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Research article

Beyond profit margins: Orchestrating social, economic, and environmental sustainability within the Norwegian Salmon Food Supply Chain

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ABSTRACT

Food Supply Chains (FSCs) have become increasingly complex with the average distance between producers and consumers rising considerably in the past two decades. Consequently, FSCs are a major source of carbon emissions and reducing transportation costs a major challenge for businesses. To address this, we present a mathematical model to promote the three core dimensions of sustainability (economic, environmental, and social), based on the Mixed-Integer Linear Programming (MILP) method. The model addresses the environmental dimension by intending to decrease the carbon emissions of different transport modes involved in the logistics network. Several supply chain network characteristics are incorporated and evaluated, with a consideration of social sustainability (job generation from operating various facilities). The mathematical model's robustness is demonstrated by testing and deploying it to a variety of problem instances. A real-life case study (Norwegian salmon supply chain) helps to comprehend the model's applicability. To understand the importance of optimizing food supply networks holistically, the paper investigates the impact of multiple supply chain permutations on total cost, demand fluctuations and carbon emissions. To address fluctuations in retail demand, we undertook sensitivity analysis for variations in demand, enabling the proposed model to revamp Norway's salmon supply chain network. Subsequently, the results are thoroughly examined to identify managerial implications.

1. Introduction

1.1. Motivation and background

For the past few decades, transport has been the largest contributor to the rise in global greenhouse gases, responsible for a projected 750 million metric tonnes of carbon emissions (OECD/ITF, 2017). Moreover, transportation costs remain a substantial burden on Supply Chain Networks (SCNs) (Wu et al., 2018). Road transportation accounts for a little more than half of all freight transportation in the European Union (EU), while maritime transport accounts for a relatively lower share (30%) (Pfoser, 2022). In inland freight movement, road transportation accounts for around 75% of the total emissions (European Commission, 2019) implying that most inland freight transportation occurs by road, resulting in a substantial carbon footprint (EEA, 2023). Specifically, road freight transportation contributes to around 53 per cent of carbon dioxide (CO_2) emissions involved emanating from global trade-related transport. Consequently, a cleaner, greener freight system is required. However, adopting more sustainable supply chain logistics practices remains challenging (Mallick et al., 2023), due to ever-increasing consumer expectations, constant pressure on product specificities and cost constraints, growing supply chain complexities, and regulatory requirements (Tumpa et al., 2019; Wu and Pagell, 2011).

With the rise in the world's population, food consumption is also increasing, placing a strain on our natural resources (Nicolau et al., 2021). The expansion of the global economy and rising living standards have increased the intake of protein-rich foods like meat, milk, and eggs (Cai et al., 2022). The production of animal protein is a major concern,

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and alternative protein sources are critically needed. To this end, the aquaculture sector has the potential to considerably boost seafood supplies leading to increased protein supply (Rowan, 2023). In the past three decades, inland aquaculture has experienced significant growth. In 2018, globally, aquaculture accounted for 52% of total fish production for human consumption (FAO, 2020). While the aquaculture industry's share has risen substantially across the world, it has also prompted considerable environmental concerns (Ahmad et al., 2022). Unsustainable aquacultural techniques, transportation, and possible detrimental consequences on ecosystems are the most prevalent issues (Klinger and Naylor, 2012). Salmon aquaculture is currently the fastest-growing food production system, and salmon consumption is three times higher today than it was in 1980 (WWF, 2023). Since salmon are predominantly farmed in North-Western Europe and North American countries like Norway, the United Kingdom, and Canada, the effects of salmon farming are among the most studied and comprehended in the aquaculture industry (Abualtaher and Bar, 2020).

In the case of Norwegian salmon aquaculture, the growth from its inception in the 1970s has been exceptional, and it has become the market leader (Straume et al., 2020). However, the sustained growth has a significant potential to negatively impact the surrounding ecosystem and wild ecology (Marvin et al., 2020). In 2017, when production output was increased, the Norwegian salmon farming sector produced around seven million tonnes of GHGs (Ziegler et al., 2022). Consequently, an important challenge is to develop supply chains that reduce carbon emissions while operating at a high level of output (Ziegler et al., 2022). Currently, the Norwegian salmon supply chain network relies on various modes of freight transportation (Ziegler et al., 2022); hence, sustainably optimizing such a large and growing industry can decrease the carbon footprint and potentially increase related profitability.

Apart from the environmental aspects of sustainability, SCNs need to be competitive and sustainable from an economic perspective as well, in that cost elements from end-to-end operations should be captured and optimized (De et al., 2023). For instance, a typical salmon supply chain network can have multiple cost drivers such as those related to transportation, fuel consumption, facility operations, inventory holding, and residuals. Further, each of these costs can have various constituent elements (De et al., 2022). For instance, transportation costs can be modelled as an aggregate of all the costs encountered in first-, mid-, and last-mile delivery. Similarly, residual costs can be characterized by the cost of handling and disposing of the residues at slaughterhouse, primary processing facility, and secondary processing facility etc. From the perspective of the social aspect of sustainability, factors such as the number of jobs opportunities created, social welfare, and balanced economic development have been considered in the extant literature (Mogale et al., 2022; Choudhary et al., 2021). However, most work on optimizing FSCs ignores the social dimension (Bellassen et al., 2022).

1.2. Paper contribution

Against the backdrop of the above discussions, the purpose of this research is to holistically evolve and optimize the multi-period Norwegian salmon SCN by employing a Mixed Integer Linear Programming (MILP) model. The proposed model's core objective is to assist food supply chain decision-makers in minimising total expected costs, mitigating demand fluctuations, reducing overall carbon emissions from different transportation modes across the SCN, and increasing employment prospects through job creation. The models also consider key real-world considerations such as transportation capacity, fluctuating customer demand, varying inventory, facility disruption, and variabilities in product supply. Furthermore, the suggested mathematical model helps to resolve the unpredictability of inventory storage, processing, and transportation costs. Furthermore, the model seeks to construct a holistic SCN by considering social, economic, and environmental factors.

The paper consists of 5 sections. Section 2 presents a review of the literature. Section 3 addresses the problem statement and model formulation (including notations and formulation). Section 4 presents and analyses the results obtained through the experiments on the Norwegian salmon case study. Finally, section 5 outlines conclusions, managerial implications, and recommendations for future research.

2. Literature review

This section presents a review of extant research concerning the sustainability of Food Supply Chains (FSCs), electrification of vehicles, and logistics and network optimization models for food supply chains, to position the current study within the literature.

2.1. Sustainability of food supply chains

Sustainable development is a global priority for policymakers and businesses operate within supply chains that face increasing environmental, social, and governance requirements (Chen et al., 2024; von Berlepsch et al., 2022). While organizations around the globe are striving to decrease their carbon footprints, they must do so in ways that achieve harmony amongst the social, environmental and economic pillars of sustainability (Tsang et al., 2023; Bellassen et al., 2022). Achieving such a harmony for FSCs is particularly challenging owing to perishability, limited storage, and safety concerns while still ensuring continuous food availability (Kumar et al., 2020; Taghikhah et al., 2021; Wu et al., 2018). However, approximately one-third of the world's food production is currently wasted (FAO, 2019). Around 230 km^3 of water and 300 million barrels of oil would be needed to produce the quantity of food that is wasted globally (Gardas et al., 2019). With rising demand for food worldwide and an expansion in logistics and transportation (Morgan et al., 2022), global food systems have become a major polluter, causing climate change (Crippa et al., 2021).

Recent estimates suggest that food-system emissions amount to 18 Gt CO_2 equivalent per year globally, accounting for 34% of total GHG emissions (Crippa et al., 2021). Consequently, policy makers and regulatory bodies increasingly focus on the sustainability practices of food systems, especially transportation as global food-miles account for almost 20% of all food-systems emissions (Li et al., 2022). Consumers have also become increasingly concerned about the sustainability and transparency of food supply chains (European Commission, 2020a), influencing substantial alterations in policy goals (European Commission, 2020b). The European Union's (EU) Climate Law, for example, specifies the aim of reaching carbon neutrality by 2050 (European Parliament and Council, 2021). Furthermore, emphasis has also shifted to more sustainable food production networks that significantly cut carbon footprints (European Commission, 2020b; Reddy et al., 2022). The reductions in GHG emissions envisaged directs attention to enhancing the efficacy of multimodal logistics (Ala-Harja and Helo, 2014). Consequently, to benchmark and improve the environmental and financial outcomes of FSCs various stakeholders, including governments, manufacturers, retailers, and consumers advocate for a higher level of transparency to identify solutions to minimize incurred carbon emissions and associated costs (European Commission, 2020b; FMI and NielsenIQ, 2022).

2.2. Electrification of vehicles

Electric Vehicles (EV) demonstrate tremendous potential for achieving resource efficiency and reducing CO_2 emissions (Gustafsson et al., 2021). EVs, including trains, buses, and cars, have a higher "well-to-wheel" energy efficiency than their internal combustion engine vehicle equivalents (Gustafsson et al., 2021). Furthermore, they benefit from transferring their emissions to the existing power production facilities, preventing them from emitting additional GHG while in operation. Consequently, governments around the world have implemented regulations and incentives to hasten the transition to sustainable mobility (Kirschstein et al., 2022). In Europe, some countries introduced subsidies for the purchase of EVs as well as tax incentives (acea, 2022). However, the introduction of EVs in commercial transportation occurs slowly and heavy-duty trucks remain a major polluter and one of the most challenging transportation components to decarbonize (Schiffer et al., 2021; Slattery et al., 2021). Aside from expensive prices, battery energy density was formerly a hurdle to the adoption of electric trucks, but the situation is improving rapidly (Nykvist and Olsson, 2021). Specifically, reductions in battery costs, and improvements in battery lifetimes and fast charging indicate that the widespread electrification of heavy-duty vehicles in the next decade is feasible (Nykvist and Olsson, 2021; Phadke et al., 2021). This offers the opportunity to reduce GHG emissions from food transportation substantially, as well as offer economic advantages (Martins-Turner et al., 2020).

2.3. Sustainable logistics

Compared to other modes of transportation, road freight transport is expanding the fastest (European Commission, 2019), resulting in adverse environmental outcomes. Consequently, the European Union seeks to develop multimodal freight transport to minimize air pollution and congestion problems (European Parliament, 2019). However, despite political attempts to encourage multimodality, trucks continue to convey most freight (Osieczko et al., 2021). Roadways are commonly employed in freight transportation due to their flexibility in conveying small amounts, delivering products door-to-door (Goswami et al., 2020; Martins-Turner et al., 2020). However, it is typically less ecologically friendly as it emits more CO_2 than rail or maritime transportation, accounting for 77% of all EU transport GHGs (European Environment Agency, 2022). Moreover, congestion across European motorways is becoming increasingly severe, resulting in substantial economic costs and further pollution (Struyf et al., 2022). Hence, multimodal freight transportation is one plausible response to this challenge (Jiang et al., 2020).

