a multipart project that is laden with substantial benefits for outsourcing companies. A further consideration

of main sub-criteria such as resource consumption, waste prevention, and eco-friendly packaging can enable firms to green their production lines and be in accordance with the demands for ecological and environmental production (Du et al., 2020). Thus, companies assure themselves not only of a positive brand image and customer loyalty but also of the shift towards a more sustainable and resource-efficient food system for the future (Li et al., 2014).

4.3.3. Social

Social sustainability in food supply chains is the aspect of sustainability that deals with the moral and social influences of food production, processing, distribution, and consumption (Mamun, 2021). The social part of sustainability in food supply chains is about ensuring that the food system positively impacts the welfare of the workers, the local communities, and the society at large (Mamun, 2021). With the increasing global flavour of the food supply chain, the management of social sustainability has become more challenging (Govindan, 2017; Kumar et al., 2022). Usually, supply chains consist of various vendors all over the world, each of which sets their ethical paths without regarding the issue of social sustainability (Kumar et al., 2022).

The focus on the items being interrelated is a necessity in social sustainability of food supply, as the former has become quite complex and broad-based over the years (O'Connor et al., 2014). The inter-relatedness of the items includes securing the workers' health and safety through the provision of safe working conditions and training (O'Connor et al., 2014), ensuring that workers can access development and training opportunities allowing them to be more empowered, skilled, and thus more supportive of a culture of continuous improvement (O'Connor et al., 2014), and making it easy for workers to achieve a sustainable livelihood, promoting the growth of the most vulnerable sections of the population, ensuring a reliable and ethical supply chain (Piaskoski et al., 2020).

Strategic partnering with social sustainability with the third-party logistics service providers in the food supply chain means responsible treatment of labour forces, respect for basic human rights, and community welfare work smoothly in tandem with one another (Mamun, 2021). The use of third-party logistics service providers alone is not enough for companies to be socially responsible. They have to ensure that their suppliers comply with the same social standards as they impose internally as the first step to be a socially responsible organisation. (Toussaint et al., 2020). An important thing to remember is that, in the food supply chain scenario, a company that outsources can really help enhance the ethical and sustainable supply chain of food (Govindan, 2017).

In conclusion, social sustainability is definitely a key to a sustainable and adaptable food supply system. By doing this, food systems will be truly sustainable by making equity and fairness their priority, through the establishment of open and shared value networks of all stakeholders (Chen et al., 2022). Similarly, Employment and training are to be provided to ensure the empowerment of workers and the reduction of unemployment, especially in those rural areas which are not so privileged (Onyeaka & Mba, 2023). Thirdly, the provision of health and safety both in food production processes and working environments is crucial for the security of the public health and the development of social trust in food chains (Yawar & Seuring, 2020).

Level Three

4.3.1.1. Cost saving

Sustainability requires a comprehensive approach in the food supply chain, integrating economic, environmental, and social dimensions to ensure long-term viability and resilience (Herrero et al., 2023), but it is imperative to consider how cost savings emerge as the fundamental subset of economic sustainability, which then directs the choice of resource allocation, technological acquisition, and operations productivity (Kalfas et al., 2024). Saving costs is not just about

reducing the expenses, but they have become a priority area for the enhancement of resource utilisation, waste reduction and adding value overall (Focker & Fels-Klerx, 2020). On the one hand, Sustainable Food Supply Chain Management includes both the forward processes of the food chain, such as the procurement of materials, production, and distribution processes, as well as the reverse process. On the other hand, sustainability is also concerned with the collection and processing of returned used or unused products, leading to their recovery, and is thus, a socioeconomically and ecologically sustainable (Bloemhof-Ruwaard & Soysal, 2016).

To sum up, the cost-saving factor is the important sub-criterion in the economic sustainability aspect of the food supply chain. This factor is a very useful one, as it gives the various operations in the whole chain of the industry the capability to work more efficiently. It equally contributes to the fact that businesses are going to employ resources in the most efficient manner, will scale the heights of competitiveness of the organisation, and consequently, will lead to the security of the citizens' food. When companies not only invest their funds the right way but also eliminate all superfluous needs, they can experience good economic growth and, at the same time, save their planet from becoming uninhabitable, thus ensuring their long-term viability and resilience (Suryawanshi et al., 2021).

4.3.1.2. Consumer preference

Consumer preferences are a major driver for the economic sustainability of the food supply chain through the way they define production methods, distribution networks, and consumption patterns (Radzyńska & Jakubowska, 2018). The growth of the global population and increasing forces of globalisation have strengthened the importance of sustainability in food supply chains; this has necessitated a full rethinking of conventional practices (Govindan, 2017). The increase in the need for reasonably priced food offered by the international food market and the subsistence of the

social model of family farming in the globalisation process have led to the heavy industrialisation of agriculture and food processing (Reisch et al., 2013). Although this industrialisation makes for larger scales, better efficiency, and lower prices, it is the main cause of the environmental degradation (e.g. soil erosion, water pollution, greenhouse gas emissions) responsible for the fact that agricultural areas will not be economically sustainable overall (Reisch et al., 2013). There are numerous areas where it is reflected the relationship between the consumer's choices and the economic sustainability of the food supply chain. The interconnectedness of food sources, the environmental dimension of food, and consumer awareness of the driving force behind sustainability in the food system are some of the most pertinent aspects.

After all, Informing the audience of consumer preferences over the economic sustainability of the food supply chain will be the major issue we will discuss. The consumer's choice for the affordability of food and the globalisation of food systems have made it possible for agriculture and food processing to be industrialised.

4.3.1.3. R&D

Research and development have been essential pillars that have driven the development and growth of the economy through different sectors, of which the food industry is one of them (Tebbutt, 1995). In most countries, innovation in food products is the priority, mainly because their governments consider it vital to the economy of both rural and urban areas (Abdullah & Putit, 2023). R&D apart from the high-tech sectors that are most of the time the focus of public investment, can bring productivity gains (Hockmann et al., n.d.). Companies are finding that the situation where explicit knowledge has become so widespread and unendurable in terms of the level of sophistication of an economy is forcing them to resort to external sources to continue with their growth patterns (Bombaywala & Riandita, 2015). The capacity of R&D to serve as the driver

of innovation is derived from the enormous need for increased productivity and efficiency (Kulatilake, 2016). The turnover growth which R&D has on the company is dependent on the type of innovation, which entails products and services and is also associated with the promotion of sales that lead to a significant increase in turnover (Majeed et al., 2021). In simpler words, the increased efficiency and productivity needed from the catalyst that makes research and development the agent of innovation.

National economies and producers need to be sufficiently creative to satisfy various consumer wants with new commodities and services to guarantee their competitiveness in the global market.

4.3.2.1. Food waste

The issue of food waste has risen significantly and now stands as the major contributor to environmental damage; hence, there is a need for crucial attention and full-scale solutions to mitigate the issue (Slorach et al., 2019). The situation of food waste has been expanding and is currently a severe challenge to the planet with the increasing population of humanity as the main factor (Paritosh et al., 2017). Not only is it a moral obligation, but it is also a core necessity for a sustainable food system to address food waste (Aschemann-Witzel, 2016).

A rough estimation shows that one-third of the food production is actually wasted globally, thereby causing great economic losses and also being a major problem for environmental pollution (Gkountani et al., 2021). The creation of the waste of food in large quantities puts an incredible burden on natural resources, increases pollution, and intensifies the ecological footprint as a whole (Ikpe & Shamsuddoha, 2024). Tackling food waste is an effective way to push the agenda of environmental sustainability forward in light of the fact that it can save resources, slow down climate change, and create a more closed-loop and resilient food system (Gokarn & Choudhary, 2021). So, we can say that dealing with food waste is not only an ethical issue but also an essential

need to provide us with a more resource-efficient and resilient food system. The sustainable future is now achievable through a balance of resources, climate change mitigation, and a circular economy, resulting from a global-targeted attempt to reduce food waste (Joshi & Visvanathan, 2019; Wani et al., 2023).

4.3.2.2. Energy usage

The determination of the energy-consumption level is of prime importance when it comes to the evaluation of food supply chains' sustainability as it is the thing that connects all the stages from production to consumption influencing all the environmental, economic, and social dimensions (Yontar & Ersöz, 2020). The food industry is a sector that is highly dependent on energy for its various activities such as agriculture, processing, packaging, transportation, storage, distribution, besides consumption and thereby is at the centre of global energy demand (Akinoso et al., 2021). The sustainable use of energy includes the use of techniques and technologies introduced to reduce energy inefficiency as well as environmental and ecological impacts on the one hand, and the use of renewable energy and auxiliary energy carriers on the other hand, one of the main features being the consideration of issues such as a standard of living, social acceptability, and fairness (Rosen, 2021). We need to address the energy consumed in the food supply chain in order to achieve the triple purpose of the environmental footprint mitigation, resource efficiency improvement, and food safety and security, while continuing the discussions raised in the article (Țibulcă & Fogarasi, 2021).

To sum up, saving energy is an essential tool for evaluating the sustainability of food supply chains. It has an impact on the three dimensions, i.e. environment, economy, and social across all stages, from production and consumption. Solving the challenge of improving the energy usage of the

food supply chains will be imperative for environmental load reduction, resource efficiency, and food security in the long term, as in the material provided.

4.3.2.3. Food transportation/GHG (Green House Emission)

Transportation is exactly what the term “supply chain” stands for - the movement of products from origin to destination (Kresnanto et al., 2021). However, besides the punctual provision of goods, it also has the potential to cause environmental and social devastation. As the primary link in the formation of the sustainable food supply chain is the transportation of food, the impact of transportation is even more crucial in this regard (Kresnanto et al., 2021). One of the most important sources of carbon dioxide emission in the agricultural sector is food transportation, particularly for food moving long distances (Afrouzi et al., 2023). A study reveals that the food supply chain accounts for 9800-16,900 million tons of CO₂ emissions annually, a figure that will certainly increase in the future (Shabir et al., 2023). Assessing the environmental and social effects of the supply chain, as well as cost-effectiveness, is a necessary step in creating a sustainable supply chain. We should also remember that the mode of transport makes a significant difference. For instance, even though it is responsible for a small number of food miles, air freight may contaminate more than maritime transport (Heller, 2017; Ritchie & Roser, 2020). Eco-friendly agri-food supply chains should prioritise green transportation to eliminate pollution, which is mostly caused by the use of fossil fuels (Kresnanto et al., 2021). Assessing the environmental and social impact of a supply chain, as well as cost-effectiveness, is thus necessary to ensure sustainability.

4.3.3.1. Equity/fairness

Food supply chain's societal sustainability has been defined as a concept that is not only about taking environmental considerations into account, but also engaging issues of ethics and morals related to the fairness and equity principles (Toussaint, C. et al., 2020). Scholars have shown their awareness about the various ethical sources, safe practices, education, and equality in their studies and have thus come with numerous research works concentrated on social sustainability in supply chains, which proved that the recognition of the trend's importance was increased (Sudusinghe, et al., 2020, Seuring, 2020). Social sustainability is the activity that ensures the industry's well-being becomes sustainable over time by addressing social problems that are primary in nature, and the process involved is of great importance and is growing (Khokhar et al, 2020). Social sustainability defines the relationships and opportunities that different stakeholders in the value chain enjoy equally from the producers to the customers. (Woodcraft, 2015). The scope of the literature in this scenario is mainly on the social dimension, discussing human safety, community development, and harm protection from products/processes, and etc. (Klassen, 2012, Vereecke, 2012). An example of this is when the supply chain management and the company's operational activities ensure and manage it. The need is to remind those at the part of the chain where the end product is produced to conduct operations that are both clean and also safe (Kalaf, et al., 2017, Klassen & Vereecke, 2012).

In conclusion, the social sustainability in the food supply chains aims at long-term well-being, which includes the emphasis on equity and fairness for all stakeholders. This work lies in implementing fair labour practices, the provision of safe working conditions, and the empowerment of marginalised communities that in the end lead to social sustainability and a healthier food system that is fairer and more robust.

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4.3.3.2. Employment/ Training

In the multifaceted field of the development, processing, and distribution of food, the training of employees of all sections is a vitally important part of the process and has a great impact on the food safety culture and operational efficiency (Pai et al., 2024). Training not only provides staff with the necessary knowledge and skills for them to be able to understand the food safety standards but also helps in identifying and controlling potential risks of the workplace; this training allows for an effective use of time especially in work of direct food processing, in the movement of logistics and in the operation of complicated machines, among other roles (El-Khishin et al., 2017). The implementation of safety-conscious behaviour encouraged by special training can decrease the number of food-poisoning and work-related accidents and additionally, will lead to a more involved and productive workforce. This, in turn, will positively influence food business operations and will not only ensure success but also a sustainable future. Specific training actions to be undertaken are those that are targeted at the tasks and duties of a particular employee, at the same time, still considering tasks that the employee is capable of performing or the various challenges the employee may encounter in his/her role (Adesokan et al., 2015). This means that making a switch from the one-size-fits-all type of training modules and resorting to making a shift from the former to tailor-made programs which are geared towards the practical side of food safety and the acquisition of critical thinking skills (Adesokan et al., 2015). The delivery of successful

training programs should integrate an assortment of instructional approaches that include hands-on presentation, interactional simulations, and actual case studies in diverse applications for varying learner preferences and speaking levels, to ensure a thorough understanding of the material delivered to staff and their compliance with guidelines of the company (Pai et al., 2024).

4.3.3.3. Health & safety

The food industry is the most important and broadest of all industries and it is given the task of health and safety that are more than just the minimal requirements of the law and of the people, and therefore of the extra sustainability (Zheng, 2016). The safety of food throughout its value chains (from production, through processing, to the retail and consumption stages) is a shared commitment by all players (Herrero et al., 2023). The globalisation of food production and trade has in fact, escalated the food safety issue up to the level of a major public health and trade worry (Acedo et al., 2024). As far as food supply chains today are concerned, we can note the emergence of a variety of channels and the large number of stakeholders across different geographies. In such a situation, swift source identification, and compliance with the regulations by the responsible authorities become urgent (Oh et al., 2025). The presence of efficient safety and health measures reflects the social context of the concept of "sustainable development" or "sustainability" (Barnea & Noble, 2009), which further highlights the consumers' demand for a safer food supply and social sustainability as the main goals to achieve.

Conclusively, social sustainability is mainly based on giving people food that is safe and healthy throughout the supply chain. the globalisation of food production and trade has elevated food safety to become a prominent public health issue that requires quick intervention measures (Acedo et al., 2024; Oh et al., 2025). The modern-day food supply chains represent an intricate enmeshment of many intermediaries all around the earth geographically, each one taking part in

the making of a specific food. The matter of transparency and the questions of consumer growth, foodborne illness outbreaks, efficient risk, and recall management, and consumer demand are the issues that ought to be tackled so as to solve the crisis, given that they are the ones that are more obvious to the population (Maruchek, 2015). The presence of efficient safety and health measures in the social context of the concept of "sustainable development" or "sustainability" (Barnea & Noble, 2009), which in fact is a typical situation (Đjekić & Tomašević, 2021), would bring benefits to consumers in the form of better health and fair labour practices, thus the demand for consumers to eat food safely and social sustainability

To sum up, the significance of sustainability dimensions in the food industry is that they can solve global problems and at the same time secure the future of the business. The environmental practices lessen the industry's footprint, the social initiatives maintain equal global growth, and the economic strategies make it more competitive. The integration of these dimensions is crucial for achieving a sustainable and secure food future.

Level Four

4.4. Outsourcing performance measures

Today, many enterprises, including food industry, outsource their non-core activities to reduce the cost and improve the efficiency. Outsourcing is an operational strategy that impacts the supply chain performance and sustainability. The food sector is continuously demanding collaboration among partners to pursue sustainable and energy-efficient food production, processing, distribution, and consumption. Therefore, all parts of food supply chain including outsourcing

companies such as 5PLs and 4PLs should make significant changes and improvements in their performance to be more sustainable.

Outsourcing has been a critical aspect of the food delivery chain, which has enabled companies to minimise the costs, enhance the delivery process, and shift their focus to the core activities. Nonetheless, it should still be the business partners' responsibility that the quality, environmental impact, and hazards are reduced. This hand in hand with building solid performance measurement systems. These systems serve to not only benchmark how well the partnership with the manufacturer is working but also check if the company's/producer's supply chain goals are attained.

This research will consider the influence and integration of outsourcing performance measures and sustainability in the food industry. These performance measures are outlined as follows:

4.4.1. Cost reduction

According to Jain et al. (2020), among the multiple benefits of outsourcing in the logistics supply chain, the first one is cost reduction. This is because, when vendors are assigned with the non-core operations such as packaging, storage, and distribution, their cost of operation is decreased, and the company can still be more resourceful in core business areas. The most common performance metrics are the overall logistics costs, the cost per unit, and the cost variance against the planned budget (Tian et al., 2021). While the cost efficiency should definitely remain a priority, this should not be done at the cost of the factors, namely, food quality, safety, and compliance. Focusing solely on low-cost outsourcing shall bring various issues to the forefront, especially in sectors like perishable products and complex cold chain operations (Kamble et al., 2020). Hence, besides just negotiating prices, the sustainable cost reduction also occurs through developing strategic alliances

with third-party logistics providers and doing continuous performance monitoring (World Bank Group, 2023). Generally, Outsourcing reduces the cost of assets, facilitates core competencies to reduce production costs, leads to strategic flexibility, and reduces administrative and overhead costs. Additionally, outsourcing can decrease costs through being sustainable, such as food waste, energy efficiency, lead time, transportation, etc (Prajapati et al., 2020; Kucukaltan et al.,2016; Rahman,2011; Hsiao et al.,2010).

4.4.2. On-Time Delivery

One of the important matters to achieve customer satisfaction is delivery time that would be applicable by integration between all parts of food supply chain. Also, this time is very vital for fresh and perishable foods (Prajapati et al., 2020; Kucukalt, 2016; Hsiao et al.,2010; Cheng et al.,2008).

Given the complex and time-sensitive demands of food supply chains, it is imperative that business decisions point to high levels of logistics efficiency, especially when the organisations are opting for a third-party logistics solution. As a result, delivery "just in time" has changed to be the most critical measure of performance particularly in time-sensitive items and swiftly changing consumer patterns (Wattanakul et al., 2018). The capability to always be prompt in the shipment will be the root of healthy, non-expired food, less wasted goods, as well as overall satisfied and loyal consumers (Kresnanto et al., 2021). Besides the fresh chain supply cycle, which is one of the profit chains of a product, delays can be the cause of rot, low nutritional value, and even poisoning, further emphasising the importance of food safety in the new product development process for consumers (Kresnanto et al., 2021). The increase in the number of suppliers, globalisation, and outsourcing of businesses have all contributed to the evolution of the food industry, thus necessitating the execution of advanced operation management techniques (Ellahi et al., 2024).

Efficient transportation systems are a key factor in ensuring that food products reach the right destination on time, with road transport being faster and more adaptive (Kresnanto et al., 2021).

4.4.3. Inventory Management

Efficient inventory management is the foundation of successful operations in the delivery of food products by third parties. A challenging issue can be seen in the complex process of keeping the inventory level, shelf life of perishable goods, and costs of storage in the right balance while absorbing variable demand. Due to the interconnected processes that need to be in place to ensure availability and reduce waste, inventory management becomes a more intricate, strategic task and not only something that is associated with mere storage (Li et al., 2014). The situation that calls for the good implementation of inventory management is one that can be justified by the nature of food products that are easily damaged and quickly become out of date thus needing not only accurate forecasts but also very responsive measures to satisfy the end users (Heizer et al., 2018). The moving of inventory is usually the task of a third-party logistics provider (3PLs), who have to organise the whole complex, multi-dimensional process wherein they interact with suppliers, execute deliveries, and sell the product to the end customers (Kaipia & Tanskanen, 2003). To carry out this partnership, the information needs to be shared fluently, and everyone should be able to grasp the level of stocks held everywhere in the supply chain to avoid stockouts or overstocking (Li et al., 2014). It is also the case that the worldwide food trade has made food supply chains more intricate, which in turn has increased the chances of food fraud in these chains, decreased trust, and awareness of food safety by the consumers (Ellahi et al., 2024).

In conclusion, being able to handle these complexities effectively will result in less waste, lower costs of operation, and the product being available as expected.

4.4.4. Social Responsibility

The rising importance of social responsibility in the food supply chain outsourcing sector is a clear sign of a major change in the direction of including ethical matters, fair labour practices, environmental sustainability, and overall societal well-being into the business operations as the core values (Hartmann, 2011). As outsourcing becomes more predominant, companies are forced to take responsibility for the social and environmental repercussions of their activities across the entire supply chain (Klassen & Vereecke, 2012). This intensified control is due to a better-informed public, more sound investors, and the government having become more concerned with the global network exploitation, environmental pollution, and human rights violations that are interwoven in the long complex supply networks (Mani & Gunasekaran, 2021).

In summary, the food supply chain outsourcing industry emerges as confirmatory of a change with clear signs towards its responsible role. Companies have now become more accountable for the ethical, social, and environmental impacts of their supply chains, following pressure from consumers, investors, and regulatory bodies. And this position opens up for an all-embracing approach that sets as a top priority the ethical part, the only fair labour practices, environmental sustainability, and overall societal well-being for the whole supply network.

4.4.5. Environmental Impact

The increasing focus on the environmental sustainability of the outsourcing companies involved in the food supply chain is one of the reasons that the operational paradigms of such companies are being reshaped, linking it with the broader global movement which has been formed in the response of the companies to the new trend of environmentally conscious business practices (Govindan, 2017). The change is the result of the growing recognition of both consumers and the

governments who expect the chain to be more eco-friendly (Stefanelli & Jabbour, 2021). As a result, the food supply chain members have no other choice but to integrate green perspectives into their strategies deeply affecting all their decisions and processes, including outsourcing (Darkow et al., 2015). With the ongoing change of both markets and operations worldwide, companies are adjusting their strategies where supply management sustainability is being given prominence (Ageron et al., 2011). So, it happened that firms are focusing more on their collaboration with suppliers, especially regarding trust and commitment to sustainable practices (Quesada et al., 2012). The use of environmental indicators in performance evaluation systems is an obligatory aspect of the food sector, and it has become relevant in the struggle for long-term viability and market competitiveness.

4.4.6. Traceability & Transparency

Traceability and transparency are two performance indicators that are of great importance to the companies being involved in the food supply chain. This is the way how the chain becomes a web of suppliers and their customers, who can during the tracking of the products naturally move from one supplier to the next and so on, and reach customers who are the ultimate users of that product. Traceability is the ability of a project manager to read the detailed history in every stage of a project (Regattieri et al., 2007). This means that he/she can obtain information on every stage of a product's journey in the supply chain (e.g., from manufacturer to retailer) and up to the last stage which is the consumer (Mishra et al., 2018). Transparency, on the other hand, is the quality of a system which makes it easy to get it or understand it (Astill et al., 2019). This allows each member of the supply chain to get the information they need and be responsible for it. The paper identifies a case, where through the implementation of sound traceability systems, firms can not only find out the immediate providers of products and the direct recipients of them but also get to know the ultimate

consumers through the retailer with a capital 'R' (Zoroja et al., 2017). When it comes to the food supply chain, traceability and transparency play a major role in overcoming the issues that emerge within the process of food safety and quality (Westerlund et al., 2021).

4.4.7. Customer Satisfaction

The rapidly growing gravity of customer satisfaction in the overall performance of environmentally friendly food supply chain outsourced firms requires a thorough investigation of all the perspectives and implications. Customer satisfaction rating, herein, has a greater span of meaning as it is not just a measure of a transaction but is actually the complete experience from the customers' side of dealing with the service provider, containing the service quality, timeliness, reaction, and what the company offers (Nayan & Hassan, 2020). In the food supply chain, where three continuous quality control, inventory management and logistics without smudges are essential, it is evident that customer satisfaction has a direct and clear effect on the business operations that are efficiency, brand establishment, and eventually profitability (Rahman & Urmi, 2020). Enterprisers claim that the creation of the goodwill requiring favourable customer feedback is in fact crucial to the long-run business continuity and thus highlighting the significance of the identification and understanding of the factors that can influence customer satisfaction with a view to designing and providing the best products and services in the market (Chun & Nyam-Ochir, 2020). The importance of the supply chain collaboration between the service channels to ensure the smooth match between demand and supply is mentioned as a prerequisite for the success of the process (Rahman & Urmi, 2020). This is by no means the end, so companies that determine what the clients want and then implement a strategy to give them that value, have actually gained a competitive advantage in the market and this has shown us that customer satisfaction plays a key role in the logistics service (Uvet, 2020).

4.4.8. Sustainable Ingredient

For outsourcing companies that operate in the complex food supply chain network, a focus on sustainable ingredient sourcing has become a very important aspect of their performance driven not only by the increased awareness and expectations on the environmental and social commitment from the regulatory bodies, customers, and other stakeholders (Açar et al., 2019; Holloway, 2024). Sustainable supply chain management is an approach that strategically involves the adoption of environmentally and socially responsible practices over the entire lifecycle of the supply chain, that is, from the inception of sourcing to the point on which the end products reach the customers (Issa et al., 2024). This full cycle is meant to be a solution to the environmental impact, the efficient use of the resources, the socially responsible behaviour, and the economic sustainability in all stages of the supply chain. Hence, firms are obliged to comply with the environmental and social problems that can be found in their supply networks as the value is being mainly generated from this level of the chain of providers and it constitutes a significant part of the core competencies of the companies (Koplin et al., 2006). The desire to highlight the transparency and traceability of food production has resulted in a spiral demand for sustainable sourcing practices, which have allowed the consumer to call to attention the companies' unethical or environmentally hazardous behaviours and thus make consumer decisions that are informed (Balkau & Sonnem, 2011)

4.4.9. Quality & Risk management

The quality and risk management demand now soared to unprecedented heights is a key performance measure for the outsourcing companies that are involved in the intricate ecosystems of the modern food supply chains. These supply chains are represented by the ability to maintain an unchangeable quality level throughout the network of the suppliers that are not only geographically dispersed but also structured in a tiered manner (Liu & Guo, 2018). This challenge

has been magnified by the complexities of the global food trade that in turn raise the level of risk for food fraud in the sense that stakeholders trust is damaged, and consumers feel more anxious about the safety of their food (Ellahi et al., 2024). Fulfilling food quality standards is necessary for safety and compliance, and ignoring them may lead to recalls, fines, legal problems, and damaged reputation (Bagnulo et al., 2024). As a result of the food scandals and incidents, customers are demanding food of high quality, but this high-quality food should be characterised by integrity, safety, and transparency (Aung & Chang, 2013).

The food industry's reputation was strongly challenged due to a subsequent series of food crises that have arisen in the last few decades, the major ones being mad cow disease, dioxin contamination in chicken feed, and the nasty visits of salmonella and E. coli, etc. (Aung & Chang, 2013). In the food supply chain, the events have uncovered certain system weaknesses and loopholes, indicating the necessity of taking serious quality and risk management strategies into account.

4.4.10. Local Sourcing

Local sourcing is a facet of the food supply chain that is quite intricate in the sense that it goes beyond simply location and has intertwined economic, agronomic, environmental, and social aspects. This concept calls for an in-depth understanding, particularly when sustainability is in question (Jarzębowski et al., 2020). The local sourcing movement is largely associated with the pursuit of sustainability that is driven by the idea that short distances of the vehicles used in transportation reduce pollution, thus creating less carbon emission. In addition, local food schemes are on the one part guided by government policies, and these can greatly revive rural areas around

them; on the other hand, the policies also make it easier for the populace to support the farmers, especially small-scale ones (Kiss et al., 2020).

Moreover, some organisational structures that increase the central control of all the cooperating stores in the process of purchasing and pricing, as well as the unreliable volume of supplies, which come from farms, may be the factors that can prevent the trust and mutual commitment from occurring in the supply chain (Dunning, 2016). However, direct-store delivery, in spite of these barriers, is still available as a tool to increase the local food systems and promote the diversification of the produce market (Dunning, 2016). Furthermore, it should not be forgotten that in the eyes of some suppliers, the business they run could be more beneficial, in terms of profitability, if they were to take the route of international markets as opposed to carrying out their selling activities through short supply chains in local markets (Stein & Santini, 2021). Hence, the local sourcing strategy cannot be only the one-size-fits-all rule and a detailed and thorough evaluation the approach is necessary (Stein & Santini, 2021).

To clarify its role within the performance logic of this framework, Local Sourcing is positioned not merely as a geographic strategy, but as a critical proxy for logistical and environmental efficiency. Within the food supply chain context, measuring 'locality' serves as an active indicator of reduced lead-times (ensuring product freshness) and minimised emissions (reducing food miles). By integrating local sourcing as a performance dimension, the framework acknowledges it as a measurable driver of supply chain resilience and carbon efficiency.

4.5. Sensitivity Analysis

Sensitivity analysis in decision-making is a critical procedure that studies what kind of variability in input variables affects the results. It not only helps to detect the most influential inputs but also tracks very well the level of uncertainty in a model. Via this method, many types of evaluations can be made of the choice under the various possible conditions (Magistral Consulting, 2023).

If we talk about multi-criteria decision analysis, the major ways to perform the sensitivity analysis are these:

1. Modifying the actual values of the criteria
2. Adjusting the importance weights of the criteria, thus changing the relative indication of these criteria.
3. Modifying the weights of the indicators in the Decision Analysis (DA) model (Zhou et al., 2024).

Current research is looking at the connections between changes in the criterion weights and the decision estimation of alternatives. Particularly, Expert Choice program is used in this investigation due to its conformance to the Analytic Hierarchy Process (AHP). In this setting, sensitivity analysis is used to check the results' consistency; a positive sign of stable rankings given the weight adjustments indicates reliable decisions (Sequeira et al., 2021; Maletič et al., 2016).

This study uses dynamic sensitivity analysis to see how the varying weights of the main decision criteria contribute to the results. The method applied is instrumental in understanding the adaptiveness of the decision-making model to variations, enhancing more confident and solid judgments.

4.5.1 Initial Sensitivity Assessment (Increment)

The figure below indicates the performance of each variable with a benchmark in terms of sensitivity. An initial sensitivity analysis was carried out to monitor the variations that occur when the weights of the three main criteria are raised by 5%, 10%, 15% and 20%, respectively. Figure 4.2 demonstrates the original base model that contains the initial parameters of the variables and the results of the sensitivity analysis without executing any changes.



Figure 4. 2: Original Base Model

4.5.1.1 Environment

5% increase

The first change was made is increasing the weight of the “Environment “by 5%, slight changes in the weights of the sub-criteria have been noticed, however, their priorities remained same, see Figure 4.3.

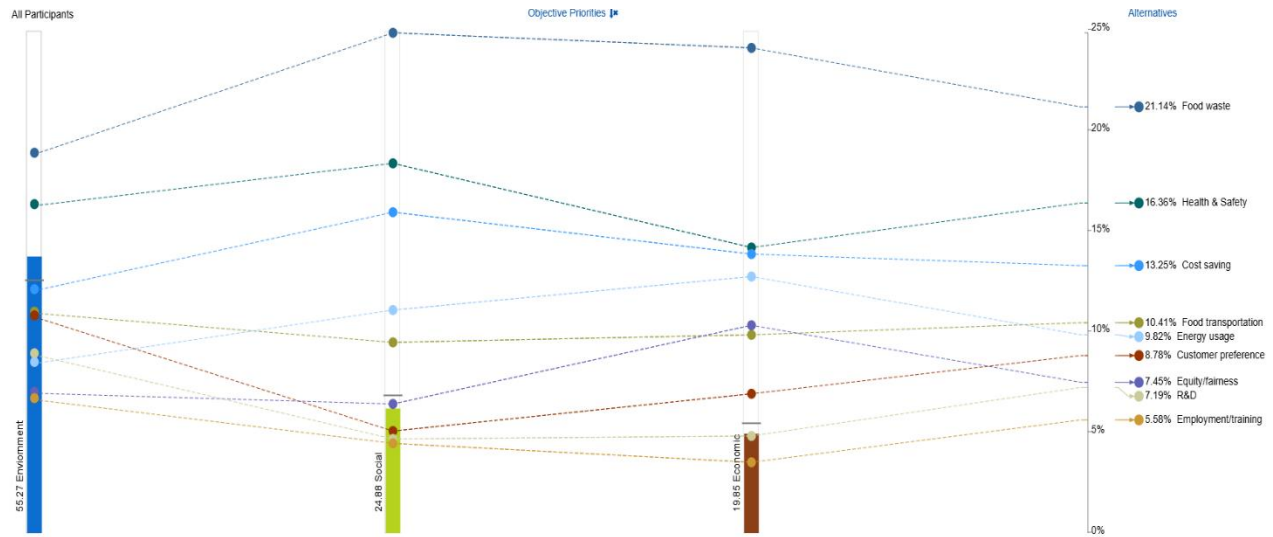


Figure 4. 3 : Sensitivity analysis for 5% increase in the Environment main criteria

10% increase

In this scenario, the weight of the “Environment” increased by 10%. It has been noticed that a slight change in the weight of the sub-criteria and similar to the previous scenario, all sub-criteria priorities remained the same, see Figure 4.4.

