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Designing a circular dual channel fish supply chain network considering sustainability: A case study

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ABSTRACT

Due to the increasing demand for seafood products driven by global population growth, the significance of supply chains, particularly for fish, has been greatly emphasized. This increase in food demand has affected the environment and raised significant environmental concerns. To tackle these issues, the circular economy (CE) and sustainability have been introduced. However, the literature shows that no study has focused on the circular fish supply chain considering sustainability dimensions. Therefore, this research presents a comprehensive study that designs a circular dual-channel fish supply chain (CDCFSC) network with sustainability pillars which is its main contribution. The proposed model is a multi-product, multi-period, multi-objective mixed-integer linear programming (MOMILP) framework that aims to maximize total profits and social impact while minimizing environmental impact. Moreover, the robust fuzzy programming (RFP) method is utilized to manage the uncertainties arising from the dynamic nature of the business environment. To solve the proposed multi-objective model, a novel solution procedure named Fuzzy Multi-Choice Chebyshev Goal Programming with Utility Function (FMCCGP-UF) is developed. To demonstrate the application of the developed framework, this research investigates a case study on a fish packaging plant in Amol, Iran. In addition to the novelties of this study, investigating discounts on the online channel and illustrating various eco-friendly packaging methods in plants within the fish supply chain are other innovations of this work. Based on the case study's findings, some fish farms and packaging centers were selected and established, along with various packaging methods. Furthermore, Sensitivity analysis highlights a 20% increase in transportation costs alongside a corresponding 25% income boost (approximately 2,000,000,000 Rials) within a circular supply chain design. These findings emphasize the sustainability and CE dimensions in uncertain fish supply chain design. Additionally, sensitivity analyses show that a 30% increase in demand amplifies social impacts, while CO_2 emissions rise during transportation. Purchasing costs increase by 20%, offset by a 34% income gain. Conversely, a 30% increase in the discount rate leads to an 86% rise in demand and a 43% increase in income, resulting in overall profit growth. In the end, managerial insights conclude this work.

1. Introduction

Today, with the global population increasing, the demand for food has significantly risen. Seafood, which is an essential part of people's diets and one of the most popular food groups, is no exception (Cai & Leung, 2017). Based on the 2024 edition of the State of World Fisheries and Aquaculture (SOFIA), global fisheries and aquaculture production experienced a significant increase in 2022, reaching 223.2 million Tonnes which is an impressive 4.4 percent increase compared to 2020 (Mojumder, 2024). On the other hand, despite the looming seafood shortage, McKinsey & Company's research predicts a 14 percent increase in global seafood demand by 2030 (Galler, 2023).

The fish supply chain, a key part of the seafood supply chain (SSC), encompasses a series of activities including production, processing, distribution, and sales of fish, from harvesting to reaching the consumer (Gopal, 2021). This typically involves various entities such as fish farms, processing plants, distributors, wholesalers, retailers, and consumers. With the increasing demand for fish in recent decades, occupations such as fish farmers and fishermen have ramped up their production and harvests. Meanwhile, processing plants have focused on producing more diverse products, and fish suppliers are seeking to boost fish supply. These activities primarily lead to increased financial flows, information

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exchange, and product movement within the chain. However, this process has also led to a significant amount of fish waste, which poses environmental problems (Fasihi et al., 2023). It should also be considered that if fish are not harvested appropriately, this process may damage animal species. Therefore, managing and controlling these flows is highly important. Nowadays, the most important environmental challenge of food supply chains is to manage and reduce waste (Luo et al., 2022; Pimentel et al., 2022). Reducing food waste is of paramount importance for several compelling reasons. As highlighted by the World Resources Institute, approximately one-third of the global food supply is lost or wasted between farm and consumer, resulting in a staggering 1 billion Tonnes annually (Goodwin, 2023; Krishnan et al., 2022). This wastage not only adversely affects human health and nutrition but also exerts significant economic and environmental pressures (Seberini, 2020). Financially, the toll is immense, with wasted food costing the global economy over $1 trillion each year (Footprint, 2014; Slorach et al., 2019). Furthermore, food loss and waste play a substantial role in climate change, contributing to a significant portion of global greenhouse gas emissions, estimated to be between 8 % and 10 % (Munesue et al., 2015). Alarming projections indicate that if current trends persist, food loss and waste will double by 2050 (Hashemi, 2024). By proactively addressing this challenge, product shelf life can be extended, profit margins can be safeguarded, consumer confidence can be fostered, and more people can be nourished while conserving precious resources (Orla & Sabrina, 2023).

Fish, as a valuable protein source, is currently cultivated in various types of aquaculture facilities. These include open-water cages, near farmlands, and isolated pools. The choice of method depends on whether the fish are cultured in cold or warm water environments (Weatherley & Cogger, 1977). However, regardless of the cultivation method, once any fish species is harvested, its fins, scales, bones, viscera, and skin are discarded before the fish reaches the consumer market (Alfio et al., 2021). Of the total fish harvests, about two-thirds are estimated to be discarded as waste, leading to significant economic concerns, which are higher than the average of most food (Coppola et al., 2021). As a result of this issue, several crises such as environmental destruction and pollution, as well as public dissatisfaction, may occur. As highlighted in the preceding paragraph, waste reduction, particularly within the food industry, has become increasingly critical in recent years (Beheshti & Heydari, 2023). The management of fish waste, akin to other forms of food industry waste, holds significant importance due to its far-reaching economic and environmental implications (Coppola et al., 2021). Therefore, the best way to deal with these crises is to use an approach that produces the least amount of waste. A method is more desirable when the amount of waste produced throughout the method is closer to zero (Shahsavani & Goli, 2023). In this regard, sustainable supply chain management (SCM) is one of the well-known approaches to deal with the mentioned issues. In general, sustainable SCM aims to incorporate the economic, environmental, and social aspects into the logistics activities, simultaneously (Alkan & Kahraman, 2024; Dehshiri & Amiri, 2024b).

On the other hand, another concept that has taken the attention of researchers is the CE which has become important in business nowadays as it promotes a circular flow and efficient utilization of resources through technological advancements to enhance sustainability practices (Lu et al., 2024). CE presents a fresh approach to production and consumption, emphasizing the principles of recycling, reuse, and remanufacturing (3Rs) systematically for organizations (Lopes de Sousa Jabbour et al., 2018). By implementing a supply chain loop, CE assists organizations in optimizing their use of resources such as materials and energy, thereby enhancing their triple bottom line (Khokhar et al., 2022). Adopting CE practices not only leads to environmental advantages by reducing production waste but also yields social and economic benefits through material savings and job creation (Lu et al., 2024; Schaltegger et al., 2012). Along with the concept of CE, we are now faced with a new concept called circular supply chain. A circular supply chain is an integration of the forward supply chain and reverse logistics. Overall, this concept has been developed to create unity in the systems to increase sustainability and aims to minimize waste while improving resource availability (Farooque et al., 2019; Meier et al., 2023).

The emergence of the coronavirus pandemic has significantly influenced consumer behaviors and prompted fundamental changes in the supply chain (Ghosh et al., 2024). The impact of COVID-19 and the activities aimed at controlling its spread have led to an increase in consumers' online shopping and motivated numerous manufacturers to move toward online product sales (Khodoomi et al., 2023). In 2019, a significant majority of US consumers (81 %) had not yet ventured into online grocery shopping, according to Forbes (2020). However, the landscape shifted dramatically with the onset of the COVID-19 pandemic. By 2020, 79 % of US consumers had embraced online grocery orders. During this period, online grocery sales in the US surged from 1.2 billion USD in August 2019 to an impressive 7.2 billion USD in June 2020 (Morgan, 2020; Tyrväinen & Karjaluoto, 2022). In Iran, the practice of purchasing FMCG (Fast-Moving Consumer Goods) products online was relatively uncommon due to cultural preferences for in-person shopping at local markets and limited familiarity with smart applications. However, the COVID-19 pandemic prompted a significant shift, causing most services to transition online. As a result, various platforms, including Digi-jet, Okala, Tapsi, and Snapp, began offering online grocery sales (Comparison of FMCG Products of Snapp, Tapsi (Golrang Group) and Digikala Online Supermarkets, 2024). Based on the statistical reports, the grocery delivery market in Iran is projected to experience a revenue growth of 28.4 % in 2025, with an estimated market volume of US$0.68 billion in 2024. On the other hand, Fig. 1 illustrates the projected growth of the online user base in Iran's Grocery Delivery market, expected to reach 12.4 million users by 2029. This figure is crucial as it highlights the significant market expansion (Jocelyn et al., 2024). This growth is mirrored in the increasing popularity of selling FMCG products, such as fish through online channels, offering customers the convenience of choosing from a diverse range of products (Bhakat & Arif, 2021). Online purchasing not only saves consumers valuable time but also allows them to benefit from discounted prices (Bucko et al., 2018). Furthermore, online platforms provide streamlined transactions that enable customers to place orders, compare prices, and enjoy doorstep delivery—all with just a few simple clicks (Li, Mirosa, & Bremer, 2020). During the pandemic, many FMCG product sellers shifted their focus to online sales through websites and applications. As the pandemic subsided, these sellers resumed in-person sales while maintaining their online presence (Gündeş et al., 2023; Jensen et al., 2021). Concurrently, the rapid progress of the internet has captured the interest of many suppliers to open an online channel alongside the traditional channel to engage directly in the marketplace. The distribution arrangement that encompasses these channels together is called a dual-channel supply chain (Askarian-Amiri et al., 2021). Additionally, utilizing discounts is an effective method for maximizing profit in the closed-loop supply chain, and its implementation could align the model more closely with real-world scenarios (Chaharmahali et al., 2022). In contemporary business practices, the adoption of dual-channel sales networks has significantly enhanced market contributions. These networks effectively address customer demands across both face-to-face and online channels (Rezakhanlou & Mirzapour Al-e-Hashem, 2024; Zhang et al., 2021). Moreover, during crises such as the COVID-19 pandemic, when physical markets may close, or during periods of internet disruptions when online platforms are inaccessible, having a dual-channel sales network enhances system flexibility and resilience (Hsieh & Lathifah, 2024).

Given the discussion above, it is evident that with the increasing demand for fish and fish-based products, live fish suppliers seek to expand their supply, producers aim to increase production, and logistics companies focus on boosting transportation activities. This surge in production and logistics activities has resulted in heightened environmental pollution, including increased CO_2 emissions and waste

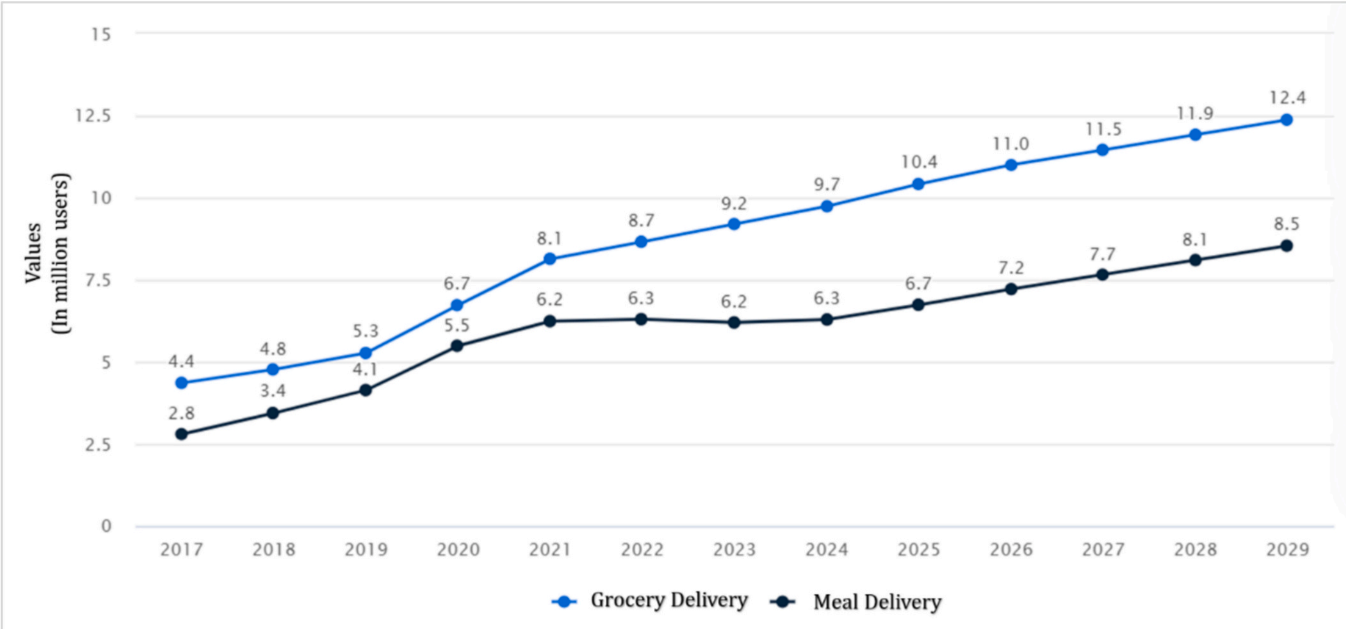

Fig. 1. Number of online users of Grocery Delivery markets in Iran (Jocelyn et al., 2024).

generation. Therefore, effective management of the fish supply chain network is of critical importance, as it allows for the control of financial flows, CO_2 emissions, and decision-making regarding generated waste. Based on the issues discussed in this introduction concerning the food supply chain, the following questions arise:

1. What constitutes a sustainable fish supply chain, and how it can simultaneously optimize economic, environmental, and social dimensions?
2. How does the CE operate within a circular supply chain, and how does it impact the improvement of a sustainable fish supply chain?
3. To what extent will a dual-channel sales network with discounts in the fish supply chain be profitable?

Also, based on the challenges that fish supply chains are facing today, some major objectives must be considered in new fish supply chains, which are written below:

1. Increase income while meeting customer demand.
2. Employ a suitable strategy that manages fish waste properly and maximizes income.
3. Minimize environmental issues such as CO_2 emissions.
4. Optimize social aspects in the fish supply chain.
5. Consider discounts in the online channel of the dual-channel fish supply chain network.

To the best of our knowledge, no single study has comprehensively addressed these questions or encompassed all the emerging objectives related to fish supply chains. While some research has explored sustainable fish supply chains and closed-loop systems, there remains a gap in the literature concerning dual-channel networks that incorporate discounts within the online selling channel. To provide an exhaustive response to these questions, this research presents a sustainable circular fish supply chain network with a dual selling channel considering discounts, involving the economic, social, and environmental elements of sustainability, indicating the major contribution of this study. Moreover, based on the problem description, four main goals (i.e. maximizing profit, eco-friendliness, and social aspects, and minimizing carbon emissions) are considered in this research. Also, to bring the problem closer to reality, the uncertainty of the parameters is accounted for in this research. Regarding this, a multi-period, multi-product, MOMILP robust fuzzy model is proposed to address the main objectives of this problem, formulated as three objective functions (OFs) (i.e. maximizing profit, optimizing environmental aspects, and maximizing social aspects) in the mathematical model. Then, the uncertainty of the model is dealt with by applying the RFP method. To highlight the innovation of this study, it is notable that the fish supply chain presented in this research is the first of its kind to consider sustainability and CE aspects simultaneously, while also including parameter uncertainty. Finally, a case study is presented, and the multi-objective problem is solved using a novel approach called FMCCGP-UF.

The rest of the paper is structured as follows: Section 2 includes the research background, a review of related literature, and a critical assessment of the literature. In Section 3 the framework of study, assumptions, and the suggested model are discussed. In Section 4 the uncertainty modeling is described. The solution approach is given in Section 5. The computational results provided in Section 6, include a real-life case study, the numerical results of the study, and sensitivity analyses. Finally, Section 7 presents the conclusions and implications.

2. Literature review

This section of research is dedicated to three parts: research background, related works, and research gaps. Initially, the research field is introduced by discussing fundamental concepts and theories that underpin the investigation. Subsequently, prior studies in the field are meticulously reviewed, identifying their contributions and gaps through a critical assessment. To aid readers in grasping key points, a summary gap table is provided. In the end, the research gaps are summarized based on the preceding gap table.

2.1. Research background

In this section, the concepts of sustainable supply chains, circular economies, and dual-channel networks are explored, as the basis of this research.

2.1.1. Sustainable supply chain

In contemporary business practices, the vitality of a sustainable supply chain cannot be overstated. It integrates economic, environmental, and social factors to ensure the long-term viability of organizations. Sustainability, in this context, refers to the ability to meet present needs without compromising the ability of future generations to meet their own needs (Pourmehdi et al., 2021). Separate explanations of sustainability aspects are provided below, emphasizing their significance.

1. Environmental Aspect: Companies adopting sustainability focus on minimizing resource use, reducing waste, and implementing eco-friendly processes (Shaikh et al., 2024). For example, they may source local raw materials to cut transportation emissions, invest in energy-efficient technologies, and establish recycling initiatives.
2. Social Aspect: Ensuring fair labor practices, safe working conditions, and community well-being are essential. Additionally, the ethical treatment of workers, diversity, inclusion, and community engagement play key roles in sustainability (Prasanna et al., 2024).
3. Economic Aspect: Balancing profitability and responsible practices is challenging. Companies achieve this by optimizing supply chain processes, reducing costs through efficiency gains, and investing in sustainable innovations (Pourmehdi et al., 2020).

2.1.2. CE

The CE strives to minimize waste by designing products for reuse, remanufacturing, and recycling. It focuses on eliminating waste and pollution, circulating products and materials, and regenerating nature (Bandh et al., 2024; Dehshiri et al., 2022). By adopting these principles, adaptable and resilient supply chains are created, while global challenges like climate change and waste are addressed (Bandh et al., 2024). These concepts are prevalent in the following supply chains:

1. Reverse Logistics: Efficiently managing returns, repairs, and recycling is a critical issue that can be managed by reverse logistics (Paydar & Olfati, 2018). Companies applying reverse logistics require robust processes for handling returned products, refurbishing them, and reintroducing them into the market (Pishvaee et al., 2010).
2. Closed-Loop Supply Chain: In a closed-loop supply chain, products are intentionally designed to re-enter the supply chain after use (Pishvaee & Torabi, 2010). For instance, smartphone manufacturers might create phones with easily replaceable components, thereby extending their lifespan. In fact, the closed-loop supply chain is a combination of forward and reverse logistics (Dehshiri et al., 2023; Dehshiri & Amiri, 2024a).
3. Circular Supply Chain: This strategy closely resembles the closed-loop supply chain, but its primary goal is to achieve zero waste. In contrast, the closed-loop supply chain may retain waste, whereas the circular approach focuses on minimizing waste rather than disposing of it, aiming to extract added value from it (Farooque et al., 2019; Romero, 2001).

2.1.3. *Dual-channel networks*

In recent years, dual-channel networks have gained prominence as a strategic approach for businesses seeking to optimize their distribution channels. These networks involve simultaneous distribution through both online and physical stores (Barzinpour & Taki, 2018). Dual-channel networks offer resilience, flexibility, and extended reach for businesses (Gao et al., 2022). The COVID-19 pandemic accelerated the adoption of dual-channel networks. As lockdowns and social distancing measures restricted physical store operations, businesses turned to online channels to survive. Businesses had to swiftly adapt to this new reality (Sato et al., 2023). Those without an established online presence scrambled to set up e-commerce platforms. As a result, dual-channel adoption became a survival strategy, allowing businesses to continue serving customers despite physical store closures. Also, Consumers shifted their preferences toward online shopping during the pandemic, driven by safety concerns, convenience, and the closure of physical stores (Sato et al., 2023). Dual-channels are mostly being used based on following reasons.

- Increased Reach: By operating across both online and offline channels, companies can effectively reach diverse customer segments (Schweidel et al., 2022). Online channels cater to tech-savvy consumers who prefer the convenience of digital shopping, while physical stores serve those who value in-person experiences (Brüggemann & Pauwels, 2024). Additionally, the synergy between these channels allows businesses to tap into broader markets and engage with customers through their preferred touchpoints (Chen et al., 2022).
- Risk Diversification: Relying solely on a single channel can expose businesses to significant risks. Market fluctuations, supply chain disruptions, or sudden shifts in consumer behavior can impact revenues. Dual-channel networks mitigate this risk by diversifying revenue sources (Li, Zheng, & Liu, 2020). When one channel faces challenges (e.g., supply chain disruptions during the pandemic), the other channel can compensate, ensuring business continuity (Fu et al., 2021).