Multimodal freight movement was proposed over four decades ago to reduce the environmental impact of logistics by shifting commodities to more environmentally sustainable modes of transportation such as railways or waterways (UNCTAD, 1980). Multimodal terminals, where diverse modes of transportation coexist, play an important role in delivering goods to their ultimate destination. However, multimodal transport has a greater organizational complexity than road transport since these terminals suffer from availability and capacity constraints (Witte et al., 2012). Moreover, pre- and post-haulage processes must often be established to operate multimodal transport, resulting in additional organizational effort and lower flexibility (Frémont and Franc, 2010). Importantly, multimodal transportation is only feasible over long distances and with large cargo volumes, as the costs and time spent increase with additional transhipment processes. Moreover, administrative bottlenecks caused by various rules, regulations and customs procedures, especially in international transit, hinder the adoption of multimodal transportation (Pfoser, 2022). Furthermore, rigid residence hours imposed by ports, railways and inland waterways limit the flexibility of multi-modal freight operations, with noncompliance potentially resulting in hefty demurrage costs (Frémont and Franc, 2010). However, Pfoser (2022) established ways to address and mitigate the abovementioned issues by developing appropriate policy measures which promote multimodal transportation. Furthermore, by combining multiple modes of transportation, the advantages of one mode could be leveraged, and the limitations of the other modes can be compensated (Fontaine et al., 2021). Similarly, the economic efficiency and durability of waterways and railways can be blended with the speed and convenience of road transportation (SteadieSeifi et al., 2014).

2.4. Network optimization models in food supply chains

Several academic researchers developed supply chain and logistic network models emphasizing sustainability (Udomwannakhet et al., 2018). These follow different approaches. Sawadogo and Anciaux (2011), to assist decision-makers in choosing the optimal plan of action from a wide variety of options in a multimodal network, employed the analytic hierarchy process and elimination and choice expressing reality methods to create a multi-decision support system that integrates the three elements of sustainability, namely economic, environment, and social factors. Although such a model aids in the determination of the shortest (optimal) route, the integration of the various modes of transportation is not adequately studied, exposing a substantial research gap in previous work that should be addressed. Furthermore, Yavari and Zaker (2019) developed a green perishable food SCN design model, considering the durability of integrated two echelons during power disruptions. They developed a bi-objective model to decrease CO_2 emissions and the overall cost of the SCN, solving the proposed model using the LP-metric approach. In addition, a four-tiered SCN for dairy foods in Iran was investigated as well by Yavari and Zaker (2019). The modelling revealed that the effects of network integration and product durability might lower a SCN's overall costs and emissions by 21% and 25% respectively.

Jabbarzadeh et al. (2020) evolved a MILP model to minimize the overall associated risks, the costs incurred and CO_2 emissions of Hazmat transportation and used a "location-routing" model in a multimodal network of highways and trains. Based on the model's findings, they suggest that uncertainty in CO_2 emissions might have a significant influence on optimum solutions. Furthermore, the researchers focused on a multimodal network with a single point of origin-destination and just a single type of hazardous material. However, restricting occurrences to a single route may not be realistic in many real-world settings. Consequently, it is preferable to develop an optimization model that reduces environmental effects and transportation costs on a broader scope.

Ambrosino and Sciomachen (2021) examined the influence of external costs on the planning and operation of green logistics networks using an optimization model. Their model considers multi-modal freight distribution channels integrating containerized flows from ports to the hinterland. External costs were incorporated to show their influence, as they can affect the structure of multimodal networks and import flow management. However, the research did not emphasize road transportation. In earlier work. Ambrosino and Sciomachen (2016) suggested another framework for capacitated multiple hub location challenges in multimodal networks. Namely and uniquely, they split the required origin-destination demand into several pathways leveraging various transport modes and hubs. The mathematical model is optimally solved using IBM ILOG CPLEX Optimization Studio (abbreviated as CPLEX). An extension of this study can provide greater depth in considering environmental considerations and outcomes.

Liotta et al. (2015) devised a model that predicts the optimal mix of industrial locations and multimodal connectivity. This indicates that a well-coordinated production and distribution network lowers total manufacturing and shipment costs by reducing transport costs and GHG emissions. Furthermore, while factoring in the plant's production capabilities and the costs incurred during transportation, procurement and supply of goods, this model effectively analysed challenges that represent the economic and environmental aspects of sustainability. Furthermore, optimizing inventory management by employing zero-inventory techniques might have a major impact. According to Pereira et al. (2013), transitioning to multimodal transportation seems more cost-effective and environmentally friendly than depending on roads since it reduces GHG emissions and promotes economies of scale. The paper proposes a novel approach for optimizing freight networks, applying it to a case study in Spain. The case study's results, however, could not be validated in that additional research and data are necessary to evaluate the suggested marine routes. The optimization strategy, on the other hand, proved effective for enhancing predictive modelling and may thus be utilized in other cases where more detailed information is accessible. This is often difficult for food systems, where detailed transport cost information is unavailable. Within the industry, cost concerns remain highly salient and managers must balance a set of economic, social and environmental objectives Most facilities placement or SCN design concerns in food supply chains are cost-related (Gholami-Zanjani et al., 2021). Consequently, a multi-period and comprehensive integration of socioeconomic and environmental elements are essential for a complete evaluation of the design of food supply chains (Mohammed and Wang, 2017).

2.5. Research gaps

We undertook a thorough review of extant research, addressing the model's properties, objective functions, adopted judgements and methodologies for solutions. Current studies on SCNs incorporate mathematical models that contain a variety of stakeholders and commodities (Mogale et al., 2023a, 2023b). However, limited work concentrates on modelling aspects, such as those observed in salmon SCNs (Shepherd et al., 2017). Most previous studies adopt the MILP method to represent the problem and handle multi-echelon scenarios. Furthermore, some models incorporate plant location and logistics as considerations. However, such models typically overlook carbon emissions from transportation. Furthermore, social objectives are either not considered or where considered do not encapsulate socioeconomic welfare components, specifically employment generation (Tautenhain et al., 2021). Past research modelling salmon supply chain logistics such as De et al. (2022) explore the economic and environmental dimensions but overlooks social aspects such as job creation, which is a critical element of triple bottom line approaches (e.g. people, planet, and profit) to sustainability (Senyo and Osabutey, 2021). The holistic integration of sustainability's three main pillars i.e., economic, environmental, and social aspects in the design of FSCs is increasingly important for policymakers, regulators and the practitioners (Bellassen et al., 2022), and this serves as a key motivation in developing the proposed optimization model,. Moreover, past research work on salmon supply chain logistics does not consider disruptions which might occur during product shipment and at the facility level, as well as the necessity of considering the electrification of transportation and its potential impact on carbon emissions and costs (De et al., 2022). This recognises the need for modelling that captures the complexity of SCNs, with various goods and transport modes (De et al., 2020). Consequently, the research addresses the complexities of the salmon SCN while considering a range of transport modes and processing operations, making the model versatile and generalizable to other food supply chains.

3. Problem description

The Norway salmon SCN consists of salmon farms, slaughterhouses, primary processing plants, secondary processing plants, wholesalers, and retailers. Salmon farms supply live salmon to slaughterhouses, which process the live fish to produce Head-on-Gutted (HOG) salmon. The HOG product is then delivered from the slaughterhouse to the primary processing factory, where it is processed into fresh HOG salmon products. At the primary processing plant, a portion of the fresh HOG salmon product procured is sent to a secondary processing plant, while the remainder is transferred to wholesalers. Secondary processing plants process fresh HOG salmon products to generate whole fillets and salmon by-products. Retailers' demands for fresh HOG salmon are fulfilled by wholesalers. Furthermore, secondary processing plants meet retailers' demand for whole fillets and salmon by-products. The distribution of such varied products necessitates the utilization of multiple transportation modes. Several product types generate residuals (waste) after processing. Specifically, residuals from processed live salmon, HOG fish, and fresh HOG salmon products occur at the slaughterhouse, primary processing plant, and secondary processing plant, respectively. The demand for salmon products mentioned above constantly varies, making it difficult for SCN managers to accurately predict demand. Consequently, inefficiencies in resource optimization often occur, negatively affecting supply chain actors with an increase in the overall costs incurred and a rise in the carbon emissions across the supply chain.

Regarding key choices, several decision variables have binary, continuous, and integer characteristics. For instance, which slaughterhouse, primary processing plant, and secondary processing plant would operate in which time-period and under which disruption scenario is characterized by binary variables. Similarly, whether to deploy electric transportation or fossil fuel-based transportation, at each of the five stages of transportation (i.e., salmon farm to slaughterhouse, slaughterhouse to primary processing plant, primary processing plant to secondary processing plant, secondary processing plant to wholesaler, and wholesaler to retailer) can be characterized by binary variables. Amounts to be transported at each of the five stages of transportation can be denoted by continuous variables. Similarly, inventory levels, processing amounts, residual amounts are characterized by continuous variables. Finally, the number of required trips for transportation across the five stages of transportation are characterized by integer variables.

4. Mathematical model

This section presents the mathematical formulation for the SCN, along with the objective functions and limitations. In the interest of brevity, Appendix A supplements the notations associated with the proposed mathematical model that includes sets, parameters, decision, variables, and indices.