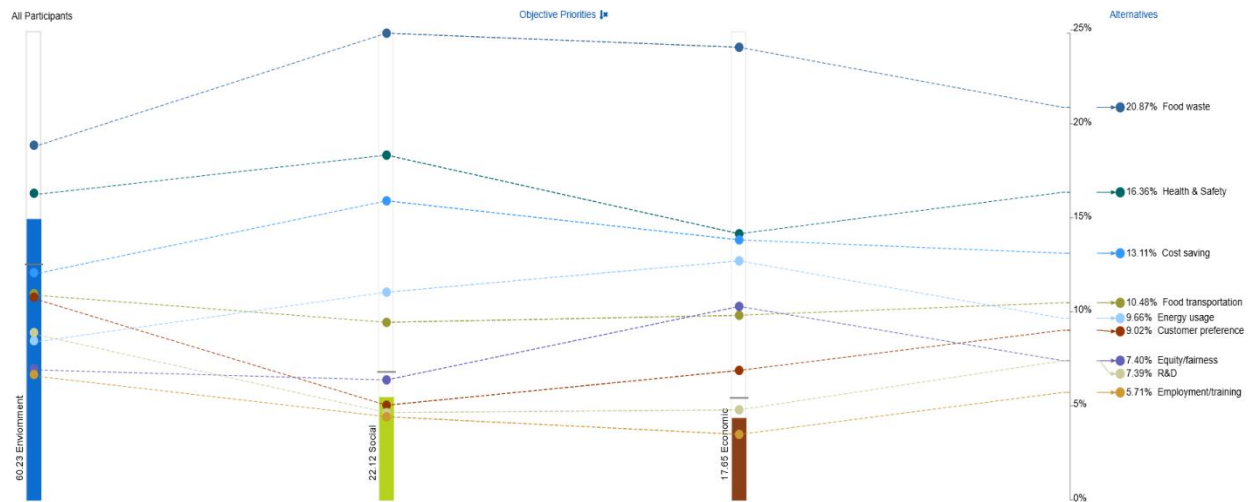


Figure 4. 4: Sensitivity analysis for 10% increase in the Environment main criteria

15% increase

With the increase in Environment by 15%, all the sub-criteria priority remains at their rank as in the previous two scenarios except the “R&D” move up to 7.61% and replace the “Equity/Fairness” with 7.34%. The recorded priorities for the other sub-criteria were Food waste, 20.58%, Health & Safety, 16.35%, Cost saving, 12.96%, Food transportation, 10.55%, Energy usage, 9.48%, and Customer preference, 9.27, Employment/training, 5.85% as seen in Figure 4.5

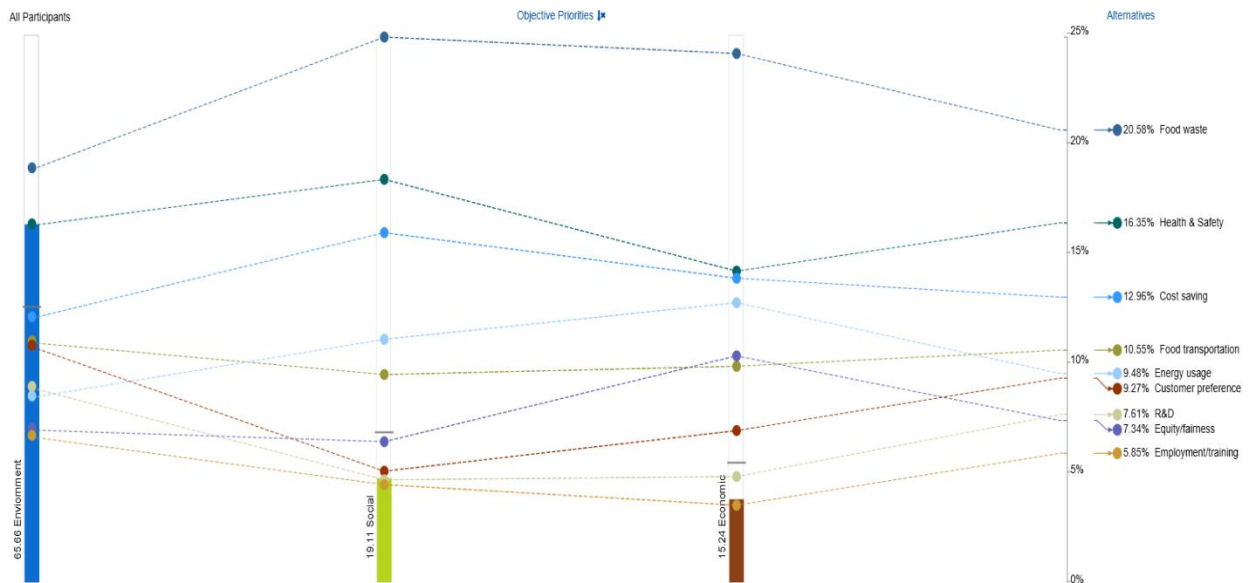


Figure 4. 5 : Sensitivity analysis for 15% increase in the Environment main criteria

20% increase

With the increase in Environment up to 20%, Food waste shows a change of 20.32%, Health & Safety shows a change of 16.34%, Cost saving shows a change of 12.83%, Food transportation shows a change of 10.61%, Energy usage shows a change of 9.33%, and Customer preference shows a change of 9.50%, Equity/fairness shows a change of 7.29%, R&D shows a change of 7.81% , Employment/training shows a change of 5.97% as seen in Figure 4.6

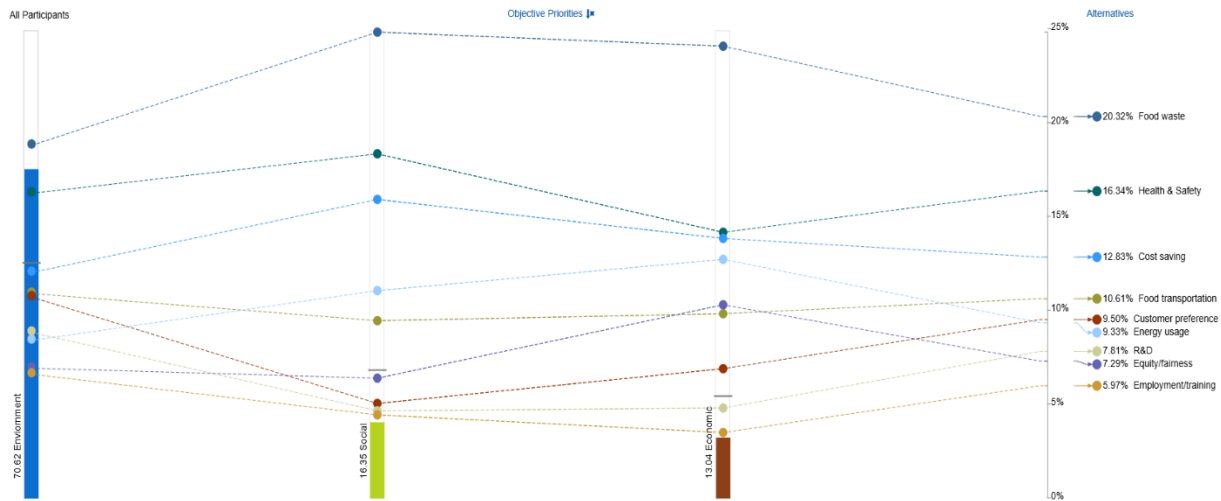


Figure 4. 6 : Sensitivity analysis for 20% increase in the Environment main criteria

Summary

The sensitivity analysis provided a clear picture of the connection between the environmental criterion and various factors. The experiments illustrated that every percentage of variation (5%,10%, 15%, 20%) brought about the same magnitude of change in all sub-criteria. The changes, in fact, appeared to be quite small, in most cases. What is more important, the total order of sub-criteria did not change drastically even when the environmental criterion was increased by 20%. An outlier among all the sub-criteria was a quite subtle shift where, in the ranking, Customer Preference overrode Energy Usage.

4.5.1.2 Social

5% increase

The second change was made is increasing the weight of the “Social” by 5%. slight changes in the weights of the sub-criteria have been noticed, however, their priorities remained same, see Figure

4.7

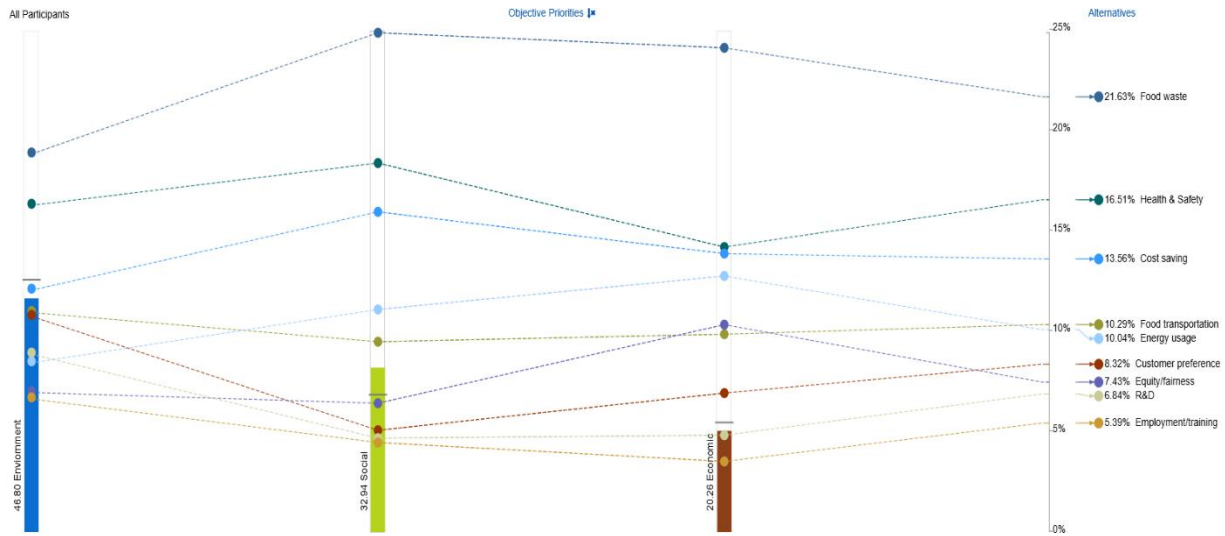


Figure 4. 7: Sensitivity analysis for 5% increase in the Social main criteria

10% increase

In this scenario, the weight of the “Social” increased by 10%. It has been noticed that a slight change in the weight of the sub-criteria and similar to the previous scenario, all sub-criteria priorities remained the same, see Figure 4.8.

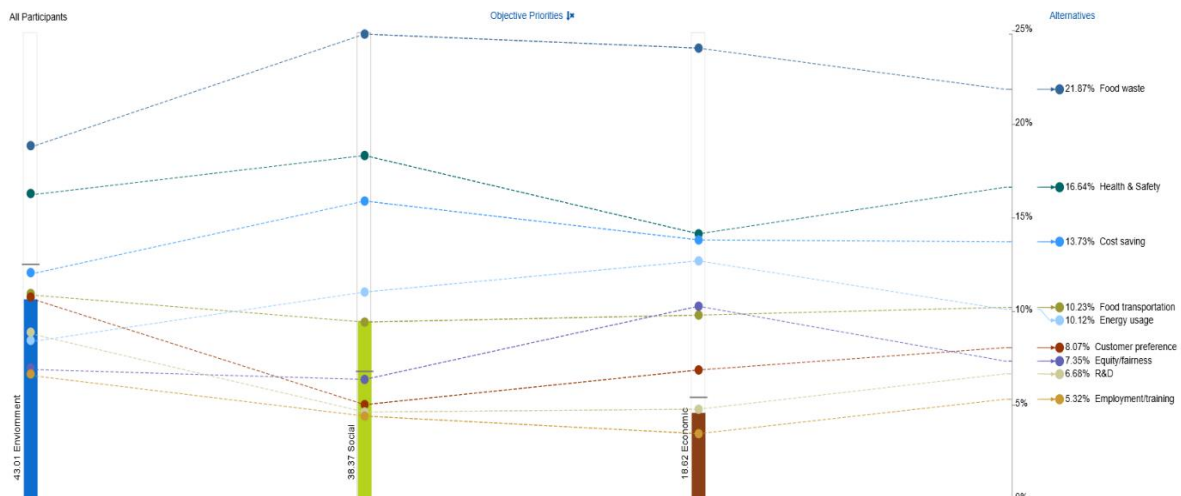


Figure 4. 8: Sensitivity analysis for 10% increase in the Social main criteria

15% increase

With the increase in weight of Social up to 15%, Food waste shows a change of 22.06%, Health & Safety shows a change of 16.75%, Cost saving shows a change of 13.87%, Food transportation shows a change of 10.18%, Energy usage shows a change of 10.17%, and Customer preference shows a change of 7.88%, Equity/fairness shows a change of 7.29%, R&D shows a change of 6.55% , Employment/training shows a change of 5.26% as seen in Figure 4.9

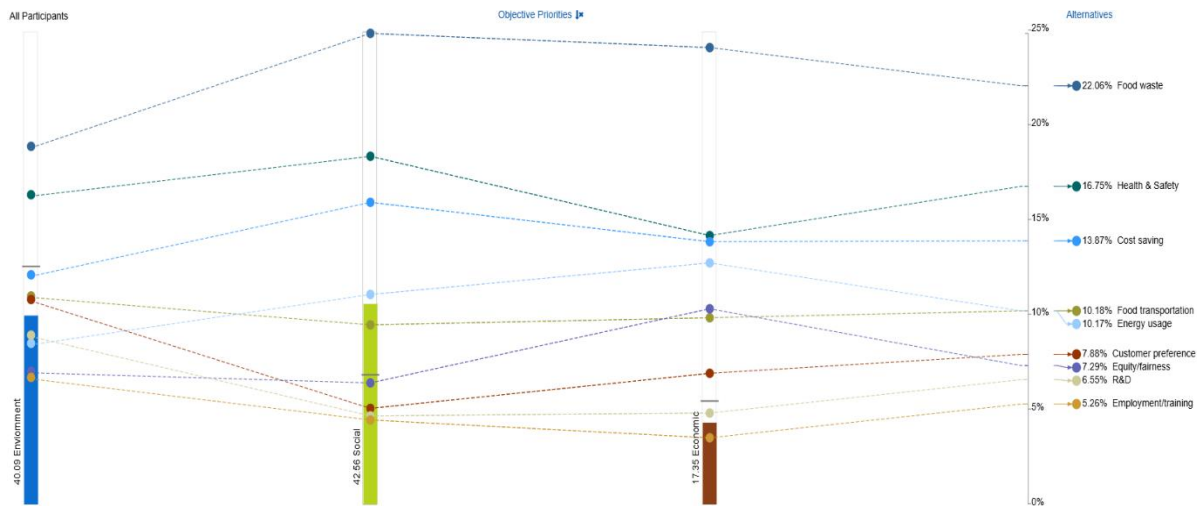


Figure 4. 9: Sensitivity analysis for 15% increase in the Social main criteria

20% increase

With the increase in Social up to 20%, Food waste shows a change of 22.28%, Health & Safety shows a change of 16.88%, Cost saving shows a change of 14.04%, Food transportation shows a change of 10.12%, Energy usage shows a change of 10.25%, and Customer preference shows a change of 7.56%, Equity/fairness shows a change of 7.21%, R&D shows a change of 6.39% , Employment/training shows a change of 5.19% as seen in Figure 4.10

In the last scenario, the weight of the “Social” increased by 20%. It has been noticed that a slight change in the weight of the sub-criteria and all sub-criteria priorities remained the same except what?????

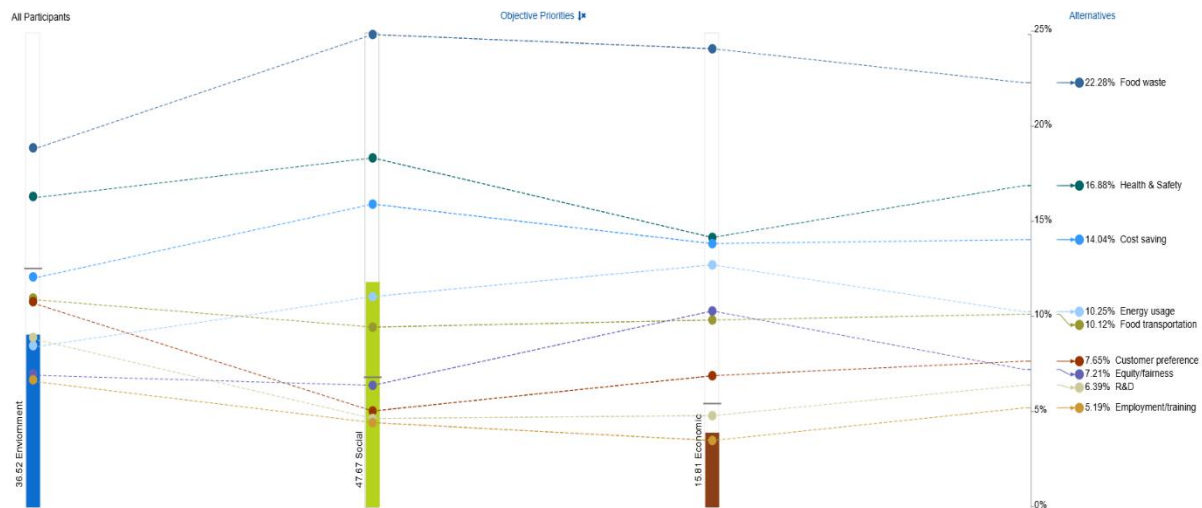


Figure 4. 10: Sensitivity analysis for 20% increase in the Social main criteria

Summary

The sensitivity analysis showed what factors were influenced by changes in the social criterion. It was seen that each level of variance (5%, 10%, 15%, and 20%) resulted in similar changes across all sub-criteria. However, these changes were mostly negligible. It is worth noting that, with as much as a 20% rise in the social criterion, changes in the sub-criteria's rankings were next to none. A very unlikely instance took place where Energy usage moved ahead of Food transportation in the ranking.

4.5.1.3 Economic

5% increase

The third change was made is increasing the weight of the “Economic “by 5%, slight changes in the weights of the sub-criteria have been noticed, however, their priorities remained same as seen in Figure 4.11.

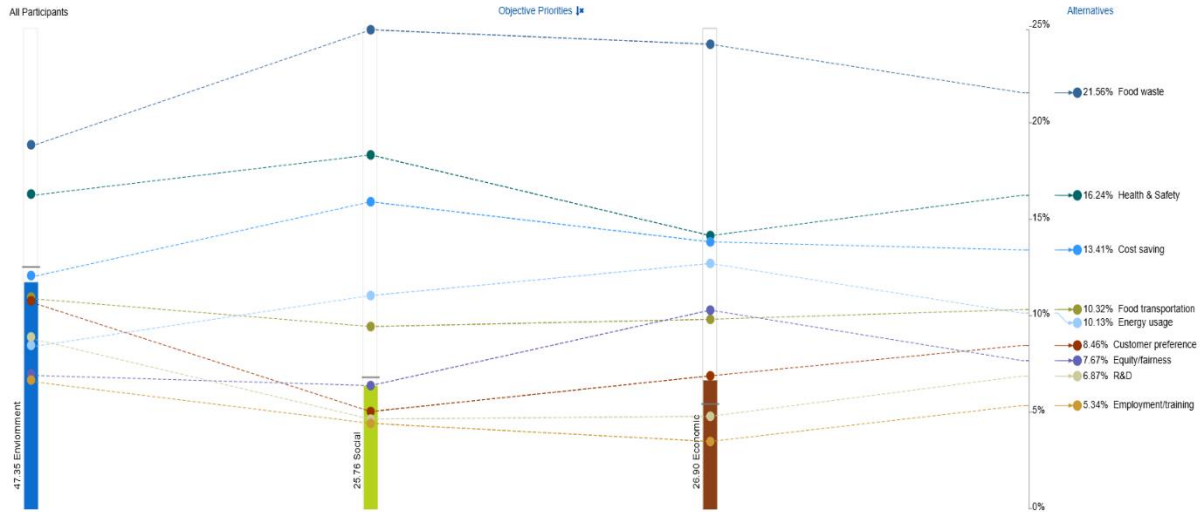


Figure 4. 11: Sensitivity analysis for 5% increase in the Economic main criteria

10% increase

In this scenario, the weight of the “Economic” increased by 10%. It has been noticed that a slight change in the weight of the sub-criteria and similar to the previous scenario, all sub-criteria priorities remained the same, see Figure 4.12

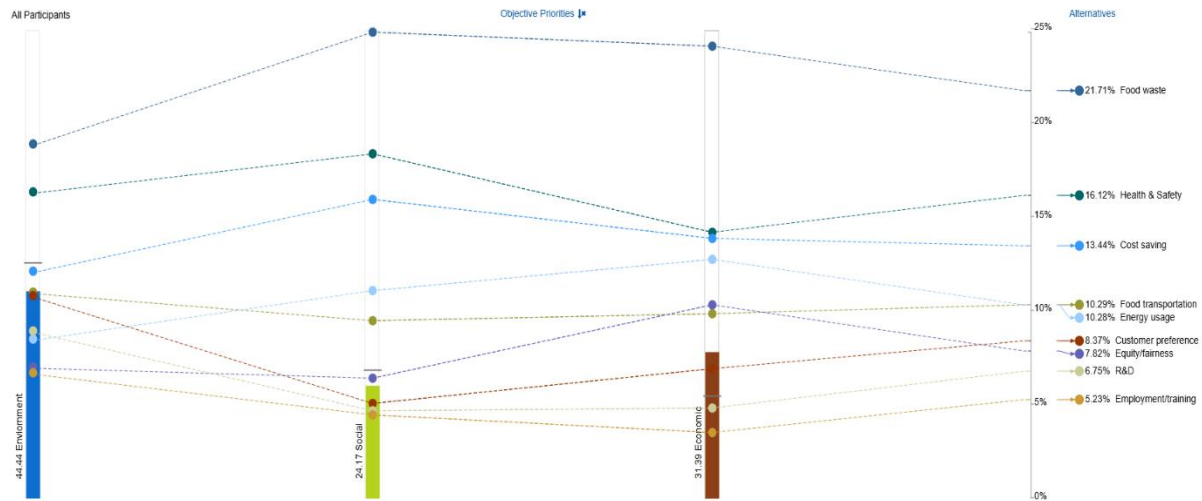


Figure 4.12: Sensitivity analysis for 10% increase in the Economic, main criteria

15% increase

With the increase in Economic up to 15%, Food waste shows a change of 21.88%, Health & Safety shows a change of 15.97%, Cost saving shows a change of 13.46%, Food transportation shows a change of 10.25%, Energy usage shows a change of 10.46%, and Customer preference shows a change of 8.25%, Equity/fairness shows a change of 8.01%, R&D shows a change of 6.60%, Employment/training shows a change of 5.10% as seen in Figure 4.13.

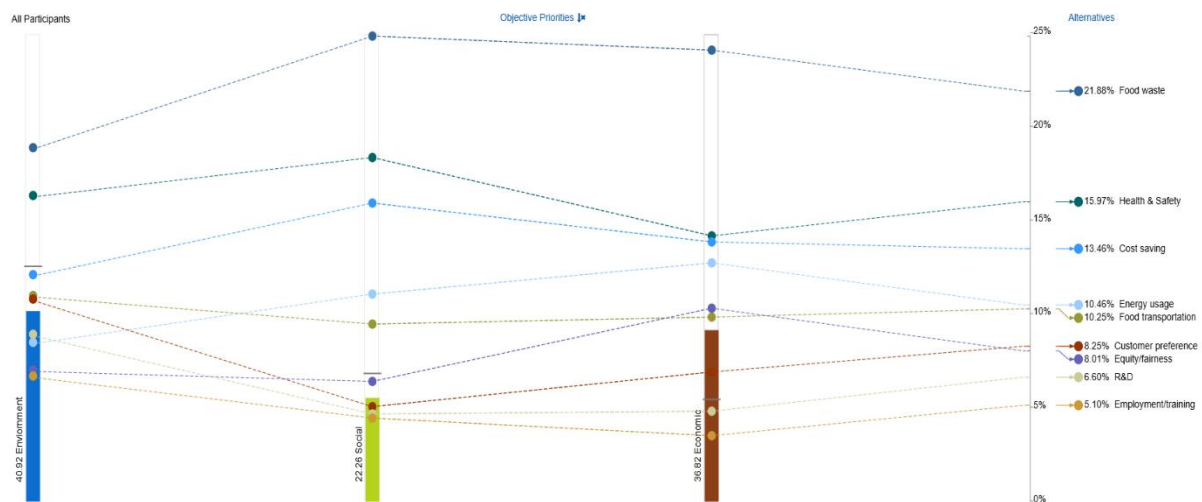


Figure 4.13: Sensitivity analysis for 15% increase in the Economic main criteria

20% increase

With the increase in Economic up to 20%, Food waste shows a change of 22.04%, Health & Safety shows a change of 15.84%, Cost saving shows a change of 13.49%, Food transportation shows a change of 10.22%, Energy usage shows a change of 10.63%, and Customer preference shows a change of 8.15%, Equity/fairness shows a change of 8.18%, R&D shows a change of 6.47%, Employment/training shows a change of 4.98% as seen in Figure 4.14

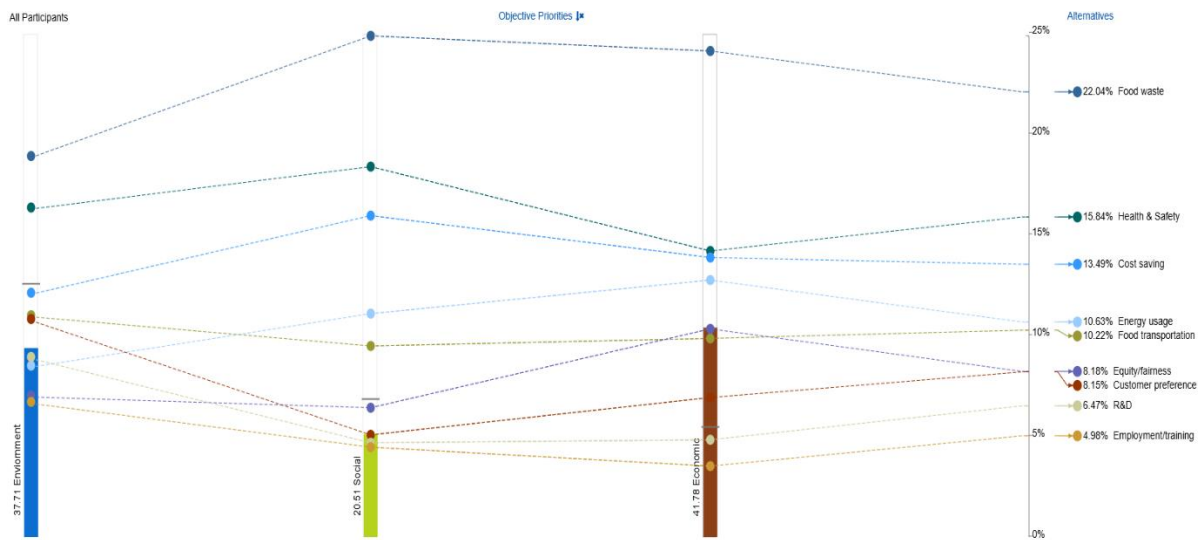


Figure 4. 14: Sensitivity analysis for 20% increase in the Economic main criteria

Summary

Analysis on the sensitivity pointed out the manner in which various factors reacted when the economic criterion was altered. It was found that each degree of change (5%, 10%, 15%, and 20%) caused a response in the same direction with all sub-criteria. Nevertheless, these changes were mostly limited. More precisely, there was a very high stability of sub-criteria ranking despite a 20% increase in the environmental criterion. The only divergence was the point at which Equity/fairness got the upper hand over Customer preference in the ranking.

4.5.2 Initial Sensitivity Assessment (Decrement)

The figure below illustrates how each variable performs in terms of sensitivity when compared to its benchmark values. A preliminary sensitivity analysis was conducted to observe the changes that occur when the weights of three key main criteria are decreased by 5%, 10%, 15% and 20%, respectively. Figure 4.15 presents the original base model, displaying the initial values and sensitivity outcomes before any adjustments were made.

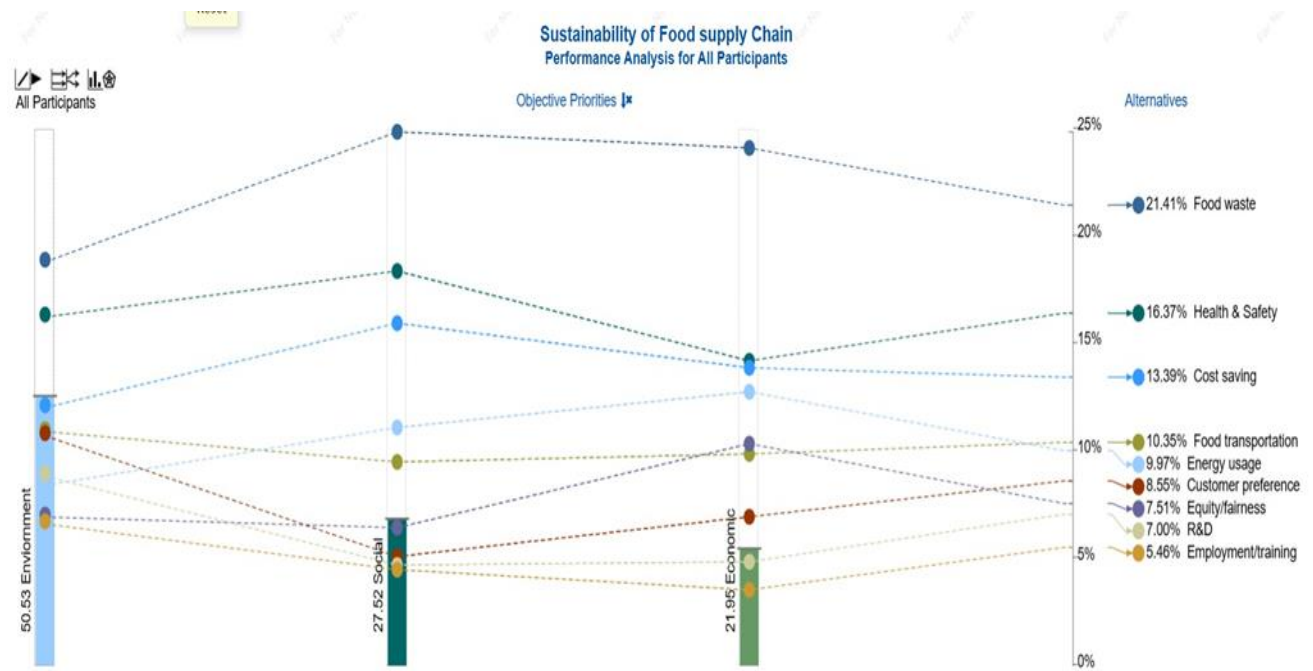


Figure 4. 15 : Original base model

4.5.2.1 Environment

5% Decrement

Figure 4.16 shows how a 5% decrease in the Environmental criterion gives us the change among other criteria and sub-criteria. The conclusion is that we only have a tiny change, with a maximum of food waste of 0.24%, and very small (which means not significant) changes in other criteria but without any ranking changes.