2.1.4. *Food supply chains*

The food supply chain encompasses essential activities associated with the supply, production, processing, transportation, and sale of food (Bourlakis & Weightman, 2008). The majority of food items either originate from agriculture or result from livestock farming (Godde et al., 2021; Routroy & Behera, 2017). Since this research investigates various types of agriculture, livestock, seafood, and especially fish supply chains, this part is dedicated to introducing them. In the subsequent sections, the key stages within these supply chains are briefly outlined.

1. *Agricultural Supply Chain:* The agricultural supply chain involves crucial steps, starting with production on the farm. After harvesting, the produce is packaged, graded, and transported to intermediate silos. Storage and warehousing facilities hold the goods, which then undergo processing and value addition. Finally, distribution ensures that the products reach clients or end customers. This intricate network requires careful decision-making and can benefit from digital and analytics technologies. Citrus, fruits, vegetables, seeds, and dairy are some examples of agriculture supply chains (Bhagat & Dhar, 2011; Routroy & Behera, 2017).
2. *Livestock Supply Chain:* The livestock supply chain involves several essential steps. It begins with breeding and the birth of livestock, such as cattle, pigs, or poultry, which farmers raise on their farms. These animals are fed, nurtured, and monitored for growth and development. When ready, they are transported to slaughterhouses or processing plants, where they are humanely slaughtered. The meat is then processed into various cuts, packaged, and labeled. Finally, the processed meat products are distributed to wholesalers, retailers, and food service outlets, involving transportation, storage, and inventory control (Houshyar et al., 2023; Staal, 2015).
3. *SSC:* The SSC involves several stages. Production encompasses fishing, aquaculture, and farming to obtain seafood. Processing includes operations such as washing and cleaning, chilling, filleting, and cooking the seafood. Distribution moves the processed seafood to retailers, wholesalers, and other outlets. At the retail level, seafood is purchased by consumers. Once purchased, seafood enters the consumption phase, where people enjoy it in various forms (Abedi & Zhu, 2017; Kelling et al., 2023).

2.2. *Related works*

This section is dedicated to reviewing the related literature in five parts: (1) SSC, (2) Sustainable/Circular Food Supply Chain, (3) Sustainable/Circular SSC, (4) Dual-Channel Supply Chain (DCSC), and (5) Critical Assessment of the Existing Research.

2.2.1. SSC

- *SSC (Except Fish)*

Rani et al. (2024) investigates the application of blockchain technology in seafood SCM. By addressing challenges such as fraud, inefficiencies, and lack of trust among stakeholders, the research proposes a blockchain-based dynamic contract, providing flexibility and security. The study provides an extensive survey of existing literature, comparing various approaches. Notably, it emphasizes the potential of blockchain to improve transparency, sustainability, and efficiency within SSCs. Bharathi et al. (2024) proposes a Blockchain-based framework for seafood SCM. By integrating technology-organization-environment (TOE) theory, situation-actor-process (SAP), and learning-action-performance (LAP) models, the transformative potential of Blockchain is emphasized by the authors. Key benefits of this research include enhanced data efficiency, transparency, and sustainability across the SSC while addressing challenges such as data accuracy, stakeholder involvement, cybersecurity, and cost-effectiveness.

- *Fish Supply Chain*

In Bassett et al. (2022), it has been said that the COVID-19 pandemic disrupted SSCs globally, leading to shortages of food and impacting livelihoods. By examining various case studies from different countries, vulnerabilities in small-scale fishery supply chains are highlighted by the study. Key findings suggest that diversifying distribution strategies, developing local markets, and reducing reliance on international markets can enhance the resilience of SSF to future shocks. Bunkar et al. (2024) explores the economic dimensions of cold-water fisheries, emphasizing sustainable practices. Cost-benefit analyses, market dynamics, and economic incentives for conservation are covered. Additionally, the role of subsidies, pricing mechanisms, and policy interventions in promoting responsible fishery management is discussed. This research underscores the need for balancing economic viability with ecological considerations to ensure long-term benefits for both fishers and the environment.

2.2.2. Sustainable/Circular food supply chain

This sub-section is dedicated to analyzing recent studies on sustainable and circular food supply chains, or CE in food supply chains, which are categorized as "Agriculture" and "Livestock" supply chains.

- *Sustainable/Circular Agriculture Supply Chain*

Alinezhad et al. (2022) tackled the design of a circular supply chain with sustainability metrics. A model with two objective functions was proposed to manage unpredictable demands and return rates of products. Additionally, a case study was conducted in the dairy industry to demonstrate the validity of the problem. The model aimed to boost supply chain earnings and customer happiness. Additionally, the carbon footprint was considered as a cost item that impacted profits, addressing environmental concerns. In the end, fuzzy linear programming and the Lp-metric method were applied to address the model's uncertainty. Krishnan et al. (2022) suggested an integrated robust model aimed at designing a food supply chain network that encompassed economic, social, and environmental sustainability, alongside valorizing food waste and supply uncertainty. The model presented in this study incorporated three OFs, focusing on minimizing greenhouse gas emissions while maximizing profit and job opportunities. This model solved a real scenario involving the Indian mango pulp supply chain and offered valuable insights for steering the food supply chain toward sustainability. In Goodarzian et al. (2023), the focus was placed on designing a citrus supply chain, encompassing production, distribution, inventory control, recycling, and locational decisions, with an emphasis on sustainability and circularity strategies to uphold the triple bottom lines. A new MOMILP model was developed to tackle the complexities of designing a sustainable citrus closed-loop supply chain network with multi-period and multi-echelon. In this study, the epsilon-constraint approach and two *meta*-heuristics algorithms were employed to solve the problems. Gholian-Jouybari et al. (2024) introduced a novel decision-making model for designing an agri-food supply chain tailored to the coconut industry, with a focus on sustainability. The research addressed the complexities of a closed-loop supply chain that integrated both reverse and forward flows. The study introduced a new optimizer, the multi-objective artificial rabbit optimizer, and evaluated their performance. Shahsavani et al. (2024) delved into a circular supply chain network specially tailored for citrus fruits, aligning with the principles of the CE that combines closed and open loops. The study utilized both exact and *meta*-heuristic methods to tackle the intricacies of the model.

- *Sustainable/Circular Livestock Supply Chain*

Schmidt & Moreno (2022) aimed to optimize three crucial OFs: minimizing operational costs, carbon emissions, and batch dispersion. To handle trade-offs among various supply chain performance indicators, a goal programming (GP) method was implemented to minimize deviations from desired goals. Remarkably, a case study for the meat industry demonstrated the benefits of this formulation. Najafi & Zolfagharinia (2024) developed a mathematical model with three sustainability objectives to integrate production product distribution, planning, and supplier selection decisions in a meat supply chain. Also, a solution approach based on the normalized normal constraint method was developed to obtain the optimal result. The model and methodology were applied to a case study in Ontario, Canada, showing that diverse and practical optimal solutions could be achieved, enhancing social and environmental aspects at a minor extra cost.

2.2.3. Sustainable/Circular SSC

This sub-section addresses relevant studies of sustainable or circular SSCs are reviewed in "Circular SSC (Except Fish)" and "Circular Fish Supply Chain" sections, since this research is about sustainable circular fish supply chains.

- *Sustainable/Circular SSC (Except Fish)*

Mosallanezhad et al. (2021) highlighted the importance of the shrimp supply chain, considering factors like high consumer demand, fluctuating market prices, and the variety of fishery or aquaculture sources. The study presented the shrimp supply chain as an interconnected system, involving distribution hubs, wholesalers, facilities to process shrimp, markets, units to produce powders out of shrimp, and shrimp powder marketplaces. In this study, a mathematical model was proposed to optimize the overall cost efficiency across the entire supply chain. Meta-heuristic methods were employed to address the computational complexity of the shrimp supply chain model. Furthermore, the model's strength was checked through an application featuring 15 test problems. Mosallanezhad et al. (2023) focused on developing a supply chain network for fresh seafood with an emphasis on sustainability and waste product recycling. The study aimed to minimize total costs while maximizing the application of shrimp waste. Meta-heuristic methods were employed to address the computational complexity of exact solution methods. In Hopkins et al. (2024), blockchain technology ensured supply chain traceability and transparency, while focusing on SSCs' global trade complexity and varying traceability levels, which emphasized the importance of a robust traceability system for ensuring sustainability. By comparing traceability performance, the research suggested technological improvements, processes, and systems for enhancing traceability in the seafood sector.

- *Sustainable/Circular Fish Supply Chain*

De et al. (2022) introduced a mixed-integer linear programming (MILP) model, designed for a Norwegian salmon supply chain network. The objective was to minimize fuel costs from various transportation methods while adhering to restrictions on carbon emissions. The study's robustness was validated through testing with various problem scenarios. Additionally, a real-world case study involving a Norwegian salmon exporter demonstrated the model's practicality. The paper emphasized the significance of optimizing food supply chains by discussing the influence of different supply chain arrangements on overall costs, including fuel costs and carbon emissions. Purnomo et al. (2022) sought to develop a mathematical framework for assessing the fish closed-loop supply chain, taking into account carbon emissions from transportation, production, and warehouse operations. A mathematical model was used to minimize total costs, including transportation costs, traceability costs, emission costs, production costs, and inventory costs. The study verified the proposed model through a numerical example and provided insights for industry management. The idea of Tseng et al. (2022) was to develop a comprehensive framework for analyzing the seafood industry in Vietnam to improve its overall performance. This proposed framework encompasses five key aspects and 21 specific criteria, which were primarily based on qualitative information. To effectively apply the complexity and uncertainty inherent in linguistic preferences, fuzzy set theory was utilized. Additionally, the reliability and validity of the attributes were tested using the fuzzy Delphi method. In (Fadeeva & Van Berkel, 2023), the relevance of the CE for achieving sustainable food systems is examined, with a focus on seafood value chains. Countries like Peru, China, the USA, Indonesia, and India play significant roles in fish supply. To enhance resource efficiency, develop sustainability, and contribute to the value chain, the CE approach offers fresh perspectives, which are operationalized through resource switch (using renewable and less harmful inputs), resource efficiency (minimizing losses in processing and distribution), and resource circularity (recovery and reuse of materials, including plastics). Fasihi et al. (2023) investigated a sustainable closed-loop supply chain for fish that concentrated on waste product recycling and the optimization of production rates. The study suggested a multi-objective mathematical model that optimized production rate while considering total costs, social issues, and environmental effects. Various algorithms were employed for solving the model, including exact, *meta*-heuristic, and hybrid *meta*-heuristic approaches. A case study involving a trout supply chain in Iran was examined, and the LINGO software was used to evaluate algorithm performance under different levels of uncertainty. John & Mishra (2024) proposed a sustainable tuna fish supply chain model with quality levels, involving a farmer, processor, and retailer. The processor stage used fish waste technology, seaweed bioplastic packaging, and green tech to minimize waste, plastic pollution, and carbon emissions.

2.2.4. Dual-channel supply chain

In this section, recent studies regarding DCSC are reviewed. For example, Askarian-Amiri et al. (2021) examined a leather supply chain network that created a discounted online channel to increase its market presence. The research developed a multi-period, multi-product mathematical model aimed at optimizing profit while evaluating how various discount strategies impact demand and sales. Mirzagoltabar et al. (2021) configured a DCSC, considering the uncertainty of pricing and demand in the lighting industry. The study introduced two innovative, modified hybrid *meta*-heuristic algorithms. The results demonstrated the model's viability for incorporating new product development within the framework of sustainable supply chain network design. Li et al. (2023) provided a model to investigate the effects of real-life online price discounts and diverse cooperative advertising approaches on a dual-channel supply chain that includes a manufacturer and an electronic platform. In this study, products are provided to consumers via a traditional and a digital channel, while the online channel is managed by the electronic platform that charges a commission based on an agency sales model. Mirzaei et al. (2023) presented a sustainable DCSC for the tea industry, designing a MILP model that optimizes costs, CO_2 emissions, and job opportunities. Customer demand in this chain is highly dependent on traditional and digital advertising rates and product prices. Liu et al. (2024) proposed a two-echelon dual-channel supply chain for fresh agricultural products, aiming to assess how sharing information affects the best decisions and to suggest a coordination mechanism for supply chain partners in information sharing. Utilizing Stackelberg game theory alongside backward induction, the research identified optimal decisions under both symmetric and asymmetric information conditions and formulated a coordination contract. Nematollahi et al. (2024) explored the theoretical implications by analyzing competition within multi-factor dependent demand in the household appliance industry. the article conducted a detailed exploration of the interaction among sales services, home delivery services, pricing strategies, and warranty decisions in DCSC.

2.2.5. Critical assessment of the existing researches

The reviewed literature indicates that many studies have been conducted on food and agricultural supply chains. Despite the importance of managing and planning fish supply chains, less research has been conducted in this area, especially considering sustainability factors, compared to other food products. With the growing focus on sustainability, recent studies have primarily aimed at designing sustainable supply chains. As mentioned, sustainability includes three main aspects: economic, environmental, and social. It has been observed that in optimizing the environmental aspect, most studies have only attempted to reduce CO_2 emissions. Additionally, many studies have examined only one or two aspects of sustainability, rather than all three. Furthermore, past research has typically combined CE and sustainability factors by designing only closed-loop sustainable fish supply chains; however, circular supply chains are more effective in managing and reducing waste. Despite the high importance of dual-channel sales networks, only one previous study has considered online sales along with traditional sales channels. However, the effect of discounts on the online channel remains understudied.

For instance, Rani et al. (2024) effectively discussed the integration of blockchain technology in sustainable SSCs. Similarly, Bharathi et al. (2024) provided a thorough evaluation of blockchain's potential in these supply chains. However, both studies fell short in addressing practical challenges in implementation and scalability, particularly in designing a mathematical model. Bassett et al. (2022) considered the dual-channel sales network and the social and economic aspects of sustainability in the fish supply chain, but they overlooked the environmental aspects. Conversely, Bunkar et al. (2024) focused on the economic and social aspects, neglecting the environmental dimensions. While these articles offered valuable insights into the fish supply chain, they didn't fully address all dimensions of sustainability, nor did they utilize mathematical modeling tools. Alinezhad et al. (2022) designed a closed-loop and sustainable dairy supply chain but didn't directly address the social aspects of sustainability, considering environmental aspects only in terms of penalty costs. Similarly, Krishnan et al. (2022) designed a closed-loop supply chain with sustainability aspects for mango pulp, considering parameter uncertainty but not presenting a dual-channel sales network. Goodarzian et al. (2023) studied the citrus market and provided useful information on designing a closed-loop and sustainable food supply chain network. However, they only covered the economic aspect of sustainability by minimizing costs, without considering the impact on incomes. Gholian-Jouybari et al. (2024) offered insights into applying the CE in the sustainable food supply chain for coconut products, but they covered only the economic aspects fully, merely monitoring other aspects. Shahsavani et al. (2024) provided good insights into mixing CE with SCM but didn't consider sustainability. Schmidt & Moreno (2022) designed a meat supply chain considering all aspects of sustainability but ignored CE aspects. Similarly, Najafi & Zolfagharinia (2024) covered all aspects of sustainability in a meat supply chain but didn't consider CE aspects in a forward flow. Mosallanezhad et al. (2021) addressed the CE well in the shrimp supply chain but focused solely on economic aspects, despite the high importance of sustainability. In a later study, Mosallanezhad et al. (2023) proposed a closed-loop and sustainable shrimp supply chain but didn't individually cover the social aspects of sustainability, considering water pollution as both an environmental and a social issue. Hopkins et al. (2024) provided good insights into traceability in an SSC but didn't apply mathematical modeling. De et al. (2022) presented a sustainable fish supply chain but didn't individually cover the social aspects of sustainability, applying environmental aspects as a penalty cost and ignoring CE aspects. In Purnomo et al. (2022), a sustainable fish supply

Table 1
Comparison of the proposed study with related studies.

Paper	Supply Chain Structure				Circular Economy	Sustainability			Dual-channel	Uncertainty	Case study	Methodology / Solving software
	Forward	Reverse	Closed-Loop	Circular		Eco	Env	Soc				
Askarian-Amiri et al. (2021)	*				–	*	–	–	*	–	Leather	LINGO
Mirzagoltabar et al. (2021)			*		*	*	*	*	*	–	Lighting industry	GA, SA, WOA, RDA
Mosallanezhad et al. (2021)			*		*	*	–	–	–	–	Shrimp	GA,SA, KA, HGASA, HKASA
Alinezhad et al. (2022)			*		*	*	*	*	–	*	Dairy industry	FLP, LP_M / CPLEX, GAMS
Krishnan et al. (2022)			*		*	*	*	*	–	*	Mango pulp	Aε-c / CPLEX
Schmidt & Moreno (2022)	*				–	*	*	*	–	–	Meat products	GP, EGP, WGP, MGP/ GAMS
De et al. (2022)	*				–	*	*	–	–	–	salmon	CPLEX
Purnomo et al. (2022)			*		*	*	*	*	–	–	Fish	GA
(Bassett et al., 2022)	–	–	–	–	–	*	–	*	*	–	Fish	Case study research, Virtual interviews
(Fadeeva & Van Berkel, 2023)	–	–	–	–	*	–	*	–	–	–	Seafood	–
Li et al. (2023)	*				–	*	*	*	*	–	–	–
Mirzaei et al. (2023)			*		*	*	*	*	*	–	Tea	MOSA, MOPSO, MOGWO, MOWOA
Goodarzian et al. (2023)			*		*	*	*	*	–	–	Citrus	ε-c, SPEA-II, PESA-II / MATLAB, GAMS
Tseng et al. (2022)	–	–	–	–	–	*	*	*	–	*	–	FDEMATEL, FDM
Fasihi et al. (2023)			*		*	*	*	*	–	*	Trout	NSGA-II, MOKA, MOSEO, MOGASEO, MOKASEO
Mosallanezhad et al. (2023)			*		*	*	*	*	–	–	Shrimp	MOST, MOGWO, MOKA, MOGEO
Liu et al. (2024)	*				–	*	–	–	*	*	–	SGT, BIM
Nematollahi et al. (2024)	*				–	*	–	–	*	–	–	Decentralized, Centralized, and Coordination DM
Gholian-Jouybari et al. (2024)			*		*	*	–	–	–	–	Coconut	MOARO, NSGA-II
Shahsavani et al. (2024)			*		*	*	*	–	–	–	Citrus	E&M
Najafi & Zolfagharinia (2024)	*				–	*	*	*	–	–	Meat	SAHP, TOPSIS
John & Mishra (2024)	*				–	*	*	*	–	–	Tuna fish	PSO / Python
(Rani et al., 2024)	–	–	–	–	–	–	–	–	–	–	Seafood	Blockchain/ JMeter
(Bharathi S et al., 2024)	–	–	–	–	–	*	*	*	–	–	Seafood	TOE, SAP, LAP
(Bunkar et al., 2024)	–	–	–	–	–	*	*	–	–	–	Fish	–
Hopkins et al. (2024)	*				–	*	*	*	–	–	Mackerel, Dover Sole, Lobster	Interviews
This study				*	*	*	*	*	*	*	**Fish**	**FMCCGP-UF / LINGO**

Eco: Economic, Env: Environmental, Soc: Social, GA: Genetic Algorithm, SA: Simulated Annealing, WOA: Whale Optimization Algorithm, RDA: Red Deer Algorithm, KA: Keshtel Algorithm, MOKA: Multi-Objective Keshtel Algorithm, HGASA: Hybrid Genetic Algorithm-Simulated Annealing, HKASA: Hybrid Keshtel Algorithm-Simulated Annealing, LP_M: LP_Metric, ε-c: Augmented Epsilon Constraint, Aε-c: Augmented Epsilon Constraint, GP: Goal Programming, EGP: Extended Goal Programming, WGP: Weighted Goal Programming, MGP: Minmax Goal Programing, MOSA: Multi-Objective Simulated Annealing, MOPSO: Multi-Objective Particle Swarm, SPEA-II: Strength Pareto Evolutionary Algorithm II, PESA-II: Pareto Envelope-based Selection Algorithm II, FLP: Fuzzy Linear Programming Optimization, MOGWO: Multi-Objective Grey Wolf Optimizer, FDEMATEL: Fuzzy DEMATEL, FDM: Fuzzy Delphi Method, NSGA-II: Non-Dominated Sorting Genetic Algorithm II, MOSEO: Multi-Objective Social Engineering Optimizer Algorithm, MOGASEO: Multi-Objective Hybrid GA and SEO, MOKASEO: Multi-Objective Hybrid KA and SEO, MOST: Multi-Objective Tabu Search, SGT: Stackelberg Game Theory, BIM: Backward Induction Method, DM: decision-making, MOARO: Multi-Objective Artificial Rabbit Optimizer, E&M: a set of exact and meta heuristic methods, MOWOA: Multi-Objective Whale Optimization Algorithm, SAHP: Stochastic Analytic Hierarchy Process, TOPSIS: Technique for Order of Preference by Similarity to Ideal Solution, MOGEO: Multi-Objective Golden Eagle Optimizer PSO: Particle Swarm Optimization, MRSPFP: Mixed Robust Stochastic, Possibilistic, and Flexible Programming, BWM: Best-Worst Method.

chain was designed with CE considerations. However, the social aspects were not individually addressed in their study, and environmental aspects were treated as penalty costs. Tseng et al. (2022) provided a comprehensive framework for analyzing the seafood industry, but they didn't include mathematical modeling or simulation to demonstrate the framework's benefits. Fadeeva & Van Berkel (2023) applied CE approaches to the seafood industry but didn't use mathematical modeling to validate these approaches. Fasihi et al. (2023) presented a closed-loop and sustainable fish supply chain, covering only fresh and processed fish products, without addressing live fish demand or dual-channel selling. John & Mishra (2024) proposed a sustainable tuna fish supply chain but didn't specifically consider social aspects or apply CE principles. Askarian-Amiri et al. (2021) considered a dual-channel in the leather market, but their network was designed as a forward flow and didn't apply CE. Mirzagoltabar et al. (2021) designed a sustainable closed-loop supply chain in the light industry with a dual channel but didn't consider parameter uncertainty. Li et al. (2023) provided insights into dual-channels and online discounts but didn't address uncertainty. Mirzaei et al. (2023) considered a sustainable closed-loop citrus supply chain with dual-channel selling but didn't include discounts in the online channel or consider parameter uncertainty. Liu et al. (2024) defined a two-echelon dual-channel supply chain for fresh agricultural products with uncertainty considerations but didn't address CE aspects. Nematollahi et al. (2024) explored the theoretical implications of the agriculture supply chain by analyzing competition within multi-factor dependent demand for the household appliance industry but didn't consider CE or parameter uncertainty.