Minimize Objective Function 1

$$\begin{aligned} \textit{Expected Total Cost} = {} & \textit{Expected Transportation Cost} + \textit{Expected Fuel Cost} \\ & + \textit{Expected EV Charging Cost} + \textit{Expected Operating Cost} \\ & + \textit{Expected Inventory Cost} + \textit{Expected} \quad \textit{Processing Cost} \\ & + \textit{Expected Residual Cost} \end{aligned} \tag{1}$$

The objective function 1 of the mathematical model, shown in Equation (1) minimises expected total costs, which includes the expected cost components from transportation, fuel consumption, electric vehicle charging, operating facilities, inventory holding at the facilities, processed amount, and residual amount.

$$\textit{Expected Transportation Cost} = \sum_{s} \pi^{s} \left[\begin{array}{c} \sum_{a,b,t} TQ^{i}_{ab} Z_{ab} N^{is}_{abt} + \sum_{b,c,t} TQ^{j}_{bc} Z_{bc} N^{js}_{bct} + \sum_{c,d,t} TQ^{k}_{cd} Z_{cd} N^{ks}_{cdt} + \sum_{c,e,t} TQ^{k}_{ce} Z_{ce} N^{ks}_{cet} + \sum_{e,f,t} TQ^{k}_{ef} Z_{ef} N^{ks}_{eft} \\ + \sum_{d,e,t} \left(TQ^{l}_{de} N^{ls}_{det} + TQ^{m}_{de} N^{ms}_{det} \right) Z_{de} + \sum_{e,f,t} \left(TQ^{l}_{ef} N^{ls}_{eft} + TQ^{m}_{ef} N^{ms}_{eft} \right) Z_{ef} \end{array} \right] \tag{2}$$

Equation (2) illustrates the expected transportation costs, which consists of seven parts that individually relate to the shipping of various types of salmon products. The first term computes the transportation costs for shipping live salmon from the salmon farms to the slaughterhouses, while the second term seeks to calculate the transportation costs for moving HOG fish from slaughterhouses to primary processing plants. The third term calculates the transportation cost for transporting fresh HOG salmon products from primary to secondary processing facilities. The fourth and fifth terms determine the cost of transportation for moving fresh HOG salmon products from primary processing plants to wholesalers to retailers respectively. The cost of transporting whole fillet products and salmon by-products from secondary processing facilities to wholesalers to retailers is determined by the sixth and seventh terms.

$$Expected\ Fuel\ Cost = \sum_{s,t} \pi^s \alpha_t \left[\begin{array}{c} \sum_{a,b} FC^i_{ab} Z_{ab} N^{is}_{abt} U_{ab} + \sum_{b,c} FC^j_{bc} Z_{bc} N^{js}_{bct} U_{bc} + \sum_{c,d} FC^k_{cd} Z_{cd} N^{ks}_{cdt} U_{cd} + \sum_{c,e} FC^k_{ce} Z_{ce} N^{ks}_{cet} U_{ce} \\ + \sum_{e,f} FC^k_{ef} Z_{ef} N^{ks}_{eft} U_{ef} + \sum_{d,e} \left(FC^l_{de} N^{ls}_{det} + FC^m_{de} N^{ms}_{det} \right) Z_{de} U_{de} + \sum_{e,f} \left(FC^l_{ef} N^{ls}_{eft} + FC^m_{ef} N^{ms}_{eft} \right) Z_{ef} U_{ef} \end{array} \right] \quad (3)$$

Equation (3) depicts the expected fuel costs and is segregated into seven components. Fuel costs are computed considering the total fuel consumed while transporting various types of salmon products and fluctuating fuel prices. Each term is related to the fuel cost for the seven transportation phases as mentioned above. The first term, for instance, determines the cost of the fuel used to transport live salmon from salmon farms to slaughterhouses. The second term aids in estimating the fuel costs incurred when transporting HOG products from slaughterhouses to the primary production plants. The third term determines the fuel cost of transporting fresh HOG products between primary and secondary processing facilities. The fourth and fifth terms determine the fuel costs of transporting fresh HOG salmon products from primary processing facilities to wholesalers and to retailers. The sixth and seventh terms compute the fuel costs for transporting whole fillet products and salmon by-products from secondary processing plants to wholesalers to retailers.

$$Expected\ EV\ Charging\ Cost = \sum_{s,t} \pi^s \beta_t \left[\begin{array}{c} \sum_{a,b} Z_{ab} N^{is}_{abt} X_{ab} + \sum_{b,c} Z_{bc} N^{js}_{bct} X_{bc} + \sum_{c,d} Z_{cd} N^{ks}_{cdt} X_{cd} + \sum_{c,e} Z_{ce} N^{ks}_{cet} X_{ce} + \sum_{e,f} Z_{ef} N^{ks}_{eft} X_{ef} \\ + \sum_{d,e} \left(N^{ls}_{det} + N^{ms}_{det} \right) Z_{de} X_{de} + \sum_{e,f} \left(N^{ls}_{eft} + N^{ms}_{eft} \right) Z_{ef} U_{ef} \end{array} \right] \quad (4)$$

Equation (4) given below depicts the expected charging costs for electric vehicles deployed on shipment routes for transporting various types of salmon products while considering fluctuating charging prices. Since we do not consider the initial acquisition cost of fossil-fuel based vehicles and rather consider the fuel costs over the planning horizon, corresponding charging cost associated with electric vehicles would have to be considered in the formulation as well (without explicitly considering the initial acquisition cost of electric vehicles). Extant studies have shown that in the case of electric vehicles, the product lifecycle cost is majorly constituted of acquisition cost, operating cost, and liquidation cost (Furch et al., 2022). Further, acquisition cost itself is a function of activities involving mining for rare earth metals for production of batteries, research and development costs, other production costs and so forth. Furch et al. (2022) further captures that the operating cost (charging costs) over lifecycle represents around 40%–50% of the lifecycle cost of electric vehicles depending upon the battery configuration. Thus, the expected charging costs for electric vehicles deployed on shipment routes captures significant portion with the lifecycle cost of deployed electric vehicle within the planning horizon. Each term is related to the charging cost for the seven transportation phases mentioned above. The first term, for instance, determines the expected charging cost for transporting live salmon from salmon farms to slaughterhouses. The second term estimates the expected charging costs incurred when transporting HOG fish from slaughterhouses to primary production plants. The third term determines the expected charging costs associated with transporting fresh HOG products between primary and secondary processing facilities. The expected charging costs of transporting fresh HOG salmon products from primary processing facilities to wholesalers to retailers are determined by fourth and fifth terms. The sixth and seventh terms compute the expected charging costs for transporting whole fillet products and salmon by-products from secondary processing plants to wholesalers to retailers.

$$Expected\ Operating\ Cost = \sum_{s} \pi^s \left[\sum_{b,t} OQ^t_b V^{st}_b + \sum_{c,t} OQ^t_c V^{st}_c + \sum_{d,t} OQ^t_d V^{st}_d \right] \quad (5)$$

The expected operating cost of the facilities is represented by equation (5), and it is comprised of three terms. The first term determines the expected cost of operating the slaughterhouses. The second term calculates the expected cost of operating the primary production plants. The third term determines the expected cost of operating the secondary processing facilities.

$$Expected\ Inventory\ Cost = \sum_{s} \pi^s \left[\begin{array}{c} \sum_{b,t} IQ^j_{bt} IL^{js}_{bt} + \sum_{c,t} IQ^k_{ct} IL^{ks}_{ct} + \sum_{e,t} IQ^k_{et} IL^{ks}_{et} + \sum_{d,t} \left(IQ^l_{dt} IL^{ls}_{dt} + IQ^m_{dt} IL^{ms}_{dt} \right) \\ + \sum_{e,t} \left(IQ^l_{et} IL^{ls}_{et} + IQ^m_{et} IL^{ms}_{et} \right) \end{array} \right] \quad (6)$$

Equation (6), consisting of five parts, represents the expected cost of holding inventories. The first term calculates the expected inventory holding cost for stocking HOG salmon in slaughterhouses. The second and third terms determine the expected inventory holding costs for fresh HOG salmon products at primary processing plants and wholesalers, respectively. The fourth and fifth terms compute the expected inventory holding costs related to whole fillet products and salmon by-products at the secondary processing facilities and wholesalers, respectively.

$$\textit{Expected Processing Cost} = \sum_{s} \pi^{s} \left[\sum_{b,t} PQ_{bt}^{j} PA_{bt}^{js} + \sum_{c,t} PQ_{ct}^{k} PA_{ct}^{ks} + \sum_{d,t} \left(PQ_{dt}^{l} PA_{dt}^{ls} + PQ_{dt}^{m} PA_{dt}^{ms} \right) \right] \tag{7}$$

The expected processing costs are represented by Equation (7), which comprises of three terms. The first term determines the expected cost of processing incurred when obtaining HOG product from the slaughterhouses. The second term computes the expected processing costs incurred at primary production plants to obtain fresh HOG products. The third term determines the expected cost of processing whole fillets and by-products of salmon at secondary processing facilities.

$$\textit{Expected Residual Cost} = \sum_{s} \pi^{s} \left[\sum_{b,t} RQ_{bt}^{i} RO_{bt}^{is} + \sum_{c,t} RQ_{ct}^{j} RO_{ct}^{js} + \sum_{d,t} RQ_{dt}^{k} RO_{dt}^{ks} \right] \tag{8}$$

Equation (8) also has three components, highlighting the expected residual costs. The first term represents the expected residual costs of live salmon products at slaughterhouses. The second term describes the expected residual costs incurred from the HOG salmon products at the primary processing facilities. The third term relates to the expected residual costs incurred from fresh HOG salmon products at the secondary processing plants.

Minimize Objective Function 2

$$\textit{Expected Unutilised Space on Transport Mode} = \sum_{s} \pi^{s} \left[\begin{array}{l} \sum_{a,b,t} \left(N_{abt}^{is} CT_{ab}^{is} - Y_{abt}^{is} \right) + \sum_{b,c,t} \left(N_{bct}^{js} CT_{bc}^{js} - Y_{bct}^{js} \right) + \sum_{c,d,t} \left(N_{cdt}^{ks} CT_{cd}^{ks} - Y_{cdt}^{ks} \right) + \sum_{c,e,t} \left(N_{cet}^{ks} CT_{ce}^{ks} - Y_{cet}^{ks} \right) \\ + \sum_{d,e,t} \left[\left(N_{det}^{ls} CT_{de}^{ls} - Y_{det}^{ls} \right) + \left(N_{det}^{ms} CT_{de}^{ms} - Y_{det}^{ms} \right) \right] + \sum_{e,f,t} \left[\begin{array}{c} \left(N_{eft}^{ks} CT_{ef}^{ks} - Y_{eft}^{ks} \right) + \left(N_{eft}^{ls} CT_{ef}^{ls} - Y_{eft}^{ls} \right) \\ + \left(N_{eft}^{ms} CT_{ef}^{ms} - Y_{eft}^{ms} \right) \end{array} \right] \end{array} \right] \tag{9}$$

Equation (9) presents the second objective function of the mathematical model aiming to minimize the expected unutilised space on a transport mode. Equation (9) comprises six terms. The first term computes the expected unutilised space on the transport mode while shipping live salmon from salmon farms to slaughterhouses. The second term estimates the expected unutilised space on the transport mode while transporting HOG products from slaughterhouses to primary processing plants. The third and fourth terms determine the expected unutilised space on the transport mode while shipping fresh HOG products from primary processing plants to secondary processing plants and from primary processing plants to wholesalers, respectively. The fifth term aim to compute the expected unutilised space on the transport mode while shipping whole fillet products and salmon by-products from secondary processing plants to wholesalers. The sixth term estimates the unutilised space available on the transport mode while shipping fresh HOG products, whole fillets and salmon by-products from wholesalers to retailers.

Variations in product sizes, packaging, and transportation conditions significantly affect the quantity of products shipped via different transportation modes. This, in turn, impacts the number of trips required. Our mathematical model assumes that the product sizes and packaging conditions remain relatively constant for different product types such as live salmon, HOG products, fresh HOG products, whole fillet, and salmon by-products. We have identified various decision variables to account for the variability in the number of products shipped from one stakeholder to another, for different product types such as Live Salmon, HOG product, fresh HOG product, Whole Fillet product, and Salmon by-product. Since all these product types are perishable, they require specific handling, and their maximum transportation mode capacity is fixed accordingly. Any increase or decrease in the quantities shipped for a specific product type will consequently change the number of trips. We have considered individual decision variables and parameters for each product type to ensure that the mathematical model is flexible enough to accommodate variability related to the number of product types shipped from one stakeholder to another.