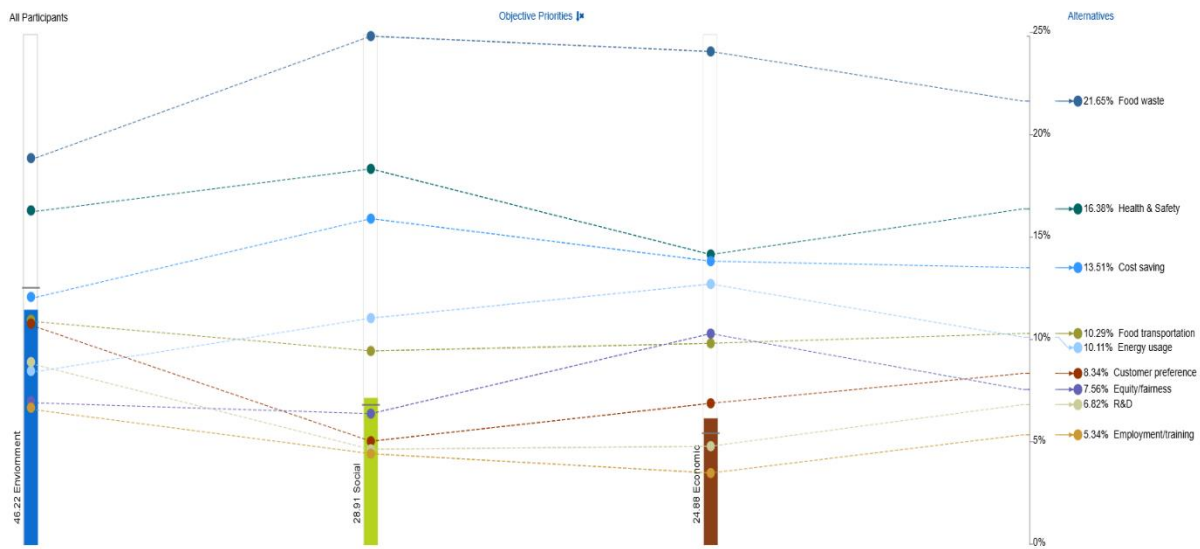


Figure 4. 16: Sensitivity analysis for 5% decrease in the Environment main criteria

10% Decrement

Following a 10% reduction in the Environmental criterion, slight to marginal changes were observed in the sensitivities of the other criteria similar to the previous scenario. Compared to the original base model, not changed in ranking, as shown in Figure 4.17.

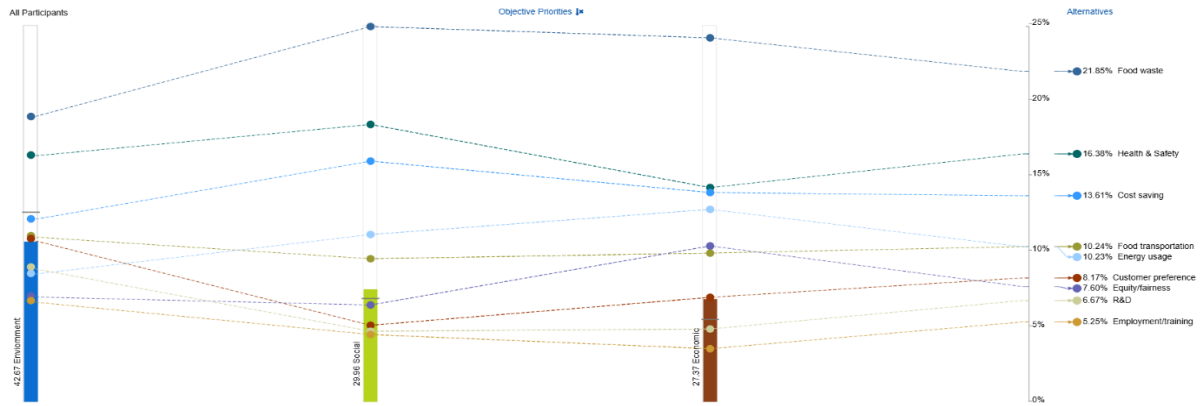


Figure 4. 17: Sensitivity analysis for 10% decrease in the Environment main criteria

15% Decrement

Following a 15% decrement in the Environmental criterion, slight changes were observed in the weights of the other criteria, Food waste 22.26%, Health & Safety 16.39%, Cost saving 13.83%, Energy usage 10.48%, Food Transportation 10.14%, Customer preference 7.81%, Equity 7.68%, R&D 6.36%, and Employment/training 5.05%. These differences are minimal when compared to the base model, as illustrated in Figure 4.18.

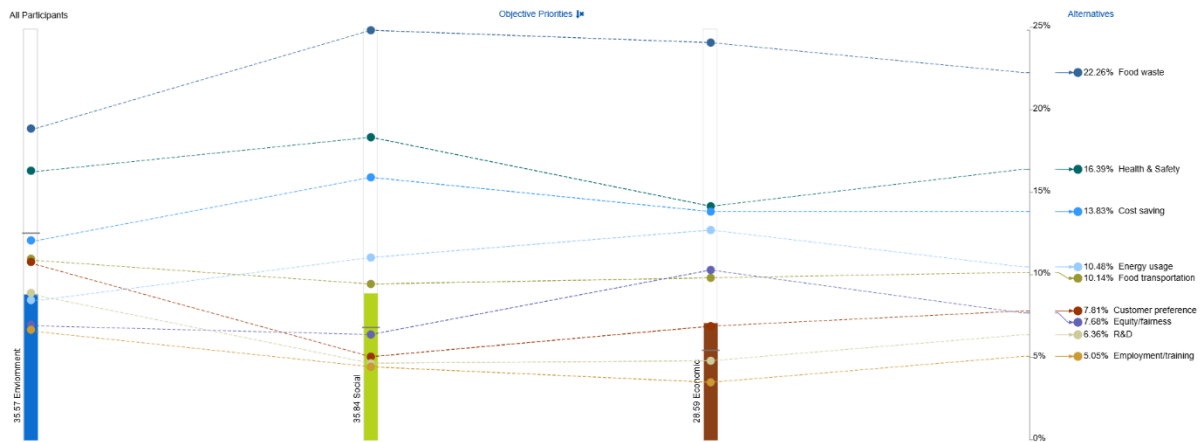


Figure 4. 18: Sensitivity analysis for 15% decrease in the Environment main criteria

20% Decrement

Following a 20% reduction in the Environmental criterion, some changes were observed in the weights of the other criteria, Food waste 22.37%, Health & Safety 16.40%, Cost saving 13.88%, Energy usage 10.54%, Food Transportation 10.12%, Customer preference 7.71%, Equity 7.71%, R&D 6.28%, and Employment/training 5%. Only one change in ranking was observed: Energy Usage moved ahead of Food Transportation, as shown in Figure 4.19.

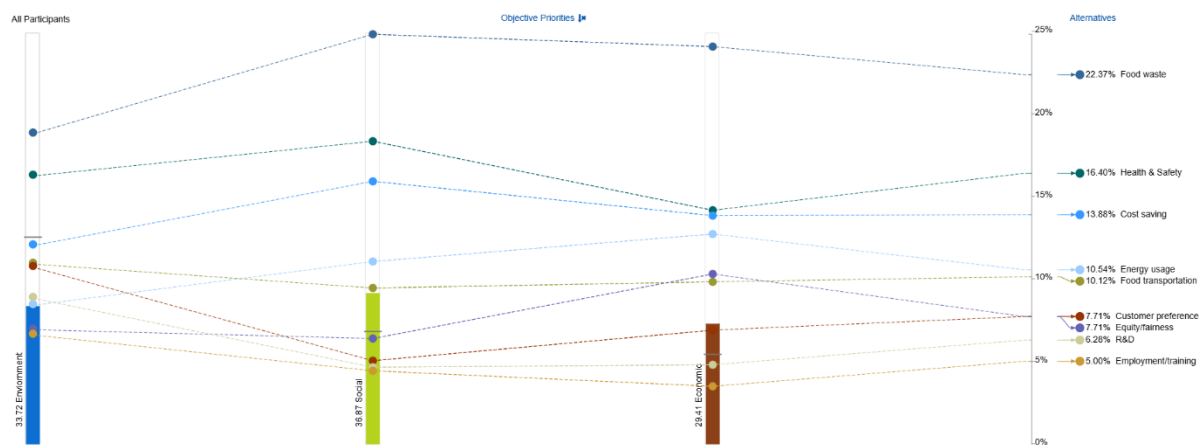


Figure 4. 19: Sensitivity analysis for 20% decrease in the Environment main criteria

4.5.2.2 Social

5% Decrement

Figure 4.20 provides a comparison of the original and the 5% reduction in weight of Social main criterion , also presenting the corresponding changes in other criteria and sub-criteria. The findings reveal that there is a very slight difference, with food waste having the biggest change of 0.24%,

while the other criteria show almost no change with rankings all remaining the same.

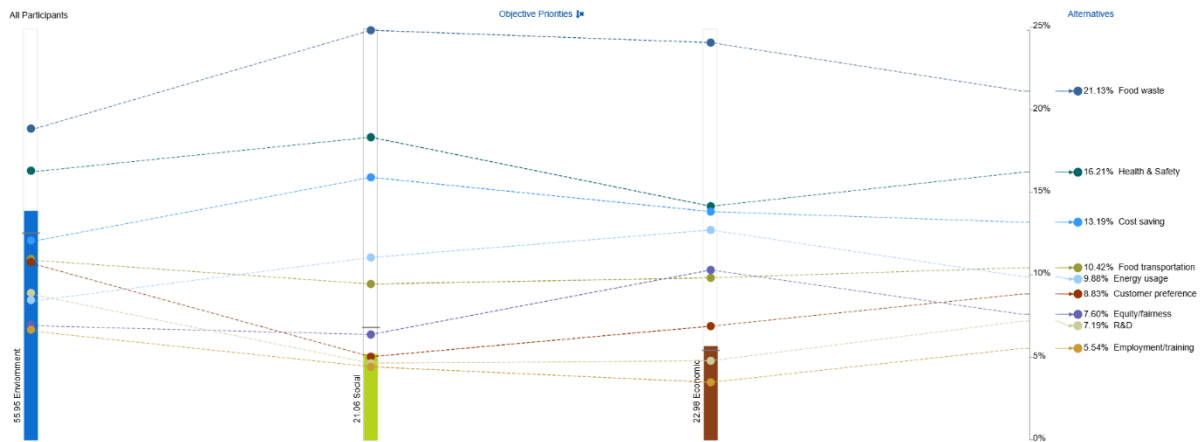


Figure 4. 20: Sensitivity analysis for 5% decrease in the Social main criteria

10% Decrement

Following a 10% reduction in the social criterion, slight to marginal changes were observed in the sensitivities of the other criteria but no changes in ranking, as shown in Figure 4.21.

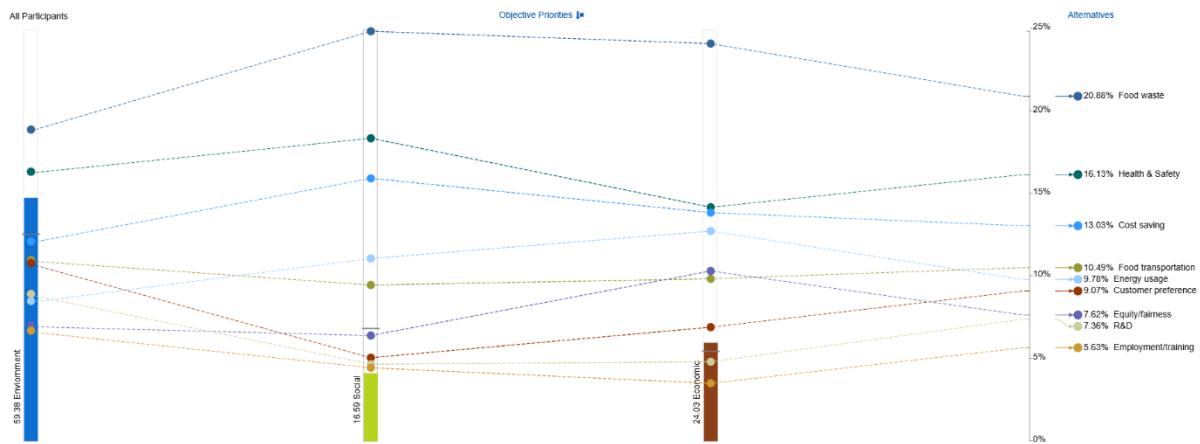


Figure 4. 21: Sensitivity analysis for 10% decrease in the Social main criteria

15% Decrement

Following a 15% decrement in the Social criterion, slight changes were observed in the weights of the other criteria, Food waste 20.78%, Health & Safety 16.01%, Cost saving 12.93%, Energy usage 9.77%, Food Transportation 10.52%, Customer preference 9.20%, Equity 7.71%, R&D 7.43%, and Employment/training 5.65%. These differences are minimal when compared to the base model, as illustrated in Figure 4.22.

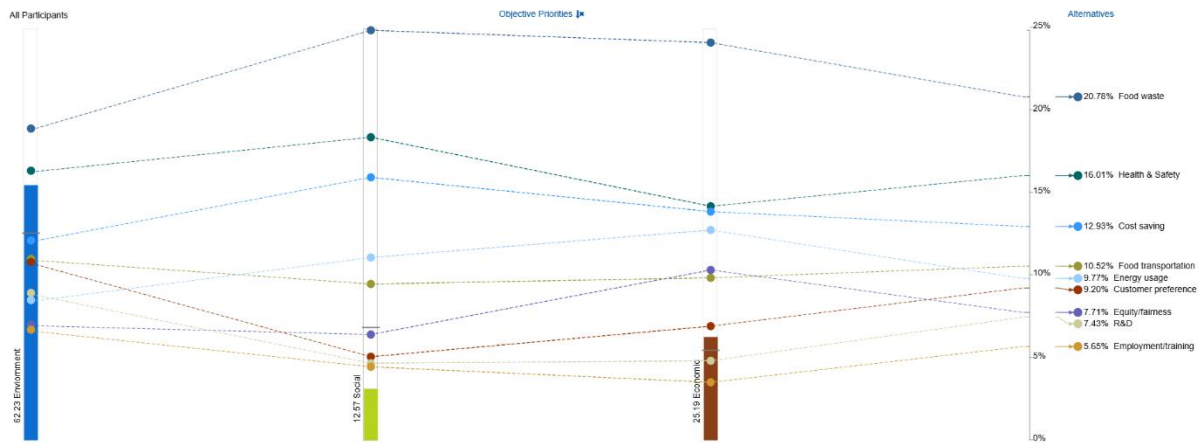


Figure 4. 22: Sensitivity analysis for a 15% decrease in the Social main criteria

20% Decrement

Following a 20% reduction in the social criterion, some changes were observed in the weights of the other criteria, Food waste 20.56%, Health & Safety 15.88%, Cost saving 12.76%, Energy usage 9.70%, Food Transportation 10.58%, Customer preference 9.42%, Equity 7.78%, R&D 7.58%, and Employment/training 5.71%. These differences are minimal when compared to the base model, as shown in Figure 4.23.

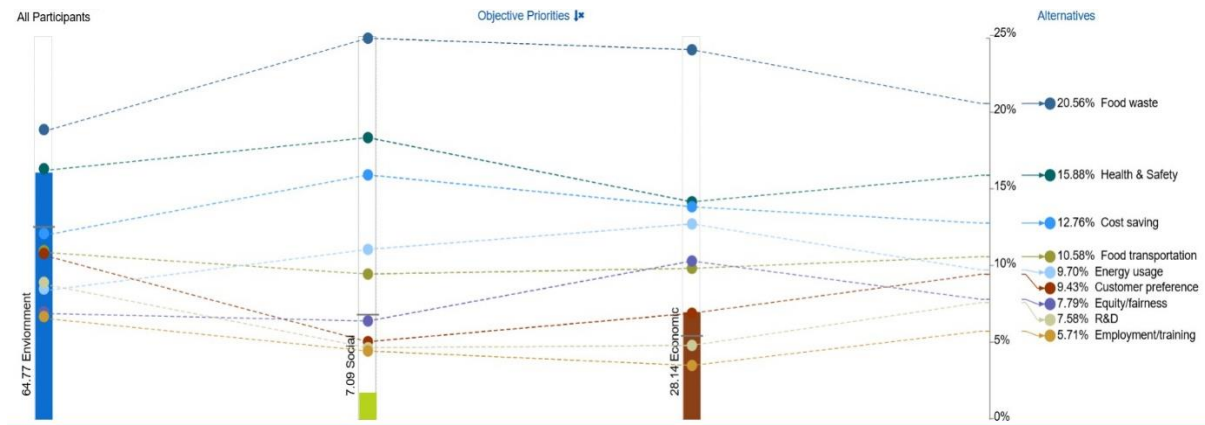


Figure 4. 23: Sensitivity analysis for 20% decrease in the Social main criteria

4.5.2.3 Economic

5% Decrement

Figure 4.24 presents the impact on other criteria and sub-criteria of a 5% reduction in the Economic criterion by also showing the resulting changes in comparison to the original base model. In other words, the data reveal that food waste had an increase of 0.16% which was the highest change while in the rest of the criteria there were only marginal changes and none of them moved to other ranks.

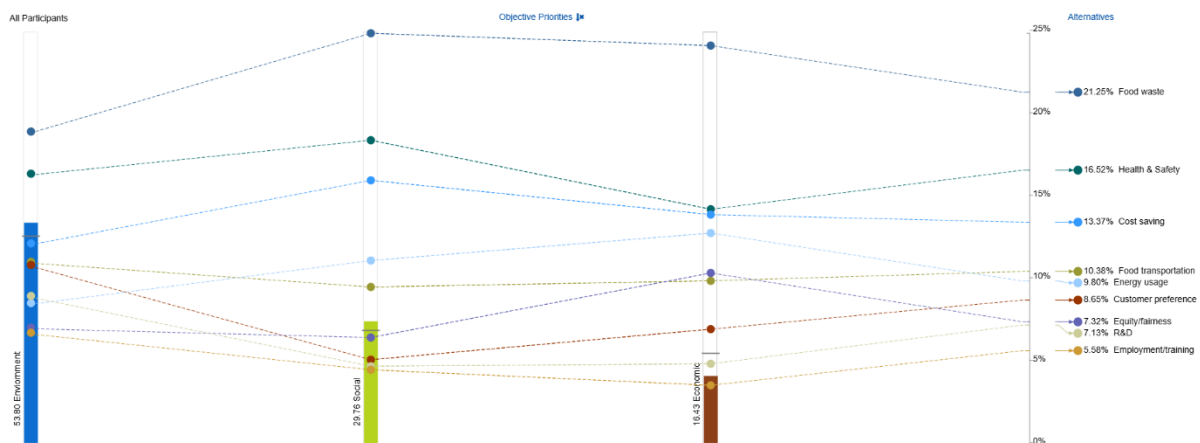


Figure 4. 24: Sensitivity analysis for 5% decrease in the Economic main criteria

10% Decrement

Following a 10% reduction in the Economic criterion, slight to marginal changes were observed in the sensitivities of the other criteria similar to the previous scenario. Compared to the original base model, all other criteria showed at least a 0.01% -0.4% change but no changes in ranking, as shown in Figure 4.25.

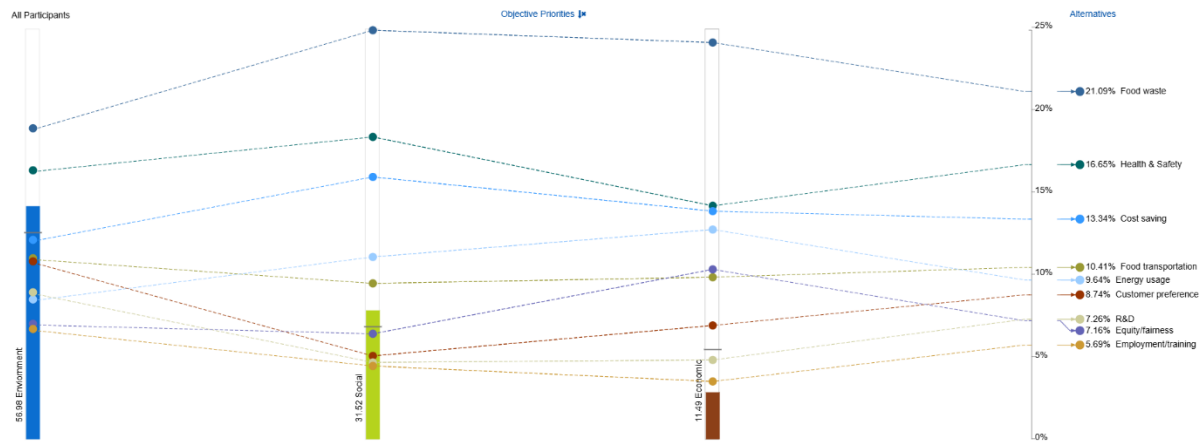


Figure 4. 25: Sensitivity analysis for 5% decrease in the Economic main criteria

15% Decrement

Following a 15% decrement in the Economic criterion, slight changes were observed in the weights of the other criteria, Food waste 20.95%, Health & Safety 16.77%, Cost saving 13.32%, Energy usage 9.49%, Food Transportation 10.44%, Customer preference 8.83%, Equity 7.01%, R&D 7.38%, and Employment/training 5.80%. These differences are minimal when compared to the base model, the only change in ranking observed R&D moved ahead of Equity, as illustrated in Figure 4.26.

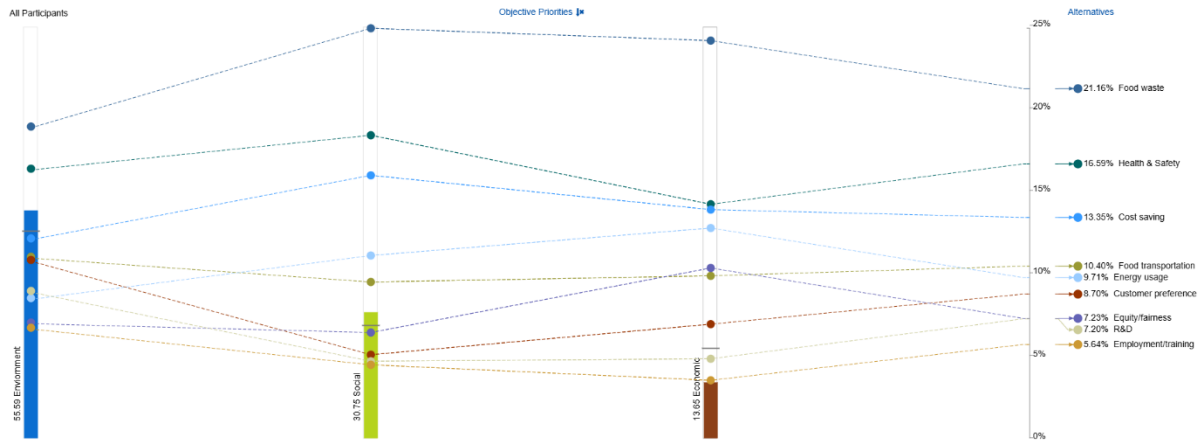


Figure 4. 26: Sensitivity analysis for a 15% decrease in the Economic main criteria

20% Decrement

Following a 20% reduction in the Economic criterion, slight changes were observed in the weights of the other criteria, Food waste 20.80%, Health & Safety 16.90%, Cost saving 13.30%, Energy usage 9.34%, Food Transportation 10.47%, Customer preference 8.93%, Equity 6.85%, R&D 7.50%, and Employment/training 5.91%. These differences are minimal when compared to the base model, as shown in Figure 4.27.

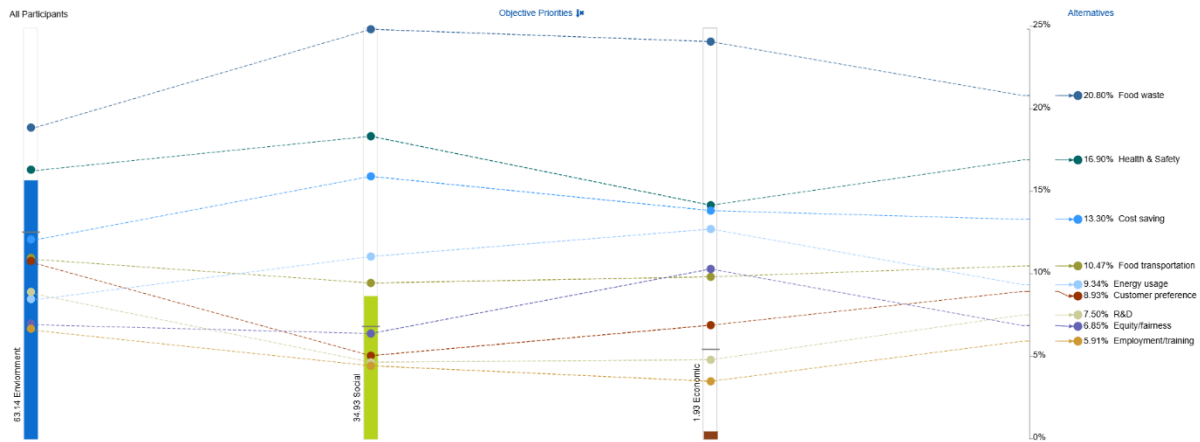


Figure 4. 27: Sensitivity analysis for 20% decrease in the Economic main criteria

4.6. Outsourcing performance measures

To ensure the credibility and empirical grounding of the proposed framework, the Level 4 performance measures were validated and ranked by 50 professionals specializing in food supply chain management. This sample was selected using a purposive sampling strategy to capture a balance of high-level academic theory and practical industrial expertise.

The participants represent two distinct groups: Academic Professionals (n=30), who provided the theoretical validation of the constructs, and Industry Practitioners (n=20), who evaluated the operational feasibility and priority of the performance measures. That all summarised in table 4.2.

Table4. 3: Profile Summary of Interview Participants

ID Group	Participant Category	Organisational Role / Academic Focus	Count	Avg. Experience (Years)
A1 – A12	Academic Professionals	Senior Lecturers / Professors in Supply Chain Management	12	18
A13 – A22	Academic Professionals	Lecturer & Senior lecturer (Food, supply chain, Sustainability & Circular Economy)	10	8
A23 – A30	Academic Professionals	PhD Researchers (Supply chain & Sustainable Logistics)	8	5
P1 – P08	Industry Practitioners	Supply Chain & Logistics Managers (Food Sector)	8	14
P09 – P13	Industry Practitioners	Sustainability & ESG Officers (Retail/Wholesale)	5	10
P14 – P20	Industry Practitioners	Procurement & Sourcing Directors	7	20
Total			50	

The results of this interview about outsourcing performance measures are shown in Figure 4.28.

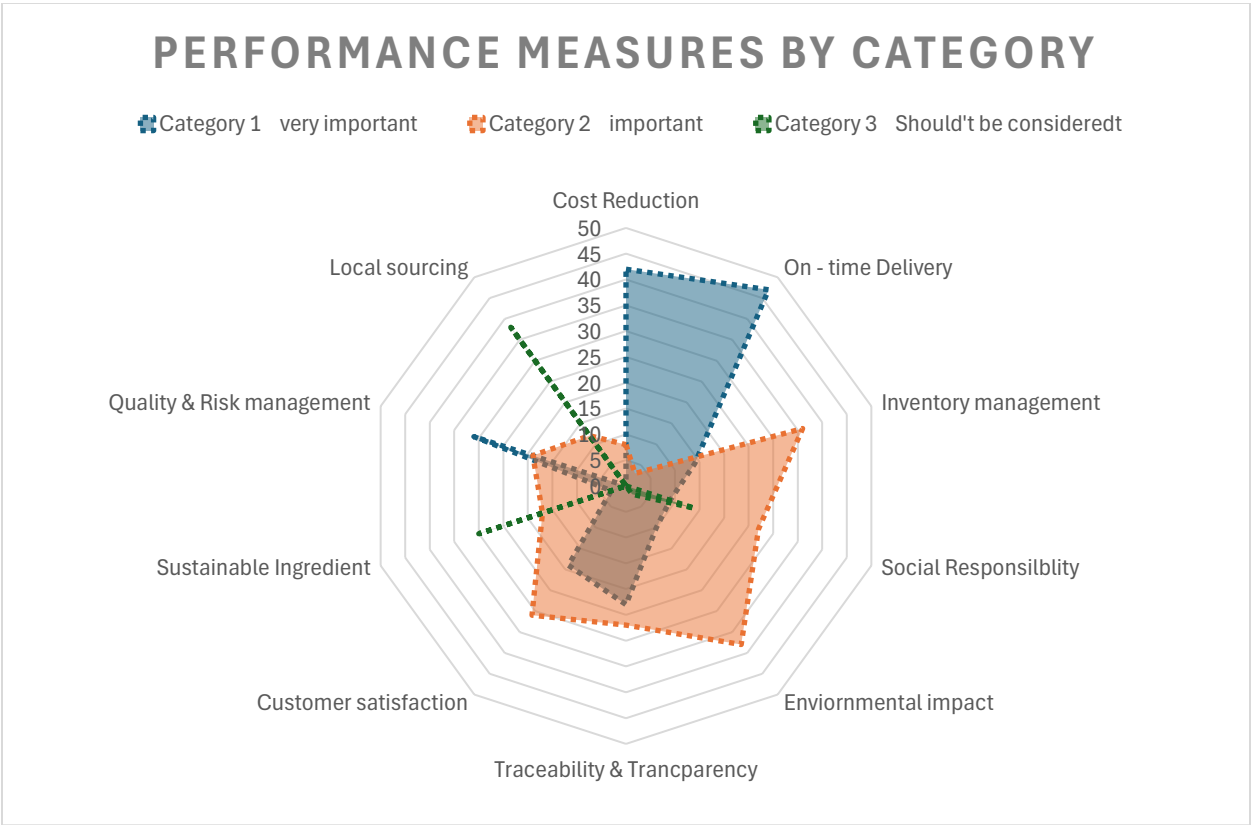


Figure 4. 28: Radar Diagram for Outsourcing performance measures

Outsourcing plays an essential role in the food supply chain from the point of view of the strategic function. Efficiency, risk, and sustainability have to be kept in a delicate balance. The present research examines the performance measures for choosing an outsourcing company using the responses from 50 food professionals. As shown in the Radar diagram, each respondent assigned ten performance indicators to one of three categories – very important, important, and should not be considered. The outcomes show a very definite order of priorities and at the same time, they make the level of satisfaction between the operational purposes, and the new environmental criteria stand out.

As seen, darker blue, denotes the most important performance indicators which the survey participants were able to recognise on time delivery and cost reduction as the top vote-getters of “very important” having 47 and 42 votes individually. These figures once again stress that the industry is steadily concentrating on the logistics efficiency and cost-effectiveness. Some of the most crucial elements in the sector where there are high rates of spoilage and price fluctuations while profit margins are very tight. Inventory Management, despite being the least voted category with just 14 votes, was still considered to be “important” even by 36 interviewees, thus the notion that it is the fundamental element of the supply chain has been redeveloped.

Quality & Risk Management was voted "very important" 31 times, showing that it is the most relevant in maintaining compliance and securing food safety. This also indicates that although the cost and delivery are necessary, the business entities are still very responsive to operational risks.

Environmental Impact, Social Responsibility, and Traceability & Transparency are the key focus of the new times, as shown by the heavy distribution of “important” ranks awarded for each of these (38, 27, and 27 votes respectively) indicating that their pivotal role is increasingly recognised. Especially with regard to Traceability, the fact that almost half of the interviewees (23) consider it "very important" can be interpreted as a clear sign of its gradual establishment in regulatory compliance and surety of the ethical sourcing.

4.7 Conclusion

The proposed framework has been verified through implementation within a pilot research project interviews and distributed questionnaires between people who elaborate on the theory in their professional practice. The positive factors of the Environment, social and economic, by which sustainability is defined as the main criterion, together with corresponding sub-criteria for each main criterion, were inspected at different levels of 5%, 10%, 15% and 20% sensitivity analysis.

In addition, the Radar diagram illustrates the important performance measures of the outsourcing companies. The upcoming chapter provides a detailed overview of the development of mathematical models to include sustainability and performance measures in the food supply chain.

Chapter 5

Science-Based Metrics for Quantifying Societal Impact

within Food Supply Chain

5.1. Introduction

This chapter introduces the formal definition of the research problem and the creation of the related mathematical models. The problem is organised by specifying the main inputs, decision variables, and constraints that describe the system under review. The goal is to pick out the fundamental concepts that were established in the earlier chapters and now represent them in a strict mathematical form that can be further by analysed and solved. Besides, solution method is briefly mentioned to confirm that the presented models hold not only theoretical but also feasible practical applications.