2.3. Research gaps contributions

The literature shows that few papers have studied circular fish supply chains and their sustainability. Since circular supply chains reduce waste and costs, and sustainability aspects increase profit while optimizing environmental and social issues, the combination of these two concepts in a supply chain improves environmental issues, including reducing waste and pollution, and optimizes the costs of the chain. Considering uncertainty is also very important because uncertainty, especially in parameters like demand, significantly impacts the results. However, considering the ease of online shopping and today's competitive market, the existence of an online sales channel is one of the most crucial elements of any supply chain. Based on the literature, a Circular Fish Supply Chain Network Considering Sustainability (CFSCNS) has rarely been studied by considering a dual-channel for selling products. Thus, it is important to consider a dual-channel in a CFSCNS. Moreover, to the best of our knowledge, uncertainty has not been considered in CFSCNSs before. In this study, a MOMILP model is introduced to establish a sustainable CDCFSC. This model assists in making crucial decisions, such as supplier selection, facility location, and packaging method selection. Additionally, it offers a versatile trade-off analysis to optimize various sustainability levels. However, previous studies have solved various problems in the field of fish supply chains. Analyzing these studies helps us to deal with other existing issues of this field. Therefore, Table 1 highlights the gaps that underscore the significance of this paper. Based on the literature and Table 1, the main contributions and novelties that distinguish this paper from existing studies are summarized as follows:

- This is the first effort to design a multi-period and multi-product circular dual-channel supply chain network by considering the sustainability and CE dimensions under uncertainty for the fish industry.
- This article considers different types of packaging methods, with different production costs and different eco-friendliness rates in fish packaging centers, besides considering CO_2 emission in environmental aspects of sustainability.
- Considering discounts in the online platform, since the concept of discount in the fish supply chain has not been investigated so far, and the effects of discount on online sales in a fish supply chain have not been studied yet.
- Proposing a novel and efficient solution procedure named the fuzzy multi-choice Chebyshev goal programming with a utility function method to solve the suggested MOMILP.

To clarify the research gaps and contributions, we have presented some summarized points about below:

(i) Main Research Gaps.

Few papers have studied circular fish supply chains and the sustainability of a fish supply chain, especially considering the ease of online shopping, competitive markets, and the importance of uncertainty, such as demand uncertainty. The concept of a Circular Fish Supply Chain Network Considering Sustainability (CFSCNS) with dual channels for selling products and incorporating uncertainty has rarely been explored. In summary, the main gaps are:

1. Fish Supply Chains: Limited research on fish supply chains compared to other food products, especially considering sustainability factors.
2. Sustainability Aspects: Most studies focus on reducing CO_2 emissions but often neglect the economic and social dimensions of sustainability.
3. Circular Economy (CE): Previous studies combining CE and sustainability often only design closed-loop supply chains; circular supply chains are more effective in reducing waste.
4. Dual-Channel Networks: Very few studies consider dual-channel sales networks (online and traditional), and the impact of online discounts has not been studied.

(ii) Contributions of This Work.

1. First Effort: Designing a multi-period and multi-product circular dual-channel supply chain network for the fish industry considering sustainability and circular economy (CE) dimensions under uncertainty.
2. Packaging Methods: Including different packaging methods with varying production costs and eco-friendliness, and considering CO_2 emissions in the environmental aspects of sustainability.
3. Online Discounts: Investigating the impact of discounts in the online platform, which has not been studied in fish supply chains before.
4. Novel Solution Procedure: Proposing an efficient solution method named the fuzzy multi-choice Chebyshev goal programming with a utility function to solve the suggested multi-objective mixed-integer linear programming (MOMILP) model.

(iii) Key Comparisons with Related Works.

1. Blockchain Integration: Rani et al. (2024) and Bharathi et al. (2024) discuss blockchain in sustainable supply chains but lack practical implementation and scalability in mathematical models.
2. Dual-Channel Sales Networks: Bassett et al. (2022) and Bunkar et al. (2024) address dual-channel sales networks but do not fully cover environmental or sustainability aspects.
3. Closed-Loop Supply Chains: Various studies (e.g., Alinezhad et al. 2022; Krishnan et al. 2022) design closed-loop supply chains but often miss social aspects or do not address dual-channel networks and uncertainty.
4. Comprehensive Frameworks: Studies like Tseng et al. (2022) and Fadeeva & Van Berkel (2023) provide frameworks and CE approaches but do not use mathematical modeling.
5. Specific Applications: Several articles (e.g., Fasihi et al. 2023; John & Mishra 2024) focus on specific supply chains but miss out on dual-channel considerations, social aspects, or CE principles.

3. Model description

This study proposes a decision-making framework for configuring a sustainable circular fish supply chain. The designed supply chain network consists of both forward and reverse flows. The forward flow includes echelons such as fish farming centers (suppliers), packaging centers, local markets (retailer type 1), physical sales centers (retailer type 2), and an online sales platform. At local markets, the sole product is live fish. By considering the demand of each customer in local markets, the retailer harvests the amount of fish that the customer asks for in kilograms. Conversely, at physical sales centers, there are different kinds of fish packages presented in fixed weights in kilograms and various cuts like fillet, steak, HOG (Head-On, Gutted), and other types, which customers can choose between these products. At the online sales platform, different types of products are presented as at physical sales centers. However, products are offered at a discount on the online platform to encourage purchases, making the price of each product lower than at the physical sales centers.

The reverse flow includes fish meal production centers serving as the recycling echelon. In summary, in this supply chain, live fish are initially transported from fish farms to regional markets and packaging centers. Fish are sold as HOG at regional markets. In packaging centers, live fish are first converted into HOG fish, from which specific products are produced in predetermined sizes and weights. Then, products are dispatched to physical sales centers and online sales platforms. In reverse logistics, the materials remaining as waste at regional markets and packaging centers are sent to fish meal production centers. Following the production of fish meal, it is then sold to fish farms. For developing a circular supply chain, a multi-objective model is proposed, where the first objective function (OF) maximizes the supply chain profit, the second OF optimizes the environmental aspects of sustainability, and the third OF maximizes the social aspects of sustainability. As mentioned, this network is designed for a fish supply chain considering sustainability, CE, and a dual-channel. In the following sections, assumptions and mathematical models of the problem are presented. The framework of this research is presented in Fig. 2, and the network of the study is illustrated in Fig. 3, which respectively outlines the steps of the problem and explains each facility in the network.

3.1. Assumptions

- The configured supply chain is multi-product and multi-period to cover more products and tackle the risk of changing parameters in each period, to make the model more realistic.
- In local markets, the sole product provided is live fish, based on field research.
- The transportation of live fish from fish farms to packaging centers and regional markets is performed by trucks with a tanker that has

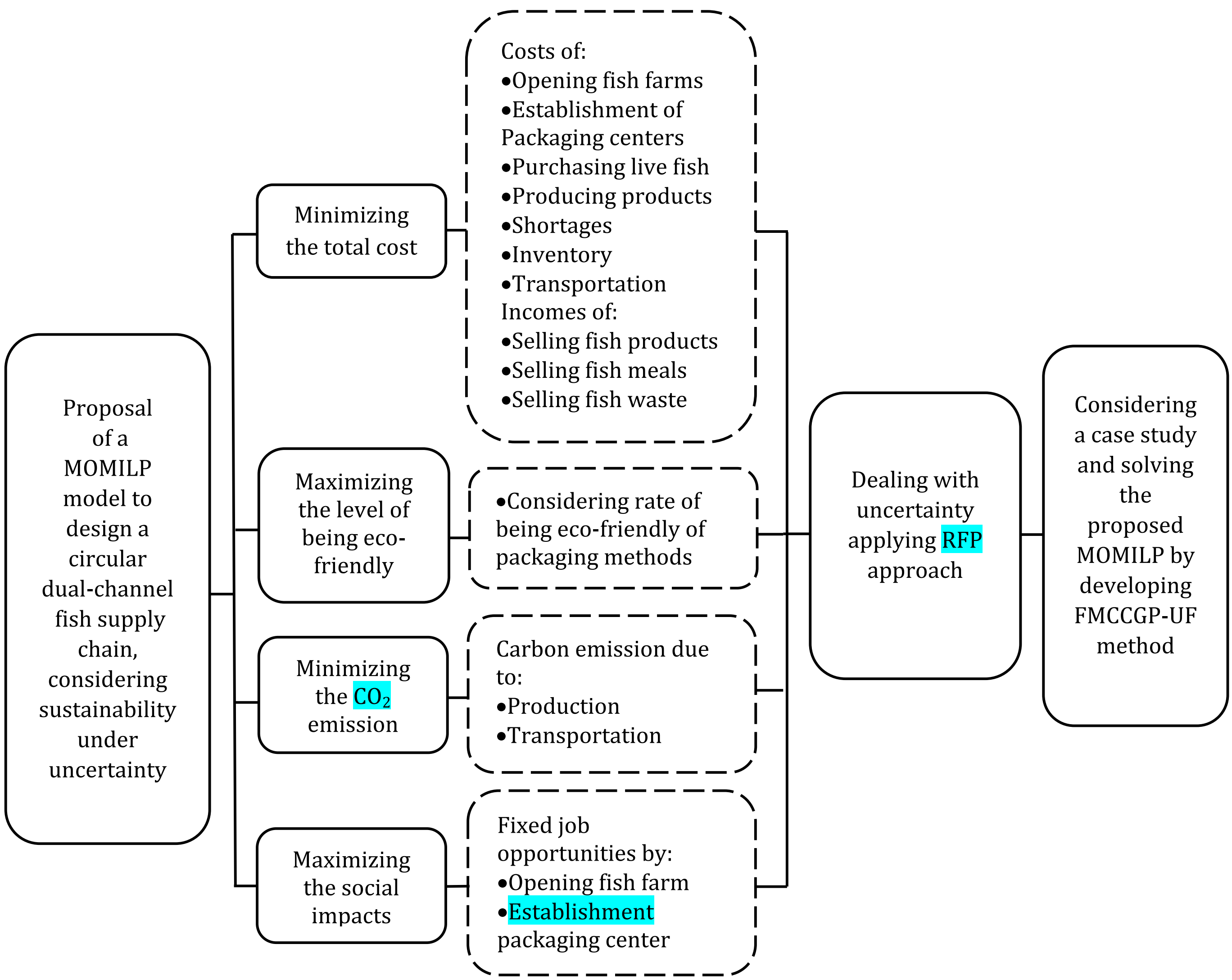

Fig. 2. The research's framework.

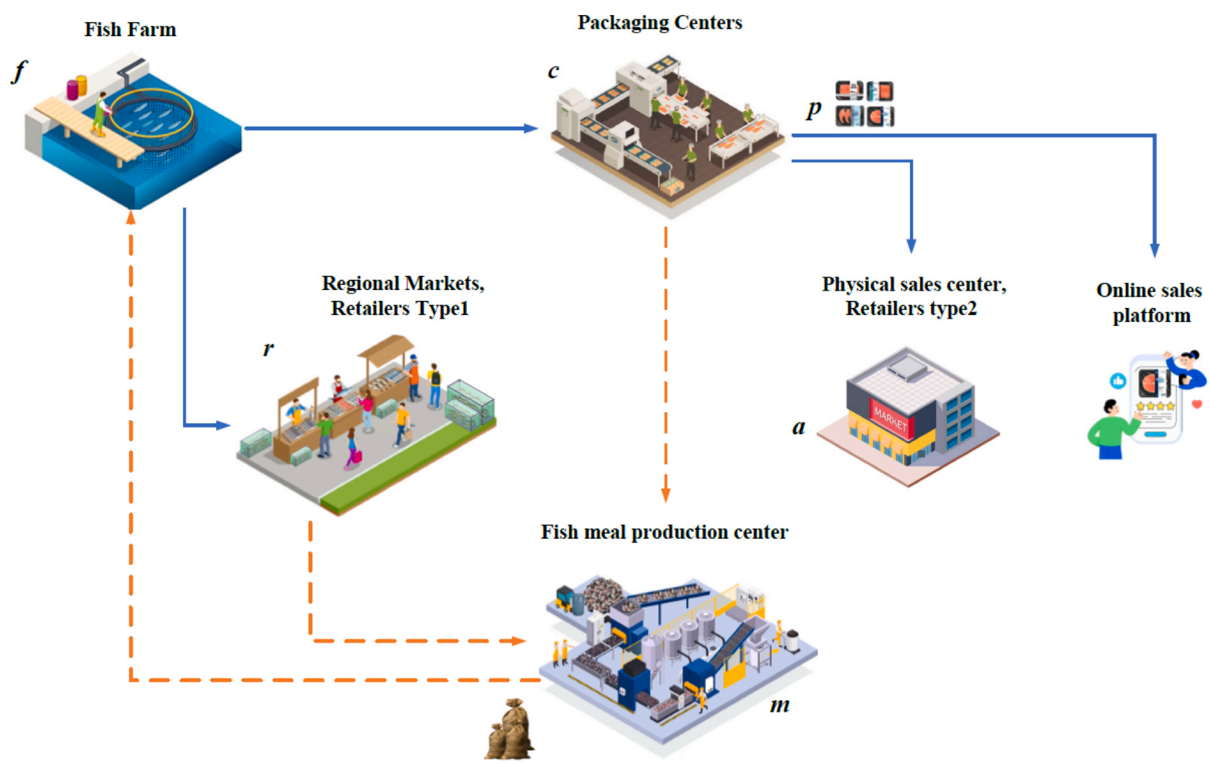

Fig. 3. Network of the supply chain.

specific capacity and carbon emission rates since it is necessary to keep fish in water.

- To keep fish products safe from perishability and to follow cold supply chain principles, freezer trucks with specific capacity and carbon emission rates are used to transport the products from the packaging center to the sales center.
- The transfer of waste products from the packaging center, regional market, and physical sales center to fish meal production centers is carried out by trucks with specified capacities and carbon emission rates.
- In packaging centers, inventory is considered to tackle the shortage.
- To make the model more realistic, demand in regional markets, physical sales centers, and online platforms are considered uncertain parameters. Establishment, operational, purchasing, holding, shortage, and transportation costs are also considered uncertain parameters. moreover, In the context of sustainability, environmental factors and job opportunities, along with the eco-friendliness rate, are regarded as uncertain parameters due to their considerable variation throughout the planning horizon.
- Sales are made through a dual-channel, physical and online, with discounts for the online channel. These discounts are assumed to motivate customers on the online platform.

In the following, Fig. 4 illustrates the conceptual outline of the research problem, providing a useful summary of the main inputs, objective functions, constraints, and main outputs of the research, which enhances both the readability and comprehensibility of the study.

3.2. Mathematical model

3.2.1. Indices

f	Index of fish farms	$(1,\cdots,F)$
c	Index of packaging centers	$(1,\cdots C)$
p	Index of products	$(1,\cdots P)$
q	Index of packaging methods	$(1,\cdots Q)$
r	Index of regional markets	$(1,\cdots,R)$
a	Index of physical sales centers	$(1,\cdots,A)$
m	Index of fish meal production center	$(1,\cdots,M)$
t	Index of the time period	$(1,\cdots,T)$

(continued on next column)

(*continued*)

3.2.2. Parameters

a) Sustainability Parameters

0a.1) Sustainability Parameters Related to Economic Indicators

$\widetilde{CSF}_f$	Fixed cost of selecting fish farm f
$\widetilde{CEC}_{cq}$	Fixed cost of establishment of packaging center c with packaging method q
$\widetilde{COP}_{cpqt}$	Operational cost for each unit of product p that produced at packaging center c with packaging method q in period t
$\widetilde{CPFF}_{ft}$	Purchasing cost for each kilogram of live fish shipped from fish farm f to regional markets and packaging centers throughout period t
$\widetilde{CSHR}_{rt}$	Shortage costs in regional market r throughout period t
$\widetilde{CSHA}_{apt}$	Shortage cost of each unit of product p in physical sales center a throughout period t
$\widetilde{CSHB}_{pt}$	Shortage cost of each unit of product p in online sales platform throughout period t
$\widetilde{CHC}_{cpt}$	Holding cost of each unit of product p in packaging center c throughout period t
$\widetilde{CTF}_t$	Transportation cost for each kilogram of live fish (per distance) throughout period t
$\widetilde{CTPA}_{pt}$	Transportation cost for each unit of product p shipped to physical sale centers (per distance) throughout period t
$\widetilde{CTPB}_{pt}$	Transportation cost for each unit of product p shipped to online sales platform (per distance) throughout period t
$\widetilde{CTW}_t$	Transportation cost for each kilogram of fish waste (per distance) throughout period t
$\widetilde{CTM}_t$	Transportation cost for each kilogram of fish meal (per distance) throughout period t
PSP_{cpqt}	The selling price of each unit of product p produced in packaging center c with the packaging method q before applying the discount throughout period t
δ_{ipt}	Rate of discount i, considered for selling product p at online platforms throughout period t

(continued on next page)

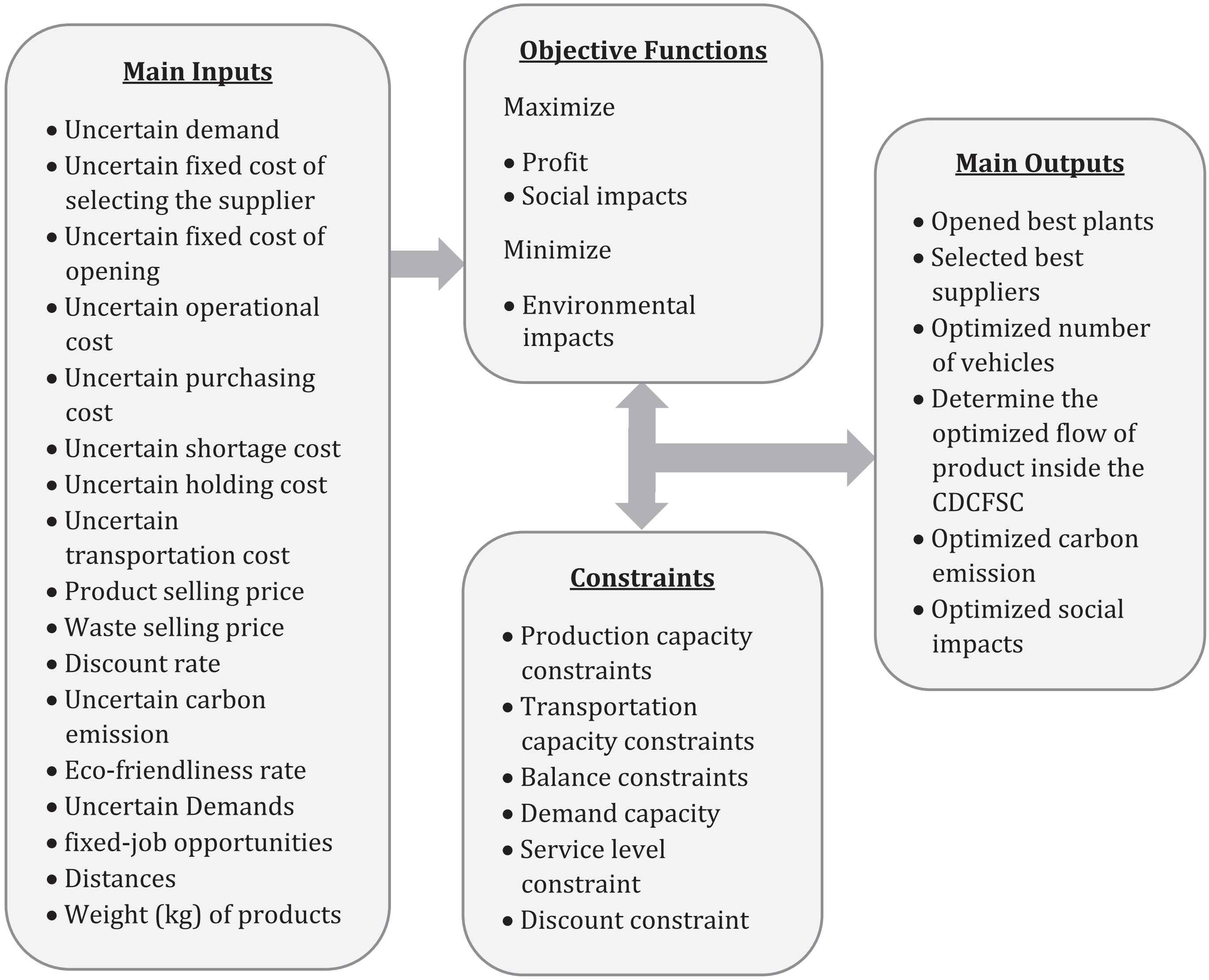

Fig. 4. The research problem's conceptual outline.