Minimize *Objective Function 3*

$$\textit{Expected Carbon Emission Incurred for Inventory, Processing and Residual operations} = \sum_{s} \pi^{s} \left[\begin{array}{l} IE^{CO_2} \left\{ \sum_{b,t} IL_{bt}^{js} + \sum_{c,t} IL_{ct}^{ks} + \sum_{e,t} IL_{et}^{ks} + \sum_{d,t} \left(IL_{dt}^{ls} + IL_{dt}^{ms} \right) + \sum_{e,t} \left(IL_{et}^{ls} + IL_{et}^{ms} \right) \right\} \\ + PE^{CO_2} \left\{ \sum_{b,t} PA_{bt}^{js} + \sum_{c,t} PA_{ct}^{ks} + \sum_{d,t} \left(PA_{dt}^{ls} + PA_{dt}^{ms} \right) \right\} + RE^{CO_2} \left\{ \sum_{b,t} RO_{bt}^{is} + \sum_{c,t} RO_{ct}^{js} + \sum_{d,t} RO_{dt}^{ks} \right\} \end{array} \right] \tag{10}$$

Equation (10) presents the third objective function, which comprises three distinct components. The first component quantifies the expected carbon emissions associated with holding inventory across various stages of the supply chain, including slaughterhouses, primary processing plants, secondary processing plants, and wholesalers. Here, we determine the inventory level for different salmon product types at various time period such as – inventory level of HOG product at slaughterhouse, inventory level for fresh HOG product at primary processing plant, inventory level for whole fillet product and salmon by-product at secondary processing plant, and inventory level for fresh HOG product, whole fillet product and salmon-by product at wholesaler. Then the overall inventory level for the planning horizon is multiplied with the parameter IE^{CO_2}, which is the carbon emissions incurred for maintaining the inventory level of one unit of salmon product at the facilities (Kg CO_2 per unit product).

The second component of equation (10) focuses on the expected carbon emissions resulting from the processing of salmon products at slaughterhouses, primary processing plants, and secondary processing plants. This entails estimating the processed amount of various salmon product types at different time period, and this include processed amount of HOG product at slaughterhouse, processed amount of fresh HOG product at the primary processing plant and finally, processed amount of whole fillet and salmon by-product at secondary processing plant. Then multiplying the total processed amount across the planning horizon by a parameter PE^{CO_2}, representing the carbon emissions incurred during the processing of one unit of salmon product at the facilities (measured in Kg CO_2 per unit product).

The third component of equation (10) addresses the expected carbon emissions associated with obtaining residuals from the slaughterhouses, primary processing plants, and secondary processing plants. Initially, we compute the residual amount while processing various salmon product types at different time periods. This includes residuals obtained after processing live salmon, HOG product and fresh HOG product at slaughterhouse, primary processing plant and secondary processing plant respectively. The total residual obtained is multiplied with the parameter RE^{CO_2}, which is the carbon emission incurred while obtaining residual from one unit of Salmon product at the facilities (Kg CO_2 per unit product).

Minimize Objective Function 4

slaughterhouses to primary production plants. This includes multiplying the parameters FC_{bc}^{j}, Z_{bc}, U_{bc}, E^{CO_2}, with the decision variable N_{bct}^{js}. Here, FC_{bc}^{j} is the fuel consumed (in litres per km) in shipping Hog product j via certain transport mode from slaughterhouse b to primary processing plant c. Z_{bc} is the distance from slaughterhouse b to primary processing plant c. U_{bc} is a binary parameter which takes a value 1, if fuel transportation mode is deployed from slaughterhouse b to primary processing plant c, and 0 Otherwise. And finally, N_{bct}^{js} is the integer variable which depicts the number of trips made by the transport mode in shipping HOG product j from slaughterhouse b to primary processing plant c in period t during disruption scenario s. Once the HOG product reaches primary processing plant, then it is processed to obtain Fresh HOG products, which is then shipped to secondary processing plants and wholesalers.

The third and fourth terms of equation (11) determines the expected carbon emissions incurred for shipping fresh HOG products from primary to secondary processing facilities and wholesalers. Third term includes multiplying the parameters FC_{cd}^{k}, Z_{cd}, U_{cd}, E^{CO_2}, with the decision variable N_{cdt}^{ks} for estimating the carbon emission incurred in transportation of fresh HOG from primary to secondary processing facilities. Here, FC_{cd}^{k} depicts the fuel consumed (in litres per km) in shipping fresh HOG salmon product k via certain transport mode from primary processing plant c to secondary processing plant d. Z_{cd} denotes the distance from Primary Processing Plant c to secondary processing plant d. U_{cd} is a binary parameter, which takes a value 1 if fuel transportation mode is deployed from Primary Processing Plant c to Secondary Processing Plant d, and 0 otherwise. Finally, N_{cdt}^{ks} is an integer variable which determines the number of trips made by the transport mode in shipping fresh HOG product k from primary processing plant c to secondary processing plant d in period t during disruption scenario s. Once the fresh HOG product

Expected Carbon Emission Incurred on Transportation aspect

$$= \sum_{s} \pi^{s} E^{CO_2} \left[\begin{array}{l} \sum_{a,b,t} FC_{ab}^{i} Z_{ab} N_{abt}^{is} U_{ab} + \sum_{b,c,t} FC_{bc}^{j} Z_{bc} N_{bct}^{js} U_{bc} + \sum_{c,d,t} FC_{cd}^{k} Z_{cd} N_{cdt}^{ks} U_{cd} + \sum_{c,e,t} FC_{ce}^{k} Z_{ce} N_{cet}^{ks} U_{ce} \\ + \sum_{e,f,t} FC_{ef}^{k} Z_{ef} N_{eft}^{ks} U_{ef} + \sum_{d,e,t} \left(FC_{de}^{l} N_{det}^{ls} + FC_{de}^{m} N_{det}^{ms} \right) Z_{de} U_{de} + \sum_{e,f,t} \left(FC_{ef}^{l} N_{eft}^{ls} + FC_{ef}^{m} N_{eft}^{ms} \right) Z_{ef} U_{ef} \end{array} \right] \tag{11}$$

Equation (11) depicts the fourth objective function of the mathematical model aiming to minimize the expected carbon emissions incurred from the shipment of salmon products considering the total number of trips on the transportation routes. Equation (11) comprises of seven terms – the first term which includes multiplying the parameters FC_{ab}^{i}, Z_{ab}, U_{ab}, E^{CO_2}, with the decision variable N_{abt}^{is}, which relates to the total expected carbon emissions incurred across the planning horizon while shipping live salmon products from salmon farms to slaughterhouses. Where FC_{ab}^{i} is the fuel consumed (in litres per km) in shipping Live Salmon i via certain mode of transport from Salmon Farm a to Slaughterhouse b. Z_{ab} depicts the distance from Salmon Farm a to Slaughterhouse b. U_{ab} is the binary parameter which takes a value 1, if fuel transportation mode is deployed from Salmon farm a to Slaughterhouse b, and 0 otherwise. E^{CO_2} is the carbon emission coefficient associated with the fuel (Kg CO_2 per litre). And finally, N_{abt}^{is} is an integer variable which depicts the number of trips made by the transport mode in shipping Live Salmon i from Salmon Farm a to Slaughterhouse b in period t during disruption scenario s. Once the live salmon product reaches the slaughterhouse then it is processed to obtained HOG products, which is then shipped to primary processing plants.

The second term of equation (11) depicts the expected carbon emissions incurred in the transportation HOG products from reaches the secondary processing plant then it is processed to obtain whole fillet and salmon by-product. The fourth term aims to determine the carbon emissions incurred in shipping fresh HOG from primary processing plant to wholesalers, we multiple the parameters FC_{ce}^{k}, Z_{ce}, U_{ce}, E^{CO_2}, with the decision variable N_{cet}^{ks}. Here, FC_{ce}^{k} refers to the fuel consumed (in litres per km) while shipping fresh HOG salmon product k via certain mode of transport from primary processing plant c to wholesaler e. Z_{ce} depicts the distance from primary processing plant c to wholesaler e. U_{ce} is a binary parameter while takes a value 1, if fuel transportation mode is deployed from primary processing plant c to wholesaler e, 0 otherwise. Finally, N_{cet}^{ks} is the number of trips made by the transport mode in shipping fresh HOG product k from primary processing plant c to wholesaler e in period t during disruption scenario s. Once the fresh HOG product reaches the wholesaler, then it is shipped to the retailer based on the demand of the product.

The sixth term of equation (11) is associated with computing expected carbon emissions incurred for transporting whole fillet products and salmon by-products from secondary processing plants to wholesalers. This is computed by adding the total fuel consumed in moving the products between secondary processing plants to wholesalers, while considering the number of trips. The overall fuel consumed is then multiplied with the following parameters Z_{de}, U_{de} and E^{CO_2} for obtaining the overall carbon emission. The following parameters and decision variables are involved in the sixth term. FC^{l}_{de} depicts the fuel consumed (in litres per km) while shipping whole fillet product l via certain mode of transport from secondary processing plant d to wholesaler e. FC^{m}_{de} represents the fuel consumed (in litres per km) while shipping salmon by-product m via certain mode of transport from secondary processing plant d to wholesaler e. N^{ls}_{det} is integer variable highlighting the Number of trips made by the transport mode in shipping whole Fillet product l from secondary processing plant d to wholesaler e in period t during disruption scenario s. N^{ms}_{det} is the integer variable depicting the number of trips made by the transport mode in shipping Salmon by-product m from secondary processing plant d to wholesaler e in period t during disruption scenario s. Among parameters, Z_{de} is the distance between secondary processing plant d to wholesaler e. U_{de} is a binary parameter which takes a value 1 if fuel transportation mode is deployed from Secondary Processing Plant d to Wholesaler e and 0 otherwise. Once the whole fillet products and salmon by-products are shipped to the wholesalers, then the quantity is used to meet the demand at the retailer end.