5.2. Problem Definition and Mathematical Model

This research focuses on designing a supply chain for the food industry by considering several crucial features like quality, time, sustainability, and resilience. The considered supply chain consists of four facilities, including suppliers, Manufacturing Sites (MSs), Distribution Centres (DCs), and customers. The considered supply chain network is depicted in Figure 5.1. In this supply chain, the flow of materials and products is as follows. At the outset, the required Raw Materials (RMs) are purchased from the relevant raw material providers (suppliers) and sent to MSs. In the next step, the manufactured products are shipped to DCs. Then, the products are sent to the demand points (customers). In this regard, it should be noted that RMs and products have its corresponding characteristics (e.g., cost, lead time, demand, etc.). Furthermore, in this study, we consider different transportation modes, each of which has its relevant cost and Greenhouse

Gas (GHG) emissions. Moreover, two types of information sharing systems (traditional system or server-based platform and blockchain platform) can be utilised in the supply chain network, each of which has its own relevant cost and visibility. In this regard, employing information-sharing systems is one of the major strategies that can be so helpful in weakening disruptions (Taheri & Moghaddam, 2022), which makes trust, reduces risk, and increases visibility. Establishing information-sharing systems discloses the supply chain issues and enhances resiliency (Breque et al., 2021; Mehrjerdi & Shafiee, 2020; Subramanian et al., 2020). In this study, to consider sustainability, we adopt three strategies as follows. First, we consider an objective function to minimise the total GHG emitted by activities of the supply chain. Furthermore, we study the research problem under the cap-and-trade carbon policy, which is a well-known strategy in the literature to handle GHG emissions (Xu et al., 2024; Zou et al., 2023). According to this policy, firms are allowed to emit a predetermined amount of GHG within a specific period which is so-called “cap.” If a firm requires more capacity to emit GHG in its supply chain activities, it can buy carbon credits from other companies in the market, which is the so-called “trade” (Rui et al., 2023). It should be noted that in the case of the GHG emission of the firm is less than its capacity credit, it can sell its carbon capacity credit in the market. The two mentioned points were related to the environmental concerns. Since sustainability also considers the social impacts, in this work, we consider three main elements as follows:

- (i) The first social impact is related to increasing customer satisfaction by enhancing the service level of the supply chain. In this regard, we consider a predefined value for the minimum service level of the supply chain.
- (ii) The second social impact considered in this work is related to the social risk of the utilised transportation mode. In this regard, the risk of community resistance to utilised

transportation mode refers to the likelihood of public opposition and protests arising from the negative environmental or social impacts associated with the employed transportation mode.

- (iii) The third social aspect in this work is fatigue of workers (Ihsan et al., 2020; Kołodziej & Ligarski, 2017), which has been incorporated into the proposed model by considering the maximum allowable working time for each worker in the facilities of the supply chain.

On the other hand, in this work, the resilience concept is considered to deal with potential risks. In this regard, to incorporate the resilience concept into the proposed model, we adopt the following well-known strategies:

- (i) Multiple-transportation modes (Kogler & Rauch, 2019; Ma et al., 2024),
- (ii) Establishing extra capacity (if needed) (Rezapour et al., 2017; Salama & McGarvey, 2021), and
- (iii) Establishing information-sharing systems (Koohkan et al., 2024; Mehrjerdi & Shafiee, 2021). Furthermore, another crucial issue this research focused on is related to reducing the total delivery time (lead time) of the supply chain, which makes the supply chain more agile and increases customer satisfaction.

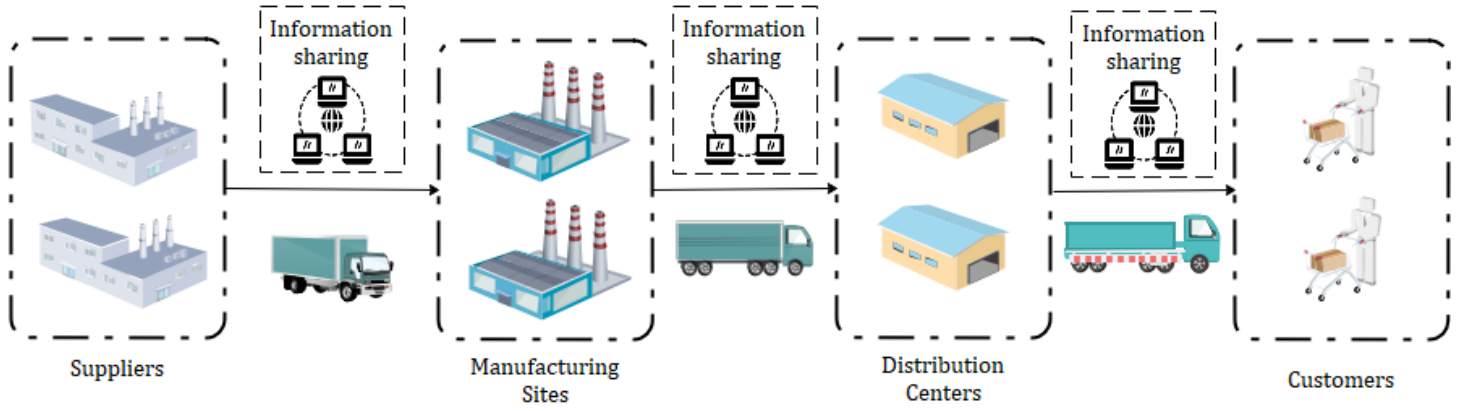


Figure 5. 1: The Considered Supply Chain Network

According to the aforementioned descriptions, we can define the following notations to formulate the research problem.

Sets

I	Set of suppliers indexed by i
J	Set of manufacturing sites indexed by j
K	Set of distribution centres indexed by k
C	Set of customers indexed by c
R	Set of raw materials indexed by r
P	Set of products indexed by p
Q	Set of quality levels indexed by q ($q = 1, 2, 3$ in which 1: low quality, 2: medium quality, and 3: high quality)
M	Set of transportation modes indexed by m
F	Set of information-sharing systems indexed by f

Parameters:

CIE_f	The establishment cost for information-sharing system f
PCR_{rqi}	The purchasing cost of RM r with quality level q from supplier i
CM_{jpq}	The cost of manufacturing product p with quality q in MS j
CD_{kp}	The operational cost of DC k for product p
FT_m	The fixed cost of utilising transportation mode m
TC_m	The unit of transportation cost for transportation mode m
CEP_{jpq}	The cost of establishing the extra capacity for product p with quality level q in MS j
CED_{kp}	The cost of establishing the extra capacity for product p in DC k
CSH_{pq}	The shortage cost for product p with quality level q

CoC	Unit buying/selling price of carbon credit
$CapS_{irq}$	The capacity of supplier i for providing raw material r with quality level q
$CapM_{jpq}$	The capacity of MS j for producing product p with quality q
$CapD_{kp}$	The capacity of DC k for dispatching product p
Dem_{cpq}	Demand of customer c for product p with quality q
ur_{rp}	The utilisation rate of raw material r in product p
SLT_{rqi}	The lead time of supplier i for RM r with quality level q
PPT_{pqj}	The processing time for manufacturing product p with quality level q in MS j
DTW_k	The required time for distributing a product in the distribution centre k
TT_m	The unit of transportation time for transportation mode m
$CCap$	The allowable capacity to emit GHG for carbon cap-and-trade policy
$DIS_{ee'}$	Distance between facility e and $e' \in \{i, j, k, c\}$
α	The predefined value for the service level of the supply chain
EIM_{pj}	The amount of GHG emissions based on the production activity for manufacturing product p in MS j
EIT_m	The amount of GHG emissions based on the transportation activity with transportation mode m
MEM_{jpq}	Maximum allowable extra capacity in MS j for product p with quality q
MED_{kp}	Maximum allowable extra capacity in DC k for product p
$SR_{mee'}$	The social risk for transportation mode m between nodes e and $e' \in \{i, j, k, c\}$
IEX_f	Percentage of information exchange in the supply chain when an information sharing system f is established
$TmaxM_j$	Maximum allowable working time for each worker in manufacturing site j
$TmaxD_k$	Maximum allowable working time for each worker in distribution centre k
NWM_j	The number of workers who worked in manufacturing site j
NWD_k	The number of workers who worked in distribution centre k
$BigM$	A large positive number

Decision Variables:

QR_{rqijm}	The quantity of RMs with quality level q shipped between nodes i and j with transportation mode m
QPM_{pqjkm}	The quantity of product p that is produced with level q shipped between nodes j and k with transportation mode m
QPD_{pqkcm}	The quantity of product p with quality level q that is produced and shipped between nodes k and c with transportation mode m
SH_{cpq}	The amount of shortage for product p with quality level q in node c
EXM_{jpq}	The amount of extra capacity established in MS j for product p with quality level q

EXD_{kp}	The amount of extra capacity established in DC k for product p
CS	Quantity of carbon credits sold
CP	Quantity of carbon credits purchased
VSI_f	The amount of visibility in the supply chain when ISS f is established under scenario s
MWL_j	Average working time for each worker in the manufacturing site j
DWL_k	Average working time for each worker in the distribution centre k
$ZT_{mee'}$	1 if transportation mode m is utilised between nodes e and $e' \in \{i, j, k, c\}$
ZF_f	1 if an information sharing system f is established; 0 otherwise

Based on the above-mentioned notations, the mathematical model for the research problem can be written as follows. Equation (1) presents the first objective function, which aims to minimise the total cost, including purchasing, production, distribution, shortage, extra capacity, transportation, and carbon credit purchase costs. It should be noted that the possible revenue from selling the surplus carbon credit has been deducted from the total cost.

$$\begin{aligned}
Min Z_1 = & \sum_f CIE_f \cdot ZF_f + \sum_i \sum_q \sum_r \sum_m \sum_j PCR_{rqi} \cdot QR_{rqijm} \\
& + \sum_p \sum_j \sum_k \sum_m \sum_q CM_{jpq} \cdot QPM_{pqjkm} \\
& + \sum_p \sum_k \sum_c \sum_m \sum_q CD_{kp} \cdot QPD_{pqkcm} + \sum_c \sum_p \sum_q CSH_{pq} \cdot SH_{cpq} \\
& + \sum_j \sum_p \sum_q CEP_{jpq} \cdot EXM_{jpq} + \sum_k \sum_p CED_{kp} \cdot EXD_{kp} \\
& + \sum_m \sum_{e, e' \in \{i, j, k, c\}} FT_m \cdot ZT_{mee'} \\
& + \sum_m TC_m \cdot \left(\sum_i \sum_q \sum_r \sum_j DIS_{ij} \cdot QR_{rqijm} \right. \\
& + \sum_p \sum_j \sum_k \sum_q DIS_{jk} \cdot QPM_{pqjkm} \\
& \left. + \sum_p \sum_k \sum_c \sum_q DIS_{kc} \cdot QPD_{pqkcm} \right) + CoC \cdot CP - CoC \cdot CS
\end{aligned} \tag{1}$$

The second objective function (equation (2)) minimises the total GHG emissions generated based on the production and transportation activities.

$$\begin{aligned}
Min Z_2 = & \sum_p \sum_j \sum_k \sum_m \sum_q EIM_{pj} \cdot QPM_{pqjkm} \\
& + \sum_m EIT_m \cdot \left(\sum_i \sum_q \sum_r \sum_j DIS_{ij} \cdot QR_{rqijm} \right. \\
& + \sum_p \sum_j \sum_k \sum_q DIS_{jk} \cdot QPM_{pqjkm} \\
& \left. + \sum_p \sum_k \sum_c \sum_q DIS_{kc} \cdot QPD_{pqkcm} \right)
\end{aligned} \tag{2}$$

The third objective function (expression (3)) minimises the total lead time of the supply chain, including the suppliers' lead time, production time, distribution time, and transportation times.

$$\begin{aligned}
Min Z_3 = & \sum_i \sum_q \sum_r \sum_m \sum_j SLT_{rqi} \cdot QR_{rqijm} \\
& + \sum_p \sum_q \sum_j \sum_m \sum_k PPT_{pqj} \cdot QPM_{pqjkm} \\
& + \sum_p \sum_q \sum_c \sum_m \sum_k DTW_k \cdot QPD_{pqkcm} \\
& + \sum_m TT_m \cdot \left(\sum_i \sum_q \sum_r \sum_m \sum_j DIS_{ij} \cdot QR_{rqijm} \right. \\
& + \sum_p \sum_j \sum_k \sum_m \sum_q DIS_{jk} \cdot QPM_{pqjkm} \\
& \left. + \sum_p \sum_k \sum_c \sum_m \sum_q DIS_{kc} \cdot QPD_{pqkcm} \right)
\end{aligned} \tag{3}$$

Objective function (4) aims to minimise the risk of social acceptance of the utilised transportation mode.

$$\begin{aligned}
Min Z_4 = & \sum_m \sum_i \sum_j SR_{mij} \cdot ZT_{mij} \\
& + \sum_m \sum_j \sum_k SR_{mjk} \cdot ZT_{mjk} \sum_m \sum_k \sum_c SR_{mkc} \cdot ZT_{mkc}
\end{aligned} \tag{4}$$

Objective function (5) maximises the visibility of the supply chain.

$$Max Z_5 = \sum_f VSI_f \tag{5}$$

Constraint (6) shows the capacity limitation of the suppliers. Equation (7) is the capacity constraint for the manufacturing sites. Relation (8) is the capacity constraint for the DCs. Constraints (9) and (10) show the maximum allowable extra capacity that can be established in MSs and DCs, respectively.

$$\sum_j \sum_m QR_{rqijm} \leq CapS_{irq} \quad \forall r, q, i \tag{6}$$

$$\sum_k \sum_m QPM_{pqjkm} \leq CapM_{jpq} + EXM_{jpq} \quad \forall p, q, j \tag{7}$$

$$\sum_k \sum_m \sum_q QPD_{pqkcm} \leq CapD_{kp} + EXD_{kp} \quad \forall p, k \tag{8}$$

$$EXM_{jpq} \leq MEM_{jpq} \quad \forall p, q, j \tag{9}$$

$$EXD_{kp} \leq MED_{kp} \quad \forall p, k \tag{10}$$

Constraint (11) shows the amount of RMs acquired from suppliers and shipped to MSs. Constraint (12) calculates the number of products sent from MSs to DCs. Constraint (13) shows the quantity of products sent to the demand points and also calculates the amount of shortage.

$$\sum_i \sum_m QR_{rqijm} = \sum_m \sum_p \sum_k ur_{rp} \cdot QPM_{pqjkm} \quad \forall r, q, j \tag{11}$$

$$\sum_j \sum_m QPM_{pqjkm} = \sum_m \sum_c QPD_{pqkcm} \quad \forall p, q, k \tag{12}$$

$$\sum_m \sum_k QPD_{pqkcm} + SH_{cpq} \geq Dem_{cpq} \quad \forall c, p, q \quad (13)$$

Constraint (14) guarantees that the supply chain's service level is greater than or equal to the predefined value. According to the literature, the service level can be computed based on the proportion of the satisfied demand over the potential demand (for example, see (Asadi et al., 2022; Ribeiro & Barbosa-Póvoa, 2023)).

$$\frac{\sum_m \sum_k \sum_p \sum_c \sum_q QPD_{pqkcm}}{\sum_c \sum_p \sum_q Dem_{cpq}} \geq \alpha \quad \forall r, q, j \quad (14)$$

Equation (15) shows the carbon cap-and-trade policy constraint.

$$\begin{aligned} & \sum_p \sum_j \sum_k \sum_m EIM_{pj} \cdot QPM_{pjkm} \\ & + \sum_m EIT_m \cdot \left(\sum_i \sum_q \sum_r \sum_m \sum_j DIS_{ij} \cdot QR_{rqijm} \right. \\ & + \sum_p \sum_j \sum_k \sum_m \sum_q DIS_{jk} \cdot QPM_{pqjkm} \\ & \left. + \sum_p \sum_k \sum_c \sum_m \sum_q DIS_{kc} \cdot QPD_{pqkcm} \right) + CS \leq CCap + CP \end{aligned} \quad (15)$$

Moreover, constraints (16)-(18) indicate that the transshipment of products and materials with a transportation mode only can be occurred when this mode has been utilised.

$$QR_{rqijm} \leq BigM \cdot ZT_{mij} \quad \forall m, i, j, r, q \quad (16)$$

$$QPM_{pqjkm} \leq BigM \cdot ZT_{mjk} \quad \forall m, j, k, p, q \quad (17)$$

$$QPD_{pqkcm} \leq BigM \cdot ZT_{mkc} \quad \forall m, c, k, p, q \quad (18)$$

Equation (19) measures the visibility of the supply chain. Also, constraint (2) shows that a sharing system should be established in the supply chain. See (Mehrjerdi & Shafiee, 2020; Nayeri et al., 2023; Taheri & Moghaddam, 2022) to read more about these constraints.

$$VSI_f = IEX_f \cdot ZI_f \quad \forall f \quad (19)$$

$$\sum_f ZI_f = 1 \quad (20)$$

Moreover, Relations (21)-(25) are relevant to workers' fatigue. In this field, according to Kołodziej and Ligarski (2017) and Ihsan et al. (2020), the fatigue effect is one of the main metrics for the workers' health issues that directly depends on the working time and workload of workers. For incorporating this concept in the proposed model, at the outset, the average working time of each worker in manufacturing sites and distribution centres are calculated (see constraints (21) and (22)). Then, to prevent excessive fatigue of workers in a facility, the value of the average working time of each worker should be smaller than a predefined value (see constraints (24 and 25)).

$$MWL_j = \frac{\sum_{p,q,k,m} PPT_{pqj} \cdot QPM_{pqjkm}}{NWM_j} \quad \forall j \quad (21)$$

$$DWL_k = \frac{\sum_{p,q,c,m} DTW_k \cdot QPD_{pqkcm}}{NWD_k} \quad \forall k \quad (22)$$

$$MWL_j \leq T_{max} M_j \quad \forall j \quad (23)$$

$$DWL_k \leq T_{max} D_k \quad \forall k \quad (24)$$

Finally, constraint (25) shows the range of the decision variables.

$$QR_{rqijm}, QPM_{pqjkm}, QPD_{pqkcm}, SH_{cpq}, EXM_{pqj}, EXD_{pk}, CS, CP, VSI_{fs}, MWL_j, DWL_k \\ \forall m, i, j, r, q \geq 0 \quad (25)$$

$$ZT_{mee'}, ZI_f \in \{0,1\}$$

5.2. Fuzzy Inference System (FIS) method to calculate Transportation Social Risk Assessment for Objective Function (4)

5.2.1 Definition of Indicators

Through a comprehensive review of the literature and expert opinions in the field of transportation and its social impacts, key indicators for assessing the social risk of transportation have been

identified. These indicators include local pollutant levels (PM2.5, PM10), noise levels in decibels, impact on residential and sensitive areas, traffic congestion caused by transportation modes, effects on travel time and stress levels of drivers and local residents, vehicle risk levels in high-traffic routes, and traffic restrictions during specific hours (Ayvaz et al., 2015; Gebeyehu & Takano, 2007; Han et al., 2024; Sagnak et al., 2021; Wahyuni et al., 2020). These criteria have been selected based on their significance in either increasing or mitigating the negative social and environmental consequences of transportation and they serve as the foundation for fuzzy modelling in this research.

The definitions and measurement methods for these indicators are detailed below.

5.2.1.1 Local Pollutant Levels (PM2.5, PM10)

Particulate matter (PM2.5 and PM10) is one of the primary air pollutants resulting from fuel combustion in transportation. These particles have a direct impact on air quality and public health.

- Measurement unit: Micrograms per cubic meter ($\mu\text{g}/\text{m}^3$).
- Measurement method: Calculation of PM2.5 and PM10 emission levels based on the type of transportation mode and fuel consumption.

5.2.1.2 Noise Levels in Various Transportation Modes

The noise generated by vehicles, particularly in residential and urban areas, contributes to noise pollution. High noise levels lead to increased stress, reduced sleep quality, and hearing problems.

- Measurement unit: Decibel (dB).
- Measurement method: Examination of standardised noise emission data for different transportation modes (e.g., pickup trucks < 75 dB, small trucks 80–85 dB, large trucks > 90 dB).

5.2.1.3 Impact on Residential and Sensitive Areas (Hospitals, Schools)

The movement of heavy and noisy transportation near sensitive zones such as schools, hospitals, medical centres, and densely populated residential areas increases noise pollution, accident rates, and decreases quality of life.

- Measurement unit: Qualitative assessment through public surveys and available data.
- Measurement method: Evaluation of public complaints and recorded social objections related to heavy transportation.

5.2.1.4 Traffic Congestion Due to Transportation Mode

The use of larger vehicles that occupy more space and move at lower speeds leads to increased travel time and congestion.

- Measurement unit: Traffic delay time (minutes).
- Measurement method: GPS data and traffic monitoring systems are used to calculate average speed and delay based on the transportation mode, with expert validation.

5.2.1.5 Impact on Travel Time and Increased Stress for Drivers and Local Residents

Longer travel times and delays in passenger mobility due to slow-moving heavy transport vehicles contribute to higher stress levels and public dissatisfaction.

- Measurement unit: Traffic Stress Index (TSI).
- Measurement method: Survey analysis from drivers and local residents regarding the impact of transportation on stress levels.

5.2.1.6 Vehicle Risk Levels in High-Traffic Routes

The likelihood of accidents increases due to the presence of heavy transport vehicles in congested or narrow routes.

- Measurement unit: Accident rate per transportation mode.

- Measurement method: Analysis of traffic police reports in high-traffic routes.

5.2.1.7 Traffic Restrictions on Transportation During Specific Hours

Certain traffic restrictions are imposed to reduce the negative effects of transportation during peak hours.

- Measurement unit: Number and severity of restrictions imposed on transportation routes.
- Measurement method: Review of municipal regulations and traffic laws regarding transportation restrictions.

This comprehensive framework enables systematic assessment and modelling of social risk in transportation, allowing for optimised decision-making to mitigate adverse impacts.

5.2.2. Definition of the Fuzzy Inference System (FIS)

This system considers seven input variables, each representing a social indicator related to transportation. Each of these variables is categorised into three levels: low, medium, and high. Based on these inputs, the social risk level of transportation is determined on a ten-point scale ranging from 0.1 to 1.0, where lower values indicate lower social risk, and higher values indicate greater social risk.

5.2.2.1 Input Variables

Each input variable is classified into three categories: low, medium, and high as shown in Table 5.1.

Table 5. 1: Range of values of input variables

Input Variable	Low	Medium	High
Local Pollutant Levels (PM2.5, PM10)	Below 20 $\mu\text{g}/\text{m}^3$	Between 20 and 40 $\mu\text{g}/\text{m}^3$	Above 40 $\mu\text{g}/\text{m}^3$
Noise Level (dB)	Below 75 dB	Between 75 and 85 dB	Above 85 dB
Impact on Sensitive Areas	Less than 25% of sensitive routes	Between 25% and 50% of routes	More than 50% of routes
Traffic Increase Due to Transportation Mode	Below 10% increase	Between 10% and 25%	Above 25%
Impact on Travel Time and Stress	Below 10% increase in travel time	Between 10% and 20%	Above 20%
Risk Level in High-Traffic Routes	Less than 10 accidents per 1000 km	Between 10 and 25 accidents per 1000 km	More than 25 accidents per 1000 km
Traffic Restrictions on Transportation	Less than 10% of routes have restrictions	Between 10% and 30% of routes have restrictions	More than 30% of routes have restrictions

5.2.2.2 Type of Membership Functions for Inputs

For each input, triangular (Triangular) or trapezoidal (Trapezoidal) membership functions are used to represent the values of "low," "medium," and "high" within numerical ranges.

5.2.2.3 Output Variable

The social risk level of transportation serves as the output variable. This output is a numerical value between 0.1 and 1.0 and is categorised into ten different levels, see Table 5.2.

Table 5. 2: Risk level classification

Social Risk	Output Value
Very Low	0.1
Low	0.2
Relatively Low	0.3
Medium-Low	0.4
Medium	0.5
Medium-High	0.6
Relatively High	0.7
High	0.8
Very High	0.9
Critical	1

5.2.2.4 Type of Membership Function for Output

In the designed model, triangular membership functions (Trimf) are used for the output variable (Social Risk). This membership function was chosen due to its computational simplicity, high processing speed, and interpretability in fuzzy models.

The model output (social risk of transportation) is defined in ten levels, and for each level, a triangular membership function is configured as shown in Table 5.3.

Table 5. 3: Type of Membership Function for Output

Fuzzy Output Level	Membership Function
Very Low	trimf([0.1, 0.1, 0.3])
Low	trimf([0.2, 0.3, 0.4])
Medium Low	trimf([0.3, 0.4, 0.5])
Medium	trimf([0.4, 0.5, 0.6])
Medium High	trimf([0.5, 0.6, 0.7])
High	trimf([0.6, 0.7, 0.8])
Very High	trimf([0.7, 0.8, 0.9])
Critical	trimf([0.9, 1.0, 1.0])

5.2.2.5 Fuzzy Rules

In this system, fuzzy rules are defined based on seven input variables, each of which has three fuzzy levels (low, medium, high). Considering all possible combinations, the total number of fuzzy rules is 2,187.

Some of the IF-THEN fuzzy rules are summarised as follows:

- IF (Local Pollutants = Low) AND (Noise Pollution = Low) AND (Impact on Sensitive Areas = Low) AND (Traffic Increase = Low) AND (Effect on Stress = Low) AND (Risk Level = Low) AND (Traffic Restriction = High); THEN (Social Risk = 0.1).
- IF (Local Pollutants = Low) AND (Noise Pollution = Low) AND (Impact on Sensitive Areas = Low) AND (Traffic Increase = Medium) AND (Effect on Stress = Low) AND (Risk Level = Low) AND (Traffic Restriction = High); THEN (Social Risk = 0.2).
- IF (Local Pollutants = Medium) AND (Noise Pollution = Medium) AND (Impact on Sensitive Areas = Medium) AND (Traffic Increase = Medium) AND (Effect on Stress =

Medium) AND (Risk Level = Medium) AND (Traffic Restriction = Medium); THEN (Social Risk = 0.5).

- IF (Local Pollutants = High) AND (Noise Pollution = High) AND (Impact on Sensitive Areas = High) AND (Traffic Increase = High) AND (Effect on Stress = High) AND (Risk Level = High) AND (Traffic Restriction = Low); THEN (Social Risk = 1.0).
- IF (Local Pollutants = Low) AND (Noise Pollution = Medium) AND (Impact on Sensitive Areas = High) AND (Traffic Increase = Medium) AND (Effect on Stress = Low) AND (Risk Level = Low) AND (Traffic Restriction = Medium); THEN (Social Risk = 0.4).
- IF (Local Pollutants = High) AND (Noise Pollution = Low) AND (Impact on Sensitive Areas = Low) AND (Traffic Increase = Low) AND (Effect on Stress = Low) AND (Risk Level = Medium) AND (Traffic Restriction = High); THEN (Social Risk = 0.3).
- IF (Local Pollutants = Medium) AND (Noise Pollution = High) AND (Impact on Sensitive Areas = High) AND (Traffic Increase = Medium) AND (Effect on Stress = High) AND (Risk Level = Medium) AND (Traffic Restriction = Medium); THEN (Social Risk = 0.7).
- IF (Local Pollutants = High) AND (Noise Pollution = High) AND (Impact on Sensitive Areas = Low) AND (Traffic Increase = High) AND (Effect on Stress = High) AND (Risk Level = High) AND (Traffic Restriction = High); THEN (Social Risk = 0.9).
- IF (Local Pollutants = Low) AND (Noise Pollution = Medium) AND (Impact on Sensitive Areas = Medium) AND (Traffic Increase = Medium) AND (Effect on Stress = Medium) AND (Risk Level = Low) AND (Traffic Restriction = Medium); THEN (Social Risk = 0.4).
- IF (Local Pollutants = Medium) AND (Noise Pollution = Medium) AND (Impact on Sensitive Areas = Medium) AND (Traffic Increase = Medium) AND (Effect on Stress = Medium) AND (Risk Level = High) AND (Traffic Restriction = Low); THEN (Social Risk = 0.6).
- IF (Local Pollutants = Low) AND (Noise Pollution = Low) AND (Impact on Sensitive Areas = High) AND (Traffic Increase = Low) AND (Effect on Stress = Low) AND (Risk Level = Low) AND (Traffic Restriction = High); THEN (Social Risk = 0.3).
- IF (Local Pollutants = High) AND (Noise Pollution = High) AND (Impact on Sensitive Areas = High) AND (Traffic Increase = High) AND (Effect on Stress = High) AND (Risk Level = High) AND (Traffic Restriction = High); THEN (Social Risk = 1.0).

- IF (Local Pollutants = Medium) AND (Noise Pollution = Low) AND (Impact on Sensitive Areas = Low) AND (Traffic Increase = Low) AND (Effect on Stress = Low) AND (Risk Level = Low) AND (Traffic Restriction = High); THEN (Social Risk = 0.2).

With this structure, the fuzzy inference system (FIS) can determine the social risk level of transportation based on input values.

5.2.3. Inference Method and Implementation

In this study, the Mamdani Inference System (Mamdani, 1975) has been used for fuzzy inference. This method was chosen due to its transparency in reasoning, high interpretability, and widespread application in decision-making problems. Additionally, the centroid method has been applied for defuzzification of output values, which determines the final social risk of transportation based on the combination of membership functions.

Following the outlined steps, the proposed approach has been implemented using Python programming language, and the desired outputs have been generated accordingly.

5.3. Solution Approach

Since the nature of the problem is a multi-objective case, a Multi-objective Decision-Making (MODM) approach should be employed to solve it. In this regard, one of the effective methods, which has been widely used in the literature to solve the multi-objective models, is Goal Programming (GP). In general, GP defines a target point (goal) for each objective function and tries to minimise deviation of the obtained value for each objective function from its corresponding target point. In recent years, researchers have developed different versions of GP to solve multi-objective mathematical models. In this study, we use one of the efficient variants named the Multi-

Choice GP with Utility Function (MCGP-UF). The main reason for selecting this approach is its advantages such as:

- (i) considering different aspiration levels for each objective function (instead of one target point),
- (ii) considering the weight for each objective function,
- (iii) decision maker's preference value to maximise her/his expected utility, and
- (iv) using linear utility function that minimises the complexity of method (Chang, 2011; Nayeri et al., 2020).