(*continued*)

$PSRM_{rmt}$	The selling price of each kilogram of fish waste produced in regional market r to fish meal production center m throughout period t
$PSCM_{cmt}$	The selling price of each kilogram of fish waste produced in packaging center c to fish meal production center m throughout period t
$PSMF_{mft}$	The selling price of each kilogram of fish meal produced at fish meal production center m to fish farm f throughout period t
a.2) Sustainability Parameters Related to Environmental Indicators	
$\widetilde{ETF}$	Carbon emission (Kg/Kg-Km) of the vehicle carrying live fish
$\widetilde{ETP}$	Carbon emission (Kg/Kg-Km) of the vehicle carrying processed products
$\widetilde{ETW}$	Carbon emission (Kg/Kg-Km) of the vehicle carrying fish waste
$\widetilde{ETM}$	Carbon emission (Kg/Kg-Km) of the vehicle carrying fish meal
$\widetilde{EPP}_{pcq}$	Carbon emission (Kg/Kg-Km) of production of one unit of product p in the packaging center c with packaging method q
$\widetilde{\lambda}_q$	Rate of being eco-friendly in packaging method q
a.3) Sustainability Parameters Related to Social Indicators	
$\widetilde{JFF}_f$	The fixed-job opportunities caused by opening fish farm f
$\widetilde{JCF}_c$	The fixed-job opportunities caused by opening packaging center c
c) Other Parameters	
DFR_{fr}	Distance between fish farm f and regional market r
DFC_{fc}	Distance between fish farm f and packaging center c
DCA_{ca}	Distance between packaging center c and physical sales center a
DCB_c	Average distance between packaging center c and online buyer
DCM_{cm}	Distance between packaging center c and fish meal production center m
DRM_{rm}	Distance between regional market r and fish meal production center m

(*continued on next column*)

(*continued*)

DMF_{mf}	Distance between fish meal production center m and fish farm f
CS_f	Maximum capacity of supplying live fish (kg) in fish farm f
CP_{cp}	Maximum capacity of producing product p in packaging center c
α	A ratio of live fish that can be used as HOG (Head-On, Gutted) fish
β	A ratio to convert fish waste to fish meal
$\widetilde{DR}_{rt}$	Demand of regional market r from live fish throughout period t
$\widetilde{DA}_{apt}$	Demand of physical sales center a product p throughout period t
$\widetilde{DB}_{pt}$	Initial demand of Online selling platform from product p throughout period t before considering discounts
θ	Discount sensitivity index for demand
y_p	Weight (kg) of product p
SLA	Service level of demand in physical sales centers
SLB	Service level of demand in the online platform
VF	The average capacity (kg) of the vehicle transporting live fish from the fish farm to packaging centers and regional markets
VP	The average capacity (kg) of the vehicle transporting processed products from packaging centers to physical selling centers and online sales platforms
VW	The average capacity (kg) of the vehicle transporting fish waste to fish meal production center
VM	The average capacity (kg) of the vehicle transporting fish meal to fish farms
MNV	The maximum number of vehicles allowed in the network
M	A very large number

3.2.3. Decision variables

OF_f	1 if fish farm f is selected, otherwise 0
OC_{cq}	1 if packaging center c with packaging method q is opened, otherwise 0
PK_{ipt}	1 if discount i is dedicated to product p throughout the period t, otherwise 0
SHR_{frt}	The amount of shortage in shipping live fish (kg) from fish farm f to regional market r throughout period t
SHA_{capt}	The amount of shortage in shipping product p from packaging center c to physical sales center a throughout period t
SHB_{cpt}	The amount of shortage in shipping product p from packaging center c to online sales platform throughout period t
DD_{pt}	Demand of online selling platform from product p throughout period t
$PSPP_{cpqt}$	Price of product p (per unit) produced in packaging center c with packaging method q throughout period t
$QLFR_{frt}$	The quantity of live fish (kg) purchased from fish farm f to regional market r throughout period t
$QLFC_{fct}$	The quantity of live fish (kg) purchased from fish farm f to packaging center c throughout period t

(continued on next column)

(continued)

NFR_{frt}	Number of vehicles that ship live fish from fish farm f to regional market r throughout period t
NFC_{fct}	Number of vehicles that ship live fish from fish farm f to packaging center c throughout period t
NCA_{cat}	Number of vehicles that ship products from packaging center c to physical sales center a throughout period t
NCB_{ct}	Number of vehicles that ship products from packaging center c to online sales platform throughout period t
NRM_{rmt}	Number of vehicles that ship wastes from regional market r to fish meal production center m throughout period t
NCM_{cmt}	Number of vehicles that ship wastes from packaging center c to fish meal production center m throughout period t
NMF_{mft}	Number of vehicles that ship fish meal from fish meal production center m to fish farm f throughout period t

3.2.4. Objective functions

Based on the presented definitions and notations, the CDCFSC network can be designed using the following model.

$$MaxZ1 = \begin{pmatrix} \left(\sum_{c,a,p,q,t} PSP_{cpqt} \times QPCA_{capqt} + \sum_{c,p,q,t} PSPP_{cpqt} \times QPCB_{cpqt}\right) \\ +\sum_{r,m,t} PSRM_{rmt} \times QWRM_{rmt} + \sum_{c,m,t} PSCM_{cmt} \times QWCM_{cmt} + \sum_{m,f,t} QMF_{mft} \times PSMF_{mft} \end{pmatrix} - \begin{pmatrix} \sum_{f} \widetilde{CSF}_f \times OF_f + \sum_{c,q} \widetilde{CEC}_{cq} \times OC_{cq} \\ +\sum_{c,a,p,q,t} \widetilde{COP}_{cpqt} \times QPCA_{capqt} + \sum_{c,p,q,t} \widetilde{COP}_{cpqt} \times QPCB_{cpqt} \\ +\sum_{f,t} \widetilde{CPFF}_{ft} \times \left(\sum_{r} QLFR_{frt} + \sum_{c} QLFC_{fct}\right) \\ +\sum_{r,t} \widetilde{CSHR}_{rt} \times SHR_{rt} + \sum_{a,p,t} \widetilde{CSHA}_{apt} \times SHA_{apt} + \sum_{p,t} \widetilde{CSHB}_{pt} \times SHB_{pt} \\ +\sum_{c,p,t} \widetilde{CHC}_{cpt} \times IPC_{cpt} \\ +\sum_{t} \widetilde{CTF}_t \times \left(\sum_{f,r} DFR_{fr} \times QLFR_{frt} + \sum_{f,c} DFC_{fc} \times QLFC_{fct}\right) \\ +\sum_{p,t} \widetilde{CTPA}_{pt} \times \left(\sum_{c,a} DCA_{ca} \times QPCA_{capqt}\right) + \sum_{c,p,t} \widetilde{CTPB}_{pt} \times \left(DCB_c \times QPCB_{cpqt}\right) \\ +\sum_{t} \widetilde{CTW}_t \times \left(\sum_{r,m} DRM_{rm} \times QWRM_{rmt} + \sum_{c,m} DCM_{cm} \times QWCM_{cmt}\right) \\ +\sum_{m,f,t} \widetilde{CTM}_t \times \left(DMF_{mf} \times QMF_{mft}\right) \end{pmatrix} \tag{1}$$

(continued)

$QPCA_{capqt}$	The amount of product p sent from packaging center c with packaging method q to physical sales center a throughout period t
$QPCB_{cpqt}$	The quantity of product p sent from packaging center c with packaging method q to online sales platform throughout period t
$QWRM_{rmt}$	The quantity of waste (kg) shipped from retail regional market r to fish meal production center m throughout period t
$QWCM_{cmt}$	The quantity of waste (kg) shipped from packaging center c to fish meal production center m throughout period t
QMF_{mft}	The quantity of fish meal (kg) shipped from fish meal production center m to fish farm f throughout period t
IPC_{cpt}	The inventory level of product p at packaging center c throughout period t

(continued on next column)

Equation (1) is the first OF, maximizing the profit. In this equation, income is gained from selling fish products, fish waste, and fish meal. At the following, fixed costs, operational costs, purchasing costs, shortage costs, holding costs, and transportation costs have been subtracted from income.

$$MinZ2 = we_1 \times \left(\frac{E^{max}_{ECO-F} - E_{ECO-F}}{E^{max}_{ECO-F} - E^{min}_{ECO-F}}\right) + we_2 \times \left(\frac{E_{CO2} - E^{min}_{CO2}}{E^{max}_{CO2} - E^{min}_{CO2}}\right) \tag{2}$$

$$E_{ECO-F} = \sum_{c,q} OC_{cq} * \widetilde{\lambda}_q \tag{3}$$

$$E_{CO2} = \widetilde{ETF} \times \left(\sum\nolimits_{f,r,t} DFR_{fr} \times NFR_{frt} + \sum\nolimits_{f,c,t} DFC_{fc} \times NFC_{fct}\right) + \widetilde{ETP} \times \left(\sum\nolimits_{c,a,p,t} DCA_{ca} \times NCA_{cat} + \sum\nolimits_{c,p,t} DCB_{c} \times NCB_{ct}\right) + \widetilde{ETW} \times \left(\sum\nolimits_{r,m,t} DRM_{rm} \times NRM_{rmt} + \sum\nolimits_{c,m,t} DCM_{cm} \times NCM_{cmt}\right) + \widetilde{ETM} \times \left(\sum\nolimits_{m,f,t} DMF_{mf} \times NMF_{mft}\right) + \sum\nolimits_{p,c,q,t} \widetilde{EPP}_{pcq} \times \left(\sum\nolimits_{a} QPCA_{capqt} + QPCB_{cpqt}\right) \quad (4)$$

Equation (2) optimizes the environmental impacts of fish supply chain using a normalized weighted sum method by considering the CO_2 emission and eco-friendly rate of each packaging method simultaneously. In this equation E^{max}_{CO-F} represents Positive Ideal Solution (PIS) and E^{min}_{ECO-F} represents Negative Ideal Solution (NIS) for the eco-friendly part of the OF, denote the maximum and minimum values of being eco-friendly in a packaging method, respectively. Also, E^{min}_{CO2} represents the PIS for the environmental impacts' objective while E^{max}_{CO2} denotes the NIS. Equation (3) is related to the rate of being eco-friendly which is looking for the best packaging method that has the least impact on the environment, while equation (4) considers different environmental aspects of sustainability that calculate the cumulative amount of carbon emitted during transportation and production of products.

$$MaxZ3 = \left(\sum_{cq} \widetilde{JCF}_c \times OC_{cq} + \sum_{f} \widetilde{JFF}_f \times OF_f\right) \quad (5)$$

Due to the importance of the social impacts of sustainability, equation (5) is about maximizing the number of jobs created in selecting and opening fish farms and packaging centers simultaneously.

3.2.5. Constraints

$$\sum_{f} QLFR_{frt} + SHR_{rt} = \widetilde{DR}_{rt} \forall r, t \quad (6)$$

Equation (6) is related to the demand constraint of regional markets, which expresses that demand in regional markets can contain shortages.

$$\sum_{f} QLFC_{fct} \times \alpha = \sum_{apq} QPCA_{capqt} \times y_p + \sum_{pq} QPCB_{cpqt} \times y_p + \sum_{p} IPC_{cpt} \times y_p \forall c, t = 1 \quad (7)$$

$$\sum_{f} QLFC_{fct} \times \alpha = \sum_{apq} QPCA_{capqt} \times y_p + \sum_{pq} QPCB_{cpqt} \times y_p - \sum_{p} IPC_{cp,t-1} \times y_p + \sum_{p} IPC_{cpt} \times y_p \forall c, t = \{2, .., T-1\} \quad (8)$$

$$\sum_{f} QLFC_{fct} \times \alpha = \sum_{apq} QPCA_{capqt} \times y_p + \sum_{pq} QPCB_{cpqt} \times y_p - \sum_{p} IPC_{cp,t-1} \times y_p \forall c, t \quad (9)$$

Equations (7) to (9) address the relation between input and output flows of packaging centers. These equations show that holding inventory in packaging centers is allowed.

$$\sum_{c,q} QPCA_{capqt} + SHA_{apt} = \widetilde{DA}_{apt} \forall p, a, t \quad (10)$$

$$\sum_{c,q} QPCB_{cpqt} + SHB_{pt} = DD_{pt} \forall p, t \quad (11)$$

Respectively, Equations (10) and (11) are demand constraints of physical sale centers and online sales platforms, which declare that demand in physical sale centers and online sales platforms can contain shortages.

$$DD_{pt} = \widetilde{DB}_{pt}\left(1 + \sum_{i} \theta.PK_{ipt}.\delta_{ipt}\right) \forall p, t \quad (12)$$

$$PSPP_{cpqt} = PSP_{cpqt} - \sum_{i} [PK_{ipt}.(1 - \delta_{ipt})] \forall c, p, q, t \quad (13)$$

$$\sum_{i} PK_{ipt} \leq 1 \forall p, t \quad (14)$$

Equations (12) and (13) are about calculating demand at online sales platforms and also calculating the price of the products for selling in the online selling platform respectively. Furthermore, equation (14) specifies that only a single type of discount is permissible for each product.

$$\sum_{f} QLFR_{frt} \times (1 - \alpha) = \sum_{m} QWRM_{rmt} \forall r, t \quad (15)$$

$$\sum_{f} QLFC_{fct} \times (1 - \alpha) = \sum_{m} QWCM_{cmt} \forall c, t \quad (16)$$

Equations (15) and (16) explain the relation between waste amount and fresh fish.

$$\left(\sum\nolimits_{r} QWRM_{rmt} + \sum\nolimits_{c} QWCM_{cmt}\right)^{*}\beta = \sum_{f} QMF_{mft} \forall m, t \quad (17)$$

Equation (17) expresses the relation between input and output flows of fish meal production center.

$$(CS_f \times OF_f) - \left(\sum_{c,t'=1}^{t-1} QLFC_{fct'} + \sum_{r,t'=1}^{t-1} QLFR_{frt'}\right) \geq \sum_{c} QLFC_{fct} + \sum_{r} QLFR_{frt} \forall f, t \quad (18)$$

$$CP_{cp} \times \sum_{q} OC_{cq} \geq \sum_{aq} QPCA_{capqt} + \sum_{q} QPCB_{cpqt} \forall c, p, t \quad (19)$$

Equations (18) and (19) are respectively the supply capacity and production capacity constraints. Equation (18) also ensures that fresh fish are not transported unless the fish farm center f is opened. Likewise, Equation (19) makes sure that products can not been transported unless the packaging center c is established.

$$QLFC_{fct} \leq NFC_{fct} \times VF \forall f, c, t \quad (20)$$

$$QLFR_{frt} \leq NFR_{frt} \times VF \forall f, r, t \quad (21)$$

$$\sum_{pq} QPCA_{capqt} \times y_p \leq NCA_{cat} \times VP \forall c, a, t \quad (22)$$

$$\sum_{pq} QPCB_{cpqt} \times y_p \leq NCB_{ct} \times VP \forall c, t \quad (23)$$

$$QWRM_{rmt} \leq NRM_{rmt} \times VW \forall r, m, t \tag{24}$$

$$QWCM_{cmt} \leq NCM_{cmt} \times VW \forall c, m, t \tag{25}$$

$$QMF_{mft} \leq NMF_{mft} \times VM \forall m, f, t \tag{26}$$

$$\begin{aligned} &\sum_{f,c} NFC_{fct} + \sum_{f,r} NFR_{frt} + \sum_{c,a} NCA_{cat} + \sum_{c} NCB_{ct} + \sum_{r,m} NRM_{rmt} \\ &+ \sum_{c,m} NCM_{cmt} + \sum_{m,f} NMF_{mft} \leq MNV_t \forall t \end{aligned} \tag{27}$$

Equations (20) to (26) are vehicle capacity constraints while determining the number of vehicles required for transportation in each direction. Also, equation (27) shows the capacity constraint of the total number of vehicles in the network.

$$\sum_{q} OC_{cq} \leq 1 \forall c \tag{28}$$

Equation (28) ensures that in establishment a packaging center, only one of the packaging methods would be applied.

$$\frac{\sum_{c,a,p,q} QPCA_{c,a,p,t}}{\sum_{a,p} DA_{a,p,t}} \geq SLA \forall t \tag{29}$$

$$\frac{\sum_{c,p,q} QPCB_{c,p,t}}{\sum_{p} DB_{p,t}} \geq SLB \forall t \tag{30}$$

Equation (29) shows the existing limitation of the minimum service level for demand points in physical sales centers and Equation (30) shows the existing limitation of the minimum service level for the demand points in the online platform.

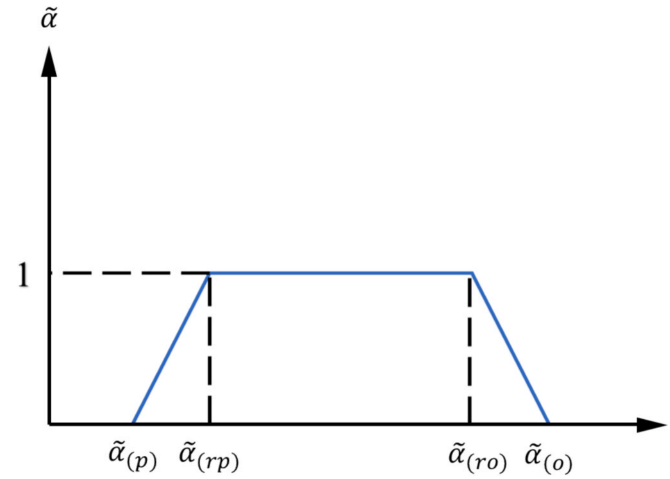

Fig. 6. Fuzzy parameter $\tilde{\alpha}$ (Delfani et al., 2022).

Finally, Equation (31) displays the type of decision variables.