The fifth and seventh terms of equation (11) aim to estimate the expected carbon emissions for shipping fresh HOG salmon products, whole fillet products and salmon by-products from wholesalers to retailers. This is determined by computing the total fuel consumed in moving the three product types from wholesalers to retailers while considering the number of trips. The total fuel consumed is then multiplied with the following parameters Z_{ef}, U_{ef} and E^{CO_2} for obtaining the overall carbon emission incurred between wholesalers to retailers. The following parameters and decision variables are used in the fifth and seventh terms. FC^{k}_{ef} is the fuel consumed (in litres per km) while shipping fresh HOG salmon product k via certain mode of transport from wholesaler e to retailer f. FC^{l}_{ef} is the fuel consumed (in litres per km) while shipping whole fillet product l via certain mode of transport from wholesaler e to retailer f. FC^{m}_{ef} is the fuel consumed (in litres per km) while shipping salmon by-product m via certain mode of transport from wholesaler e to retailer f. N^{ks}_{eft} is the number of trips made by the transport mode in shipping fresh HOG product k from wholesaler e to retailer f in period t during disruption scenario s. N^{ls}_{eft} is the number of trips made by the transport mode in shipping whole fillet product l from wholesaler e to retailer f in period t during disruption scenario s. N^{ms}_{eft} is the number of trips made by the transport mode in shipping salmon by-product m from wholesaler e to retailer f in period t during disruption scenario s. Among the parameters, Z_{ef} is the distance from wholesaler e to retailer f. U_{ef} is a binary parameter which takes a value 1, if fuel transportation mode is deployed from wholesaler e to retailer f, 0 otherwise.

Maximize Objective Function 5

$$Expected\,Number\,of\,Jobs\,Created = \sum_{s}\pi^{s}\left[\sum_{b,t}O^{t}_{b}V^{st}_{b} + \sum_{c,t}O^{t}_{c}V^{st}_{c} + \sum_{d,t}O^{t}_{d}V^{st}_{d}\right] \tag{12}$$

Equation (12) highlights the fifth objective function of the mathematical model which, in line with social proprieties, seeks to maximize the expected number of jobs created operating various facilities. The first, second, and third terms of equation (12) determine the expected number of job opportunities created by operating the slaughterhouses, primary production plants, and secondary processing plants, respectively. Constraints associated with the proposed multiple objectives mathematical model are given as follows:

$$N^{is}_{abt} \geq \frac{Y^{is}_{abt}}{CT^{is}_{ab}}\ \forall a \in A, b \in B, s \in S, t \in T \tag{13}$$

$$N^{js}_{bct} \geq \frac{Y^{js}_{bct}}{CT^{js}_{bc}}\ \forall b \in B, c \in C, s \in S, t \in T \tag{14}$$

Equations (13) and (14) helps to estimate the number of trips made on a particular transportation route considering the total number of products sent and the capacity of the transportation mode. Equation (13) depicts the number of trips performed from salmon farms to slaughterhouses and Equation (14) estimates the number of trips from slaughterhouses to primary processing plants.

$$N^{ks}_{cdt} \geq \frac{Y^{ks}_{cdt}}{CT^{ks}_{cd}} \forall c \in C, d \in D, s \in S, t \in T \tag{15}$$

$$N^{ks}_{cet} \geq \frac{Y^{ks}_{cet}}{CT^{ks}_{ce}}\ \forall c \in C, e \in E, s \in S, t \in T \tag{16}$$

$$N^{\delta s}_{det} \geq \frac{Y^{\delta s}_{det}}{CT^{\delta s}_{de}}, For\ \delta = l, m\ \forall d \in D, e \in E, s \in S, t \in T \tag{17}$$

Equations (15) and (16) highlight the number of trips made on a particular transportation mode while shipping fresh HOG salmon products along the route from a primary processing plant toa secondary processing plant and from a primary processing plant to a wholesaler respectively. Equation (17) depicts the number of trips made via a certain transportation mode while shipping whole fillets and salmon by-products from secondary processing facilities to wholesalers.

$$N^{\delta s}_{eft} \geq \frac{Y^{\delta s}_{eft}}{CT^{\delta s}_{ef}}, For\ \delta = k, l, m\ \forall e \in E, f \in F, s \in S, t \in T \tag{18}$$

Equation (18) helps to estimate the number of trips made via a particular transport mode in shipping fresh HOG products, whole fillets, and salmon by-products from wholesalers to retailers. The equation also considers the capacity of the transport mode and the total number of different products sent between wholesalers and retailers.

$$\sum_{b \in B} Y^{is}_{abt} \leq CA^{is}_{at}\ \forall a \in A, s \in S, t \in T \tag{19}$$

Equation (19) represents the supply constraint of salmon farms, which ensures that the amount of live salmon delivered from one salmon farm to various slaughterhouses must be less than or equal to the available supply of live salmon products at the farm. The processing and residuals constraints are given in equations (20)–(29).

$$\left(\sum_{a \in A} Y^{is}_{abt} - PA^{js}_{bt} - RO^{is}_{bt}\right) V^{st}_{b} = 0\ \forall b \in B, s \in S, t \in T \tag{20}$$

$$\left(\sum_{b \in B} Y^{js}_{bct} - PA^{ks}_{ct} - RO^{js}_{ct}\right) V^{st}_{c} = 0\ \forall c \in C, s \in S, t \in T \tag{21}$$

$$\left(\sum_{c \in C} Y^{ks}_{cdt} - PA^{ls}_{dt} - PA^{ms}_{dt} - RO^{ks}_{dt}\right) V^{st}_{d} = 0\ \forall d \in D, s \in S, t \in T \tag{22}$$

Equation (20) states that, if the slaughterhouse is operating during a specific time period and under a certain disruption scenario, then the total quantity of HOG salmon and the residual amount obtained after processing depends on the total quantity of live salmon received at the slaughterhouse from various salmon farms. Equation (21) highlights that if the primary processing plant is operating during a specific time period and under a certain disruption scenario, then the total quantity of fresh HOG salmon products and residual amount obtained after processing HOG products at a primary processing plant is obtained considering the HOG products received from various slaughterhouses. Equation (22) depicts that if the secondary processing plant is operating in a specific time period and under a certain disruption scenario, then the overall quantity of whole fillets and salmon by-products obtained after processing depends on the amount of HOG fresh salmon products supplied to the secondary processing plant from different primary processing facilities.

$$0.05\sum_{a\in A}Y^{is}_{abt} \le RO^{is}_{bt} \le 0.2\sum_{a\in A}Y^{is}_{abt}\ \forall b\in B, s\in S, t\in T \tag{23}$$

$$0.05\sum_{b\in B}Y^{js}_{bct} \le RO^{js}_{ct} \le 0.2\sum_{b\in B}Y^{js}_{bct}\ \forall c\in C, s\in S, t\in T \tag{24}$$

$$0.05\sum_{c\in C}Y^{ks}_{cdt} \le RO^{ks}_{dt} \le 0.2\sum_{c\in C}Y^{ks}_{cdt}\ \forall d\in D, s\in S, t\in T \tag{25}$$

Equations (23)–(25) highlight the range of residuals produced after processing live salmon at slaughterhouses, HOG products at primary processing plants and fresh HOG products at secondary processing plants. The range values are obtained after consulting with industry professionals and salmon exporter organizations. Processing 100% of the salmon product (such as live salmon, HOG products, and fresh HOG products) produces 5%–20% residuals.

$$\left(PA^{js}_{bt} - MC^{js}_{b} + IL^{js}_{b(t-1)}\right)V^{st}_{b} \le 0\ \forall b\in B, s\in S, t\in T, IL^{js}_{b(t=0)} = 0 \tag{26}$$

$$\left(PA^{ks}_{ct} - MC^{ks}_{c} + IL^{ks}_{c(t-1)}\right)V^{st}_{c} \le 0\ \forall c\in C, s\in S, t\in T, IL^{ks}_{c(t=0)} = 0 \tag{27}$$

Equation (26) ensures that if the slaughterhouse is operating during a specific time period and under a certain disruption scenario, then the total amount of HOG salmon products processed obtained plus the available inventory from the previous period will not exceed the maximum storage capacity for HOG salmon at the slaughterhouse. At the beginning of the planning horizon, it is assumed that there is no HOG salmon product available at the slaughterhouse or $IL^{js}_{b(t=0)} = 0$, hence during time period $t = 1$ equation (26) is represented as $\left(PA^{js}_{b(1)} - MC^{js}_{b}\right)V^{s(1)}_{b} \le 0$. Equation (27) ensures that if the primary processing plant is operating during a specific time period and under a certain disruption scenario, then the sum of the available inventory of fresh HOG salmon products from the preceding period and the total amount of fresh HOG salmon products processed must be less than or equal to the maximum storage capacity for fresh HOG salmon products at the primary processing plant. It is assumed that the initial inventory of fresh HOG salmon products at the primary processing plant is zero, or $IL^{ks}_{c(t=0)} = 0$, hence equation (27) can be represented as $\left(PA^{ks}_{c(1)} - MC^{ks}_{c}\right)V^{s(1)}_{c} \le 0$ during $t = 1$.

$$\left(PA^{ls}_{dt} - MC^{ls}_{d} + IL^{ls}_{d(t-1)}\right)V^{st}_{d} \le 0\ \forall d\in D, s\in S, t\in T, IL^{ls}_{d(t=0)} = 0 \tag{28}$$

$$\left(PA^{ms}_{dt} - MC^{ms}_{d} + IL^{ms}_{d(t-1)}\right)V^{st}_{d} \le 0\ \forall d\in D, s\in S, t\in T, IL^{ms}_{d(t=0)} = 0 \tag{29}$$

Equations (28) and (29) help to maintain the secondary processing plant's storage capacity for both whole fillets and salmon by-products by taking into consideration the available inventory from the previous period and the overall quantity of each type of product that was transported from various primary processing plants. At the start of the planning horizon, it is assumed that the initial inventory of whole fillets or salmon-by products in the secondary processing plant is zero, or $IL^{ls}_{d(t=0)} = 0$ and $IL^{ms}_{d(t=0)} = 0$, so that equations (28) and (29) are represented as $\left(PA^{ls}_{d(1)} - MC^{ls}_{d}\right)V^{s(1)}_{d} \le 0$ and $\left(PA^{ms}_{d(1)} - MC^{ms}_{d}\right)V^{s(1)}_{d} \le 0$ respectively for time period $t = 1$. Furthermore, equations (28) and (29) are valid only when the secondary processing plant is operating during a specific time period and under a certain disruption scenario.

$$\sum_{c\in C}Y^{ks}_{cet} \le MC^{ks}_{e} - IL^{ks}_{e(t-1)}\ \forall e\in E, s\in S, t\in T, IL^{ks}_{e(t=0)} = 0 \tag{30}$$

Equation (30) ensures that the total quantity of fresh HOG salmon products transported from various primary processing facilities to a specific wholesaler and the amount of HOG fresh salmon products available from the previous period at the wholesaler should be less than or equal to the maximum storage capacity of the fresh HOG salmon products at the wholesaler. At the beginning of the planning horizon, it is assumed that the wholesaler's initial inventory of fresh HOG salmon products is zero or $IL^{ks}_{e(t=0)} = 0$. In such a scenario or time period $t = 1$, equation (30) is represented as $\sum_{c\in C}Y^{ks}_{ce(1)} \le MC^{ks}_{e}$.