The mathematical formulation of this approach has been presented in Equations (26)-(31).

$$\text{Min } \sum_k [w_k^d (d_k^+ + d_k^-) + w_k^\xi (\xi_k^-)] \quad (26)$$

subject to

$$f_k(X) + d_k^- - d_k^+ = y_k \quad \forall k, \quad (27)$$

$$\lambda_k \leq \frac{U_{k,max} - y_k}{U_{k,max} - U_{k,min}} \quad \forall k, \quad (28)$$

$$U_{k,min} \leq y_k \leq U_{k,max} \quad \forall k, \quad (29)$$

$$\lambda_k + \xi_k^- = 1 \quad \forall k, \quad (30)$$

$$d_k^+, d_k^-, y_k, \lambda_k, \xi_k^- \geq 0 \quad \forall k, \quad (31)$$

In this model, the k^{th} objective function is denoted by $f_k(X)$, upper bound and lower bound of the aspiration levels for k^{th} objective function are respectively shown by $U_{k,max}$ and $U_{k,min}$, the normalised deviation of y_k (a continuous variable) from $U_{k,min}$ is demonstrated by ξ_k^- , the positive and negative deviations of $f_k(X)$ from y_k are respectively denoted by d_k^+ and d_k^- , the utility value

is shown by λ_k , the weights of objective functions are demonstrated by w_k^d , and the weight of ξ_k^- is shown by w_k^ξ . Furthermore, if needed, this model can be normalised using Equation (32) where:

$$MinF_k = \{\min f_k(X)\} \text{ and } MaxF_k = \{\max f_k(X)\}.$$

$$\text{Min} \sum_k \left[w_k^d \left(\frac{d_k^+ + d_k^-}{MaxF_k - MinF_k} \right) + w_k^\xi (\xi_k^-) \right]. \quad (32)$$

According to the above-mentioned points, the MCGP-UF formulation for the research problem can be written as follows.

$$\begin{aligned} \text{Min } w_1^d \left(\frac{d_1^+ + d_1^-}{MaxF_1 - MinF_1} \right) + w_2^d \left(\frac{d_2^+ + d_2^-}{MaxF_2 - MinF_2} \right) + w_3^d \left(\frac{d_3^+ + d_3^-}{MaxF_3 - MinF_3} \right) \\ + w_4^d \left(\frac{d_4^+ + d_4^-}{MaxF_4 - MinF_4} \right) + w_5^d \left(\frac{d_5^+ + d_5^-}{MaxF_5 - MinF_5} \right) + w_1^\xi \cdot \xi_1^- \\ + w_2^\xi \cdot \xi_2^- + w_3^\xi \cdot \xi_3^- + w_4^\xi \cdot \xi_4^- + w_5^\xi \cdot \xi_5^- \end{aligned} \quad (33)$$

Subject to:

$$Z1 + d_1^- - d_1^+ = y_1 \quad (34)$$

$$Z2 + d_2^- - d_2^+ = y_2 \quad (35)$$

$$Z3 + d_3^- - d_3^+ = y_3 \quad (36)$$

$$Z4 + d_4^- - d_4^+ = y_4 \quad (37)$$

$$Z5 + d_5^- - d_5^+ = y_5 \quad (38)$$

$$\lambda_1 \leq \frac{U_{1,max} - y_1}{U_{1,max} - U_{1,min}} \quad (39)$$

$$\lambda_2 \leq \frac{U_{2,max} - y_2}{U_{2,max} - U_{2,min}} \quad (40)$$

$$\lambda_3 \leq \frac{U_{3,max} - y_3}{U_{3,max} - U_{3,min}} \quad (41)$$

$$\lambda_4 \leq \frac{U_{4,max} - y_4}{U_{4,max} - U_{4,min}} \quad (42)$$

$$\lambda_5 \leq \frac{y_5 - U_{5,min}}{U_{5,max} - U_{5,min}} \quad (43)$$

$$U_{1,min} \leq y_1 \leq U_{1,max} \quad (44)$$

$$U_{2,min} \leq y_2 \leq U_{2,max} \quad (45)$$

$$U_{3,min} \leq y_3 \leq U_{3,max} \quad (46)$$

$$U_{4,min} \leq y_4 \leq U_{4,max} \quad (47)$$

$$U_{5,min} \leq y_5 \leq U_{5,max} \quad (48)$$

$$\lambda_1 + \xi_1^- = 1 \quad (49)$$

$$\lambda_2 + \xi_2^- = 1 \quad (50)$$

$$\lambda_3 + \xi_3^- = 1 \quad (51)$$

$$\lambda_4 + \xi_4^- = 1 \quad (52)$$

$$\lambda_5 + \xi_5^- = 1 \quad (53)$$

5.4. Conclusion

Basically, the first phase of the research work is about defining the research problem precisely and converting it into a mathematical framework. The chapter also depicts how the MCGP-UF model has been completely formulated by specifying all necessary inputs, decision variables, and constraints. Additionally, the main suitable solution methods were also recognised for solving the indicated problem. Such a model specification, being the core of the upcoming empirical study, guarantees that the proposed models are stable, complete, and correspond to the objectives of the research.

Chapter 6

Results and sensitivity analysis of the developed mathematical models

6.1. Introduction

The food supply chain is the backbone of the system that provides people with safe and healthy food in an effective and environmentally friendly way. It is a network that arrows the journey of a product from the farm all the way to the consumer's table. A strong and stable food supply chain system is one that not only guarantees the continuity of food availability but also revitalizes the local economies and greatly reduces the amount of food waste produced. This system is also very important in crisis situations such as the climate change, the outbreak of pandemics, and economic decline as it can adjust its operations to elevate the level of resilience. Furthermore, knowing this network results in an increase in trust and taking responsibility by the suppliers, hence, consumers have access to more accurate and reliable information, and they can make the right choices regarding the foods that they consume. In the end, Healthy supply chains are one of the main factors for promoting public health and taking care of the society as a whole. Therefore, the main emphasis of this research has been on designing and planning a supply chain network that is viable and effective for the food industry. For this purpose, a multi-objective mathematical programming model has been proposed that aims to minimise the total cost, GHG emissions, delivery time, and social risk while maximising the visibility. In this regard, after presenting the research methodology in Chapter Three and the proposed developed mathematical models in Chapter 5, the numerical results are presented in this chapter.

6.2. Input Data

This section provides the required parameters to solve the proposed mathematical model. The size of the problem considered is presented in Table 6.1. Also, the current research considers three transportation modes consisting of Small Truck, Mid Truck, and Heavy Truck. The transportation costs and GHG emissions related to each transportation mode have been provided in Table 6.2 (inspired by the literature). Moreover, the values of other parameters have been presented in Table 6.3. Additionally, inspired by the literature, this work considers two types of information sharing systems, including (i) traditional systems (client-server systems) and (ii) the information system using blockchain technology, where its information is presented in Table 6.4. It should be noted that the blockchain-based system has more establishment costs but it can exchange more percentage of information in comparison with the traditional system (Nayeri et al., 2023; Taheri & Moghaddam, 2022). In this field, considering traditional and blockchain-based platform and their associated data shown in Table 6.4, we relied on insights from the existing literature (e.g., Jafari et al., 2025; Koohkan et al., 2024; Nayeri et al., 2023; Taheri & Moghaddam, 2022) rather than calculating the data ourselves. Furthermore, the maximum working time is calculated based on 22 working days in a month and 8 hours per day. It should be noted that the values of social risk related to transportation modes are provided in Section 6.3.1. The values of other parameters are estimated based on the literature and experts.

Table 6. 1: the size of the problem

Facility	Suppliers	Manufacturing site	Distribution centres	Customers	Raw materials	Products
Number	5	1	3	10	4	3

Table 6. 2: Transportation cost and GHG emissions for each transportation mode

Mode	Cost	Capacity	GHG emission factor
Small Truck	0.110	10000	0.048
Mid truck	0.118	25000	0.025
Heavy truck	0.125	35000	0.297

Table 6. 3: Values of some parameters of the proposed model

Parameter	Value
PCR_{rqi}	<i>Uniform</i> [0.5 1.5]
CM_{jpq}	<i>Uniform</i> [0.7 2.5]
CD_{kp}	<i>Uniform</i> [0.1 0.15]
FT_m	<i>Uniform</i> [10000 20000]
CEP_{jpq}	<i>Uniform</i> [0.2 0.8]
CED_{kp}	<i>Uniform</i> [0.1 0.5]
CSH_{pq}	<i>Uniform</i> [150 350]
CoC	<i>Uniform</i> [5 15]
$CapS_{irq}$	<i>Uniform</i> [20000 30000]
$CapM_{jpq}$	<i>Uniform</i> [20000 30000]
$CapD_{kp}$	<i>Uniform</i> [30000 35000]
Dem_{cpq}	<i>Uniform</i> [1000 4000]
α	<i>Uniform</i> [0.80 0.95]

Table 6. 4: Data relevant to information sharing systems

	CIE_f	IEX_f
Traditional	<i>Uniform</i> [100 120] $\times 10^3$	<i>Uniform</i> [0.55 0.65]
Blockchain-based	<i>Uniform</i> [350 450] $\times 10^3$	<i>Uniform</i> [0.80 0.90]

6.3. Computational Results

6.3.1. FIS's Outputs

Social risk in the supply chain is one of the key factors in evaluating the sustainability and efficiency of transportation systems. The supply chain consists of interactions between suppliers, the producer, distributors, and customers, all of whom are connected through different transportation routes. Along each of these routes, social risk associated with transportation can be influenced by various factors such as environmental pollutants, noise pollution, impact on sensitive areas such as schools, hospitals, medical centres, and densely populated residential areas, increased traffic, stress caused by delays, and the risk level of vehicles.

As discussed in previous sections, this study develops a fuzzy inference system (FIS) to assess social risk across various transportation routes. This model utilises quantitative and qualitative indicators and, based on collected data from the supply chain, determines the social risk level of each transportation route.

The evaluation of social risk in transportation is based on a set of key indicators, each of which directly affects the social and environmental consequences of transportation. These indicators include:

- Local air pollution levels (PM2.5 and PM10): This indicator reflects the level of air pollution caused by fuel combustion in transportation vehicles, significantly affecting air quality and public health.
- Noise levels (dB): Noise generated by vehicles can lead to issues such as stress, reduced sleep quality, and hearing impairments.

- Impact on sensitive areas: The effect of heavy transportation traffic near hospitals, schools, and residential areas is considered a critical social factor.
- Traffic congestion caused by vehicle type: Larger and heavier vehicles typically lead to increased travel time and traffic congestion.
- Effect on stress levels of drivers and local residents: Delays in transportation routes and traffic-induced pressure contribute to increased public stress.
- Risk level of vehicles in high-traffic routes: The likelihood of accidents due to heavy vehicles operating on congested roads.
- Traffic restrictions: Certain transportation routes may have time-based or location-specific restrictions due to urban regulations or specific conditions, affecting social risk levels.

These features serve as input variables for the fuzzy inference model, and ultimately, the social risk level for each transportation route is calculated as the output.

6.3.2 Structure of the Supply Chain and Transportation Scenarios

6.3.2.1 Supplier-to-Producer Transportation

In this supply chain, there are five suppliers that deliver raw materials to the producer. This delivery occurs via three different transportation modes. Given that there is only one producer in this network, the number of transportation scenarios between suppliers and the producer is:

$$3 \times 5 \times 1 = 15$$

Each of these 15 transportation scenarios has unique characteristics in terms of social risk and environmental impact, which must be analysed individually.

6.3.2.2 Producer-to-Distributor Transportation

After production, goods are shipped to three distributors. Each distributor can receive products from the producer through three different transportation modes. Since there is only one producer in the system, the number of transportation routes in this stage is:

$$\text{Number of transportation routes} = 3 \times 1 \times 3 = 9$$

6.3.2.3 Distributor-to-Customer Transportation

At the final stage of the supply chain, distributors deliver goods to 10 end customers. Each customer can receive their orders through three distributors, using three different transportation modes. Therefore, the number of transportation scenarios in this stage is:

$$\text{Number of transportation scenarios} = 3 \times 3 \times 10 = 90$$

6.3.3 Total Number of Transportation Scenarios in the Supply Chain

By aggregating all transportation cases from suppliers to customers, the total number of transportation relationships in the supply chain is:

$$\text{The total number of transportations scenarios} = 15 + 9 + 90 = 114$$

These 114 transportation scenarios must be assessed in terms of social risk to determine which routes have the highest negative social and environmental impacts.

A comprehensive evaluation of key indicators across all 114 transportation cases is provided in Table 6.5.

Table 6. 5: Index values for different situations

Relation Type	Transport Mode	Air Pollution Level (PM2.5, $\mu\text{g}/\text{m}^3$)	Noise Level (dB)	Impact on Sensitive Areas	Traffic Increase	Impact on Travel Time & Stress	Accident Risk Level	Traffic Restrictions
Supplier → Manufacturer	Small Truck	Low	Low	High	Low	Medium	Medium	Low
Supplier → Manufacturer	Small Truck	Low	High	High	Low	Medium	High	High
Supplier → Manufacturer	Small Truck	Medium	Low	High	Medium	Low	High	Medium
Supplier → Manufacturer	Small Truck	Medium	High	High	Medium	Medium	High	Low
Supplier → Manufacturer	Small Truck	High	Low	Low	Low	Low	Low	High
Supplier → Manufacturer	Mid truck	Low	High	High	Low	High	Medium	Low
Supplier → Manufacturer	Mid truck	Medium	High	Low	Medium	Low	Low	Medium
Supplier → Manufacturer	Mid truck	High	Medium	Medium	Low	High	High	Low
Supplier → Manufacturer	Mid truck	High	High	Low	Medium	Low	Low	Low
Supplier → Manufacturer	Mid truck	Low	Medium	Low	Medium	Medium	High	High
Supplier → Manufacturer	Heavy Truck	High	Low	Medium	Medium	Low	Medium	Low
Supplier → Manufacturer	Heavy Truck	Low	High	Low	Low	Low	Low	High
Supplier → Manufacturer	Heavy Truck	High	High	Medium	Low	High	Low	High
Supplier → Manufacturer	Heavy Truck	Medium	Low	Low	High	Medium	High	Medium
Supplier → Manufacturer	Heavy Truck	Low	High	Low	Medium	Low	Low	Medium
Manufacturer → Distributor	Small Truck	Medium	High	Medium	Medium	Medium	Medium	Medium
Manufacturer → Distributor	Small Truck	Low	High	High	Medium	Low	Low	High
Manufacturer → Distributor	Small Truck	Low	High	Low	Low	High	Medium	Medium

Relation Type	Transport Mode	Air Pollution Level (PM2.5, $\mu\text{g}/\text{m}^3$)	Noise Level (db)	Impact on Sensitive Areas	Traffic Increase	Impact on Travel Time & Stress	Accident Risk Level	Traffic Restrictions
Manufacturer → Distributor	Mid truck	Low	Low	Low	High	High	Low	Medium
Manufacturer → Distributor	Mid truck	Low	Medium	Low	Low	High	Medium	Low
Manufacturer → Distributor	Mid truck	Low	Medium	Low	Medium	Medium	Low	Low
Manufacturer → Distributor	Heavy Truck	Medium	High	Low	High	High	High	Medium
Manufacturer → Distributor	Heavy Truck	Medium	Medium	Medium	Low	Low	Medium	High
Manufacturer → Distributor	Heavy Truck	Medium	High	High	Medium	Low	High	Low
Distributor → Customer	Small Truck	Low	High	High	Medium	Medium	Medium	Low
Distributor → Customer	Small Truck	Low	High	Medium	Medium	Low	Medium	High
Distributor → Customer	Small Truck	High	Medium	Medium	High	Low	Medium	Low
Distributor → Customer	Small Truck	Low	Medium	Low	High	Low	High	Medium
Distributor → Customer	Small Truck	Low	High	High	Medium	Low	High	Low
Distributor → Customer	Small Truck	Medium	Medium	Low	High	Medium	High	Low
Distributor → Customer	Small Truck	High	Medium	Medium	Medium	Medium	Medium	High
Distributor → Customer	Small Truck	High	High	Low	Low	Low	Medium	Low
Distributor → Customer	Small Truck	High	Low	Medium	High	Low	High	High
Distributor → Customer	Small Truck	Low	Medium	High	Low	Medium	High	Medium
Distributor → Customer	Small Truck	Medium	Low	Low	Low	Low	High	Medium
Distributor → Customer	Small Truck	Low	High	Medium	High	Low	Medium	Medium
Distributor → Customer	Small Truck	Medium	Low	High	Low	Medium	Medium	Low

Relation Type	Transport Mode	Air Pollution Level (PM2.5, $\mu\text{g}/\text{m}^3$)	Noise Level (db)	Impact on Sensitive Areas	Traffic Increase	Impact on Travel Time & Stress	Accident Risk Level	Traffic Restrictions
Distributor → Customer	Small Truck	Medium	Low	High	High	Low	Low	High
Distributor → Customer	Small Truck	Medium	High	High	Low	High	High	High
Distributor → Customer	Mid truck	Low	Low	Low	High	Medium	Medium	Medium
Distributor → Customer	Mid truck	Medium	Low	Low	Low	Low	High	Low
Distributor → Customer	Mid truck	High	High	Medium	Low	High	Medium	Medium
Distributor → Customer	Mid truck	High	Low	High	Medium	Low	Low	High
Distributor → Customer	Mid truck	High	Low	Medium	Medium	Medium	Low	High
Distributor → Customer	Mid truck	Low	Medium	Low	Medium	Low	Low	Medium
Distributor → Customer	Mid truck	High	Low	High	Medium	High	Medium	Medium
Distributor → Customer	Mid truck	Medium	Medium	High	Medium	High	Low	High
Distributor → Customer	Mid truck	High	Low	Medium	Low	High	Low	Medium
Distributor → Customer	Mid truck	High	Medium	Low	High	Medium	High	Medium
Distributor → Customer	Mid truck	Low	High	High	High	Medium	Medium	Low
Distributor → Customer	Mid truck	Low	Low	Medium	High	Low	Low	Low
Distributor → Customer	Mid truck	High	Medium	Low	High	Low	Low	High
Distributor → Customer	Mid truck	High	Low	Medium	Medium	Low	High	Low
Distributor → Customer	Mid truck	High	Medium	Medium	Medium	Low	High	Medium
Distributor → Customer	Mid truck	Low	Low	High	High	Medium	High	Medium
Distributor → Customer	Mid truck	Medium	High	High	Medium	High	Medium	Low

Relation Type	Transport Mode	Air Pollution Level (PM2.5, $\mu\text{g}/\text{m}^3$)	Noise Level (db)	Impact on Sensitive Areas	Traffic Increase	Impact on Travel Time & Stress	Accident Risk Level	Traffic Restrictions
Distributor → Customer	Mid truck	High	High	Medium	Medium	Medium	Medium	Low
Distributor → Customer	Mid truck	High	Low	High	Low	High	Medium	Medium
Distributor → Customer	Mid truck	Medium	Low	Low	High	Medium	High	High
Distributor → Customer	Mid truck	Low	High	Medium	Medium	Medium	Low	Low
Distributor → Customer	Mid truck	Low	High	Medium	High	Medium	Medium	Medium
Distributor → Customer	Mid truck	Low	Low	Low	Low	Low	Low	Low
Distributor → Customer	Mid truck	Medium	High	High	Medium	Medium	High	Low
Distributor → Customer	Mid truck	Medium	Medium	Low	High	High	High	Low
Distributor → Customer	Mid truck	Low	Low	Low	High	Medium	High	Medium
Distributor → Customer	Mid truck	Medium	Low	Medium	Medium	Medium	Low	Medium
Distributor → Customer	Mid truck	Low	Medium	Low	Medium	Low	Medium	Medium
Distributor → Customer	Mid truck	Medium	Medium	Low	Low	Low	Low	Low
Distributor → Customer	Mid truck	High	High	High	Medium	Low	Medium	Low
Distributor → Customer	Mid truck	High	High	High	Low	Medium	Medium	Low
Distributor → Customer	Mid truck	High	Low	Low	Medium	Low	Medium	Medium
Distributor → Customer	Mid truck	Low	High	High	Low	Medium	High	High
Distributor → Customer	Mid truck	Low	High	High	High	Low	High	Medium
Distributor → Customer	Mid truck	Medium	Medium	High	Medium	Low	Low	High
Distributor → Customer	Mid truck	Medium	Medium	Medium	Medium	High	Low	High

Relation Type	Transport Mode	Air Pollution Level (PM2.5, $\mu\text{g}/\text{m}^3$)	Noise Level (db)	Impact on Sensitive Areas	Traffic Increase	Impact on Travel Time & Stress	Accident Risk Level	Traffic Restrictions
Distributor → Customer	Mid truck	Medium	Medium	High	Low	Medium	High	High
Distributor → Customer	Heavy Truck	Low	Low	Medium	Medium	Medium	Low	High
Distributor → Customer	Heavy Truck	Low	High	High	Medium	Low	Medium	High
Distributor → Customer	Heavy Truck	Low	Medium	Medium	Medium	Low	Medium	Medium
Distributor → Customer	Heavy Truck	High	Low	Medium	High	High	Low	Medium
Distributor → Customer	Heavy Truck	Medium	Medium	Low	Low	High	High	High
Distributor → Customer	Heavy Truck	Medium	Low	High	Low	High	High	Low
Distributor → Customer	Heavy Truck	Medium	Medium	Medium	High	High	High	Medium
Distributor → Customer	Heavy Truck	Medium	Low	Medium	Low	High	Medium	High
Distributor → Customer	Heavy Truck	Low	Medium	High	Medium	Medium	High	Medium
Distributor → Customer	Heavy Truck	Low	Low	Low	High	Medium	High	Low
Distributor → Customer	Heavy Truck	Low	Low	Medium	High	Medium	Medium	Medium
Distributor → Customer	Heavy Truck	Low	Low	Low	Medium	High	High	Medium
Distributor → Customer	Heavy Truck	Low	Low	Medium	Medium	Low	Medium	Low
Distributor → Customer	Heavy Truck	Medium	High	Medium	Low	High	Medium	High
Distributor → Customer	Heavy Truck	Low	Medium	Medium	High	Medium	High	High
Distributor → Customer	Heavy Truck	Medium	Medium	Low	High	High	Medium	Low
Distributor → Customer	Heavy Truck	High	High	Medium	High	High	Medium	High
Distributor → Customer	Heavy Truck	Low	High	Low	Medium	High	Medium	High

Relation Type	Transport Mode	Air Pollution Level (PM2.5, $\mu\text{g}/\text{m}^3$)	Noise Level (db)	Impact on Sensitive Areas	Traffic Increase	Impact on Travel Time & Stress	Accident Risk Level	Traffic Restrictions
Distributor → Customer	Heavy Truck	Low	Low	High	Low	Medium	Medium	Low
Distributor → Customer	Heavy Truck	Medium	High	Low	Medium	High	High	Low
Distributor → Customer	Heavy Truck	High	Medium	Low	High	Medium	Medium	Medium
Distributor → Customer	Heavy Truck	Medium	High	Medium	Medium	Low	High	Medium
Distributor → Customer	Heavy Truck	High	Low	High	Medium	Medium	Low	Medium
Distributor → Customer	Heavy Truck	Low	Medium	Low	Low	High	High	High
Distributor → Customer	Heavy Truck	Low	High	High	Low	High	High	Medium
Distributor → Customer	Heavy Truck	High	High	Medium	Medium	Low	Low	High
Distributor → Customer	Heavy Truck	Low	Low	High	Low	Low	High	Medium
Distributor → Customer	Heavy Truck	High	Medium	High	Low	High	Medium	High
Distributor → Customer	Heavy Truck	Medium	Medium	Low	Medium	Low	Medium	High
Distributor → Customer	Heavy Truck	Medium	Medium	Low	Low	High	Medium	Medium
Distributor → Customer	Heavy Truck	Medium	Low	High	High	High	High	Medium
Distributor → Customer	Heavy Truck	Low	Medium	High	Medium	Medium	Medium	Medium
Distributor → Customer	Heavy Truck	High	Low	High	Medium	Medium	Low	Medium
Distributor → Customer	Heavy Truck	Low	High	Low	Medium	Low	Low	Low
Distributor → Customer	Heavy Truck	Low	High	Low	Low	Medium	Medium	Low
Distributor → Customer	Heavy Truck	High	High	Low	High	Medium	High	Medium
Distributor → Customer	Heavy Truck	High	Low	Medium	Low	Medium	High	High

Relation Type	Transport Mode	Air Pollution Level (PM2.5, $\mu\text{m}/\text{m}^3$)	Noise Level (db)	Impact on Sensitive Areas	Traffic Increase	Impact on Travel Time & Stress	Accident Risk Level	Traffic Restrictions
Distributor → Customer	Heavy Truck	Medium	High	Medium	High	High	Medium	Low

For each of the 114 transportation scenarios, the social risk level has been calculated using the fuzzy inference system (FIS) model. In this model:

- Seven key transportation indicators are considered as input variables.
- The output value for social risk varies between 0.1 and 1.0.
- Lower values indicate low-risk transportation scenarios, while values closer to 1.0 represent critical social risk cases.

By running the fuzzy inference system, the social risk value for each transportation scenario is presented in Table 6.6.

Table 6. 6: Index values for different situations

Relation Type	Transportation mode	Social Risk Score
Supplier → Manufacturer	Small Truck	0.598
Supplier → Manufacturer	Small Truck	0.387
Supplier → Manufacturer	Small Truck	0.450
Supplier → Manufacturer	Small Truck	0.450
Supplier → Manufacturer	Small Truck	0.559
Supplier → Manufacturer	Small Truck	0.513
Supplier → Manufacturer	Small Truck	0.635
Supplier → Manufacturer	Small Truck	0.513
Supplier → Manufacturer	Small Truck	0.558
Supplier → Manufacturer	Small Truck	0.525
Supplier → Manufacturer	Small Truck	0.462
Supplier → Manufacturer	Small Truck	0.665
Supplier → Manufacturer	Small Truck	0.442
Supplier → Manufacturer	Small Truck	0.370

Relation Type	Transportation mode	Social Risk Score
Supplier → Manufacturer	Small Truck	0.665
Manufacturer → Distributor	Small Truck	0.450
Manufacturer → Distributor	Small Truck	0.562
Manufacturer → Distributor	Small Truck	0.583
Manufacturer → Distributor	Small Truck	0.659
Manufacturer → Distributor	Small Truck	0.608
Manufacturer → Distributor	Small Truck	0.606
Manufacturer → Distributor	Small Truck	0.360
Manufacturer → Distributor	Small Truck	0.450
Manufacturer → Distributor	Small Truck	0.450
Distributor → Customer	Small Truck	0.450
Distributor → Customer	Small Truck	0.462
Distributor → Customer	Small Truck	0.450
Distributor → Customer	Small Truck	0.589
Distributor → Customer	Small Truck	0.450
Distributor → Customer	Small Truck	0.378
Distributor → Customer	Small Truck	0.408
Distributor → Customer	Small Truck	0.495
Distributor → Customer	Small Truck	0.337
Distributor → Customer	Small Truck	0.438
Distributor → Customer	Small Truck	0.598
Distributor → Customer	Small Truck	0.450
Distributor → Customer	Small Truck	0.450
Distributor → Customer	Small Truck	0.562
Distributor → Customer	Mid Truck	0.387
Distributor → Customer	Mid Truck	0.619
Distributor → Customer	Mid Truck	0.598
Distributor → Customer	Mid Truck	0.360
Distributor → Customer	Mid Truck	0.492
Distributor → Customer	Mid Truck	0.408
Distributor → Customer	Mid Truck	0.673
Distributor → Customer	Mid Truck	0.450
Distributor → Customer	Mid Truck	0.443
Distributor → Customer	Mid Truck	0.598
Distributor → Customer	Mid Truck	0.370
Distributor → Customer	Mid Truck	0.450
Distributor → Customer	Mid Truck	0.635
Distributor → Customer	Mid Truck	0.559
Distributor → Customer	Mid Truck	0.462
Distributor → Customer	Mid Truck	0.462
Distributor → Customer	Mid Truck	0.479

Relation Type	Transportation mode	Social Risk Score
Distributor → Customer	Mid Truck	0.513
Distributor → Customer	Mid Truck	0.389
Distributor → Customer	Mid Truck	0.450
Distributor → Customer	Mid Truck	0.337
Distributor → Customer	Mid Truck	0.462
Distributor → Customer	Mid Truck	0.438
Distributor → Customer	Mid Truck	0.665
Distributor → Customer	Mid Truck	0.450
Distributor → Customer	Mid Truck	0.438
Distributor → Customer	Mid Truck	0.550
Distributor → Customer	Mid Truck	0.450
Distributor → Customer	Mid Truck	0.671
Distributor → Customer	Mid Truck	0.621
Distributor → Customer	Mid Truck	0.360
Distributor → Customer	Mid Truck	0.360
Distributor → Customer	Mid Truck	0.598
Distributor → Customer	Mid Truck	0.387
Distributor → Customer	Mid Truck	0.360
Distributor → Customer	Mid Truck	0.562
Distributor → Customer	Mid Truck	0.455
Distributor → Customer	Mid Truck	0.387
Distributor → Customer	Heavy Truck	0.575
Distributor → Customer	Heavy Truck	0.450
Distributor → Customer	Heavy Truck	0.462
Distributor → Customer	Heavy Truck	0.450
Distributor → Customer	Heavy Truck	0.400
Distributor → Customer	Heavy Truck	0.513
Distributor → Customer	Heavy Truck	0.367
Distributor → Customer	Heavy Truck	0.450
Distributor → Customer	Heavy Truck	0.438
Distributor → Customer	Heavy Truck	0.572
Distributor → Customer	Heavy Truck	0.556
Distributor → Customer	Heavy Truck	0.659
Distributor → Customer	Heavy Truck	0.575
Distributor → Customer	Heavy Truck	0.450
Distributor → Customer	Heavy Truck	0.337
Distributor → Customer	Heavy Truck	0.500
Distributor → Customer	Heavy Truck	0.337
Distributor → Customer	Heavy Truck	0.583
Distributor → Customer	Heavy Truck	0.598
Distributor → Customer	Heavy Truck	0.513

Relation Type	Transportation mode	Social Risk Score
Distributor → Customer	Heavy Truck	0.438
Distributor → Customer	Heavy Truck	0.462
Distributor → Customer	Heavy Truck	0.438
Distributor → Customer	Heavy Truck	0.525
Distributor → Customer	Heavy Truck	0.450
Distributor → Customer	Heavy Truck	0.447
Distributor → Customer	Heavy Truck	0.598
Distributor → Customer	Heavy Truck	0.387
Distributor → Customer	Heavy Truck	0.582
Distributor → Customer	Heavy Truck	0.450
Distributor → Customer	Heavy Truck	0.360
Distributor → Customer	Heavy Truck	0.438
Distributor → Customer	Heavy Truck	0.438
Distributor → Customer	Heavy Truck	0.665
Distributor → Customer	Heavy Truck	0.583
Distributor → Customer	Heavy Truck	0.370
Distributor → Customer	Heavy Truck	0.387
Distributor → Customer	Heavy Truck	0.513

6.4. Results of Solving the Proposed Model

To solve the proposed model using the employed goal programming, we should solve several sub-problems to calculate the aspiration levels for each objective function. In this regard, to calculate the aspiration levels, the following procedure has been implemented: for calculation of the lower bound of the aspiration level, the related objective function is solved in the minimisation mode by considering all constraints. Also, to compute the upper bound of the aspiration level, the relevant objective function is solved in the maximisation mode by considering all constraints. In the next step, we solve the final model to achieve the optimal solution. In this regard, it should be noted that the weights of objective functions are respectively considered equal to 0.3, 0.15, 0.2, 0.15, and 0.2. These weights are selected based on the opinions of the experts. Figure 6.1 shows the solution procedure. As shown in this figure, 10 sub-problems should be solved to calculate the parameters

of the solving method. After implementing the final model, the values of the objective functions are as follows: $Z_1=4280384$ (£), $Z_2= 44164.40$ (g), $Z_3=4599527$ (S), $Z_4=8.615000$, $Z_5=0.90$. The results also showed that the model prefers to establish the blockchain-based information sharing system.

Moreover, Table 6.7 shows the values of QR_{rqijm} decision variable. Moreover, Table 6.8 demonstrates the values of QPM_{pqjkm} decision variable. Also, Table 6.9 is the values of QPD_{pqkcm} decision variable. Additionally, Table 6.10 shows the values of SH_{cpq} decision variable.