3.3. Linearizing the model

Based on equation (1), the model is nonlinear because of the multiplication of continuous and integer variables ($PSPP_{cpqt} \times QPCB_{cpqt}$). Let $ZZ, P1$, and $P2$ are three continuous positive variables, where $ZZ = P1 \times P2$, $P1 = PSPP_{cpqt}$, and $P2 = QPCB_{cpqt}$. To convert this non-linear equation to linear form, an upper and a lower bound are defined for each variable. Then, the equation is linearized using equation (32), which converts to equation (33) for the mentioned problem.

$$\begin{gathered} OF_f, OC_c \in \{0,1\} \\ SHFR_{frt}, QLFR_{frt}, QLFC_{fct}, QWRM_{rmt}, QWCM_{cmt}, QMF_{mft}, ILR_{frt} \geq 0 \\ SHCA_{capt}, SHCB_{cpt}, QPCA_{capt}, QPCB_{cpt}, IPC_{cpt}, IPA_{capt}, VFR_{frt}, VFC_{fct}, VCA_{cat}, \forall f, c, r, a, m, t \\ VRM_{rmt}, VAM_{amt}, VBM_{mt}, VCM_{cmt}, VMF_{mft} \in integer \end{gathered} \tag{31}$$

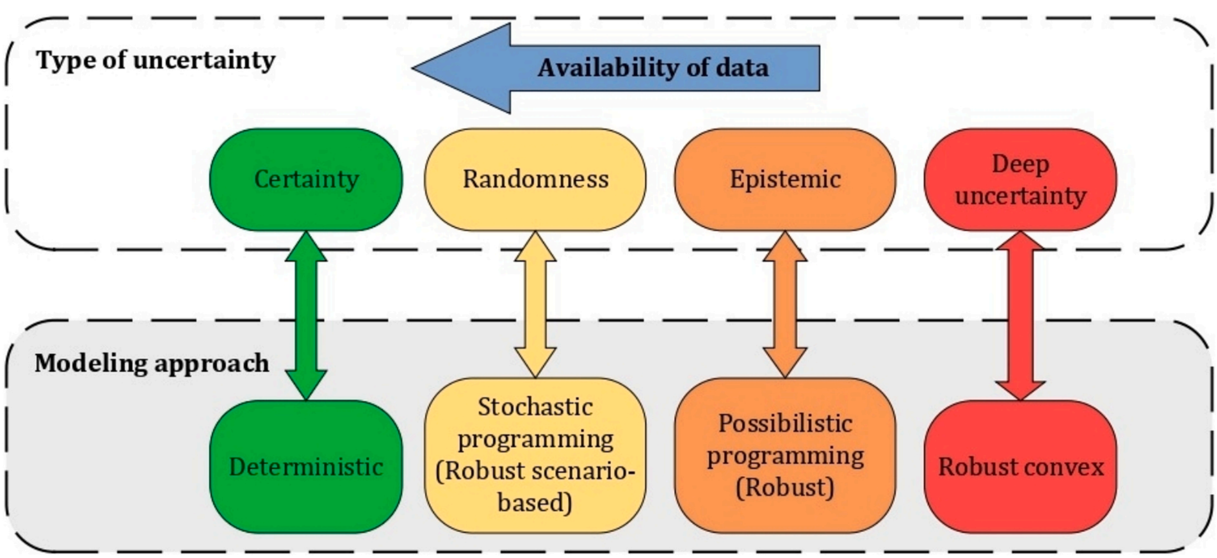

Fig. 5. Categorizing various uncertainties and the approaches to manage them (Nayeri et al., 2020).

$$\begin{aligned} MinP1 \leq P1 \leq MaxP1 \\ MinP2 \leq P2 \leq MaxP2 \\ P1 \times MinP2 \leq ZZ \leq P1 \times MaxP2 \\ P2 \times MinP1 \leq ZZ \leq P2 \times MaxP1 \end{aligned} \tag{32}$$

$$\begin{aligned} MinPSPP_{cpqt} \leq PSPP_{cpqt} \leq MaxPSPP_{cpqt} \\ MinQPCB_{cpqt} \leq QPCB_{cpqt} \leq MaxQPCB_{cpqt} \\ PSPP_{cpqt} \times MinQPCB_{cpqt} \leq ZZ \leq PSPP_{cpqt} \times MaxQPCB_{cpqt} \\ QPCB_{cpqt} \times MinPSPP_{cpqt} \leq ZZ \leq QPCB_{cpqt} \times MaxPSPP_{cpqt} \end{aligned} \tag{33}$$

4. Uncertainty modeling

In general, uncertainty is defined as the gap between the data needed to complete a task and the data that is actually available (Galbraith, 1973; Mamashli et al., 2021). To reach realistic results, it is recommended to define parameters as non-deterministic amounts in the problem. The uncertainty in parameters we are encountering primarily stems from inaccuracies in measurements, errors in sampling, inherent variability, and reliance on substitute data (Petersen, 2010). Uncertainties are classified as randomness, epistemic, and deep based on Bairamzadeh et al. (2018). When ample data is available to determine the probability distribution function of parameters, the resulting uncertainty is called randomness, while Epistemic uncertainty refers to a situation with a lack of knowledge and information in input data, which typically involves judgmental data on linguistic attributes that can be sourced from experienced experts (Nayeri et al., 2020; Sazvar et al., 2021). In the context of the study, Fig. 5 illustrates the demonstrates the utilization of robust stochastic programming for addressing randomness uncertainty, robust possibilistic programming for managing epistemic uncertainty, and robust convex optimization for handling deep uncertainty. Even though some historical data is available for the research problem, the input data are incomplete, necessitating accurate data collection. Therefore, the robust fuzzy optimization approach, which is a subset of robust possibilistic programming, deals with epistemic uncertainty.

To cope with the uncertainty of parameters in the OFs and constraints in Section 3, a well-known possibilistic programming method called the Chance-Constrained Fuzzy Programming (CCFP) model has been used. This approach relies on various mathematics concepts, including the expected value of a fuzzy number, Possibility (Pos), and Necessity (Nec) (Inuiguchi & Ramık, 2000; Talaei et al., 2016). Additionally, there are different fuzzy number logics such as triangular and trapezoidal to tackle the uncertainty (Zadeh, 1965). In this study, trapezoidal fuzzy numbers (TFN) are applied. TFN are defined by four key points (i.e. $\widetilde{\alpha} = \alpha_{(p)}, \alpha_{(rp)}, \alpha_{(ro)}, \alpha_{(o)}$) and have a membership function that forms a trapezoidal shape (i.e. Fig. 6) (Dubois, 1980). They are applied in supply chain programming to model uncertain parameters (Sivakumar & Appasamy, 2024). TFN offer several advantages over triangular fuzzy numbers, which is why they were used in this research. They provide flexibility in representation by allowing a range of values with equal possibility (the flat top), which is useful when data suggests a wider range of equally likely values (Uluçay et al., 2019). They handle uncertainty better by offering a more realistic representation, especially in complex systems where the likelihood of certain outcomes is spread over a range (Ponnialagan et al., 2018). Additionally, they simplify mathematical operations involved in fuzzy arithmetic and decision-making processes due to the flat top of the trapezoid (Vahidi & Rezvani, 2013; Zadeh, 1965). Therefore, a basic fuzzy model is proposed as follows:

$$\begin{aligned} &MinE[Z] = E[H]y + E[\widetilde{c}]x \\ &s.t. \\ &Nec\{Ax \geq \widetilde{d}\} \geq \tau_m \\ &Nec\{Bx = \widetilde{e}\} \geq \tau_{m\forall m \in M} \\ &Nec\{Gx \leq \widetilde{f}y\} \geq \tau_m \\ &y \in \{0,1\}, x \geq 0 \end{aligned} \tag{34}$$

As mentioned, in equation (34) a basic model with uncertainty is provided in which c, d, e, and f are uncertain parameters. To tackle these uncertain parameters, as mentioned, by using TFN, it is assumed that $\widetilde{\alpha}$ is a trapezoidal fuzzy parameter. In equation (35) the membership function of $\widetilde{\alpha}$ is shown by four sensitive points, including $\alpha_{(p)}$, $\alpha_{(rp)}$, $\alpha_{(ro)}$, and $\alpha_{(o)}$ which is illustrated in Fig. 6.

$$\mu_{\widetilde{\alpha}}(x) \begin{cases} 1, rp < x < ro \\ \dfrac{x - \alpha^p}{x^{rp} - \alpha^p}, p \leq x \leq rp \\ \dfrac{\alpha^0 - x}{\alpha^0 - \alpha^{ro}}, ro \leq x \leq o \\ 0, x > o \, or \, x < p \end{cases} \tag{35}$$

Along the equation (34) and what was described in the previous part, as mentioned in Ghahremani-Nahr et al. (2019) the uncertain parameters need to meet a minimum level of τ_m (i.e. satisfaction level), so the deterministic model of equation (34) is defined as follows in equation (36):

$$\begin{aligned} &MinE[Z] = Hy + \left(\frac{c^p + c^{rp} + c^{ro} + c^o}{4}\right)x \\ &s.t. \\ &Ax \geq (1 - \tau_m)d^{ro} + (\tau_m)d^o \\ &Bx \geq (\tau_m)e^{rp} + (1 - \tau_m)e^p \\ &Bx \leq (\tau_m)e^o + (1 - \tau_m)e^{ro} \\ &Gx \leq [(1 - \tau_m)f^{rp} + (\tau_m)f^p]y \\ &y \in \{0,1\}, \ x \geq 0, \ 0 \leq \tau_m \leq 1 \end{aligned} \tag{36}$$

According to Nayeri et al. (2020), the RFP counterpart of equation (36) is formulated as equation (37) where $Z_{max} = H.y + c^o.x$. To establish this robust counterpart, some parts have been added to the equation (36) which are explained in the following. The first part of the equation (37), minimizes the expected value of each OF, while the second part, which is written as $\eta(Z_{max} - E[Z])$, is dedicated to minimize the gap between the most pessimistic and expected values of each OF, where η represents the optimality robustness coefficient and Z_{max} is the worst case of the initial OF (for minimizing OF). As mentioned, η is the coefficient of the proposed expression which plays a significant role in determining and managing the solution vector's optimality robustness. Additionally, the third part assesses the degree of conservatism for each chance constraint. This expression represents the penalties of each unit of probable deviations from any chance constraint with uncertain parameters. The coefficient φ_n in this expression signifies the variance between the most pessimistic values of the uncertain parameter and the value set in the constraints; essentially, this expression governs the feasibility robustness of the solution vector (Nayeri et al., 2020; Talaei et al., 2016; Sazvar et al., 2021).

$$\begin{gathered}
Min\ E[Z]+\eta(Z_{max}-E[Z]) \\
+\varphi_1(d^o-(1-\tau_m)d^{ro}-(\tau_m)d^o) \\
+\varphi_2(e^{ro}-(1-\tau_m)e^{ro}-(\tau_m)e^o+(1-\tau_m)e^p+(\tau_m)e^{rp}-e^p) \\
+\varphi_3\left[(1-\tau_m)f^{rp}+(\tau_m)f^p-f^p\right].y \\
s.t. \\
Ax\geq(1-\tau_m)d^{ro}+(\tau_m)d^o \\
Bx\geq(\tau_m)e^{rp}+(1-\tau_m)e^p \\
Bx\leq(\tau_m)e^o+(1-\tau_m)e^{ro} \\
Gx\leq[(1-\tau_m)f^{rp}+(\tau_m)f^p].y \\
y\in\{0,1\},\ x\geq0,\ 0.5\leq\tau_m\leq1
\end{gathered} \tag{37}$$

5. Solution approach

To solve the proposed MOMILP model, a novel approach called FMCCGP_UF is developed from classical GP. As one of the well-known techniques of decision-making, GP was first used by Charnes & Cooper (1957) and named in 1961. GP helps decision-makers achieve multiple objectives by converting qualitative goals into quantitative targets. The main concept is to define aspiration levels for each OF and find a solution that minimizes the differences between actual and aspiration levels while meeting constraints and preferences. This is achieved by minimizing deviational variables, which are weighted based on the importance of each OFs to ultimately minimize the weighted sum of deviational variables (Bankian-Tabrizi et al., 2012). Different types of GP were developed in the literature. As mentioned above, in this paper we are presenting a new method named FMCCGP-UF, which is a development of the CMCGP-UF approach, proposed by Nayeri et al. (2023).

CMCGP-UF approach, which is presented in equation (38), is a developed method from the MCGP-UF approach presented by Chang (2011). where $f_k(X)$ is the kth OF and y_k is a continuous decision variable. d_k^+ and d_k^- are respectively positive and negative deviation of $f_k(X)$ from y_k. Additionally, $U_{k,max}$ and $U_{k,min}$ respectively denote the upper and lower bound of the aspiration level for OF k. Here, ξ_k^- shows the normalized deviation of y_k from $U_{k,min}$ and w_k^{ξ} displays the weight of ξ_k^-, and ϕ_k is the utility value of kth OF. In this method, a linear utility function is considered, which is a mathematical representation used to model a decision maker's preferences. In the context of multi-choice goal programming, utility functions help in quantifying the satisfaction or utility derived from different choices or outcomes. Also, utility functions are applied to capture and represent the decision maker's preferences more accurately, which is crucial when balancing multiple goals and choices. They facilitate better decision-making by providing a structured way to evaluate and compare different options based on their utility values. Additionally, in scenarios involving multiple criteria and objectives, utility functions help simplify the complexity by converting qualitative preferences into quantitative measures (Chang, 2011).

$$\begin{gathered}
min=\left[\mu.D+(1-\mu)\left(\sum\nolimits_k\left[w_k^d(d_k^++d_k^-)+w_k^{\xi}.\xi_k^-\right]\right)\right] \\
\text{s.t.} \\
f_k(X)+d_k^--d_k^+=y_k\forall k \\
w_k^d.(d_k^++d_k^-)+w_k^d.\xi_k^-\leq D\forall k \\
\phi_k\leq\frac{U_{k,max}-y_k}{U_{k,max}-U_{k,min}}\forall k \\
U_{k,min}\leq y_k\leq U_{k,max}\forall k \\
\phi_k+\xi_k^-=1\forall k \\
d_k^+,d_k^-,y_k,U_k,\xi_k^-\geq0\forall k
\end{gathered} \tag{38}$$

It should be noted that there are two types of preferences in the GP approach, MAXMIN preferences (equity) and additive preferences (efficiency), and creating a trade-off among them has high importance (Arenas-Parra et al., 2010). As mentioned in Nayeri et al. (2023), the CMCGP-UF method covers these preferences simultaneously in the OF of its methodology. This approach offers numerous benefits, including (1) integrating multiple aspiration levels, (2) accounting for decision-makers' value preferences, (3) employing a linear utility function, and (4) achieving a balanced compromise between efficiency and equity of goals (Nayeri et al., 2023). Despite the mentioned points, method CMCGP-UF has some weaknesses. This method assumes that attribute values are constantly certain, which leads to a inflexibility in the method. Additionally, in the related literature, it has been recommended that in developing a solving methodology, it is better to consider uncertainty. Therefore, in this research, the CMCGP-UF method has been changed in a fuzzy way to tackle the inflexibility and uncertainty of problems. this new approach called FMCCGP-UF, is presented as follows in equation (39). where λ_k shows the achievement degree of objective k, y_k is a continuous variable, MED_k is the maximum expected deviation for the kth OF (which is determined by decision-makers) and $U_{k,min}$ and $U_{k,max}$ show the range of the kth OF's aspiration level. FMCCGP-UF, covers all benefits of Nayeri et al. (2023) method, and also flexibility. So, the FMCCGP-UF method offers several advantages, including: (1) integrating multiple aspiration levels, (2) accounting for decision-makers' value preferences, (3) employing a linear utility function, (4) balancing efficiency and equity in goal achievement, and (5) providing flexibility.

$$\begin{gathered}
Max=\sum\nolimits_k\lambda_k-\sum\nolimits_k w_k^{\xi}.\xi_k^- \\
\text{s.t.} \\
\lambda_k\leq1-\frac{\tau.D+(1-\tau).\left(w_k^d.(d_k^++d_k^-)\right)}{MED_k}\forall k \\
f_k(X)+d_k^--d_k^+=y_k\forall k \\
w_k^d.(d_k^++d_k^-)+w_k^d.\xi_k^-\leq D\forall k \\
\phi_k\leq\frac{U_{k,max}-y_k}{U_{k,max}-U_{k,min}}\forall k \\
U_{kmin}\leq y_k\leq U_{kmax}\forall k \\
\phi_k+\xi_k^-=1\forall k \\
d_k^+,d_k^-,y_k,U_k,\xi_k^-\geq0\forall k
\end{gathered} \tag{39}$$

6. Computational results

6.1. Case study

In this study, a packaging manufacturer named "Pemina" located in Amol, Mazandaran, Iran, is considered as a case study. "Pamina Food Industrial Company" operates as a subsidiary of the "Solico (Kalleh Amel)" company. The activity of Solico Group (Kalleh) in the food industry dates back to 1973 in Tehran. In 2021, the "Fillet Amol Industrial Unit" was established in Imamzadeh Abdallah Industrial Town near Amol to produce seafood products such as shrimp and various types of fish, following the expansion of the product range. Today, this brand offers over 130 different products across various food categories, including Fried Items, Burgers, Vegetables, Seafood, Doner Kebabs, and Convenience Foods. Its seafood products include Peeled Shrimp in

Table 2
Assessment of carbon emission parameters in production.

	q	p	rp	ro	o
EPP (g)	1 (TLV)	U(68,75)	U(76,84)	U(93,103)	U(102,112)
	2 (MAP)	U(51,56)	U(57,63)	U(70,74)	U(76,84)

Table 3
Assessment of carbon emission parameters in transportation.

	p	rp	ro	o
ETF (g)	2.52	2.835	3.465	3.78
ETP (g)	2.8	3.15	3.85	4.2
ETW (g)	3.2	3.6	4.4	4.8
ETM (g)	2.96	3.33	4.07	4.44

Table 4
Weight of the products.

y_p	Weight
Product 1 (Sticky trout)	0.5 (kg)
Product 2 (HOG Trout)	1 (kg)
Product 3 (Single HOG Trout)	0.45 (kg)

Table 5
Costs related parameters.

Parameters	Range			
	p	rp	ro	o
$\widetilde{CSF}_f(Rial)$	$U[5, 5.5] \times 10^7$	$U[5.5, 6] \times 10^7$	$U[6, 6.5] \times 10^7$	$U[6.5, 7] \times 10^7$
$\widetilde{CEC}_{cq}(Rial)$	$U[3.75, 3.89] \times 10^9$	$U[3.89, 4.03] \times 10^9$	$U[4.03, 4.16] \times 10^9$	$U[4.16, 4.3] \times 10^9$
$\widetilde{COP}_{cpqt}(Rial)$	$U[0.8, 1.063] \times 10^5$	$U[1.063, 1.36 \times 10^5$	$U[1.36, 1.59] \times 10^5$	$U[1.59, 1.85] \times 10^5$
$\widetilde{CPFF}_{ft}(Rial)$	$U[18, 18.5] \times 10^5$	$U[18.5, 19] \times 10^5$	$U[19, 19.5] \times 10^5$	$U[19.5, 20] \times 10^5$
$\widetilde{CSHR}_{rt}(Rial)$	$U[3, 3.5] \times 10^5$	$U[3.5, 4] \times 10^5$	$U[4, 4.5] \times 10^5$	$U[4.5, 5] \times 10^5$
$\widetilde{CSHA}_{apt}(Rial)$	$U[2.9, 3.45] \times 10^5$	$U[3.45, 4] \times 10^5$	$U[4, 4.55] \times 10^5$	$U[4.55, 5.1] \times 10^5$
$\widetilde{CSHB}_{pt}(Rial)$	$U[2.7, 3.33] \times 10^5$	$U[3.33, 3.95] \times 10^5$	$U[3.95, 4.58] \times 10^5$	$U[4.58, 5.2] \times 10^5$
$\widetilde{CHC}_{cpt}(Rial)$	$U[3.5, 3.85] \times 10^5$	$U[3.85, 4.2] \times 10^5$	$U[4.2, 4.55] \times 10^5$	$U[4.55, 4.9] \times 10^5$
$\widetilde{CTF}_t(Rial)$	$U[3.5, 3.85] \times 10^5$	$U[3.85, 4.2] \times 10^5$	$U[4.2, 4.55] \times 10^5$	$U[4.55, 4.9] \times 10^5$
$\widetilde{CTPA}_{pt}(Rial)$	$U[3, 3.25] \times 10^5$	$U[3.25, 3.5] \times 10^5$	$U[3.5, 3.75] \times 10^5$	$U[3.75, 4] \times 10^5$
$\widetilde{CTPB}_{ct}(Rial)$	$U[3, 3.25] \times 10^5$	$U[3.25, 3.5] \times 10^5$	$U[3.5, 3.75] \times 10^5$	$U[3.75, 4] \times 10^5$
$\widetilde{CTW}_t(Rial)$	$U[3, 3.25] \times 10^5$	$U[3.25, 3.5] \times 10^5$	$U[3.5, 3.75] \times 10^5$	$U[3.75, 4] \times 10^5$
$\widetilde{CTM}_t(Rial)$	$U[3.5, 3.88] \times 10^5$	$U[3.88, 4.25] \times 10^5$	$U[4.25, 4.63] \times 10^5$	$U[4.63, 5] \times 10^5$

Table 6
Parameters related to the social and environmental impact.