$$\sum_{d\in D}Y^{ls}_{det} \le MC^{ls}_{e} - IL^{ls}_{e(t-1)}\ \forall e\in E, s\in S, t\in T, IL^{ls}_{e(t=0)} = 0 \tag{31}$$

$$\sum_{d\in D}Y^{ms}_{det} \le MC^{ms}_{e} - IL^{ms}_{e(t-1)}\ \forall e\in E, s\in S, t\in T, IL^{ms}_{e(t=0)} = 0 \tag{32}$$

Equations (31) and (32) highlight that the wholesaler must maintain the storage capacity for salmon by-products and whole fillets, respectively, while considering the quantity of each product transported from different secondary processing facilities and the available inventory of each product from the previous period. At the beginning of the planning horizon, it is assumed that the wholesaler's initial inventory of whole fillets and salmon by-products is zero, or $IL^{ls}_{e(t=0)} = 0$ and $IL^{ms}_{e(t=0)} = 0$ respectively. Therefore, during time period $t = 1$, equations (31) and (32) can be represented as $\sum_{d\in D}Y^{ls}_{de(1)} \le MC^{ls}_{e}$ and $\sum_{d\in D}Y^{ms}_{de(1)} \le MC^{ms}_{e}$. Furthermore, the inventory balancing constraints for the suggested mathematical formulation are represented by equations (33)–(39) below.

$$\left(\sum_{c\in C}Y^{js}_{bct} - IL^{js}_{b(t-1)} - PA^{js}_{bt} + IL^{js}_{bt}\right)V^{st}_{b} = 0\ \forall b\in B, s\in S, t\in T, IL^{js}_{b(t=0)} = 0, IL^{js}_{b(t=T)} = 0 \tag{33}$$

Equation (33) shows the inventory balancing restrictions at the slaughterhouse for HOG salmon and the constraint is valid only when the slaughterhouse is operating during a specific time period and under a certain disruption scenario. The total amount of HOG product transported from a slaughterhouse to various primary processing plants is determined by considering the total processed amount of HOG salmon at the slaughterhouse during that period, the inventory of HOG salmon at the slaughterhouse at the end of the previous period, and te possible inventory level at the slaughterhouse at the end of current period. During $t = 0$, or the initial inventory level of HOG product at the slaughterhouse is considered as zero or, $IL^{js}_{b(t=0)} = 0$ and accordingly, equation (33) can be expressed as $\left(\sum_{c\in C}Y^{js}_{bc(1)} - PA^{js}_{b(1)} + IL^{js}_{b(1)}\right)V^{s(1)}_{b} = 0$ for time period $t = 1$. During $t = T$, the inventory level is considered as zero or $IL^{js}_{b(t=T)} = 0$ and hence, equation (33) is represented as $\left(\sum_{c\in C}Y^{js}_{bc(T)} - IL^{js}_{b(T-1)} - PA^{js}_{b(T)}\right)V^{s(T)}_{b} = 0$.

$$\left(\sum_{d\in D}Y^{ks}_{cdt} + \sum_{e\in E}Y^{ks}_{cet} - IL^{ks}_{c(t-1)} - PA^{ks}_{ct} + IL^{ks}_{ct}\right)V^{st}_{c} = 0\ \forall c\in C, s\in S, t\in T, IL^{ks}_{c(t=0)} = 0, IL^{ks}_{c(t=T)} = 0 \tag{34}$$

$$\sum_{f\in F}Y^{ks}_{eft} = IL^{ks}_{e(t-1)} + \sum_{c\in C}Y^{ks}_{cet} - IL^{ks}_{et}\ \forall e\in E, s\in S, t\in T, IL^{ks}_{e(t=0)} = 0, IL^{ks}_{e(t=T)} = 0 \tag{35}$$

The inventory balancing constraints for fresh HOG salmon products at the primary processing plant and the wholesaler are given by equations (34) and (35). Equation (34) estimates the overall amount of fresh HOG salmon products shipped from a primary processing plant to various secondary processing plants and wholesalers should be equal to the inventory level of fresh HOG salmon products from the previous period, plus the processed amount of fresh HOG salmon product at the primary processing plant and minus the inventory level of fresh HOG salmon products within the primary processing plant at the end of current period. Equation (34) considers that the inventory level during $t = 0$ and $t = \mathrm{T}$, should be equal to zero or $IL^{ks}_{c(t=0)} = 0$ and $IL^{ks}_{c(t=T)} = 0$. During time period $t = 0$, equation (34) can be represented as $\left(\sum_{d\in D} Y^{ks}_{cd(1)} + \sum_{e\in E} Y^{ks}_{ce(1)} - PA^{ks}_{c(1)} + IL^{ks}_{c(1)}\right) V^{s(1)}_{c} = 0$ and at the end of the planning horizon, or $t = T$, equation (34) is given as $\left(\sum_{d\in D} Y^{ks}_{cd(T)} + \sum_{e\in E} Y^{ks}_{ce(T)} - IL^{ks}_{c(T-1)} - PA^{ks}_{c(T)}\right) V^{s(T)}_{c} = 0$. Furthermore, equation (34) is valid only when the primary processing plant is operating during a specific time period and under a certain disruption scenario. Equation (35) computes the amount of fresh HOG salmon products shipped from the wholesaler to various retailers which is equal to the inventory level of fresh HOG salmon products at the wholesaler from the previous period, plus the amount of fresh HOG salmon products shipped from various primary processing plants to the wholesaler and minus the inventory level of fresh HOG salmon products at the wholesaler available at the end of current period. Equation (35) also depicts the amount of fresh HOG salmon products shipped to various retailers from the wholesaler from the start and until the end of the planning horizon. Equation (35) considers the initial inventory during $t = 0$ and the inventory level during $t = \mathrm{T}$ as zero. Hence, during time period $t = 1$, equation (35) can be represented as $\sum_{f\in F} Y^{ks}_{ef(1)} = \sum_{c\in C} Y^{ks}_{ce(1)} - IL^{ks}_{e(1)}$ given that $IL^{ks}_{e(t=0)} = 0$ and during time period $t = T$, equation (35) is represented as $\sum_{f\in F} Y^{ks}_{ef(T)} = IL^{ks}_{e(T-1)} + \sum_{c\in C} Y^{ks}_{ce(T)}$ given that $IL^{ks}_{e(t=T)} = 0$.

$$\left(\sum_{e\in E} Y^{ls}_{det} - IL^{ls}_{d(t-1)} - PA^{ls}_{dt} + IL^{ls}_{dt}\right) V^{st}_{d} = 0 \;\forall d\in D, s\in S, t\in T, IL^{ls}_{d(t=0)} = 0, IL^{ls}_{d(t=T)} = 0 \tag{36}$$

$$\left(\sum_{e\in E} Y^{ms}_{det} - IL^{ms}_{d(t-1)} - PA^{ms}_{dt} + IL^{ms}_{dt}\right) V^{st}_{d} = 0 \;\forall d\in D, s\in S, t\in T, IL^{ms}_{d(t=0)} = 0, IL^{ms}_{d(t=T)} = 0 \tag{37}$$

Equations (36) and (37) present the inventory balancing constraints at the secondary processing facility for whole fillets and salmon by-products, while considering that the equations are valid when the secondary processing facility operates during a specific time period and under a certain disruption scenario. Equations (36) and (37) estimate the amount of whole fillets and salmon by-products to be transported to various wholesalers from the secondary processing plant while considering previous time periods' inventory levels, total processed amounts for whole fillets and salmon by-products at the secondary processing plant, and the inventory level of whole fillets and salmon by-products to be kept at the end of current period. Equations (36) and (37) considers that the initial inventory level at $t = 0$, or $IL^{ls}_{d(t=0)} = 0$ and $IL^{ms}_{d(t=0)} = 0$ and accordingly during $t = 1$, equations (36) and (37) can be represented as $\left(\sum_{e\in E} Y^{ls}_{de(1)} - PA^{ls}_{d(1)} + IL^{ls}_{d(1)}\right) V^{s(1)}_{d} = 0$ and $\left(\sum_{e\in E} Y^{ms}_{de(1)} - PA^{ms}_{d(1)} + IL^{ms}_{d(1)}\right) V^{s(1)}_{d} = 0$. Furthermore, the inventory level at the last time period or $t = T$ should be equal to zero for equations (36) and (37), or $IL^{ls}_{d(t=T)} = 0$ and $IL^{ms}_{d(t=T)} = 0$. Accordingly, during $t = T$ equation (36) is given as $\left(\sum_{e\in E} Y^{ls}_{de(T)} - IL^{ls}_{d(T-1)} - PA^{ls}_{d(T)}\right) V^{s(T)}_{d} = 0$ and equation (37) is represented as $\left(\sum_{e\in E} Y^{ms}_{de(T)} - IL^{ms}_{d(T-1)} - PA^{ms}_{d(T)}\right) V^{s(T)}_{d} = 0$.

$$\sum_{f\in F} Y^{ls}_{eft} = IL^{ls}_{e(t-1)} + \sum_{d\in D} Y^{ls}_{det} - IL^{ls}_{et}, for\; t > 1 \;\forall e\in E, s\in S, t\in T, IL^{ls}_{e(t=0)} = 0, IL^{ls}_{e(t=T)} = 0 \tag{38}$$

$$\sum_{f\in F} Y^{ms}_{eft} = IL^{ms}_{e(t-1)} + \sum_{d\in D} Y^{ms}_{det} - IL^{ms}_{et}, for\; t > 1 \;\forall e\in E, s\in S, t\in T, IL^{ms}_{e(t=0)} = 0, IL^{ms}_{e(t=T)} = 0 \tag{39}$$

Equations (38) and (39) provide the inventory balancing constraints for whole fillets and salmon by-products, respectively, at the wholesaler. The total amount of whole fillets and salmon by-products shipped from a wholesaler to various retailers should be equal to the inventory level of the product type at the wholesaler from the previous period, plus the quantity of product type transported from various secondary processing plants to the wholesaler and minus the inventory level available with the wholesaler at the end of current period. Equations (38) and (39) highlight that the initial inventory level during $t = 0$ and the inventory level during the last time period or, $t = T$ at the wholesaler for whole fillets and salmon by-products is assumed to be zero. Therefore, during $t = 1$, equations (38) and (39) can be represented as $\sum_{f\in F} Y^{ls}_{ef(1)} = \sum_{d\in D} Y^{ls}_{de(1)} - IL^{ls}_{e(1)}$ and $\sum_{f\in F} Y^{ms}_{ef(1)} = \sum_{d\in D} Y^{ms}_{de(1)} - IL^{ms}_{e(1)}$ respectively, given that $IL^{ls}_{e(t=0)} = 0$ and $IL^{ms}_{e(t=0)} = 0$. Furthermore, during the last time period $t = T$, equations (38) and (39) are given as $\sum_{f\in F} Y^{ls}_{ef(T)} = IL^{ls}_{e(T-1)} + \sum_{d\in D} Y^{ls}_{de(T)}$ and $\sum_{f\in F} Y^{ms}_{ef(T)} = IL^{ms}_{e(T-1)} + \sum_{d\in D} Y^{ms}_{de(T)}$ respectively, as $IL^{ls}_{e(t=T)} = 0$ and $IL^{ms}_{e(t=T)} = 0$.

$$\sum_{e\in E} Y^{ks}_{eft} = DM^{k}_{ft} \;\forall f\in F, s\in S, t\in T \tag{40}$$

$$\sum_{e\in E} Y^{ls}_{eft} = DM^{l}_{ft} \;\forall f\in F, s\in S, t\in T \tag{41}$$

$$\sum_{e\in E} Y^{ms}_{eft} = DM^{m}_{ft} \;\forall f\in F, s\in S, t\in T \tag{42a}$$

Equations (4), (40) and (41)2a) demonstrate the retail demand constraints for various types of products, such as fresh HOG salmon products, whole salmon fillets, and salmon by-products, which are shipped from the various wholesalers to the retailer.