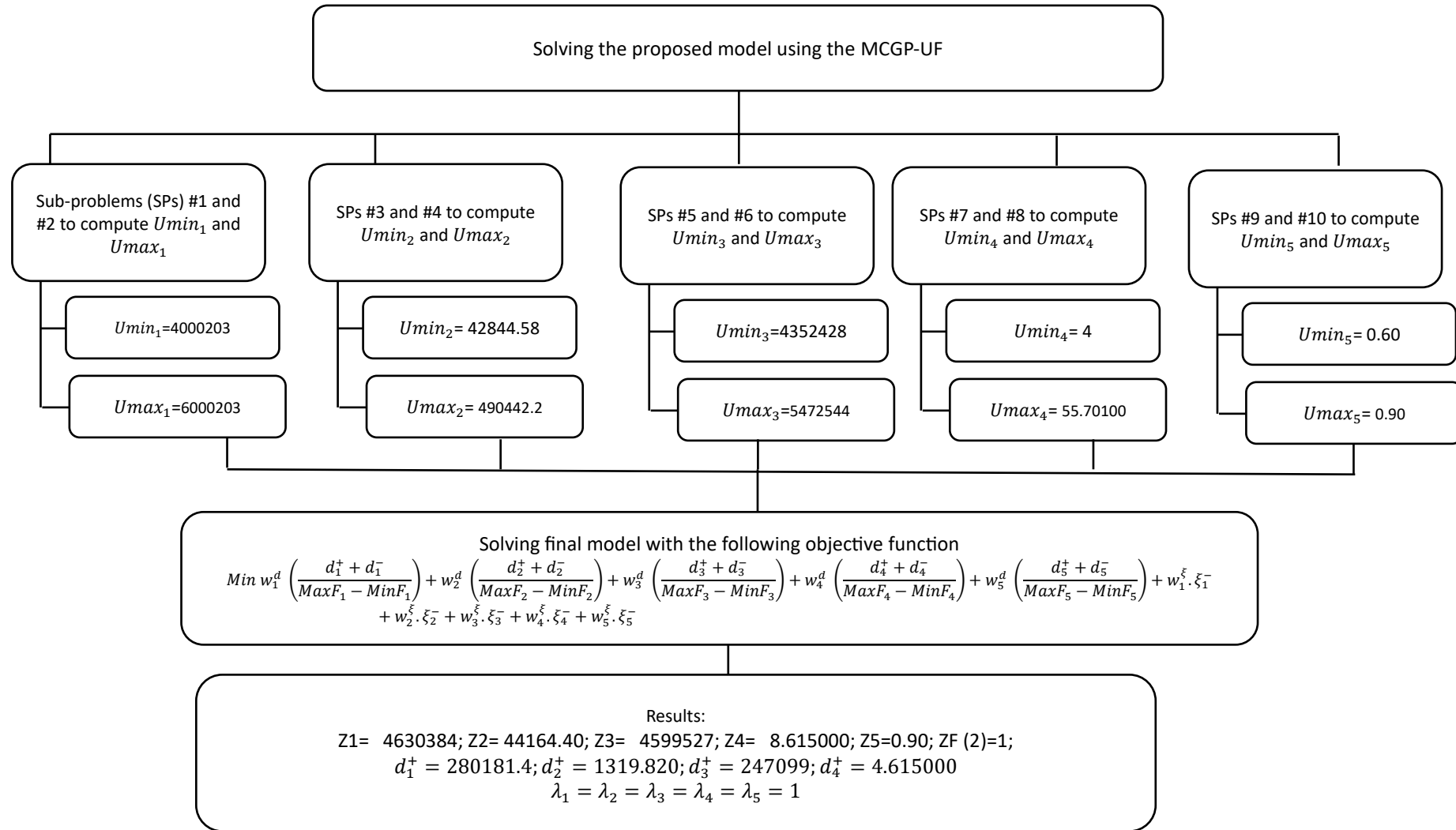


Figure 6.1: Results of Solving the Model

Table 6. 7: Values of QR_{rqijm}

QR_{rqijm}	Value	QR_{rqijm}	Value
QR(1, 1, 1, 1, 2)	21323	QR(1, 1, 2, 1, 3)	29045
QR(1, 1, 3, 1, 3)	27810	QR(1, 1, 4, 1, 3)	28129
QR(1, 1, 5, 1, 2)	20758	QR(1, 2, 1, 1, 3)	25117
QR(1, 2, 2, 1, 2)	23003	QR(1, 2, 3, 1, 2)	22143
QR(1, 2, 4, 1, 2)	23471	QR(1, 2, 5, 1, 2)	21674
QR(1, 3, 1, 1, 3)	29655	QR(1, 3, 2, 1, 2)	23104
QR(1, 3, 3, 1, 3)	25665	QR(1, 3, 4, 1, 1)	5821
QR(1, 3, 5, 1, 3)	29349	QR(2, 1, 1, 1, 2)	21185
QR(2, 1, 2, 1, 3)	25604	QR(2, 1, 3, 1, 3)	29344
QR(2, 1, 5, 1, 2)	22423	QR(2, 2, 1, 1, 2)	21478
QR(2, 2, 2, 1, 2)	20228	QR(2, 2, 3, 1, 2)	22703
QR(2, 2, 4, 1, 1)	3617	QR(2, 2, 5, 1, 2)	23836
QR(2, 3, 1, 1, 2)	21400	QR(2, 3, 2, 1, 2)	22693
QR(2, 3, 3, 1, 3)	29440	QR(2, 3, 5, 1, 2)	15589
QR(3, 1, 1, 1, 2)	22430	QR(3, 1, 2, 1, 2)	22790
QR(3, 1, 3, 1, 3)	25648	QR(3, 1, 4, 1, 3)	26565
QR(3, 1, 5, 1, 3)	26682	QR(3, 2, 1, 1, 2)	23648
QR(3, 2, 2, 1, 2)	22682	QR(3, 2, 3, 1, 2)	19246
QR(3, 2, 4, 1, 2)	23656	QR(3, 2, 5, 1, 3)	25639
QR(3, 3, 1, 1, 2)	21824	QR(3, 3, 2, 1, 3)	25181
QR(3, 3, 3, 1, 2)	19564	QR(3, 3, 4, 1, 3)	26515
QR(3, 3, 5, 1, 2)	21760	QR(4, 1, 1, 1, 2)	23333
QR(4, 1, 2, 1, 1)	3471	QR(4, 1, 3, 1, 2)	21925
QR(4, 1, 4, 1, 3)	26478	QR(4, 2, 1, 1, 3)	25780
QR(4, 2, 3, 1, 3)	25211	QR(4, 3, 1, 1, 3)	27710
QR(4, 2, 4, 1, 2)	18099	QR(4, 3, 3, 1, 3)	25497
QR(4, 3, 4, 1, 2)	14365		

Table 6. 8: Values of QPM_{pqjkm}

QPM_{pqjkm}	Value
QPM(1, 1, 1, 1, 1)	5895
QPM(1, 1, 1, 2, 1)	9108
QPM(1, 1, 1, 3, 1)	8346
QPM(1, 2, 1, 1, 1)	4649
QPM(1, 2, 1, 2, 1)	8968
QPM(1, 2, 1, 3, 1)	9155
QPM(1, 3, 1, 1, 1)	4920
QPM(1, 3, 1, 2, 1)	9551
QPM(1, 3, 1, 3, 1)	7079
QPM(2, 1, 1, 1, 1)	5518
QPM(2, 1, 1, 2, 2)	9490
QPM(2, 1, 1, 3, 2)	11291
QPM(2, 2, 1, 1, 1)	4923

QPM_{pqjkm}	Value
QPM(2, 2, 1, 2, 1)	8874
QPM(2, 2, 1, 3, 1)	9512
QPM(2, 3, 1, 1, 1)	1650
QPM(2, 3, 1, 2, 2)	10380
QPM(2, 3, 1, 3, 1)	8270
QPM(3, 1, 1, 1, 1)	5365
QPM(3, 1, 1, 2, 1)	9181
QPM(3, 1, 1, 3, 2)	11013
QPM(3, 2, 1, 1, 1)	4239
QPM(3, 2, 1, 2, 2)	9466
QPM(3, 2, 1, 3, 2)	9304
QPM(3, 3, 1, 1, 1)	6351
QPM(3, 3, 1, 2, 2)	10367
QPM(3, 3, 1, 3, 1)	9004

Table 6. 9: Values of QPD_{pqkcm}

QPD_{pqkcm}	Value	QPD_{pqkcm}	Value
QPD(1, 1, 1, 3, 1)	3158	QPD(1, 1, 1, 4, 2)	2737
QPD(1, 1, 2, 5, 1)	2206	QPD(1, 1, 2, 6, 2)	2904
QPD(1, 1, 2, 8, 1)	1570	QPD(1, 1, 2, 9, 2)	2428
QPD(1, 1, 3, 1, 1)	1517	QPD(1, 1, 3, 2, 2)	3064
QPD(1, 1, 3, 7, 1)	1471	QPD(1, 1, 3, 10, 2)	2294
QPD(1, 2, 1, 3, 1)	1970	QPD(1, 2, 1, 4, 2)	2679
QPD(1, 2, 2, 5, 2)	1801	QPD(1, 2, 2, 6, 2)	2151
QPD(1, 2, 2, 8, 1)	2100	QPD(1, 2, 2, 9, 2)	2916
QPD(1, 2, 3, 1, 2)	2197	QPD(1, 2, 3, 2, 1)	1742
QPD(1, 2, 3, 7, 2)	3020	QPD(1, 2, 3, 10, 2)	2196
QPD(1, 3, 1, 3, 1)	1956	QPD(1, 3, 1, 4, 2)	2964
QPD(1, 3, 2, 5, 2)	3028	QPD(1, 3, 2, 6, 1)	1468
QPD(1, 3, 2, 8, 1)	2728	QPD(1, 3, 2, 9, 2)	2327
QPD(1, 3, 3, 1, 2)	1359	QPD(1, 3, 3, 2, 1)	1293
QPD(1, 3, 3, 7, 2)	3061	QPD(1, 3, 3, 10, 1)	1366
QPD(2, 1, 1, 3, 2)	2916	QPD(2, 1, 1, 4, 2)	2602
QPD(2, 1, 2, 5, 2)	2943	QPD(2, 1, 2, 6, 2)	2656
QPD(2, 1, 2, 8, 2)	2261	QPD(2, 1, 2, 9, 1)	1630
QPD(2, 1, 3, 1, 1)	3255	QPD(2, 1, 3, 2, 2)	1969
QPD(2, 1, 3, 7, 2)	3441	QPD(2, 1, 3, 10, 2)	2626
QPD(2, 2, 1, 3, 2)	3679	QPD(2, 2, 1, 4, 1)	1244
QPD(2, 2, 2, 5, 1)	2705	QPD(2, 2, 2, 6, 1)	1683
QPD(2, 2, 2, 8, 2)	2149	QPD(2, 2, 2, 9, 2)	2337
QPD(2, 2, 3, 1, 1)	2149	QPD(2, 2, 3, 2, 1)	1989
QPD(2, 2, 3, 7, 1)	2829	QPD(2, 2, 3, 10, 1)	2545
QPD(2, 3, 1, 4, 1)	1650	QPD(2, 3, 2, 6, 2)	2692
QPD(2, 3, 2, 8, 2)	3760	QPD(2, 3, 2, 9, 2)	3928
QPD(2, 3, 3, 1, 2)	2854	QPD(2, 3, 3, 2, 2)	3106
QPD(2, 3, 3, 7, 1)	1959	QPD(2, 3, 3, 10, 1)	351
QPD(3, 1, 1, 3, 2)	3109	QPD(3, 1, 1, 4, 2)	2256

QPD_{pqkcm}	Value	QPD_{pqkcm}	Value
QPD(3, 1, 2, 5, 1)	1964	QPD(3, 1, 2, 6, 1)	2175
QPD(3, 1, 2, 8, 2)	3334	QPD(3, 1, 2, 9, 1)	1708
QPD(3, 1, 3, 1, 2)	2558	QPD(3, 1, 3, 2, 2)	3991
QPD(3, 1, 3, 7, 1)	1397	QPD(3, 1, 3, 10, 2)	3067
QPD(3, 2, 1, 3, 2)	3032	QPD(3, 2, 1, 4, 1)	1207
QPD(3, 2, 2, 6, 2)	3628	QPD(3, 2, 2, 8, 1)	2143
QPD(3, 2, 2, 9, 2)	3694	QPD(3, 2, 3, 1, 1)	2753
QPD(3, 2, 3, 2, 2)	3519	QPD(3, 2, 3, 7, 2)	3032
QPD(3, 3, 1, 3, 2)	3615	QPD(3, 3, 1, 4, 2)	2736
QPD(3, 3, 2, 5, 1)	3730	QPD(3, 3, 2, 6, 2)	2321
QPD(3, 3, 2, 8, 2)	2235	QPD(3, 3, 2, 9, 2)	2081
QPD(3, 3, 3, 1, 2)	2136	QPD(3, 3, 3, 2, 1)	1956
QPD(3, 3, 3, 7, 1)	1523	QPD(3, 3, 3, 10, 2)	3389

Table 6. 10: Values of SH_{cpq}

SH_{cpq}	Value
SH(1, 2, 1)	668
SH(3, 2, 3)	2680
SH(4, 3, 2)	2343
SH(5, 1, 1)	1729
SH(5, 2, 3)	2338
SH(5, 3, 2)	2294
SH(10, 2, 3)	3463
SH(10, 3, 2)	2238

6.5. Sensitivity Analysis

Sensitivity analysis of model parameters plays a crucial role in the development of mathematical models, as it enables us to understand how fluctuations in the model outputs can be attributed to variations in the model inputs. This insight guides further research to reduce output variability. Hence, this section is dedicated to conducting several sensitivity analyses to examine the impact of key parameters of the proposed model on the achieved results.

6.5.1. Demand

In this section, the proposed model has been solved under various values for the demand parameter (i.e., -30%, -20%, -10%, base case, +10%, +20%, and +30%) to observe the influence of the demand parameter on the achieved outcomes. In this regard, Figure 6.2 shows the changes in the first objective function due to changing in demand. This figure shows that the first objective function significantly increases when the demand parameter rises. Moreover,

Figure 6.3, 6.4 demonstrates the sensitivity analysis of the second and third objective functions against changing the demand parameter. As shown in this figure, by raising the demand parameter, both Z_2 and Z_3 have increased. Eventually, Figure 6.5 depicts the changes in Z_4 and based on changes in the demand parameter. Figure 6.6 shows the demand parameter has no impact on Z_5 because this function is visibility of information that does not change by demand. in summary, the four objective functions have increased when the demand parameter increases.

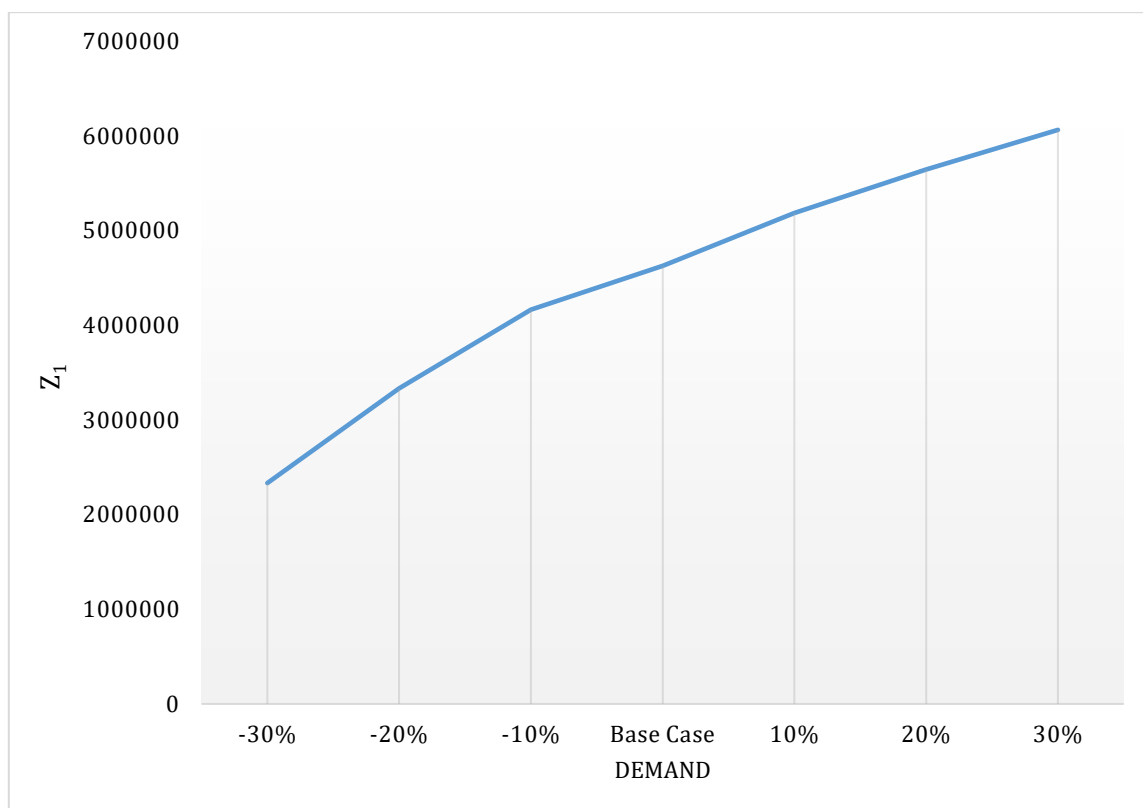


Figure 6.1: Changes in Z_1 due to the change in the demand parameter

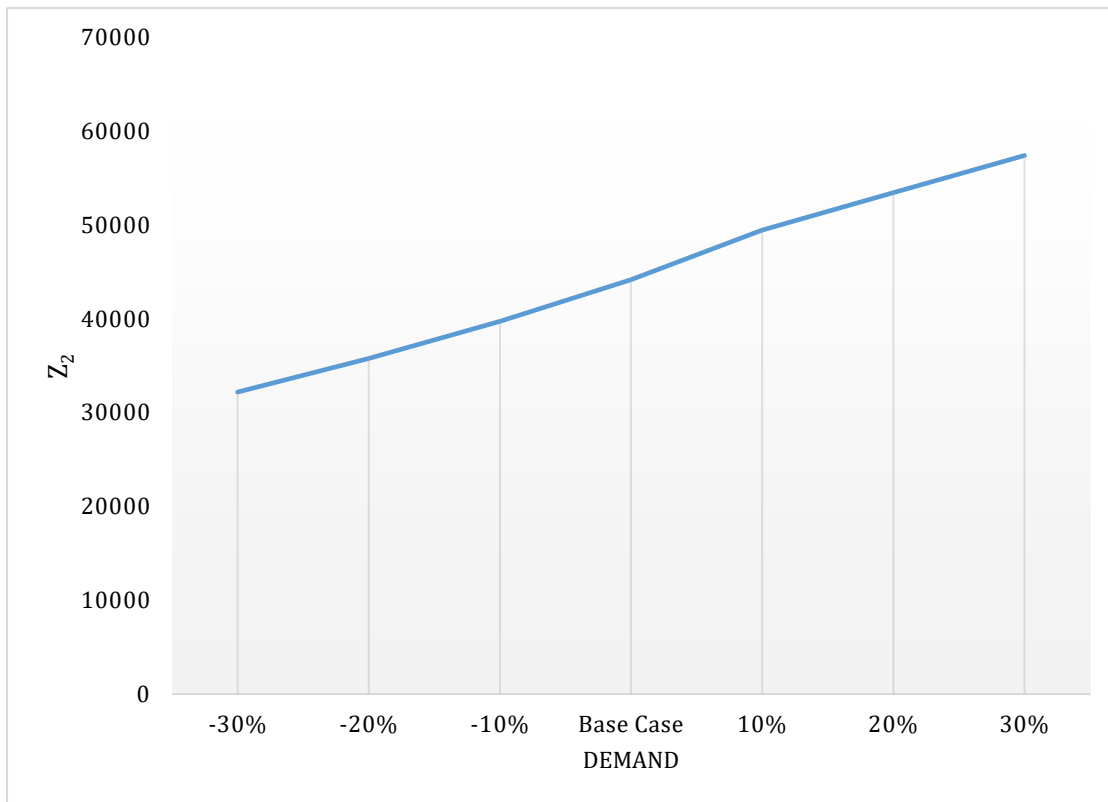


Figure 6.2: Changes in Z_2 due to changing the demand parameter

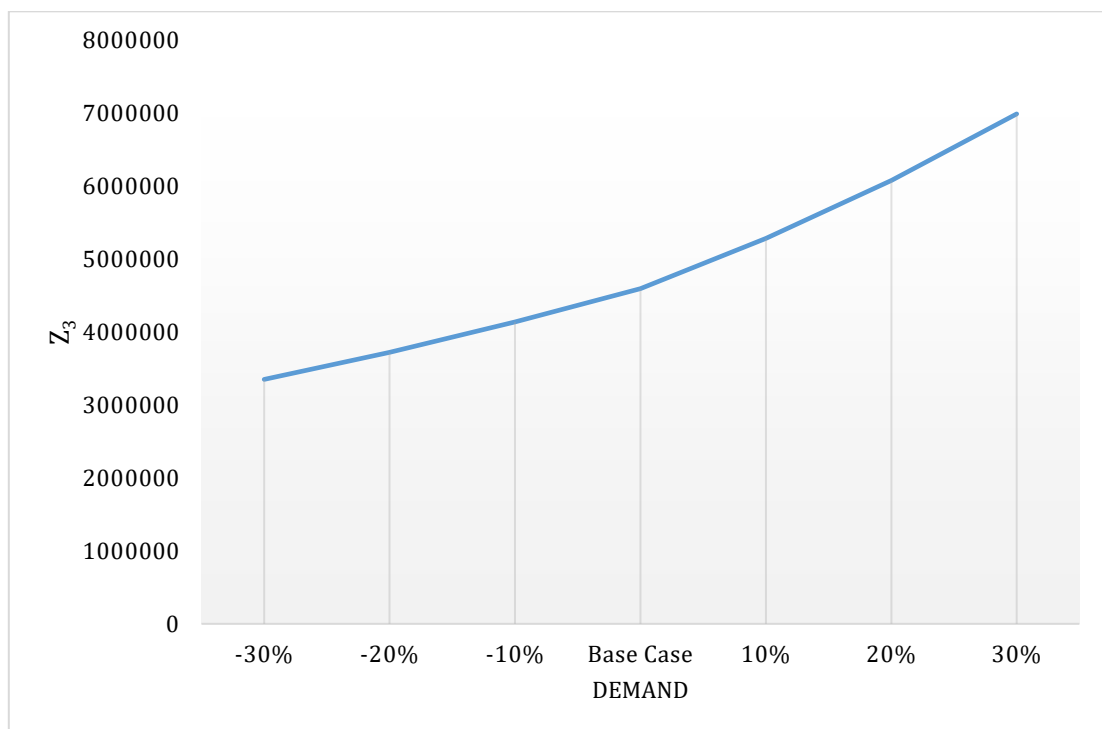


Figure 6.3: Changes in Z_3 due to changing the demand parameter.

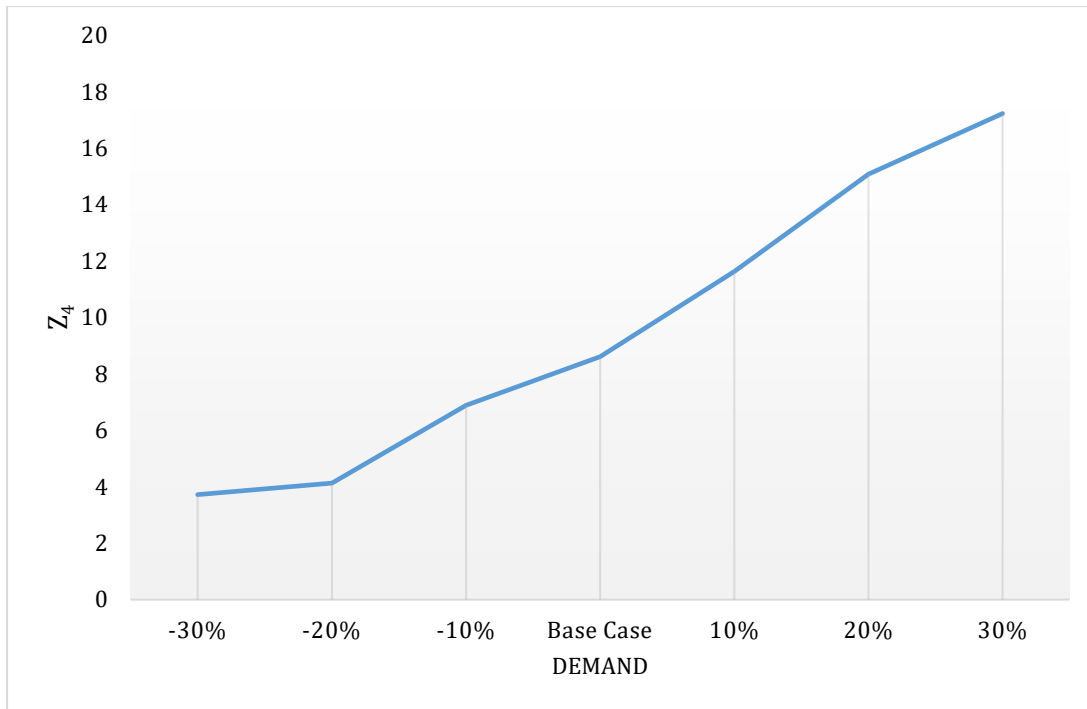


Figure 6.5: Changes in Z_4 due to changing the demand parameter.

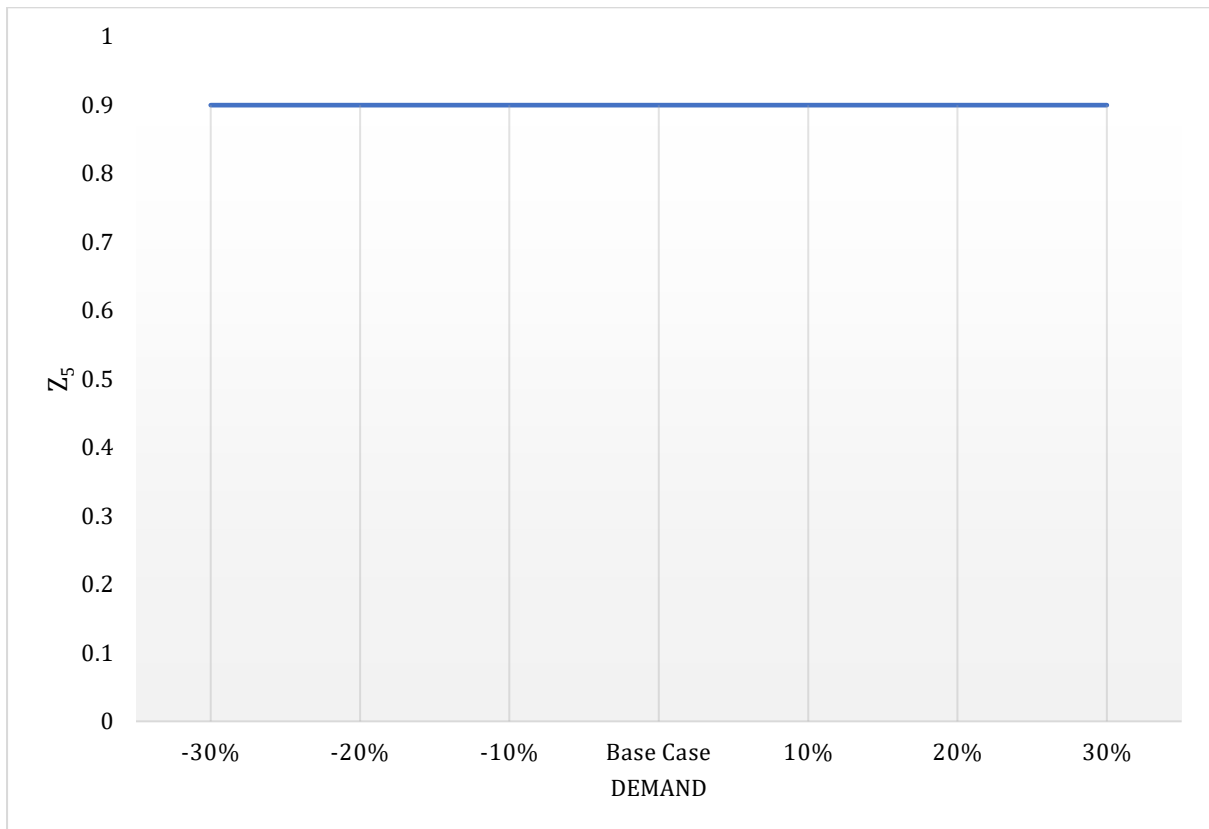


Figure 6.4: Changes in Z_5 due to changing the demand parameter

6.5.2. Information Sharing

In this section, the role of the information-sharing systems in the research problem has been investigated. As mentioned, in this research, we consider two different ISSs, including the traditional and blockchain platforms. It should be noted that considering these types and also their relevant data (i.e., costs and information exchange) have been inspired by the literature. In this way, two different modes are considered. In the first mode, the traditional information-sharing system is established. Also, in the second mode, the blockchain-based information-sharing system is established. Figures 6.7 and 6.8 show the results of the sensitivity analysis. As shown in this figure, although establishing the blockchain-based information-sharing system resulted in more costs, it significantly improves the visibility of the supply chain, which can considerably enhance resilience, transparency, and trust in the supply chain.

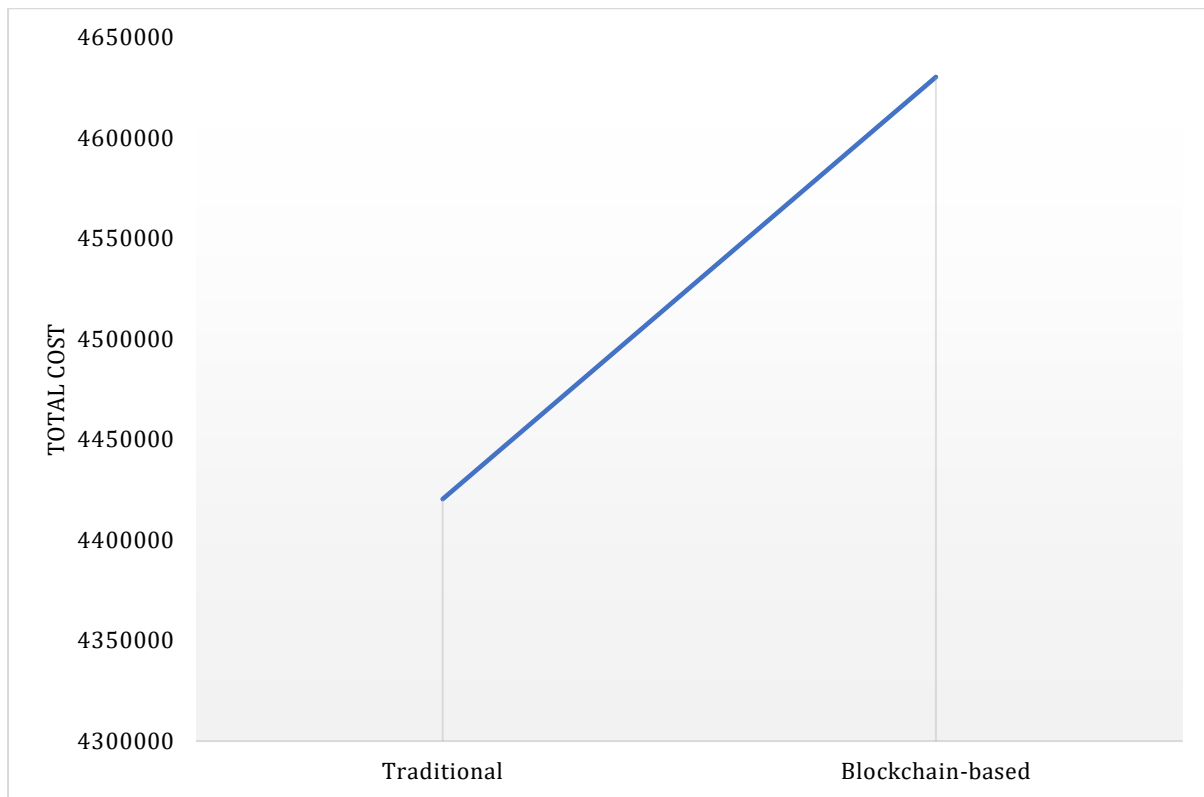


Figure 6.5: The impact of the information-sharing system on the total cost

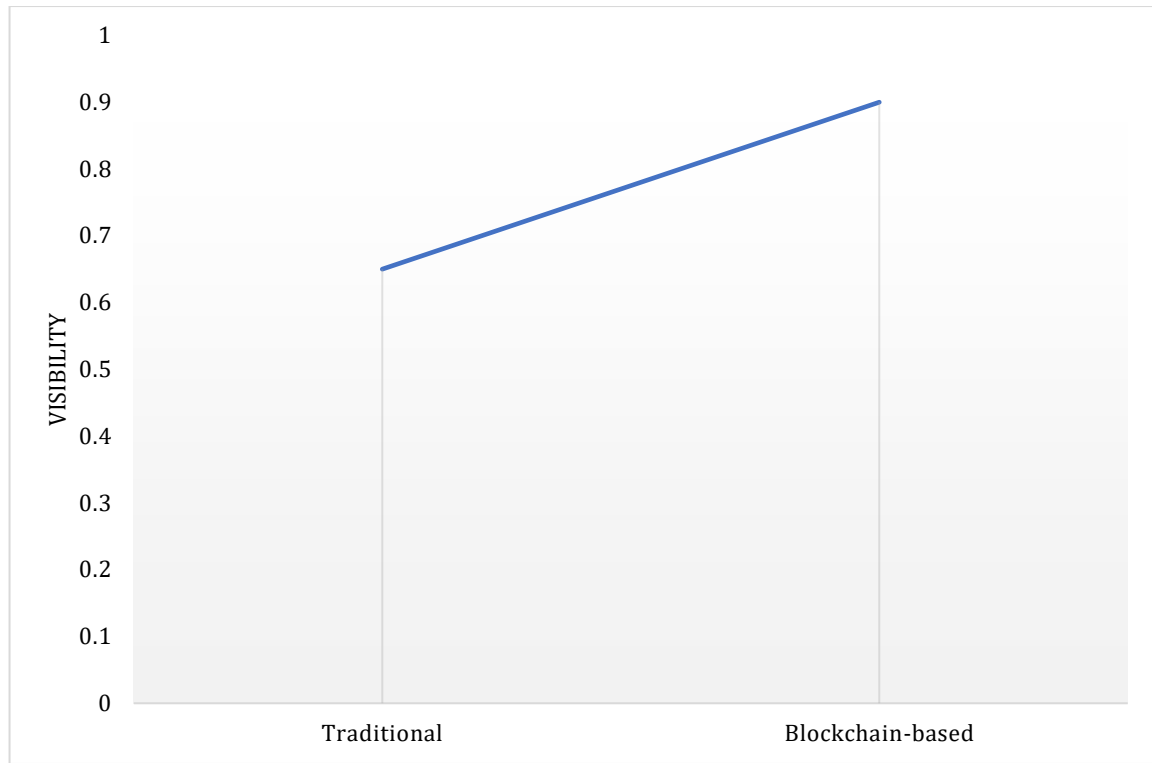


Figure 6.6: The impact of the information-sharing system on visibility

6.5.3. Capacity

The target of this section is to examine the influence of the capacity parameter on the achieved outputs. It should be noted that here, by capacity, we mean the capacity of all facilities in the supply chain network, i.e., the manufacturer, supplier, and distributor. In this regard, Figure 6.9 shows the behaviour of the first objective function based on changing the mentioned parameter. As can be seen in Figure 6.9, an enhancement in the capacity parameter leads to a decrease in the total cost. Additionally, Figures 6.10 and 6.11 illustrate the changes in Z_2 and Z_3 according to the capacity fluctuations. These figures indicate that the environmental impacts and lead time have decreased when the capacity parameter increases. Finally, Figures 6.12 and 6.13 demonstrate the sensitivity analysis of Z_4 and Z_5 based on changes in the capacity parameter.