Parameter	Range			
	p	rp	ro	o
$\widetilde{JCF}_c(people)$	$UD[9, 10]$	$UD[9, 11]$	$UD[11, 12]$	$UD[12, 13]$
$\widetilde{JFF}_f(people)$	$UD[7, 8]$	$UD[8, 9]$	$UD[9, 10]$	$UD[10, 11]$
$\widetilde{\lambda}_q$	$U[0.1, 0.15]$	$U[0.15, 0.2]$	$U[0.2, 0.25]$	$U[0.25, 0.3]$

different sizes, Sticky Trout, Fillet Salmon, HOG Trout, Single HOG Trout, Greater Lizardfish, Black Sea Sprat, Gutted Black Sea Sprat, and Otolithes Ruber. Due to the diverse range of marine products produced at this industrial unit, many centers across Iran supply this company. For instance, the fresh Shrimp required by this company is sourced from Gorgan, Golestan province, and most of the Trout is farmed in the Hazar mountain area, Mazandaran. Given the variety of products, this company has numerous customers throughout Iran and even internationally, especially in neighboring countries. One of the most important marine products of the factory is Trout-based products, including 0.5 kg Sticky Trout, 1 kg HOG Trout, and 0.45 kg HOG Trout (Single Trout). These mentioned products are variant in demand, production capacity, and other factors, yet the overall production process remains consistent. This plant prioritizes supply chain profitability and also considers environmental and social impacts to reflect sustainability principles.

In the problem, 5 points are being considered as potential fish farms, 3 potential locations are being evaluated for establishment of packaging centers, and also 2 potential locations are considered for fish meal-producing centers. Amol, Fereydunkenar, and Sari are 3 cities of Mazandaran which considered for regional markets and also 2 locations proposed by experts for physical sales centers, which one of them represents Mazandaran's physical sales centers and the other represents Tehran's physical sales centers respectively. The online sales center for

Table 8
Price of products.

Price	Value of price	Price	Value of price
$PSP_{cpqt}(rial)$	$U[1.7, 3.44] \times 10^6$	$PSRM_{rmt}(rial)$	$U[4.2, 5.5] \times 10^3$
$PSCM_{cmt}(rial)$	$U[4.5, 5.7] \times 10^3$	$PSMF_{mft}(rial)$	$U[4, 5.2] \times 10^3$
Discount	Value of Discount	Discount sensitivity index for demand	Value of Discount sensitivity index for demand
δ_{ipt}	5%, 10%, 15%	θ	0.15

Table 9
Capacity of fish farms, packaging centers, and vehicles.

Supply capacity	Value	Production capacity	Value
$CS_f(kg)$	U[320000, 390000]	$CP_{cp}(product)$	UD[22400, 102300]
Vehicle Capacity	Value	Vehicle Capacity	Value
$VF(kg)$	4000	$VW(kg)$	3000
$VP(kg)$	5000	$VM(kg)$	2000

Table 10
Conversion ratio of live fish to HOG and fish waste to fish meal.

Ratio of conversion live fish to HOG	Value	Conversion ratio of fish waste to fish meal	Value
α	0.7	β	0.8

Table 7
Demand of products.

Parameter	Range			
	p	rp	ro	o
$\widetilde{DR}_{rt}(kg)$	$U[500, 530]$	$U[530, 560]$	$U[560, 590]$	$U[590, 620]$
$\widetilde{DA}_{apt}$(product)	$UD[1900, 101925]$	$UD[101925, 201925]$	$UD[201925, 301975]$	$UD[301975, 402000]$
$\widetilde{DB}_{pt}$(product)	$UD[1470, 2403]$	$UD[2403, 3335]$	$UD[3335, 4268]$	$UD[4268, 5200]$

Table 11
Service level.

Service level	Value	Service level	Value
SLA	92%	*SLB*	92%

Table 12
Distances between facilities.

Distances	Value	Distances	Value
DFR (*km*)	UD[65, 150]	*DCM* (*km*)	UD[30, 60]
DFC (*km*)	UD[60, 105]	*DCA* (*km*)	UD[90, 180]
DRM (*km*)	UD[5, 55]	*DCB* (*km*)	UD[160, 180]
Distances		Value	
DMF (*km*)		UD[90, 130]	

the problem is only active in Tehran, so just 1 online sales center is considered in this case.

Furthermore, during the entire supply process from fish farms to fish meal producing centers, especially in processing operations, a significant amount of carbon is emitted. According to the field investigations, the amount of emitted carbon in this chain is related to transportation and packaging operations the most. Different vehicles are applied in this chain including trucks with water tanks to transport live fish from fish farms to regional markets and fish packaging centers, trucks with refrigerators to transport processed fish to physical sales centers and online sales centers, and light trucks to Also, 2 types of packaging methods are considered in this problem. One of these methods produces less CO_2 during the packaging operation, and on the other hand, in terms of being eco-friendly, it is more compatible with the environment, and it is more expensive to use. However, the value of parameters related to the other method is completely opposite to the mentioned method. These methods are Modified Atmosphere Packaging (MAP) and Two-Layer Vacuum (TLV) respectively.

To estimate the amount of carbon emitted by the mentioned operations, a methodological tool called Life Cycle Assessment (LCA) has been used. LCA serves as a valuable analytical tool for evaluating the environmental impact associated with products or activities across their entire life cycle. Widely applied in various sectors, LCA examines aspects such as product design, manufacturing processes, and transportation methods. The primary objective of employing LCA is to steer decision-making processes toward sustainable solutions that minimize environmental footprints. The LCA process consists of four primary stages: establishment goals and scope, performing inventory analysis, evaluating impacts, and interpreting the results (Menoufi, 2011). Utilizing the Eco-it software, an analysis of the Life Cycle Inventory (LCI) is conducted. The Eco-it software employs the Eco-indicator point system, which is based on the ReCiPe impact assessment method and measures

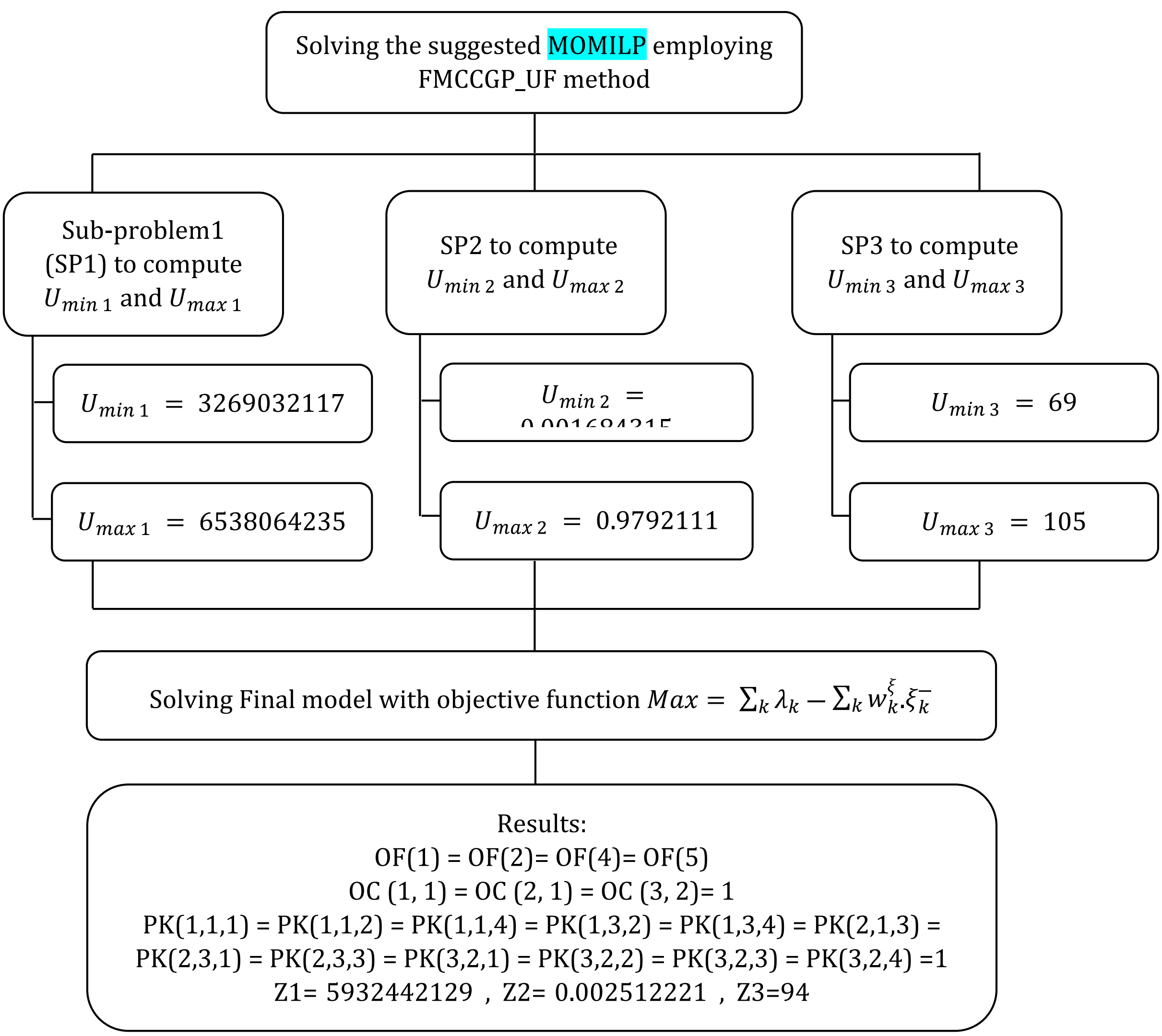

Fig. 7. Results of solving the proposed model.

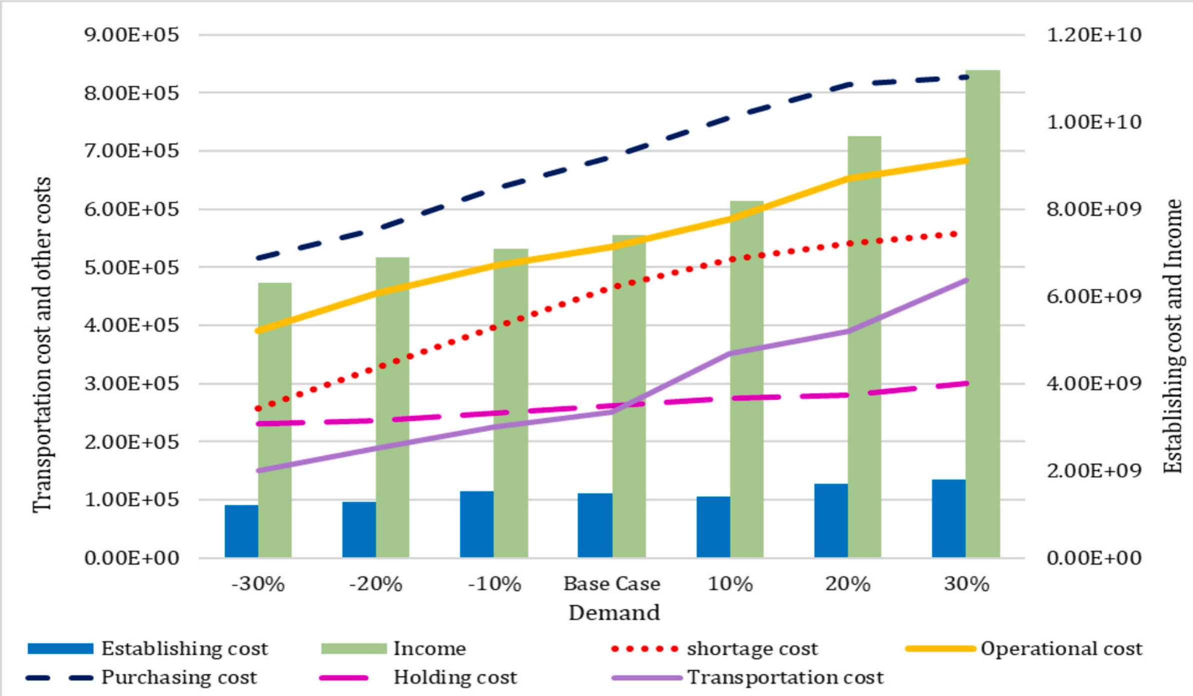

Fig. 8. The behavior of the first OF by changing demand.

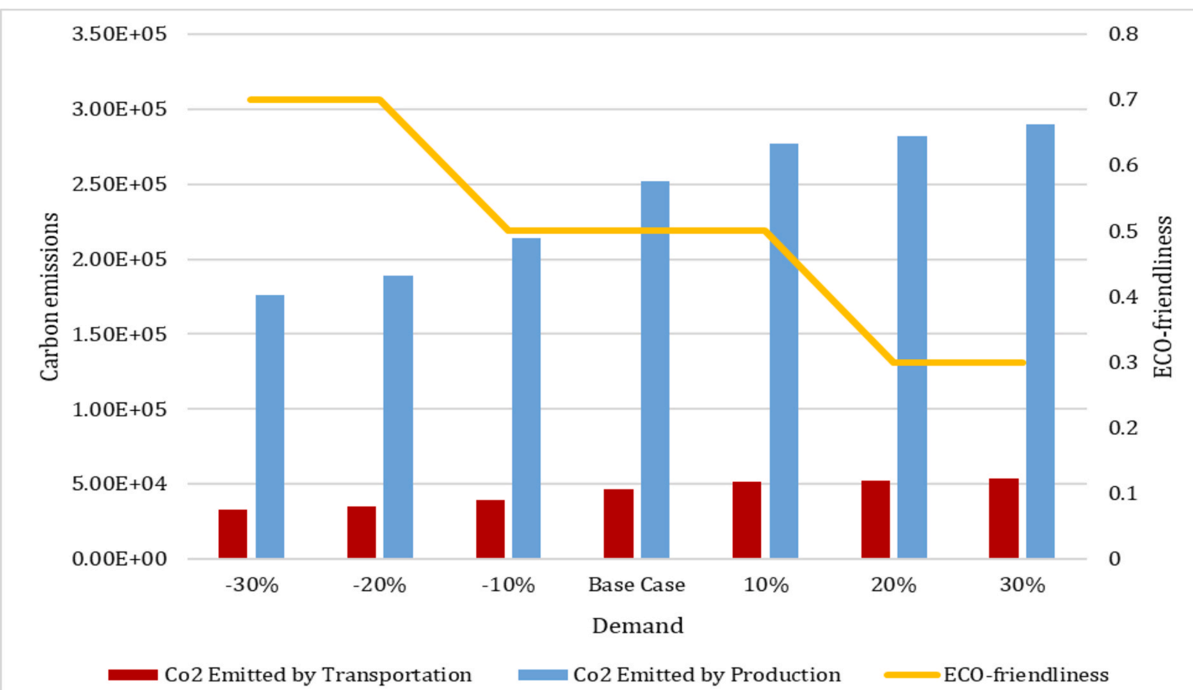

Fig. 9. Impacts of changing demand on the behavior of the second OF.

environmental impact using CO_2 equivalents throughout the life cycle of a process or product. In Table 2 and Table 3, these trapezoidal fuzzy estimated parameters are presented.

6.2. Input data

This section presents the values of the main parameters. In Section 6.1, the size of the problem is given. It is noticeable that based on the proposed case study, there is a fish packaging center that is working already (packaging center number 1 with packaging method 1) and the model is deciding to open 2 remaining packaging centers. Also, based on the fact that fish is a perishable product and perishability is not in the scope of this research, the horizon of the model recommended by experts is about 4 weeks. The data used in this research were obtained through various methods. Some were derived from the relevant research literature, while others were collected through field research and

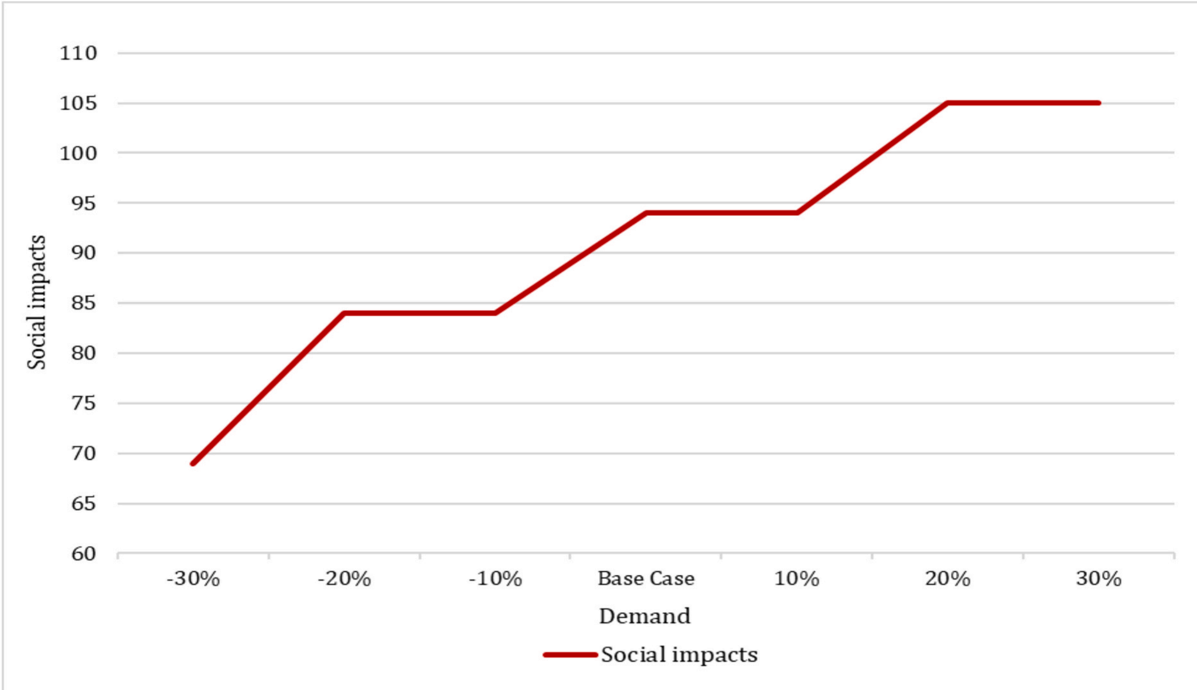

Fig. 10. Impacts of changing demand on the behavior of the third OF.

Table 13
The outcome of the sensitivity analysis regarding the weights of the OFs.

	w1	w2	w3	Profit	CO_2 emitted by-production	CO_2 emitted by transportation	ECO-friendliness	Socialimpacts
1	0.333	0.333	0.333	5.93E + 09	10536.8	52817.6	0.5	94
2	0.8	0.1	0.1	6.23E + 09	10,621	55458.5	0.5	84
3	0.1	0.8	0.1	5.72E + 09	9904.55	53028.8	0.7	84
4	0.1	0.1	0.8	5.70E + 09	11274.3	57571.2	0.3	105

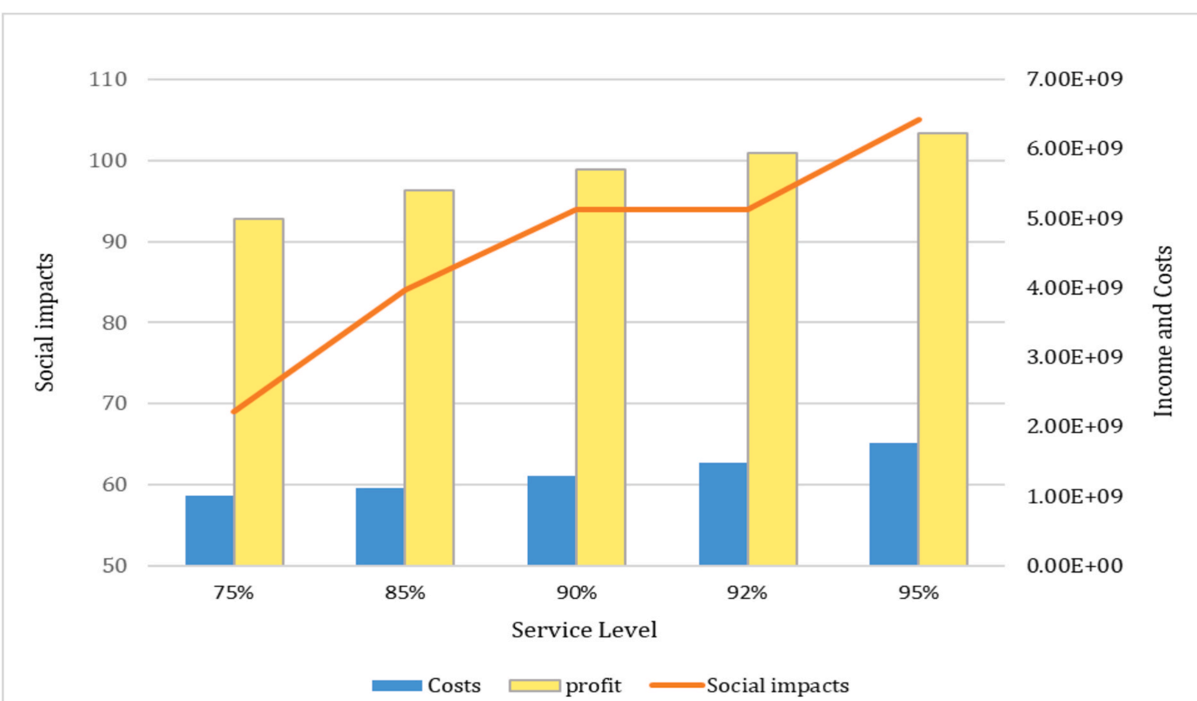

Fig. 11. Impacts of changing service level on the behavior of the first and third OFs.

interviewing the company's experts. For example, data related to capacities, demand, service level, discount, and costs related to the establishment, production, purchasing, and prices of selling products, are obtained by assessing and interviewing the company's experts, while environmental and social aspects of sustainability, distances, costs of shortage, holding, transportation, and Conversion ratios, are provided from literature and field research. Hence, in Table 4, the weight of the products is given, which is obtained through field research. In Table 5 all fuzzy costs are presented. The fuzzy social parameters and the rate of being eco-friendly of packaging methods are given In Table 6, which, as like as the parameters of carbon emission, are obtained through the LCA method. In Table 7, fuzzy demands of the model are presented. Also as follows, different prices of products in the supply chain, different discount rates and discount sensitivity index for demand are provided in Table 8.