The mathematical model is composed of multiple objectives, each serving distinct purposes. Objective 1, represented by equation (1), calculates the expected total cost by considering various cost components related to transportation, fuel consumption, electric vehicle charging, facility operation, inventory storage at the facilities, and residual costs. Objective 2, as expressed in equation (9), focuses on unutilised space in the transportation mode. Objectives 1 and 2 are closely tied to the economic objectives of the supply chain organization. Moving on, objectives 3 and 4, described in equations (10) and (11) respectively, are associated with quantifying the carbon emissions stemming from inventory, processing, residual, and transportation operations, aligning with the organization's commitment to environmental sustainability. Finally, the fifth objective, often referred to as objective 5, pertains to the number of jobs created and is intrinsically linked to the social objective of the supply chain organization.

To streamline the optimization process, the multiple objectives are integrated into a single objective by assigning weights to each objective and it is represented in equation (42b).

$$Minimize\ [W_1 * Objective\ 1 + W_2 * Objective\ 2 + W_3 * Objective\ 3 + W_4 * Objective\ 4 - W_5 * Objective\ 5] \tag{42b}$$

$$\text{Where, } W_1 + W_2 + W_3 + W_4 + W_5 = 1 \tag{42c}$$

Equation (42b) highlights how the five objectives are converted into a single objective. W_1, W_2, W_3, W_4, and W_5 are the weights associated with Objectives 1, 2, 3, 4 and 5 respectively. Equation (42c) depicts that the sum of all the weights should be equal to 1. Furthermore, we consider equal weights for all the five objectives as the supply chain organizations aims to provide equal importance to the economic, social and environmental objectives. Hence, equation (42d) presents the value of the weights in the following way,

$$W_1 = W_2 = W_3 = W_4 = W_5 = 0.2 \tag{42d}$$

This also allows for the utilization of specialized optimization software such IBM CPLEX to derive the optimal solution. Furthermore, the proposed mathematical formulation takes the form of a multiple objective mixed integer non-linear programming model, incorporating several non-linear equations ((20)–(22) and (26)–(29) and (33) and (34) and (36) and (37), necessitating linearization for compatibility with optimization software. In section 5, we delve into the intricate details of the linearization techniques adopted to address the non-linear equations, providing a comprehensive understanding of the processes involved.

5. Linear reformulation

In this section, we aim to linearize the non-linear equations and transform the proposed mathematical model into a mixed integer linear programming model. The feasible region of the non-linear equations within the proposed formulation has the following non-linear structure:

$$\{(p,q)|pf(q) = 0, p \in \{0,1\}, q \in Q\} \tag{43}$$

Where $f(q)$ is a function with domain Q. After comparing equations (20) and (43), the following can be represented, $q_1 := \left(Y^{is}_{abt}, PA^{js}_{bt}, RO^{is}_{bt}\right)$, $p_1 := V^{st}_b$ and $f(q_1) := \sum_{a\in A} Y^{is}_{abt} - PA^{js}_{bt} - RO^{is}_{bt}$. Suppose there is a set, $W := \{(p,q)|pf(q) = 0, p \in \{0,1\}, q \in Q\}$, then $\{f(q)|q \in Q\}$ is compact or there exist certain bounds $[I,J]$, such that $I \le f(q) \le J$, $\forall q \in Q$. Therefore, set W can be represented in the following way,

$$W: = \{(p,q)|I(1-p) \le f(q) \le J(1-p), p \in \{0,1\}, q \in Q\} \tag{44}$$

For equation (20), $f(q_1) := \sum_{a\in A} Y^{is}_{abt} - PA^{js}_{bt} - RO^{is}_{bt}$ is linear with MC^{js}_b and $-MC^{js}_b$ as the valid upper and lower bounds. If we maximize $f(q_1)$, then the maximum value it can take is the maximum storage capacity of slaughterhouse b for HOG product j and hence the upper bound is MC^{js}_b. Similarly, if we minimize $f(q_1)$, then the minimum value we get is $-MC^{js}_b$, which is the lower bound. So, equation (20) can be linearized in the following way:

$$\sum_{a\in A} Y^{is}_{abt} - PA^{js}_{bt} - RO^{is}_{bt} + MC^{js}_b V^{st}_b \le MC^{js}_b\ \forall b \in B, s \in S, t \in T \tag{45}$$

$$\sum_{a\in A} Y^{is}_{abt} - PA^{js}_{bt} - RO^{is}_{bt} - MC^{js}_b V^{st}_b \ge -MC^{js}_b\ \forall b \in B, s \in S, t \in T \tag{46}$$

In the same way, for equation (21) $f(q_2) := \sum_{b\in B} Y^{js}_{bct} - PA^{ks}_{ct} - RO^{js}_{ct}$ is linear with MC^{ks}_c and $-MC^{ks}_c$ as the valid upper and lower bounds respectively. Furthermore, for equation (22) $f(q_3) := \sum_{c\in C} Y^{ks}_{cdt} - PA^{ls}_{dt} - PA^{ms}_{dt} - RO^{ks}_{dt}$ is linear with $\left(MC^{ls}_d + MC^{ms}_d\right)$ and $-\left(MC^{ls}_d + MC^{ms}_d\right)$ as the upper and lower bounds respectively. Hence, the linearized version of equation (21) is represented as equations (47) and (48) and linearized form of equation (22) is given as equations (49) and (50).

$$\sum_{b\in B} Y^{js}_{bct} - PA^{ks}_{ct} - RO^{js}_{ct} + MC^{ks}_c V^{st}_c \le MC^{ks}_c\ \forall c \in C, s \in S, t \in T \tag{47}$$

$$\sum_{b\in B} Y^{js}_{bct} - PA^{ks}_{ct} - RO^{js}_{ct} - MC^{ks}_c V^{st}_c \ge -MC^{ks}_c\ \forall c \in C, s \in S, t \in T \tag{48}$$

$$\sum_{c\in C} Y^{ks}_{cdt} - PA^{ls}_{dt} - PA^{ms}_{dt} - RO^{ks}_{dt} + \left(MC^{ls}_d + MC^{ms}_d\right) V^{st}_d \le \left(MC^{ls}_d + MC^{ms}_d\right)\ \forall d \in D, s \in S, t \in T \tag{49}$$

$$\sum_{c\in C} Y^{ks}_{cdt} - PA^{ls}_{dt} - PA^{ms}_{dt} - RO^{ks}_{dt} - \left(MC^{ls}_d + MC^{ms}_d\right) V^{st}_d \ge -\left(MC^{ls}_d + MC^{ms}_d\right)\ \forall d \in D, s \in S, t \in T \tag{50}$$

Now, equations (26)–(29) depict the storage capacity constraints having the same structure as that of equation (43). The following setting can be represented after comparing equations (26) and (43), $q_4 := \left(PA^{js}_{bt}, IL^{js}_{b(t-1)}\right)$, $p_4 := V^{st}_b$ and $f(q_4) := PA^{js}_{bt} - MC^{js}_b - IL^{js}_{b(t-1)}$. Given equation (26) is an inequality constraint, so considering an upper bound on $f(q_4)$ as η (a large number), the linearized version of equation (26) can be expressed as,

$$PA^{js}_{bt} - MC^{js}_b + IL^{js}_{b(t-1)} + \eta V^{st}_b \le \eta, for\ t > 1\ \forall b \in B, s \in S, t \in T \tag{51}$$

When $t = 1$, the linearized form for equation (26) is expressed as $PA^{js}_{b(1)} - MC^{js}_b + \eta V^{s(1)}_b \le \eta$, given than the initial inventory level is equal to zero, or $IL^{js}_{b(t=0)} = 0$. In a similar manner, comparing equations (27)–(29) with equation (43), then the following setting can be expressed – for equation (27) $q_5 := \left(PA^{ks}_{ct}, IL^{ks}_{c(t-1)}\right)$, $p_5 := V^{st}_c$ and $f(q_5) := PA^{ks}_{ct} - MC^{ks}_c + IL^{ks}_{c(t-1)}$, similarly for equation (28) $q_6 := \left(PA^{ls}_{dt}, IL^{ls}_{d(t-1)}\right)$, $p_6 := V^{st}_d$ and $f(q_6) := PA^{ls}_{dt} - MC^{ls}_d + IL^{ls}_{d(t-1)}$, and for equation (29) $q_7 := \left(PA^{ms}_{dt}, IL^{ms}_{d(t-1)}\right)$, $p_7 := V^{st}_d$ and $f(q_7) := PA^{ms}_{dt} - MC^{ms}_d + IL^{ms}_{d(t-1)}$. As equations (27)–(29) are considered as inequality constraints, so considering an upper bound on $f(q_5)$, $f(q_6)$ and $f(q_7)$ as η (a large number), the linearized version of equations (27)–(29) are expressed within equations (52)–(54) respectively.

$$PA^{ks}_{ct} - MC^{ks}_c + IL^{ks}_{c(t-1)} + \eta V^{st}_c \le \eta, for\ t > 1\ \forall c \in C, s \in S, t \in T \tag{52}$$

$$PA^{ls}_{dt} - MC^{ls}_d + IL^{ls}_{d(t-1)} + \eta V^{st}_d \le \eta, for\ t > 1\ \forall d \in D, s \in S, t \in T \tag{53}$$

$$PA^{ms}_{dt} - MC^{ms}_d + IL^{ms}_{d(t-1)} + \eta V^{st}_d \le \eta, for\ t > 1\ \forall d \in D, s \in S, t \in T \tag{54}$$

When $t = 1$, the linearized form of equations (52)–(54) are expressed as $PA^{ks}_{c(1)} - MC^{ks}_c + \eta V^{s(1)}_c \le \eta$, $PA^{ls}_{d(1)} - MC^{ls}_d + \eta V^{s(1)}_d \le \eta$ and $PA^{ms}_{d(1)} - MC^{ms}_d + \eta V^{s(1)}_d \le \eta$ respectively, where the initial inventory levels at the primary processing plants and secondary processing plants is zero, or $IL^{ks}_{c(t=0)} = 0$, $IL^{ls}_{d(t=0)} = 0$ and $IL^{ms}_{d(t=0)} = 0$. Equations (33), (34), (36) and (37) represent the inventory balancing constraints having the same structure as that of equation (43). The following setting can be obtained after comparing equations (33) and (43), $q_8 := \left(Y^{js}_{bct}, IL^{js}_{b(t-1)}, PA^{js}_{bt}, IL^{js}_{bt}\right)$, $p_8 := V^{st}_b$ and $f(q_8) := \sum_{c\in C} Y^{js}_{bct} - IL^{js}_{b(t-1)} - PA^{js}_{bt} + IL^{js}_{bt}$. Furthermore, $f(q_8)$ is linear with MC^{js}_b as the upper bound and $-MC^{js}_b$ as the lower bound.