Figure 6.12 shows that Z_4 has decreased by enhancing the capacity parameter. Also, Z_5 has no relationship with this parameter.

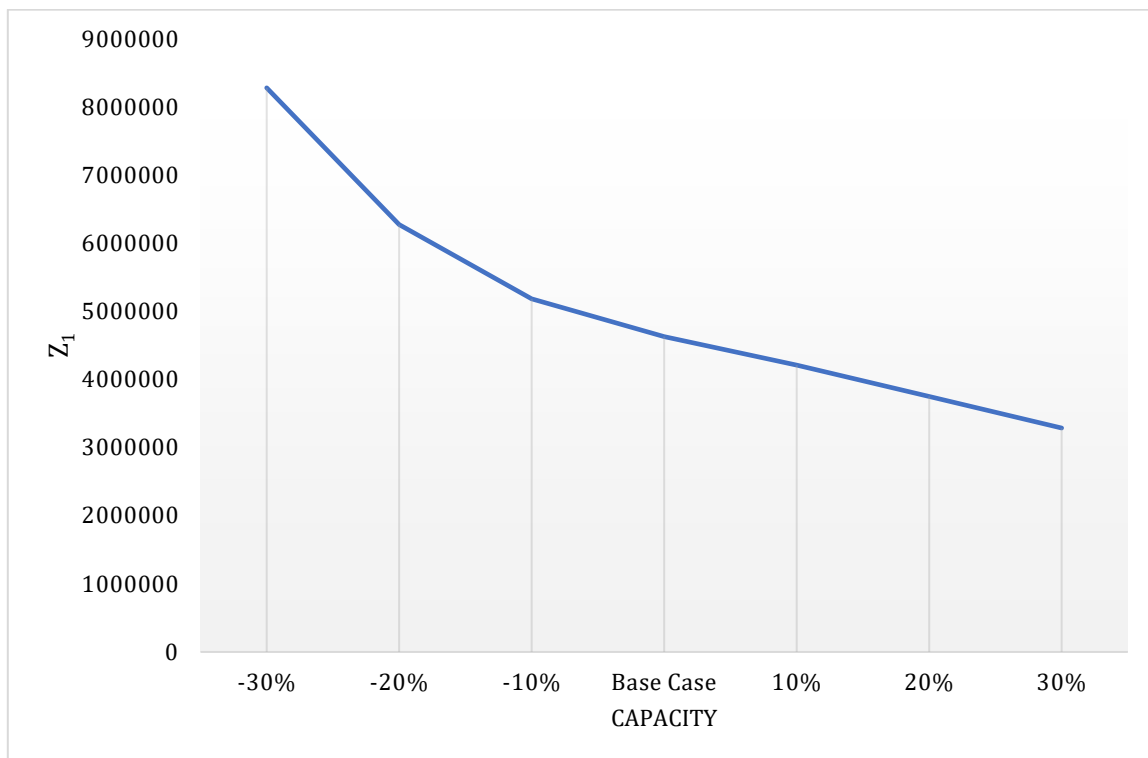


Figure 6.7: Changes in Z_1 due to changing the capacity parameter

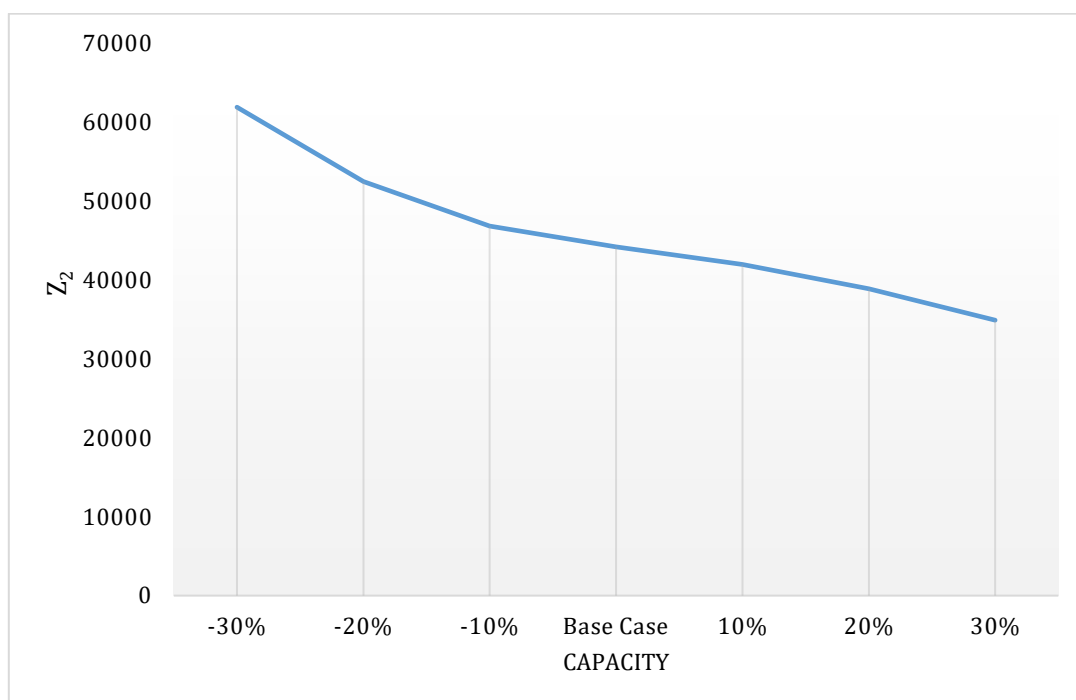


Figure 6.8: Changes in Z_2 due to changing the capacity parameter

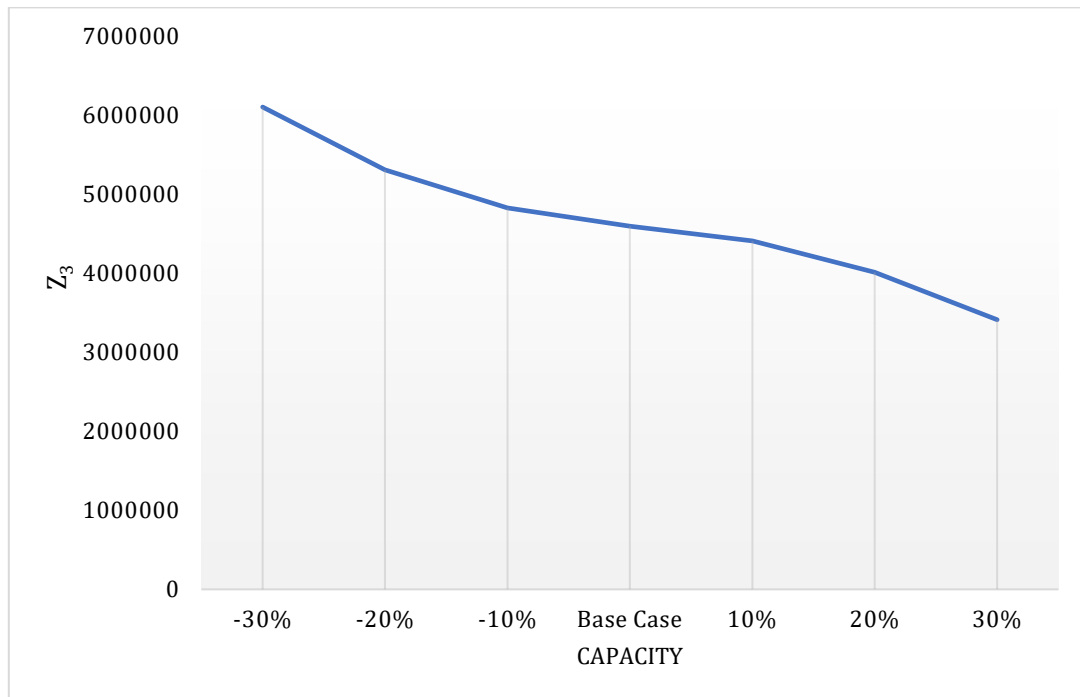


Figure 6.9: Changes in Z_3 due to changing the capacity parameter

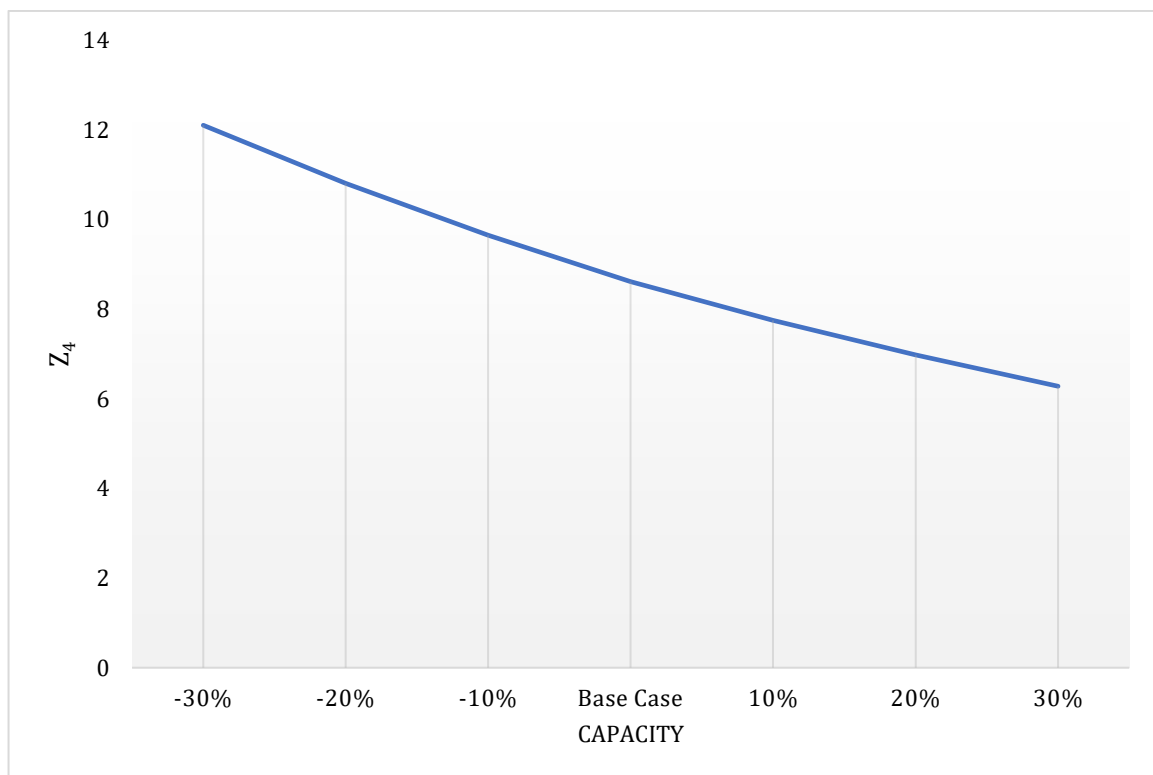


Figure 6.10: Changes in Z_4 due to changing the capacity parameter

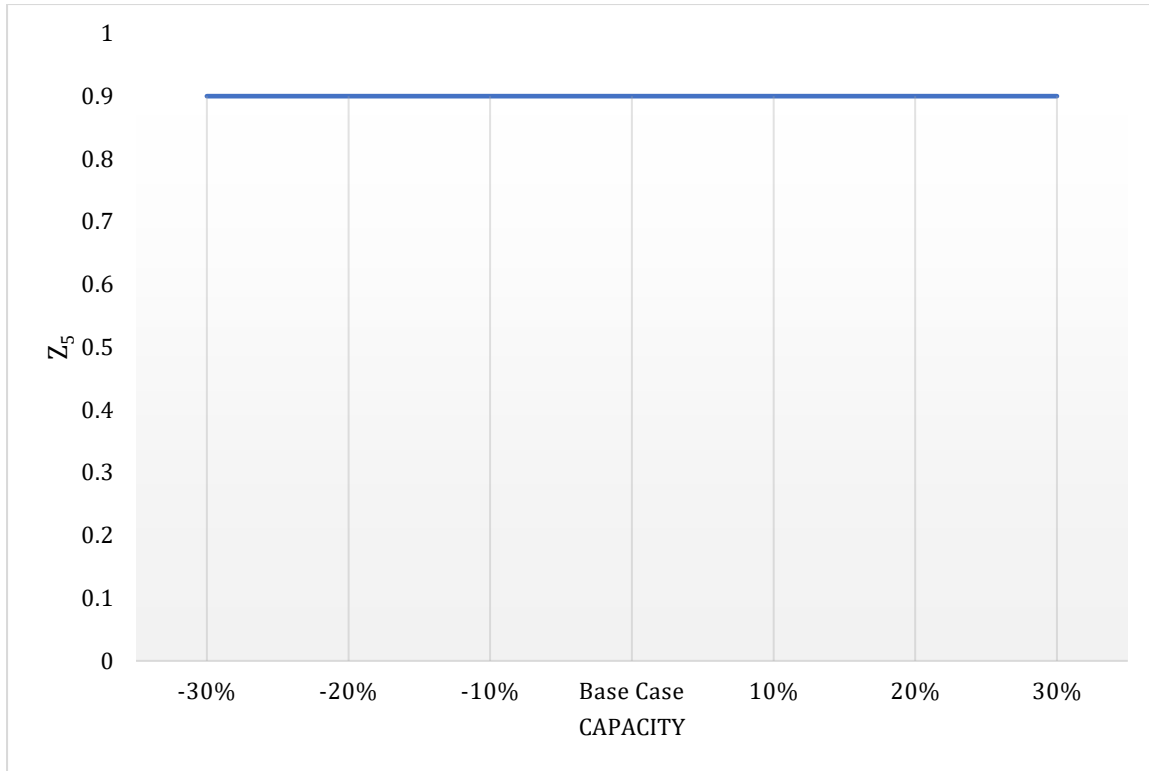


Figure 6.11: Changes in Z_5 due to changing the capacity parameter

6.5.4. Service Level

One of the key parameters of the proposed model is the service level. To examine the role of this parameter, this section aims to conduct a sensitivity analysis. In this regard, by considering different values for the service level, the proposed model is solved, and the results are analysed. Figures 6.14, 6.15, 6.16 depict the behaviour of Z_1 , Z_2 , and Z_3 due to changes in the mentioned parameter. These figures indicate that raising the service level leads to an increase in all Z_1 , Z_2 , and Z_3 . Also, Figure 6.17 shows the changes in Z_4 due to changing the service level. Based on this figure, Z_4 has increased by increasing the service level.

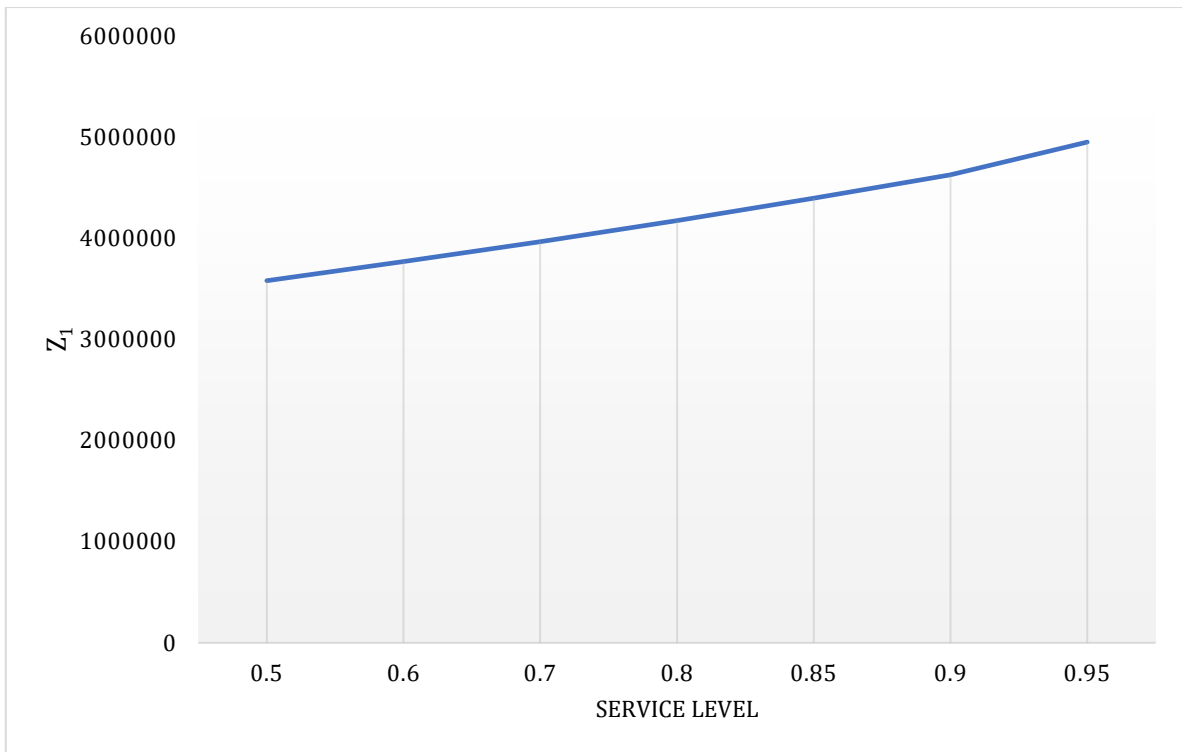


Figure 6. 12: Changes in Z_1 due to changing the service level

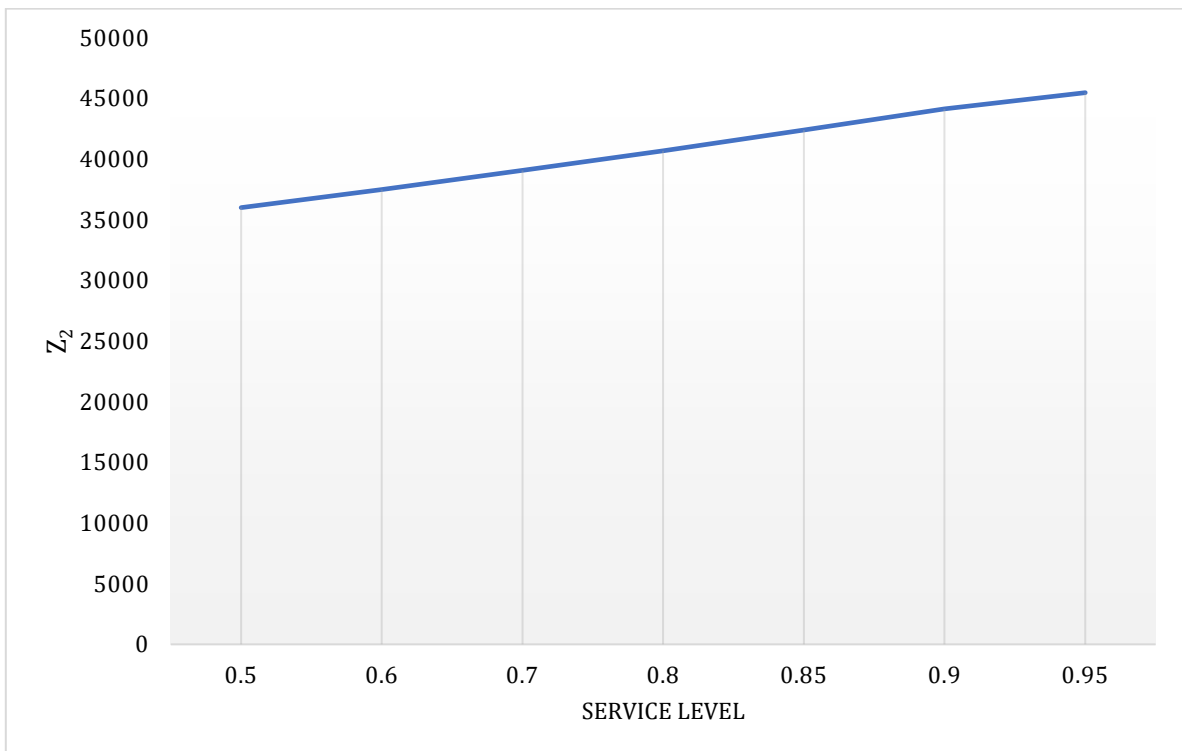


Figure 6. 13: Changes in Z_2 due to changing the service level

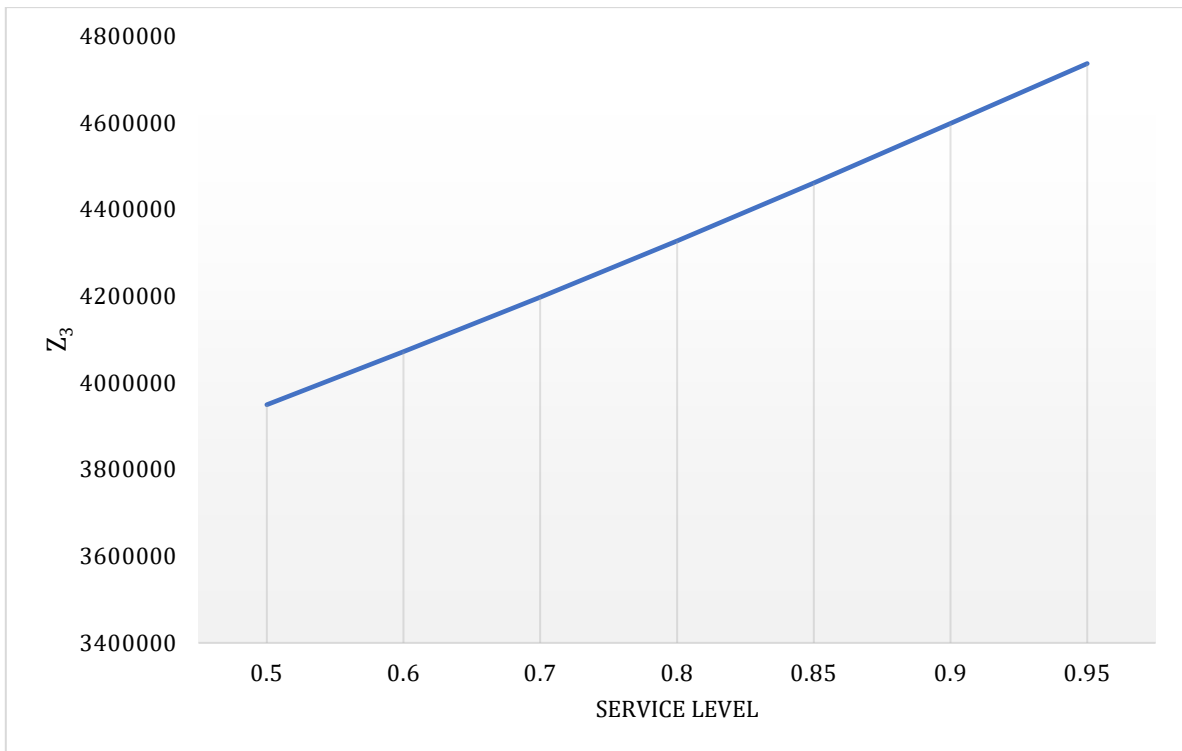


Figure 6. 14: Changes in Z_3 due to changing the service level

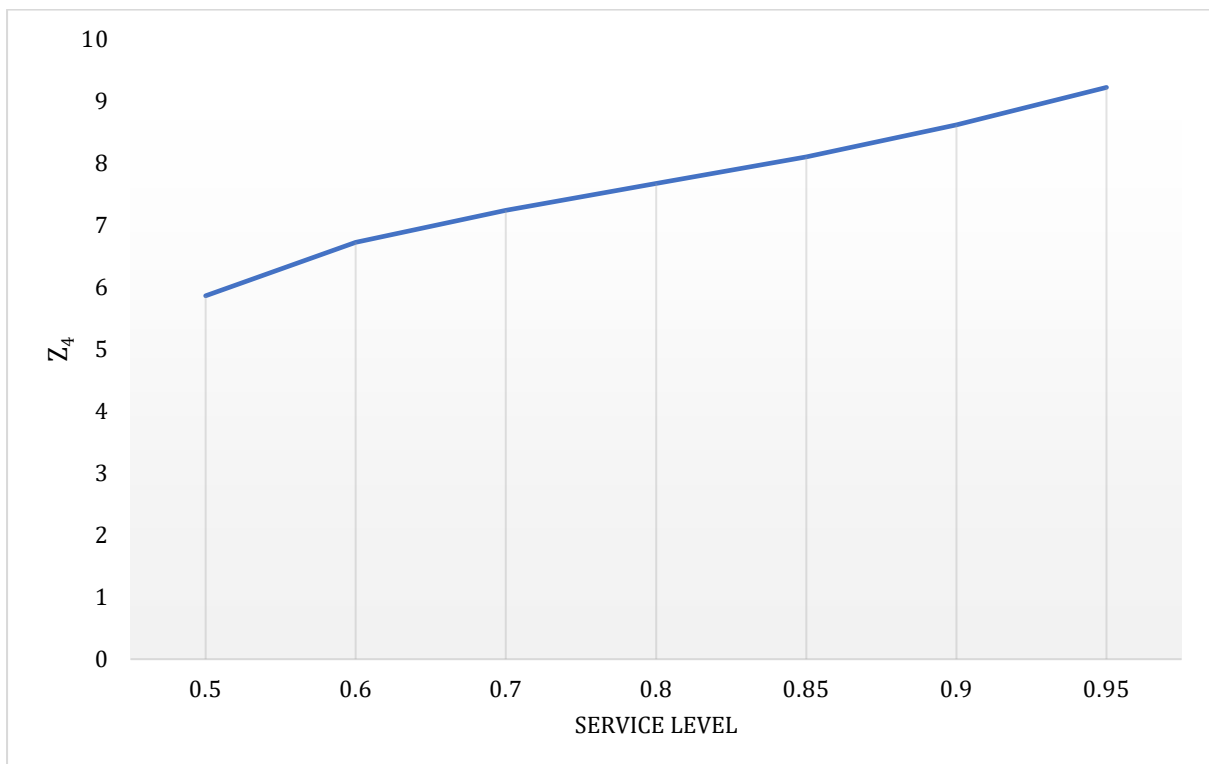


Figure 6.15: Changes to Z_4 due to changing the service level

6.5.5. Carbon Capacity

As aforementioned, the current study has investigated the research problem under carbon cap-and-trade policy. In this regard, to observe the impact of this policy on the research problem, a sensitivity analysis on the carbon capacity parameter has been conducted in this section. Figures 6.18 and 6.19 show the results of the sensitivity analysis, which indicate that the total cost has decreased but the amount of carbon emitted in the supply chain has increased by increasing the capacity of carbon emission.

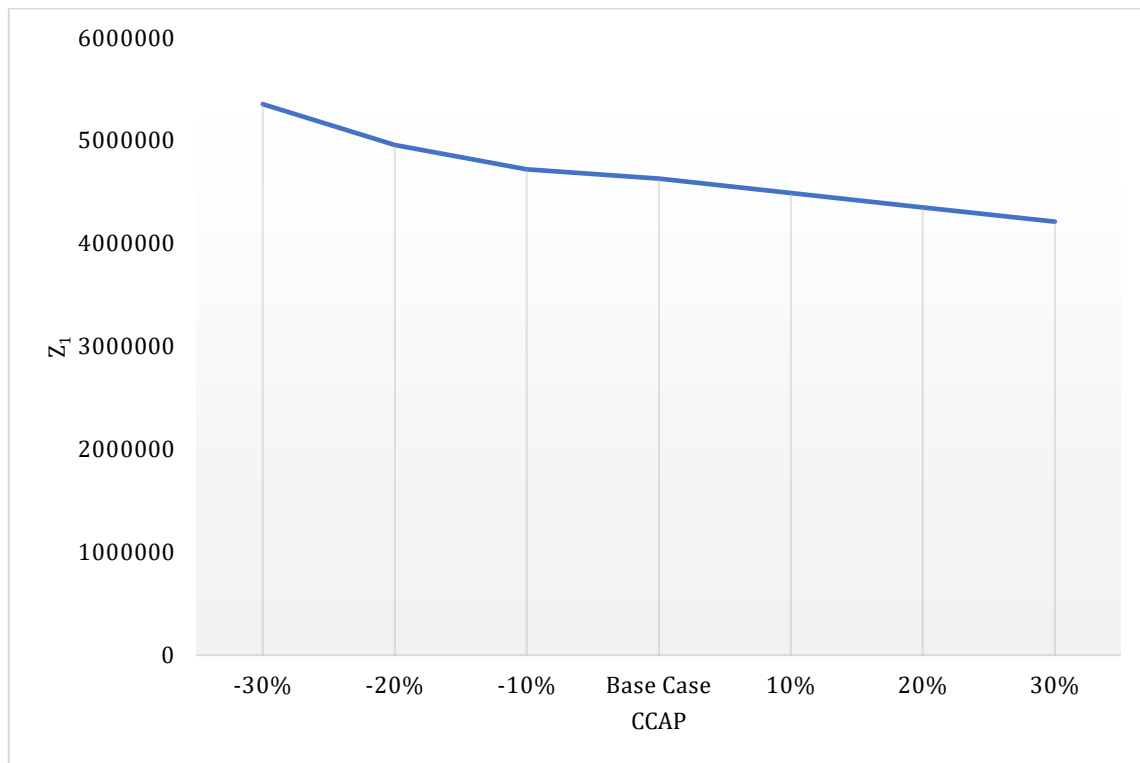


Figure 6. 16: Changes in Z_1 due to changing $CCap$

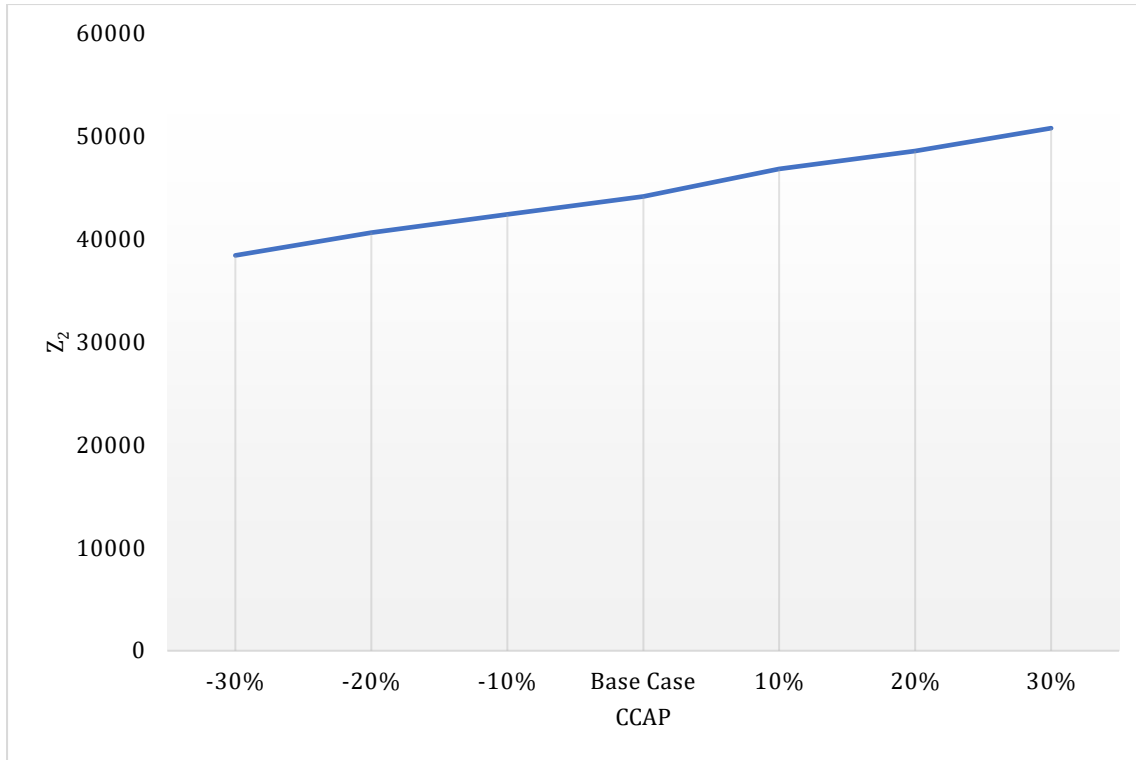


Figure 6. 17: Changes in Z_2 due to changing $Ccap$

6.6. Managerial Insights

In addition to the theoretical implications, the practical and managerial insights of each academic work are important. Therefore, in this section, we present some of the major managerial implications of the current study. This research has focused on designing a supply chain network for the food industry by considering different features like environmental impacts, social impacts, risks, quality, and lead time. In this regard, this study can provide a comprehensive perspective to managers of the food industry to be familiar with the main elements of the mentioned features (i.e., environmental impacts, social impacts, risks, quality, and lead time) in the food supply chain and understand how they can configure an effective food supply chain with these concepts. Also, based on the results achieved, the total cost has increased by raising the demand parameter. One of the main reasons for this behaviour is probably to increase the shortage costs. Hence, managers can adopt some strategies such as outsourcing or defining extra working time to handle this issue. Moreover, based on the

outcomes of the sensitivity analysis, increasing the demand parameter has significantly increased the GHG emissions. In this regard, since providing a green image from the company can considerably enhance customer satisfaction in today's world, managers should try to utilise clean technologies and green transportation modes to reduce environmental impacts. Another important point in the obtained results was that establishing the blockchain-based information sharing system leads to an increase in the total cost while enhancing the visibility of the supply chain. In this regard, practical managers should know that increasing the visibility can significantly improve the transparency and resilience of the supply chain, which can enhance the productivity of the company. Eventually, based on the results achieved, all of the key performance indicators of the supply chain have improved when the capacity parameter has increased. In this regard, it is recommended that relevant managers assign the required budget to enhance the capacity of the facilities of the supply chain in order to improve the efficiency of the company.