In Table 9, the capacity of supply, production, and vehicles of the model are shown as follows. Four different types of vehicles are applied in this problem for transporting different kinds of materials and products in the chain. To transport live fish from fish farms to regional markets and packaging centers, a diesel truck with a water tanker with a capacity of 8–10 CBM is considered which has a capacity equal to VF (kg) to carry live fish. To transport products from fish packaging centers to physical sales centers and the online platform, a truck works with CNG, which has a refrigerator that can control the temperature between −18 to 0 Celsius degrees, with a capacity of VP (kg) to carry products. To transport fish waste from different parts to fish meal production centers, a diesel truck with a capacity of VW (kg) is considered, and at last, a diesel truck with a capacity of VM (kg) is considered to transport fish meals from fish production centers to fish farms. In Table 10 the Conversion ratio of live fish to HOG fish and fish waste to fish meal are given. Also, the service level rate in physical sales centers and online channels is provided in Table 11. At last, distances between each facility, are given in Table 12.

6.3. Reporting the results

The results from utilizing the FMCCGP-UF method to solve the research problem are illustrated in Fig. 7. It is important to highlight that, according to expert evaluations, the weights assigned to the OFs stand at 0.3 each. Similarly, the goal weights are set at 0.3 for each as well. The mathematical model proposed is formulated and optimized using LINGO 17.0 software, under Windows 10 Pro, on a PC with an Intel® Core™ i7-1065G7 CPU running at 1.50 GHz with RAM 16.0 GB, which the total CPU time of the problem is calculated in 583.2 (s). Based on the obtained results, fish farms #1, #2, #4, and #5 are selected for purchasing live fish (i.e. OF in Fig. 7). Furthermore, packaging centers #2 with packaging method #1, and packaging centers #3 with packaging method #2 are opened (i.e. OC in Fig. 7), and the output of the discount decision (i.e. PK) is also presented in Fig. 7.

6.4. Sensitivity analyses

In this section, the model's behavior under varying parameters is examined. Specifically, changes in demands, service levels, discounts, and the eco-friendliness rate of packaging methods are analyzed for their impact on the model. Additionally, the outcomes of the problem with different weights and a robustness analysis of penalty costs assigned to the objective functions are evaluated.

6.4.1. Demand

The model is analyzed for 6 demand scenarios (from −30 % to + 30 %) to evaluate the impact of demand variations on OFs. The outputs of different demand scenarios for the first OF are pictured in Fig. 8. With an increase in demand, all cost elements show an upward trend. while the demand decreases by 30 % from the base case, operational cost, shortage cost, purchasing cost, holding cost, transportation cost, establishment cost, and income decrease by 27 %,45 %, 25 %, 12 %, 40 %, 17 %, and 15 % respectively, as illustrated in Fig. 8. Conversely, by 30 % increasing demand, mentioned costs increase by 28 %, 20 %, 20 %, 15 %, 90 %, 22 %, and 34 % respectively.

Fig. 9 displays the effect of different demand scenarios on the second OF (environmental aspects of sustainability). Fig. 9 shows how the amount of CO_2 emissions from production and transportation activities, along with the eco-friendliness level, changes with varying demand. It

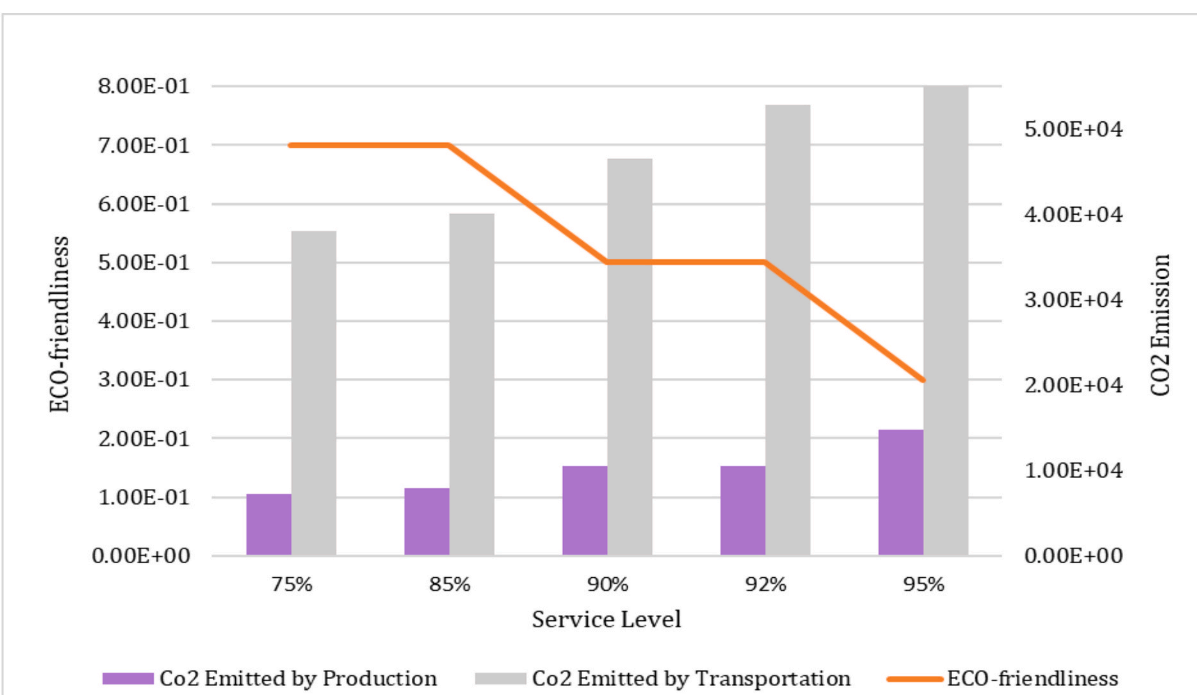

Fig. 12. Impacts of changing service level on the behavior of the second OF.

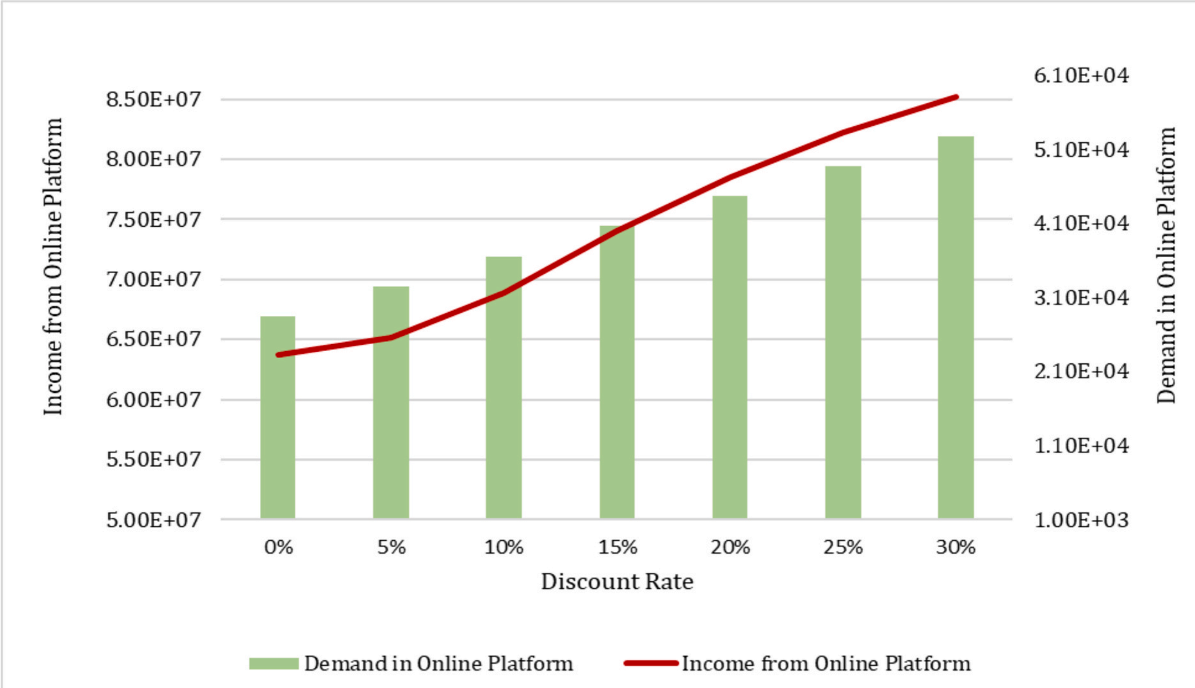

Fig. 13. Impacts of changing discount rate on the behavior of the demand and income on the online platform.

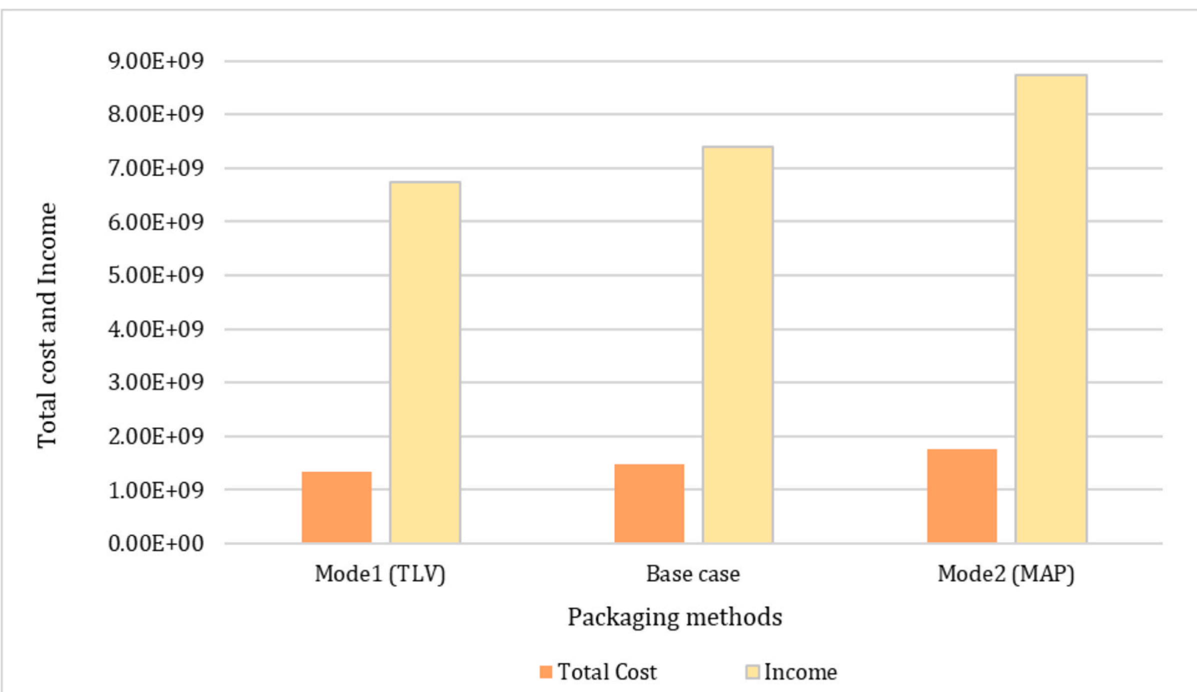

Fig. 14. Impacts of using different packaging methods on the behavior of total cost and income.

also shows that increasing demand by 30 % from the baseline case results in a 15 % increase in CO_2 emissions from production activities and a 17 % increase from transportation activities while reducing the eco-friendliness level to 0.3. Conversely, a 30 % reducing demand from the base case, reduces CO_2 emissions from production and transportation activities by 28 % and 35 % respectively and increases the eco-friendliness level to 0.7.

Fig. 10 outlines the behavior of social impact, which is the third OF, in different demands. It shows that a 30 % increase in demand raises social impacts to a value of 105 compared to the base case, while a 30 % decrease in demand lowers social impacts to a value of 69 compared to the base case. See (Table 13).

6.4.2. *Service level*

In this section, behaviors of the research problem are discussed, by changing the amount of service level considered for the supply chain. In

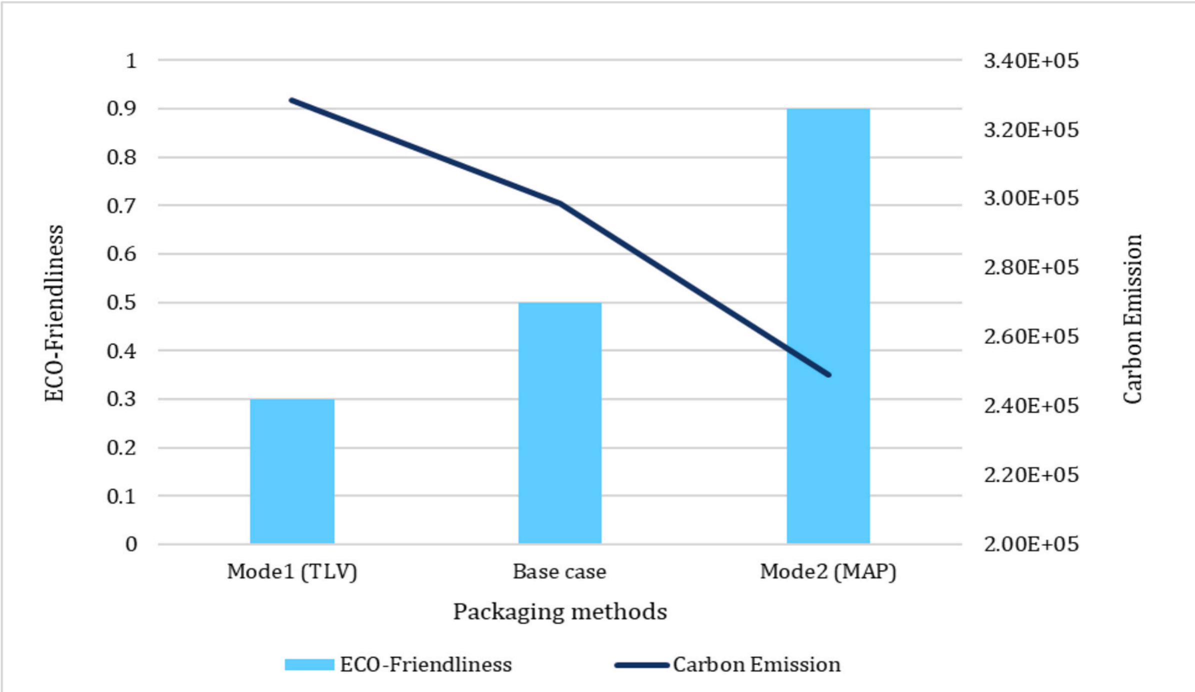

Fig. 15. Impacts of using different packaging methods on the behavior of eco-friendliness and carbon emission.

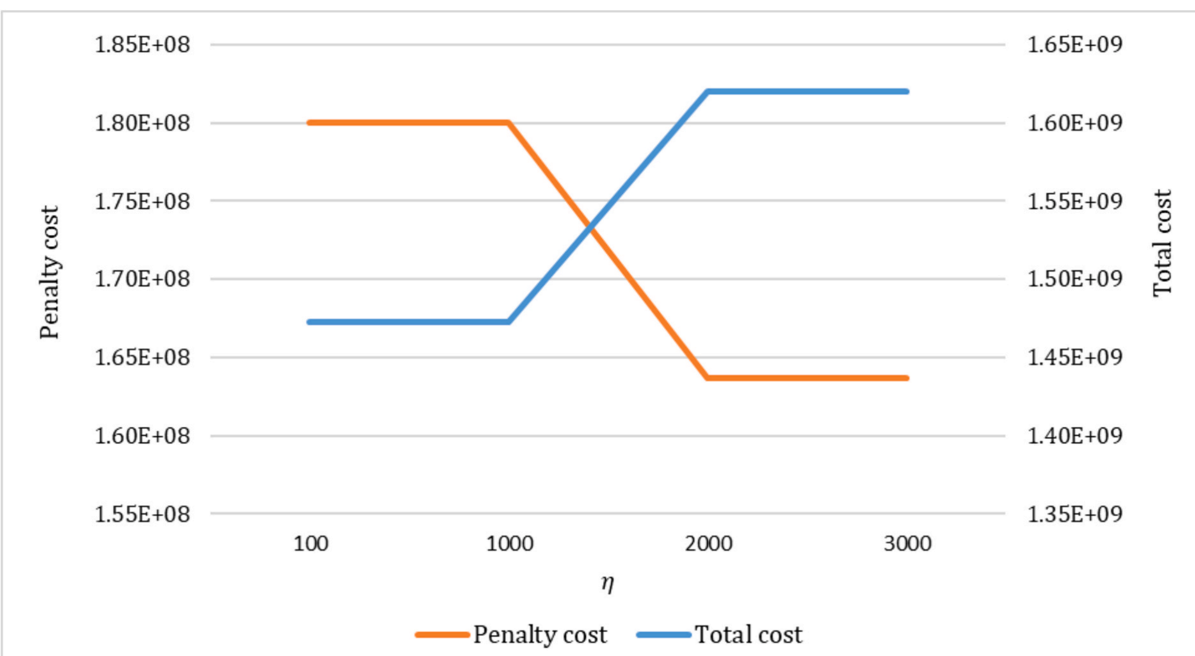

Fig. 16. Sensitivity analysis on η.

this regard, Fig. 11 shows the behavior of the first and third OFs based on different rates of service level. As presented in Fig. 11, the increase in the service level leads to an increase in costs, profit, and social impacts on the supply chain.

Moreover, the performance of the second OF, based on the changes in service level, is shown in Fig. 12. It shows that increasing the rate of service level from 75 % to 95 % increases carbon emitted by transportation and production by 46 % and 106 % respectively. Also increasing the rate of service level from 75 % to 95 % decreases eco-friendliness to 57 %.

6.4.3. *Discount*

In this section, changes in demand and income in the online platform are discussed by considering the change in discount rate for the proposed supply chain. In this regard, as illustrated in Fig. 13, by increasing the rate of discount, demand on the online platform and income gained from the online platform are significantly increased. As it is shown, by increasing the rate of discount from 0 to 30 %, demand and income respectively increase by 86 % and 34 %.