6.7. Conclusion

Based on the crucial role of the food industry, this research addressed the food supply chain network design problem by considering different features related to sustainability and resilience. In this way, the current work has proposed an effective decision-making approach by combining multi-objective decision-making and FIS methods to investigate the research problem. In this Chapter at the outset, the required data has been estimated. Then, the results of implementing the FIS method have been presented. Afterwards, the outcomes of solving the mathematical programming model have been provided. Moreover, to examine the role of the key parameters in the research problem, several sensitivity analyses have been conducted. In the next Chapter, the conclusions and future research directions will be presented.

Chapter Seven

Conclusions, Recommendations, Contribution to Knowledge, Limitations and Future Work

7.1 Introduction

This chapter links the key findings of the study to the broader academic and practical concepts of the sustainable food supply chain. After a summary of the main findings, the chapter states clear suggestions to the professionals and decision-makers, recognises the contribution to knowledge, and mentions the limitations of the study along with potential future research areas. Overall, these sections represent the benefits of the novel framework and the mathematical model, signifying their possible uses and the degree of their application.

7.2 Conclusion and Interpretation of Findings

This research has developed a comprehensive decision framework for designing a sustainable, resilient, and efficient food supply chain. By integrating economic, environmental, and social dimensions alongside outsourcing performance measures that resulted in resilience and agility.

The research contributes to bridging the gap between theory and practice in supply chain network design. The model explicitly details five main objectives: minimising total costs, greenhouse gas emissions, delivery time, and social risks, while maximising supply chain visibility. Moreover, the study integrates advanced strategies such as information-sharing systems (including blockchain-based platforms), multiple transportation modes, extra capacity options, and worker fatigue considerations, making the framework both realistic and innovative.

The use of the MCGP-UF method has made it possible to assess these different goals at the same time and still show the preferences of the decision-makers. The way the solution works,

by enabling several aspiration levels and using utility-based weighting, offers a more balanced decision-making process. This is a crucial step that makes the new framework not only a solid one in theory but also more flexible in dealing with complicated decision-making situations. The incorporation of the fuzzy inference system for the assessment of social risks related to transport, further extends the model by measuring the less tangible aspects of noise, pollution, congestion, and accident risks.

The computational results highlight several significant findings. First, the mathematical model favours the adoption of blockchain-based information-sharing platforms despite their higher establishment costs, due to their superior visibility and contribution to resilience. Second, the analysis of transportation modes shows trade-offs between environmental impacts, costs, and social risks, emphasising that supply chain sustainability requires a holistic evaluation rather than a single-objective focus. Third, the final solutions demonstrate that the proposed model can reduce greenhouse gas emissions and social risks while maintaining service levels and minimising costs. These outcomes validate the effectiveness of integrating sustainability and resilience strategies into supply chain planning.

Overall, the findings reveal that the suggested method supplies a strong decision-support tool for the policymakers and the managers of the food industry. The research indicates that including the multi-dimensional sustainability aspects and using technology like blockchain can significantly improve the performance and resilience of supply chains. The research here shows that it is possible to strike a balance between the four aspects mentioned - cost, environmental responsibility, social acceptance, and resilience - by means of well-thought-out optimisation models. Consequently, this not only uplifts the academic knowledge base in sustainable supply chain management area but also opens up avenues for practical application of this knowledge in dealing with the issues of the changing climate, tightening of regulations, and rising social expectations.

7.3 Addressing the Research Aim, Objectives and Questions:

This research effectively addresses a critical gap in the literature by developing a framework that integrates the performance of outsourcing companies with sustainability indicators in the food supply chain. It is clear that the study has accomplished its aims and objectives, which were:

- Objective 1 (Comprehensive Literature Review): The review identified a significant gap in the literature regarding a unified framework that integrates sustainable performance measures with the specific roles of 4PL and 5PL providers.
- Objective 2 (Sustainability Dimensions): The research investigated the influence of economic, environmental, and social dimensions, demonstrating the critical role of outsourcing companies in shaping these outcomes.
- Objective 3 (Conceptual Framework): A validated conceptual framework was developed, successfully integrating sustainability dimensions with outsourcing performance measures.
- Objective 4 (Mathematical Model): A multi-objective mathematical model was developed to represent and integrate outsourcing outcomes with sustainability dimensions. This provides a novel quantitative tool for decision-making.
- Objective 5 (Model Implementation): The model was successfully implemented using Lingo software and validated through experimental design, demonstrating its applicability in a simulated environment.

7.3.1 Answers to the Research Questions

RQ1: How do the interrelationships between the economic, environmental, and social dimensions of sustainability determine the overall resilience and performance of the food supply chain?

The research concludes that these dimensions are not isolated but are interdependently linked through operational drivers. The findings from the 50 interviews and the subsequent mathematical modelling reveal that:

- **Economic-Environmental Link:** Environmental policies like Cap-and-Trade act as a financial constraint that forces the supply chain to optimise for carbon efficiency to avoid economic penalties.
- **Social-Performance Link:** High social performance (e.g., reducing Worker Fatigue and Traffic Noise in the 114 scenarios) directly enhances the Service Level ($Z_5=0.90$), proving that a socially responsible chain is a high-performing one.
- **Resilience as the Outcome:** Resilience is achieved when 4PL/5PL providers use these interrelationships to create "slack," such as Extra Capacity and Multi-modal transport, ensuring that a disruption in one dimension (e.g., a carbon cap breach) does not collapse the entire economic performance.

RQ2: How can a multi-dimensional performance framework for 4PL and 5PL providers be optimised to enhance food supply chain sustainability amidst modern regulatory and environmental pressures?

The optimisation of 4PL and 5PL performance is achieved through the transition from "Logistics Provider" to "Information Integrator." The framework demonstrates that:

- **Optimisation through Visibility:** The model (Z_3 and Z_5) proves that the most effective way to enhance sustainability is to maximise Supply Chain Visibility via Blockchain-based platforms. Despite higher initial costs, this optimisation reduces the "hidden" social and environmental risks that 4PLs/5PLs providers must manage.
- **Agility through Multi-modality:** By optimizing across multiple transportation modes (Small, Mid, and Heavy trucks), 5PLs can dynamically shift routes to meet strict lead times while staying within the carbon "cap."
- **Decision Support:** The MCGP-UF method used in this study provides the mathematical "engine" for 5PLs to handle conflicting goals, allowing them to provide a Sustainability-as-a-Service model to their clients, which is essential for meeting modern regulatory pressures.

7.4. Knowledge Contribution

This research makes several significant contributions to the existing knowledge in sustainable supply chain management. One of the most important contributions is the simultaneous consideration of sustainability, resilience, transportation risks, different product quality levels, and information-sharing systems in designing a food supply chain network. While previous studies have typically focused on separate elements such as cost minimisation, emission reduction, or resilience strategies, this research integrates these diverse but interdependent dimensions into a unified decision-making framework. This holistic perspective allows for capturing the real complexities of modern food supply chains, making the results both theoretically meaningful and practically relevant.

Another major contribution lies in the development and application of a comprehensive decision-making approach by combining a multi-objective mathematical programming model,

FIS, and MCHP-UF to address five conflicting objectives: minimising total costs, greenhouse gas emissions, delivery time, and social risks, while maximising supply chain visibility. Moreover, the current work has incorporated both quantitative and qualitative elements, such as worker fatigue, community acceptance of transportation modes, and carbon cap-and-trade policies. The model enhances the current literature and provides a more sophisticated representation of supply chain dynamics.

At last, the outcomes of this study add up to the managerial know-how by providing tangible insights for the decision-makers in the food supply chain. Specifically, this research advances the understanding of 4PL and 5PL providers not merely as transport subcontractors, but as strategic integrators. The results confirm that the 5PL 'Control Tower' approach utilizing blockchain and multi-modal coordination is the primary driver for achieving the high visibility ($Z_5=0.90$) required for sustainable food supply chains. This moves the discourse beyond traditional 3PL cost-focused outsourcing toward a 5PL-led sustainability-as-a-service model.

Among the main findings is that, though blockchain-based information-sharing systems are more expensive, they substantially become the supply chain visibility and the supply chain resilience. Further, the study reveals the relationships between the three objectives, the economic, environmental, and social ones, providing a vivid example of how co-ordinated planning can lead to lower emissions, become less risky from a social point of view, and at the same time keep the level of service by the customer. These inputs, taken together, make a big step forward in academic theory and managerial practice, thus, establishing a strong platform for the design of food supply chains which are not only sustainable, resilient, and socially responsible but also economically viable. Here are some examples:

- **Investment Priority:** Managers should prioritize investment in Information Sharing Systems (ISS) over fleet expansion, as visibility is the highest driver of social and environmental compliance.
- **Route Risk Management:** Using the 114-scenario analysis, 5PL managers can now identify "High Social Risk" routes and proactively switch to mid-size or electric trucks to avoid community resistance and carbon penalties.
- **Operationalizing Fatigue:** The inclusion of worker fatigue constraints provides a practical tool for HR and Operations managers to ensure ethical labour standards are maintained during peak demand periods.

7.4.1 Distinct Novelty and Advancement over Previous Work

To make the academic significance of this work absolutely clear, Table 7.1 provides a direct comparison between the shortcomings of previous sustainable supply chain research and how this thesis addresses them.

Table7. 1: Novelty and Academic Advancement

Core Focus Area	Previous Literature & Limitations	This Thesis's Advancement & Novelty
Outsourcing Lens	Most models focus strictly on 3PL cost-minimisation (e.g., Ageron et al., 2011; Govindan et al., 2021). They treat logistics as a simple subcontracted cost.	Advances to a 5PL "Control Tower" perspective. The model optimises systemic variables like Blockchain infrastructure and multi-modal fleet balancing positioning the 5PL as a sustainability integrator.
Social Pillar Operationalization	Social impacts are typically omitted or limited to generic job creation metrics (e.g., Allaoui et al., 2019).	Mathematical integration of human-centric constraints. Realistically models Worker Fatigue (via maximum working time limits) and Community Resistance (Fuzzy Inference System modelling of transport noise/pollution across 114 routes).
Information Systems (ISS)	Information sharing is usually treated as a static binary variable or ignored in physical network design (e.g., Mohammed et al., 2021).	Dynamic trade-off modelling of Blockchain vs. Traditional platforms. Quantifies the mathematical relationship between the high setup costs of digital platforms and the resulting visibility ($Z5=0.90$) and risk reduction.
Algorithmic Approach	Heavy reliance on basic single-objective or weighted-sum solutions that allow cost to dominate environmental targets.	Deploying the MCGP-UF method divided into 10 sub-problems (Figure 6.1) to force multi-aspiration level balancing across 5 fiercely conflicting objectives (Z1 to Z5).

7.5 Limitations and Future Research Directions

Even though the research has been helpful, it is still necessary to acknowledge a number of its limitations. Among them, the major limitation is that the issue has been examined only in a deterministic setting. The latter statement may limit the relevance of the results, due to the intricate and changeable nature of the current business environment. It is possible that subsequent researchers might develop further the present framework by considering the uncertainty, and using methods like fuzzy programming, stochastic optimisation, or robust optimisation for producing more dependable and applicable solutions.

One more limitation is inside the range of the supply chain dimensions that were considered. A study of these aspects was done simultaneously in this research, dealing with the environmental, social and economic aspects, supply chain resilience, transportation risks, product quality levels, and information-sharing systems; however, it has not uncovered the significant aspects of the supply chain such as the impact of globalisation, the extensive use of digital technologies for the supply chain, or the sustainable supply chain for the future. These extra dimensions may be included in the next supply chain research to create more extensive and flexible models.

Moreover, the suggested design, because of its complexity and intricacies, might be somewhat limited with extensive practical supply chains. This, in turn, leads to the problem of computational complexity and scalability. To overcome this difficulty, the problem of practical-scale applications, the need for innovation in the solution methods like the decomposition algorithms, metaheuristics, or hybrid approaches that would facilitate efficient processing of large datasets and industrial applications arises.

Another essential limitation of the study was that, similarly to most of the previous works, the exact quantity of information that was exchanged via the information-sharing systems (ISSs), i.e., the traditional client–server platform and the blockchain-based platform, was not determined. However, limitation is the reliance on hypothetical data parameters to validate the model's logic. While these were based on literature and expert opinion, the generalisability of the Z values may vary across different regional food sectors. Future research should apply the model to a primary industry dataset to further refine the coefficients.

Although this method may deliver quite a few reasonable approximations, it will probably not reflect the complexity and variability of the actual information flows in supply chain networks. Thus, the focus of future research could be on the conduct of more granular, data-driven studies to really measure the information exchange rate for every single ISS to get a correct calculation of the visibility.

Finally, the current research explicitly focused on the food supply chain and was dependent on a stylized instance with details that were drawn from the literature. Although this approach provides valuable insights, it may limit the generalisability of the results. Therefore, future studies could validate the proposed model empirically with real-world data across different industries, such as pharmaceuticals, healthcare, or electronics, to investigate sector-specific trade-offs and strengthen the practical relevance of the findings.

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Appendix A

Survey Questionnaire

Development of Sustainable Food Supply Chain Framework - Outsourcing Performance Measures perspective

Introduction

Nowadays, all manufacturing companies, particularly food industries, are moving towards sustainable strategies within the whole supply chain. Due to the various challenges and extensive network in the food supply chain from farm to fork to deliver safe food to the customers on one side and globalisation, climate change, and reduction of natural resources on the other side, sustainable food supply chain needs attention more than before.

This research aims to “Development of a Sustainable Supply Chain framework from outsourcing performance measures perspective within food industry.”

The proposed framework is shown in Figure 1, including criteria, sub-criteria, and outsourcing performance measures to reach the goal of this research.

This questionnaire aims to gather the opinions of researchers, practitioners, and industrialists of the proposed framework by conducting a pairwise comparison between the criteria and sub-criteria and the role of outsourcing performance measures within the proposed framework.

The questionnaire consists of only thirteen questions, and it is expected to take 20 minutes of your time. Your contribution will be highly appreciated, and I would be grateful for your effort in completing the questionnaire.

Confidential Disclosure Agreement

This is to confirm that any information provided by participants shall NOT be communicated or made available to any third party, and the recipient will keep all the information secret and confidential and will take all reasonable security precautions in the safekeeping of the information.

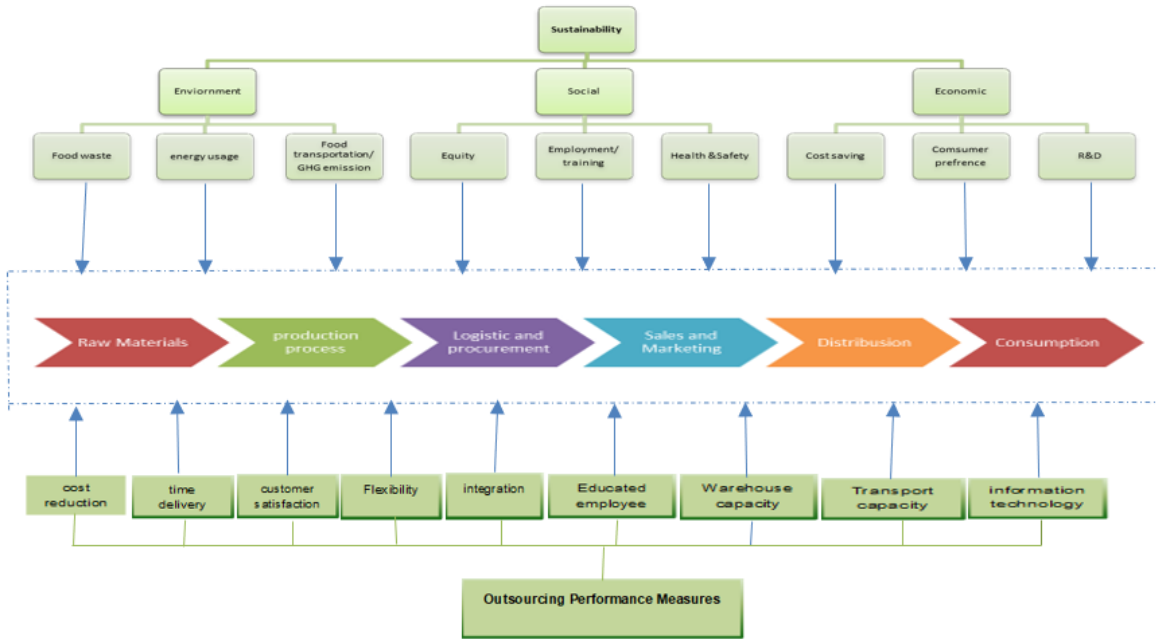


Figure 1: The proposed framework of sustainable supply chain regarding outsourcing performance measures

Guidance on answering questions:

The following questions provide the list of required pairwise comparisons of the importance of all criteria and sub-criteria in line with the goal of the proposed framework. Each question has a scale 1, 3, 5, 7 and 9; please select only one answer for each question by a tick/shade/circle in the relevant box.

Here is an example that shows pairwise comparison of two criteria, Environmental and Social criteria. If you think Environment is 7 times more important than Social, please select 7 on that question, if you think they have equal importance, please tick number 1

Questions

1. Compare the relative importance between **Environment** and **Social** criteria with respect to the main goal, which is the “Development of a Sustainable Supply Chain framework from outsourcing performance measures perspective within food industry”

- 9 Environment is extremely more important than Social
 - 7 Environment is very strongly more important than Social
 - 5 Environment is strongly more important than Social
 - 3 Environment is moderately more important than Social
 - 1 Environment and Social are equally important
 - 3 Social is moderately more important than Environment
 - 5 Social is strongly more important than Environment
 - 7 Social is very strongly more important than Environment
 - 9 Social is extremely more important than Environment
2. Compare the relative importance between ***Environment*** and ***Economic*** criteria with respect to the main goal which is the “Development of a Sustainable Supply Chain framework from outsourcing performance measures perspective within food industry”
- 9 Environment is extremely more important than Economic
 - 7 Environment is very strongly more important than Economic
 - 5 Environment is strongly more important than Economic
 - 3 Environment is moderately more important than Economic
 - 1 Environment and Economic are equally important
 - 3 Economic is moderately more important than Environment
 - 5 Economic is strongly more important than Environment
 - 7 Economic is very strongly more important than Environment
 - 9 Economic is extremely more important than Environment
3. Compare the relative importance between ***Social*** and ***Economic*** criteria with respect to the main goal which is the “Development of a Sustainable Supply Chain framework from outsourcing performance measures perspective within food industry”
- 9 Social is extremely more important than Economic
 - 7 Social is very strongly more important than Economic

- 5 Social is strongly more important than Economic
- 3 Social is moderately more important than Economic
- 1 Social and Economic are equally important
- 3 Economic is moderately more important than Social
- 5 Economic is strongly more important than Social
- 7 Economic is very strongly more important than Social
- 9 Economic is extremely more important than Social

4. Compare the related importance between *Food Waste* and *Energy Usage* with respect to **Environment** criteria

- 9 Food Waste is extremely more important than Energy Usage
- 7 Food Waste is very strongly more important than Energy Usage
- 5 Food Waste is strongly more important than Energy Usage
- 3 Food Waste is moderately more important than Energy Usage
- 1 Food Waste and Energy Usage or equally important
- 3 Energy Usage is moderately more important than Food Waste
- 5 Energy Usage is strongly more important than Food Waste
- 7 Energy Usage is very strongly more important than Food Waste
- 9 Energy Usage is extremely more important than Food Waste

5. Compare the related importance between *Food Waste* and *Food Transportation/GHG emission* with respect to **Environment** criteria

- 9 Food Waste is extremely more important than Food Transportation/GHG emission
- 7 Food Waste is very strongly more important than Food Transportation/GHG emission
- 5 Food Waste is strongly more important than Food Transportation/GHG emission
- 3 Food Waste is moderately more important than Food Transportation/GHG emission
- 1 Food Waste and Food Transportation/GHG emission or equally important
- 3 Food Transportation/GHG emission is moderately more important than Food Waste
- 5 Food Transportation/GHG emission is strongly more important than Food Waste
- 7 Food Transportation/GHG emission is very strongly more important than Food Waste

- 9 Food Transportation/GHG emission is extremely more important than Food Waste

6. Compare the related importance between *Energy Usage* and *Food Transportation/GHG emission* with respect to **Environment** criteria

- 9 Energy Usage is extremely more important than Food Transportation/GHG emission
- 7 Energy Usage is very strongly more important than Food Transportation/GHG emission
- 5 Energy Usage is strongly more important than Food Transportation/GHG emission
- 3 Energy Usage is moderately more important than Food Transportation/GHG emission
- 1 Energy Usage and Food Transportation/GHG emission or equally important
- 3 Food Transportation/GHG emission is moderately more important than Energy Usage
- 5 Food Transportation/GHG emission is strongly more important than Energy Usage
- 7 Food Transportation/GHG emission is very strongly more important than Energy Usage
- 9 Food Transportation/GHG emission is extremely more important than Energy Usage

7. Compare the relative importance between *Equity/Fairness* and *Employment/Training* with respect to **Social** criteria

- 9 Equity/Fairness is extremely more important than employment/Training
- 7 Equity/Fairness is very strongly more important than Employment/Training
- 5 Equity/Fairness is strongly important than Employment/Training
- 3 Equity/Fairness is moderately more important than Employment/Training
- 1 Equity/Fairness and Employment/Training are equally important
- 3 Employment/Training is moderately more important than Equity/Fairness
- 5 Employment/Training is a strongly more important than Equity/Fairness
- 7 Employment/Training is very strongly more important than Equity/Fairness
- 9 Employment/Training is extremely more important than Equity/Fairness

8. Compare the relative importance between *Equity/Fairness* and *Health & Safety* with respect to **Social** criteria

- 9 Equity/Fairness is extremely more important than Health & Safety
- 7 Equity/Fairness is very strongly more important than Health & Safety
- 5 Equity/Fairness is strongly important than Health & Safety
- 3 Equity/Fairness is moderately more important than Health & Safety
- 1 Equity/Fairness and Health & Safety are equally important
- 3 Health & Safety is moderately more important than Equity/Fairness
- 5 Health & Safety is a strongly more important than Equity/Fairness
- 7 Health & Safety is very strongly more important than Equity/Fairness
- 9 Health & Safety is extremely more important than Equity/Fairness

9. Compare the relative importance between *Employment/Training* and *Health & Safety* with respect to **Social** criteria

- 9 Employment/Training is extremely more important than Health & Safety
- 7 Employment/Training is very strongly more important than Health & Safety
- 5 Employment/Training is strongly important than Health & Safety
- 3 Employment/Training is moderately more important than Health & Safety
- 1 Employment/Training and Health & Safety are equally important
- 3 Health & Safety is moderately more important than Employment/Training
- 5 Health & Safety is a strongly more important than Employment/Training
- 7 Health & Safety is very strongly more important than Employment/Training
- 9 Health & Safety is extremely more important than Employment/Training

10. Compare the relative importance between *Cost Saving* and *Consumer Preference* with respect to **Economic** criteria

- 9 Cost Saving is extremely more important than Consumer Preference
- 7 Cost Saving is very strongly more important than Consumer Preference

- 5 Cost Saving is strongly important than Consumer Preference
- 3 Cost Saving is moderately more important than Consumer Preference
- 1 Cost Saving and Consumer Preference are equally important
- 3 Consumer Preference is moderately more important than Cost Saving
- 5 Consumer Preference is a strongly more important than Cost Saving
- 7 Consumer Preference is very strongly more important than Cost Saving
- 9 Consumer Preference is extremely more important than Cost Saving

11. Compare the relative importance between *Cost Saving* and *Research & Development(R&D)* with respect to **Economic** criteria

- 9 Cost Saving is extremely more important than R&D
- 7 Cost Saving is very strongly more important than R&D
- 5 Cost Saving is strongly important than R&D
- 3 Cost Saving is moderately more important than R&D
- 1 Cost Saving and R&D are equally important
- 3 R&D is moderately more important than Cost Saving
- 5 R&D is a strongly more important than Cost Saving
- 7 R&D is very strongly more important than Cost Saving
- 9 R&D is extremely more important than Cost Saving

12. Compare the relative importance between *Consumer Preference* and *Research & Development(R&D)* with respect to **Economic** criteria

- 9 Consumer Preference is extremely more important than R&D
- 7 Consumer Preference is very strongly more important than R&D
- 5 Consumer Preference is strongly important than R&D
- 3 Consumer Preference is moderately more important than R&D
- 1 Consumer Preference and R&D are equally important
- 3 R&D is moderately more important than Consumer Preference
- 5 R&D is a strongly more important than Consumer Preference

- 7 R&D is very strongly more important than Consumer Preference
- 9 R&D is extremely more important than Consumer Preference

13. Outsourcing performance measures

There are many performance measures for outsourcing companies which can be used within the sustainable supply chain. I have listed some of them below. Please indicate whether you agree about each one:

Outsourcing performance measures:

Tick (✓) the relevant boxes in this table		
Performance measure	Yes	No
Cost reduction		
Delivery time		
Customer satisfaction		
Flexibility		
Integration		
Educated employee		
Warehouse capacity		
Transport Capacity		
Information Technology		

If you think there are other performance measures that need to be added to this list or you want to mention some notes, please write them in the note box below:

Notes:

Appendix B

Interview Questions and Sample Transcript

▪ Interview Design and context:

The main aim of conducting semi-structured interviews was to provide an empirical basis for the mathematical model through identifying which KPIs are regarded as essential for sustainable outsourcing in modern food supply chains (specifically from a 4PL/5PL perspective).

To all the 50 experts in the industry, we gave a presentation of 10 essential performance measures which were consolidated from the literature. For each measure, participants were explicitly requested to justify and categorize the indicator into one of the three strict operational priority categories:

Category 1: Very Important (Core objective functions/mandatory constraints in the model)

Category 2: Important (Secondary operational targets or system parameters)

Category 3: Should not be Considered (Excluded from the final model scope)

▪ Semi-Structured Interview Guide(Questions):

Section 1: Economic and Operational Indicators

Cost Reduction: How critical is total logistics cost reduction when choosing to outsource to a 4PL or 5PL provider? Under what conditions would you prioritize other metrics over pure cost?

On-time Delivery: How do you rank on-time delivery constraints against environmental constraints (like carbon caps) during peak demand cycles?

Inventory Management: Does inventory velocity across storage nodes play a primary or secondary role when shifting toward a digitalized 5PL network?

Section 2: Social and Environmental Sustainability Indicators

Social Responsibility: To what extent should social criteria such as driver fatigue, community disruption, and ethical labour be explicitly built into routing optimisation software?

Environmental Impact: Given tightening greenhouse gas (GHG) regulations, does tracking and limiting transport emissions represent a mandatory "Very Important" constraint, or is it treated as a compliance secondary target?

Sustainable Ingredients: From a logistics coordination perspective, how critical is the validation of sustainable sourcing origins during multi-facility transfers?

Local Sourcing: Does your outsourcing framework intentionally prioritize local transportation loops over extended, cheaper international routes to satisfy regional sustainability expectations?

Section 3: Technology, Visibility, and Risk Indicators

Traceability & Transparency: Why is end-to-end data traceability increasingly categorized as "Very Important" by advanced logistics operators? How does it affect your willingness to accept higher upfront setup costs?

Customer Satisfaction: How directly is your customer retention level linked to the real-time visibility provided by your logistics integrators?

Quality & Risk Management: How do you assess non-deterministic risks (such as perishability, cold-chain failures, and route disruptions) when establishing multi-modal transportation relationships?

▪ Sample Transcript

Interviewer: Let us look at the intersection of technology and sustainability. In our matrix, I need you to categorize Traceability & Transparency and Environmental Impact.

Participant: "Without a doubt, both must go straight into Category 1 (Very Important). For a 5PL operating as a 'Control Tower' in the food sector, transparency is not a luxury anymore. If we cannot guarantee an immutable trace of the cold chain, the risk of food spoilage and regulatory fines is too high.

The same goes for Environmental Impact. With carbon cap-and-trade policies changing rapidly, optimizing for cost reduction alone is a massive risk. We have to treat emission tracking as a hard mathematical constraint. If a route drops our emissions but raises costs slightly, the model must still favour it to avoid long-term penalties."

Interviewer: Understood. Now, where would you place Inventory Management or Local Sourcing in this framework?

Participant: "I would mark Inventory Management as Category 2 (Important). It matters for liquidity, but our 4PL partners handle the physical tracking; as a 5PL, we care more about the system-wide visibility and on-time delivery."

Local Sourcing is tricky. While it has great sustainability benefits, in our specific multi-tier food distribution setup, complete local sourcing is not always mathematically feasible due to seasonal supply limits. So, for this specific network architecture, it 'Shouldn't be Considered' as a mandatory optimisation driver (Category 3), but rather managed as a flexible variable."

▪ **Distribution of Participant Priorities for Performance Measures (N = 50)**

Performance Measure	Category 1 Very Important	Category 2 Important	Category 3 Should not be considered
Cost Reduction	42	8	0
On - time Delivery	47	3	0
Inventory management	14	36	0
Social Responsibility	9	27	14
Environmental impact	10	38	2
Traceability & Transparency	23	27	0
Customer satisfaction	19	31	0
Sustainable Ingredient	3	17	30
Quality & Risk management	31	19	0
Local sourcing	0	12	38