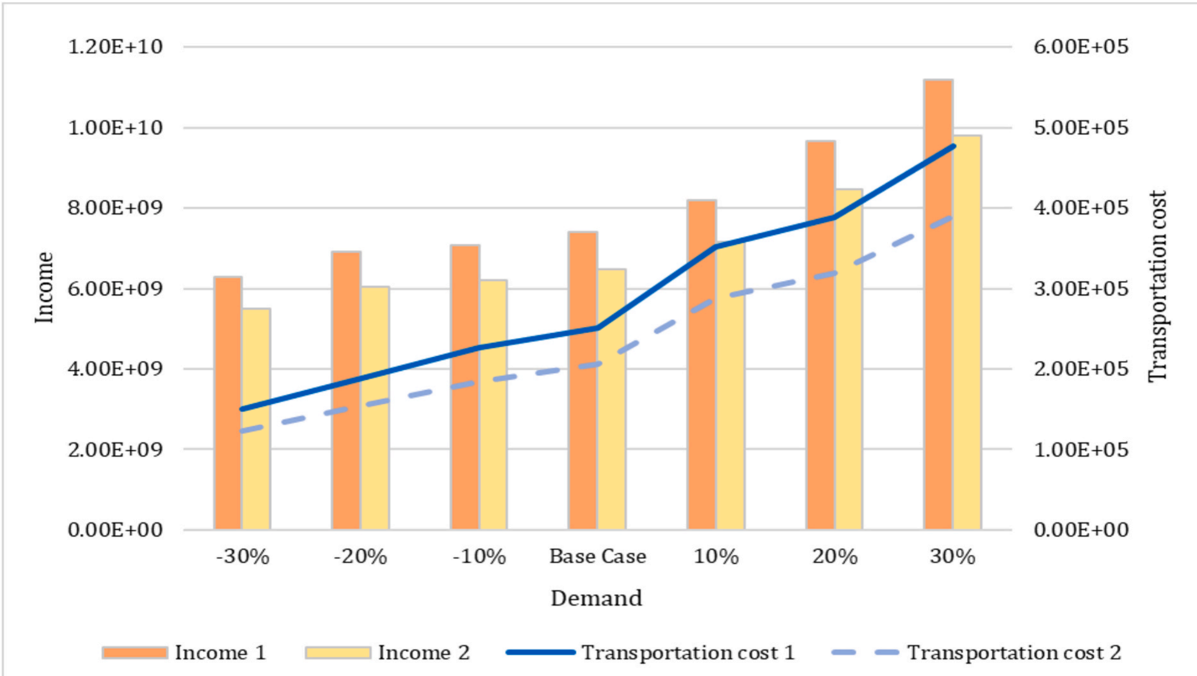

Fig. 17. The resulting changes in revenue and transportation costs without considering circularity in the chain.

Table 14
Test problems to check the performance of the FMCCGP_UF model.

		Indices							
Test Problem		*f*	*c*	*q*	*p*	*r*	*a*	*m*	*t*
	1	3	2	2	2	2	2	2	3
	2	5	3	2	3	3	2	2	4
	3	6	4	3	4	4	3	3	5
	4	7	5	4	5	5	4	4	6
	5	8	6	5	6	6	5	5	7

6.4.4. *Eco-friendliness rate of packaging methods*

As mentioned in the previous sections, in this research, different packaging methods with different costs and different eco-friendliness rates in the fish packaging centers are considered. Also, the products produced by these two methods have different selling prices. Therefore, in this section, these rates are analyzed to see their impact on cost, income, and environmental factors. In this analysis, two modes are examined. Mode 1: if only the TLV packaging method is used in the network and mode 2: if only the MAP packaging method is used. In this regard as shown in Fig. 14, if mode 1 is only being used in the chain, costs decrease by 10 % and income by 9 %. On the other hand, if only mode 2 is used in the chain, the costs and income will increase by 20 % and 18 %, respectively.

It is noticeable that based on Fig. 15, in mode 2, CO_2 emission decreases by 20 % percent, while it increases by 10 % percent in mode 1. On the other hand, the eco-friendliness rate increased to 0.9 in mode 2 while it decreased to 0.3 in mode 1. As shown in Fig. 15 and Fig. 14 respectively, not only using the MAP method is better for environmental aspects, but it also causes an increase in the income gained.

6.4.5. *Objective functions' weights*

In this part, the impacts of the assigned weights on OFs are explored. Referring to Table 10, through analysis across 4 different cases, it becomes evident that in case 2, the first OF aligns with its PIS while other objectives exhibit poorer outcomes compared to case 1 (the base case). In case 3, where the weight of the second OF surpasses others, improvements are noted in CO_2 emissions from production and transportation, as well as eco-friendliness when contrasted with other scenarios. On the other hand in case 4, social impact is higher in comparison to other cases.

6.4.6. *Robustness analysis on penalty cost*

As the penalty cost is a crucial parameter in assessing robustness, this section is dedicated to analyzing the effects of changing the penalty cost on the model's robustness. In this regard, in Fig. 16 sensitivity analysis on the penalty cost parameter is shown (i.e. η). Fig. 16 illustrates that for $100 \leq \eta \leq 1000$ and $2000 \leq \eta \leq 3000$ the penalty cost and the total cost stay consistent. however, for $1000 \leq \Omega \leq 2000$, the total cost increases while lowering the penalty cost.

6.5. *Results without the CE*

In this section, the problem is solved without considering the circularity of the chain to compare the obtained results with the presented network. Therefore, we remove the fish meal production center from the chain. By removing the fish meal production center, the transportation cost and revenue of the problem change. Hence, in Fig. 17, the changes in transportation cost and revenue are shown at different levels of demand. In Fig. 17, it is well seen that the elimination of circularity, due to the lack of transporting waste to the fish meal production center, reduces transportation costs, while the income gained in the circular supply chain is significantly higher than the chain without circularity. This happens because in the circular supply chain, in addition to the sale of fish meal, the chain also earns money through selling waste. (i.e. income 1 and transportation 1 are the results of the circular supply chain model).

6.6. *Performance of the FMCCGP_UF model*

Given that this study introduces a new solution approach (FMCCGP_UF), it is crucial to evaluate its effectiveness. To achieve this, comparing it with traditional methods, as suggested in the literature, is appropriate. Accordingly, five test problems of varying scales are provided in Table 14, with test problem #2 being the primary version applied in the study. The problem is also solved using three similar

Table 15
Performance of the FMCCGP_UF.

Test Problem	Metrics	FMCCGP_UF	CMCGP-UF	FMCGP	MCGP-UF
1	CPU Time (s)	452.5	376.3	376.5	351.9
	λ_1	0.901	–	0.820	–
	λ_2	0.897	–	0.801	–
	λ_3	1	–	0.975	–
	(d_1^+, d_1^-)	(0,24.6)	(0, 141.7)	(0, 315.7)	(0, 304.5)
	(d_2^+, d_2^-)	(0.0009,0)	(0.101,0)	(0.154,0)	(0.157,0)
	(d_3^+, d_3^-)	(0,0)	(0,10)	(0,10)	(0,10)
	ϕ_1	0.9885	0.715	–	0.605
	ϕ_2	0.9905	0.805	–	0.751
	ϕ_3	0.9909	0.856	–	0.755
	ξ_1^-	0.0115	0.285	–	0.395
	ξ_2^-	0.0095	0.195	–	0.249
	ξ_3^-	0.0091	0.144	–	0.245
2	CPU Time (s)	583.2	495.5	494	474.6
	λ_1	0.874	–	0.735	–
	λ_2	0.831	–	0.717	–
	λ_3	1	–	0.941	–
	(d_1^+, d_1^-)	(0,52.3)	(0, 263.4)	(0, 401.2)	(0, 425.3)
	(d_2^+, d_2^-)	(0.0056,0)	(0.162,0)	(0.215,0)	(0.243,0)
	(d_3^+, d_3^-)	(0,0)	(0,10)	(0,10)	(0,10)
	ϕ_1	0.9803	0.687	–	0.562
	ϕ_2	0.9836	0.714	–	0.645
	ϕ_3	0.989	0.792	–	0.653
	ξ_1^-	0.0197	0.313	–	0.438
	ξ_2^-	0.0164	0.286	–	0.355
	ξ_3^-	0.011	0.208	–	0.347
3	CPU Time (s)	945.6	803.8	801	769.8
	λ_1	0.802	–	0.667	–
	λ_2	0.754	–	0.634	–
	λ_3	1	–	0.865	–
	(d_1^+, d_1^-)	(0,202.5)	(0, 443.5)	(0, 585.2)	(0, 602.5)
	(d_2^+, d_2^-)	(0.0185,0)	(0.208,0)	(0.324,0)	(0.335,0)
	(d_3^+, d_3^-)	(0,0)	(0,10)	(0,10)	(0,10)
	ϕ_1	0.9005	0.601	–	0.431
	ϕ_2	0.9021	0.625	–	0.554
	ϕ_3	0.9051	0.605	–	0.566
	ξ_1^-	0.0995	0.399	–	0.569
	ξ_2^-	0.0979	0.375	–	0.446
	ξ_3^-	0.0949	0.395	–	0.434
4	CPU Time (s)	1025.2	871.5	608.4	834.6
	λ_1	0.774	–	0.605	–
	λ_2	0.703	–	0.595	–
	λ_3	0.973	–	0.813	–
	(d_1^+, d_1^-)	(0,511.3)	(0, 615.2)	(0, 752.1)	(0, 802.5)
	(d_2^+, d_2^-)	(0.0352,0)	(0.425,0)	(0.523,0)	(0.548,0)
	(d_3^+, d_3^-)	(0,10)	(0,10)	(0,21)	(0,21)
	ϕ_1	0.865	0.571	–	0.351
	ϕ_2	0.8501	0.578	–	0.465
	ϕ_3	0.8651	0.515	–	0.475
	ξ_1^-	0.135	0.429	–	0.649
	ξ_2^-	0.1499	0.422	–	0.535
	ξ_3^-	0.1349	0.485	–	0.525
5	CPU Time (s)	1203.4	1022.9	1019.3	979.6
	λ_1	0.704	–	0.558	–
	λ_2	0.646	–	0.524	–
	λ_3	0.905	–	0.768	–
	(d_1^+, d_1^-)	(0,835.7)	(0, 911.5)	(0, 1043.8)	(0, 1107.8)
	(d_2^+, d_2^-)	(0.0685,0)	(0.689,0)	(0.752,0)	(0.785,0)
	(d_3^+, d_3^-)	(0,10)	(0,21)	(0,21)	(0,21)
	ϕ_1	0.805	0.502	–	0.304
	ϕ_2	0.8001	0.502	–	0.412
	ϕ_3	0.8051	0.504	–	0.416
	ξ_1^-	0.195	0.498	–	0.696
	ξ_2^-	0.1999	0.498	–	0.588
	ξ_3^-	0.1949	0.496	–	0.584

methods proposed by Nayeri et al. (2023) (i.e., CMCGP-UF), Bankian-Tabrizi et al. (2012) (i.e., FMCGP), and Chang (2011) (i.e., MCGP-UF). Table 15 presents a comparison of results from each method, highlighting the efficiency of FMCCGP_UF. As shown in Table 15, the FMCCGP_UF method outperforms other methods across all metrics. For instance, in terms of deviations (d_k^+, d_k^-), FMCCGP_UF consistently shows the least deviations across all test problems. Additionally, for the third objective function (OF), d_k^+ and d_k^- are zero, and the results are nearly zero for the second OF in test problems #1 to #3. Furthermore, the normalized deviation of y_k (ξ_k^-) and the utility value of the kth OF (ϕ_k) are better in the FMCCGP_UF method. However, as the scale of the test problems increases, ϕ_k decreases and ξ_k^- increases across all methods. Since FMCCGP_UF and FMCGP are fuzzy methods, there is a variable that indicates the achievement degree of the kth objective, denoted by λ_k. As shown in Table 15, λ_k equals one for the third OF and is very close to one for the first and second OFs in test problems #1 to #3. In contrast, the FMCGP method never achieves better λ_k values than FMCCGP_UF, further demonstrating the superior performance of the developed method. Despite these advantages, FMCCGP_UF is not as fast as other methods in terms of CPU time. However, it performs better in other metrics.

6.7. *Research limitations and outlooks*

Similar to other academic works, this article has some limitations, too. Ignoring perishability is the main limitation of this study because this work has considered a short planning horizon. However, seafood products, especially fish products, are perishable and cannot be consumed after the expiration date. In this way, one of the future research directions is to incorporate perishability into the proposed model. Also, another limitation of this study is that it only focused on the fuzzy environment. In this regard, due to the importance of uncertainty in these days global and competitive marketplace, future works can investigate the study under mixed uncertainty. Due to the high impact of competition on the world's markets, supply chains have moved to become global, therefore another limitation of this study is related to its scale, which based on the complexity of the network, has not been considered on a global scale. According to this, for future studies, global supply chain factors can be included, which means different types of transportation such as transportation by airplanes and ships can be considered. It is evident that incorporating resiliency and responsiveness into the supply chain, with a focus on addressing risks and disruptions, holds significant importance. Furthermore, strategies like Transportation by lateral vehicles and having some suppliers as backup, raise the responsiveness and the flexibility of the network. Additionally, considering the complexity of the model in larger scenarios, exploring efficient *meta*-heuristic algorithms could be a promising direction for future research.

6.8. *Discussion*

This section discusses the results obtained from solving the model. The current study is compared with similar studies to highlight its unique contributions, and the suggested model is evaluated against existing references. In Nematollahi et al. (2024) and Bassett et al. (2022), a dual-channel network was presented. However, this study also develops a mathematical model and implements online discounts to motivate customers. Askarian-Amiri et al. (2021) introduced a dual-channel network, and this research incorporates online discounts as well. Mirzagoltabar et al. (2021) designed a sustainable, closed-loop supply chain with a dual-channel network, and this study adds online discounts. Li et al. (2023) and Mirzaei et al. (2023) designed a sustainable dual-channel network, while this study also considers CE aspects. Liu et al. (2024) designed a dual-channel network under uncertainty, and this study includes a circular supply chain focused on sustainability.

Schmidt & Moreno (2022) and Najafi & Zolfagharinia (2024) established a sustainable supply chain network, and this study also considers CE aspects. Bunkar et al. (2024) considered both economic and environmental sustainability. Rani et al. (2024) presented valuable concepts related to the SSC. Bharathi et al. (2024), Hopkins et al. (2024), and John & Mishra (2024), outlined principles of a sustainable SSC. In Tseng et al. (2022), concepts regarding a sustainable SSC under uncertainty are discussed, but none of these articles (i.e., Bunkar et al. (2024), Rani et al. (2024), Bharathi et al. (2024), Hopkins et al. (2024), John & Mishra (2024), and Tseng et al. (2022)) provide a mathematical model for the fish supply chain. This research offers a mathematical model for the sustainable fish supply chain network, considering uncertainty. In De et al. (2022), a sustainable fish supply chain network was designed, whereas this research provides a circular and sustainable supply chain network for the fish industry. Purnomo et al. (2022) established a sustainable closed-loop fish supply chain, while this study also considers a dual-channel sales network. Fadeeva & Van Berkel (2023) presented useful concepts regarding the CE but did not mention sustainability principles. Gholian-Jouybari et al. (2024), Shahsavani et al. (2024), and Mosallanezhad et al. (2021), designed a supply chain network incorporating CE concepts in the form of a closed-loop supply chain. This study presents a supply chain network that integrates CE concepts in the form of a circular supply chain, which performs better in waste management. Moreover, sustainability concepts are also considered in this study. Goodarzian et al. (2023) presented a closed-loop and sustainable supply chain network. Additionally, Alinezhad et al. (2022) and Krishnan et al. (2022), designed closed-loop and sustainable supply chain networks considering uncertainty. This study designs a sustainable circular supply chain network considering uncertainty and dual-channel sales. Mosallanezhad et al. (2023) presented a closed-loop and sustainable SSC network, and Fasihi et al. (2023) designed a closed-loop and sustainable SSC network considering uncertainty. This study also presents a dual-channel sales system with discounts for the online channel. Earlier studies did not account for discounts in dual-channel systems and have not designed a circular supply chain. Hence, designing a circular supply chain network by including discounts in the online channel, has resulted in increased profitability. Moreover, this design has enhanced waste management, leading to the creation of byproducts from waste materials.

7. Conclusions and implications

7.1. Remarks

This study has addressed a significant gap in the literature by developing a circular dual-channel fish supply chain model that considers multi-period and multi-product dimensions, aimed at enhancing sustainability under uncertainty. The MOMILP model introduced in this research aims to maximize profitability, optimize environmental impacts (by minimizing carbon emissions and maximizing eco-friendliness), and enhance social aspects (such as job creation). To manage uncertainties, a novel fuzzy robust programming optimization model, FMCCGP_UF, was developed and validated using real-world data from a case study. In summary, the main findings are as follows:

- Novelty: This study is the first to design a multi-period and multi-product circular dual-channel supply chain network for the fish industry, incorporating sustainability and CE dimensions under uncertainty.
- Environmental Impact: By considering various packaging methods with different production costs, eco-friendliness rates, and CO_2 emissions, this study promotes sustainable practices. The design also minimizes waste by converting it into byproducts within the network.
- Social and Economic Benefits: The inclusion of online platform discounts and their effects on sales provides new economic insights. Moreover, The circular supply chain boosts revenue through the sale of byproducts.
- Methodological Contribution: The FMCCGP_UF method offers a robust and efficient solution to the MOMILP model, facilitating a versatile trade-off analysis to optimize sustainability.

7.2. Managerial insights

The proposed MOMILP model serves as a strategic tool for industry managers to address cost reduction while mitigating social and environmental impacts. It aids in optimizing facility selection and location, responding effectively to the demands of fish products and byproducts derived from fish waste. Key managerial insights include:

- Demand Management: As demonstrated in Fig. 8, larger demands result in higher costs due to the necessity of managing shortages and adding new facilities. Supply chain managers can adopt strategies such as subcontracting to handle temporary capacity increases without high costs, implementing overtime work, and leveraging advanced demand forecasting techniques to buffer against demand fluctuations. These strategies can help maintain high service levels and manage rising shortage costs effectively.
- Eco-friendly Practices: Fig. 9 illustrates how increased demand can lead to higher transportation and production activities, diminishing focus on eco-friendliness and increasing carbon emissions. Prioritizing eco-friendly packaging methods can mitigate this impact. Research indicates that consumers are willing to pay a premium for products produced through eco-friendly methods, which enhances brand loyalty and attracts environmentally conscious consumers. Companies adopting eco-friendly practices can also avoid potential fines and sanctions and benefit from long-term savings through reduced waste management costs and potential tax incentives.
- Circular Economy: As shown in Fig. 17, applying CE principles to the fish supply chain reduces waste and increases income from the sale of byproducts. Managers are encouraged to consider selling waste to by-product plants instead of disposing of it, thereby generating additional revenue and contributing to sustainability.
- Service Levels: Fig. 11 and Fig. 12 indicate that enhancing the service level leads to higher profits and positive social impacts but also increases costs and CO_2 emissions. To maintain high service levels without increasing emissions, it is recommended to invest in energy-efficient equipment and processes. Additionally, investing in carbon offset programs can balance out emissions that cannot be eliminated, ensuring sustainability.
- Discounting Strategies: As depicted in Fig. 13, discounting is an effective factor in increasing demand and income. Applying discounts on online sales platforms can enhance money, information, and product flows within the network. Over the long term, this strategy can improve customer satisfaction by making products more accessible. Managers are advised to consider integrating online sales channels with physical sales to maximize these benefits.

7.3. Theoretical implications

This research significantly contributed to the theoretical understanding of supply chain design, particularly with an emphasis on sustainability and the CE. Key theoretical contributions include:

- Integration of Sustainability: The research focused on designing a supply chain network with a crucial emphasis on sustainability. Therefore, sustainability has been defined by integrating economic, environmental, and social elements into the approach.
- Combination of Sustainability and CE: By combining sustainability aspects and circular economy principles, this study addressed both waste management and environmental protection. This dual focus

not only prevents environmental damage but also enhances income generation within the supply chain network.
- Fuzzy Robust Programming Method: To address uncertainty, the fuzzy robust programming method was utilized. Unlike previous studies, this research demonstrated the various states of the proposed method by considering equal, greater than, and less than constraints within the robust counterpart model. This comprehensive approach has highlighted the versatility and applicability of the method under different conditions.
- Limitations of CMCGP-UF Method: The conventional CMCGP-UF method assumed constant attribute values, limiting its flexibility. Recognizing this, the CMCGP-UF method was adapted by incorporating fuzzy logic to address the inherent uncertainties. This novel approach, termed FMCCGP_UF, incorporated utility function constraints to align with decision-makers' preferences and integrated fuzziness constraints. This methodology effectively has aided decision-makers in navigating the imprecise and uncertain aspects of the business environment, enhancing the overall robustness and applicability of the solution process.

CRediT authorship contribution statement

Parand Sojoudi: Writing – original draft, Software, Resources, Investigation, Formal analysis, Data curation. **Mohammad Mahdi Paydar:** Writing – review & editing, Validation, Supervision, Project administration, Conceptualization. **Sina Nayeri:** Writing – original draft, Visualization, Project administration, Investigation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cie.2025.111017.

Data availability

Data will be made available on request.

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