Therefore, the linearized version of equation (33) can be expressed in the following way,

$$\sum_{c\in C} Y^{js}_{bct} - IL^{js}_{b(t-1)} - PA^{js}_{bt} + IL^{js}_{bt} + MC^{js}_{b} V^{st}_{b} \le MC^{js}_{b}, for\ t > 1\ \forall b \in B, s \in S, t \in T \tag{55}$$

$$\sum_{c\in C} Y^{js}_{bct} - IL^{js}_{b(t-1)} - PA^{js}_{bt} + IL^{js}_{bt} - MC^{js}_{b} V^{st}_{b} \ge -MC^{js}_{b}, for\ t > 1\ \forall b \in B, s \in S, t \in T \tag{56}$$

When $t = 1$, the linearized version of equation (33) is expressed as $\sum_{c\in C} Y^{js}_{bc(1)} - PA^{js}_{b(1)} + IL^{js}_{b(1)} + MC^{js}_{b} V^{s(1)}_{b} \le MC^{js}_{b}$ and $\sum_{c\in C} Y^{js}_{bc(1)} - PA^{js}_{b(1)} + IL^{js}_{b(1)} - MC^{js}_{b} V^{s(1)}_{b} \ge -MC^{js}_{b}$, given that the initial inventory level at the slaughterhouse is zero or, $IL^{js}_{b(t=0)} = 0$. Furthermore, for the last time period of the planning horizon or, $t = T$, the inventory level at the slaughterhouse is given as $IL^{js}_{b(t=T)} = 0$ and accordingly, the linearized version of equation (33) is given as $\sum_{c\in C} Y^{js}_{bc(T)} - IL^{js}_{b(T-1)} - PA^{js}_{b(T)} + MC^{js}_{b} V^{s(T)}_{b} \le MC^{js}_{b}$ and $\sum_{c\in C} Y^{js}_{bc(T)} - IL^{js}_{b(T-1)} - PA^{js}_{b(T)} - MC^{js}_{b} V^{s(T)}_{b} \ge -MC^{js}_{b}$. Moreover, equation (34) can be compared with equation (43) and the following setting can be obtained $q_9 := \left(Y^{ks}_{cdt}, Y^{ks}_{cet}, IL^{ks}_{c(t-1)}, PA^{ks}_{ct}, IL^{ks}_{ct}\right)$, $p_9 := V^{st}_{c}$ and $f(q_9) := \sum_{d\in D} Y^{ks}_{cdt} + \sum_{e\in E} Y^{ks}_{cet} - IL^{ks}_{c(t-1)} - PA^{ks}_{ct} + IL^{ks}_{ct}$. Furthermore, $f(q_9)$ is linear with MC^{ks}_{c} and $-MC^{ks}_{c}$ as the upper and lower bounds respectively. Therefore, the linearized version of equation (34) can be represented in the following way using equations (57) and (58),

$$\sum_{d\in D} Y^{ks}_{cdt} + \sum_{e\in E} Y^{ks}_{cet} - IL^{ks}_{c(t-1)} - PA^{ks}_{ct} + IL^{ks}_{ct} + MC^{ks}_{c} V^{st}_{c} \le MC^{ks}_{c}, for\ t > 1\ \forall c \in C, s \in S, t \in T \tag{57}$$

$$\sum_{d\in D} Y^{ks}_{cdt} + \sum_{e\in E} Y^{ks}_{cet} - IL^{ks}_{c(t-1)} - PA^{ks}_{ct} + IL^{ks}_{ct} - MC^{ks}_{c} V^{st}_{c} \ge -MC^{ks}_{c}, for\ t > 1\ \forall c \in C, s \in S, t \in T \tag{58}$$

The inventory level at the secondary processing plant during period $t = 0$ is zero or, $IL^{ks}_{c(t=0)} = 0$, hence during period $t = 1$, the linearized form of equation (34) is given as $\sum_{d\in D} Y^{ks}_{cd(1)} + \sum_{e\in E} Y^{ks}_{ce(1)} - PA^{ks}_{c(1)} + IL^{ks}_{c(1)} + MC^{ks}_{c} V^{s(1)}_{c} \le MC^{ks}_{c}$ and $\sum_{d\in D} Y^{ks}_{cd(1)} + \sum_{e\in E} Y^{ks}_{ce(1)} - PA^{ks}_{c(1)} + IL^{ks}_{c(1)} - MC^{ks}_{c} V^{s(1)}_{c} \ge -MC^{ks}_{c}$. Furthermore, during time period $t = T$, the linearized version of equation (34) is given as $\sum_{d\in D} Y^{ks}_{cd(T)} + \sum_{e\in E} Y^{ks}_{ce(T)} - IL^{ks}_{c(T-1)} - PA^{ks}_{c(T)} + MC^{ks}_{c} V^{s(T)}_{c} \le MC^{ks}_{c}$ and $\sum_{d\in D} Y^{ks}_{cd(T)} + \sum_{e\in E} Y^{ks}_{ce(T)} - IL^{ks}_{c(T-1)} - PA^{ks}_{c(T)} - MC^{ks}_{c} V^{s(T)}_{c} \ge -MC^{ks}_{c}$, given that the inventory level of a secondary processing plant at the end of the planning horizon ($t = T$) is zero or, $IL^{ks}_{c(t=T)} = 0$. In the similar way, comparing equations (36) and (37) with equation (43), the following structure can be represented – for equation (36) $q_{10} := \left(Y^{ls}_{det}, IL^{ls}_{d(t-1)}, PA^{ls}_{dt}, IL^{ls}_{dt}\right)$, $p_{10} := V^{st}_{d}$ and $f(q_{10}) := \sum_{e\in E} Y^{ls}_{det} - IL^{ls}_{d(t-1)} - PA^{ls}_{dt} + IL^{ls}_{dt}$, similarly for equation (37) $q_{11} := \left(Y^{ms}_{det}, IL^{ms}_{d(t-1)}, PA^{ms}_{dt}, IL^{ms}_{dt}\right)$, $p_{11} := V^{st}_{d}$ and $f(q_{11}) := \sum_{e\in E} Y^{ms}_{det} - IL^{ms}_{d(t-1)} - PA^{ms}_{dt} + IL^{ms}_{dt}$. Moreover, $f(q_{10})$ is linear with MC^{ls}_{d} as the upper bound and $-MC^{ls}_{d}$ as the lower bound. $f(q_{11})$ is also linear with MC^{ms}_{d} and $-MC^{ms}_{d}$ as the upper and lower bounds

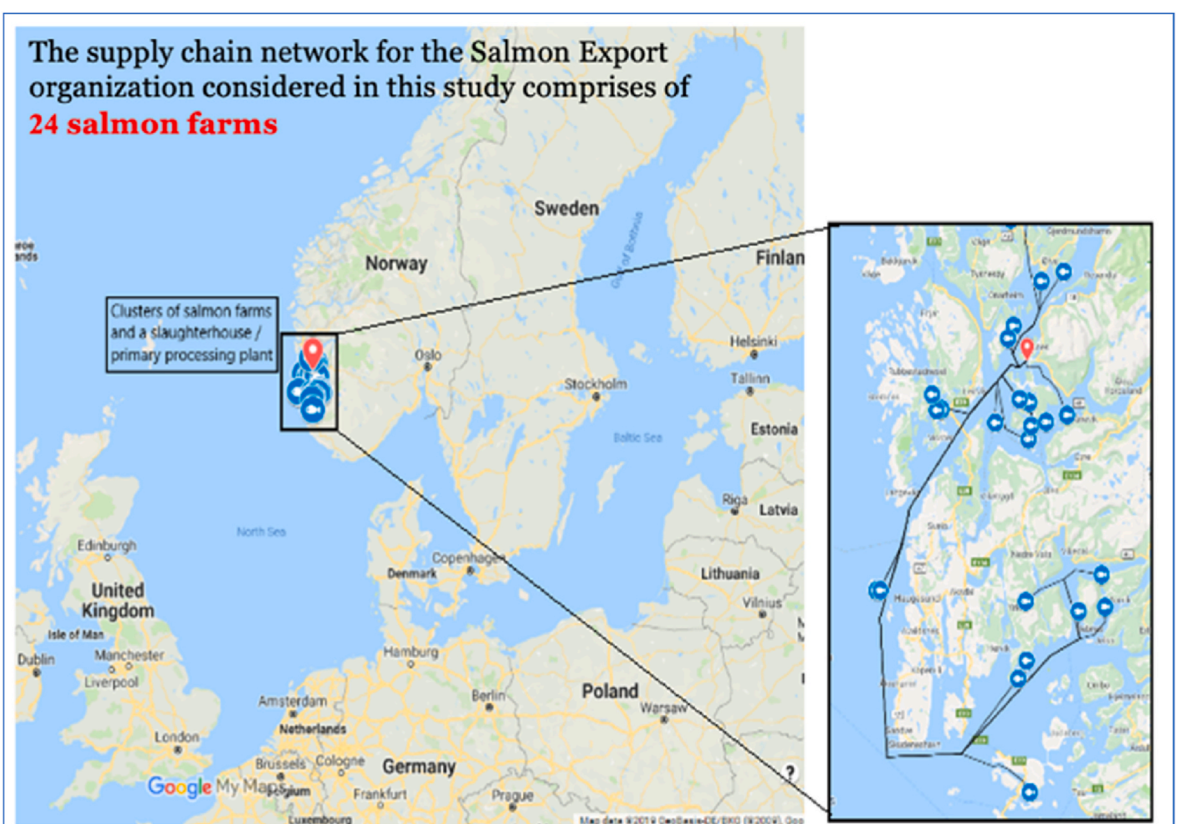

Figure (1). Salmon farms dispersed in the south of Norway.

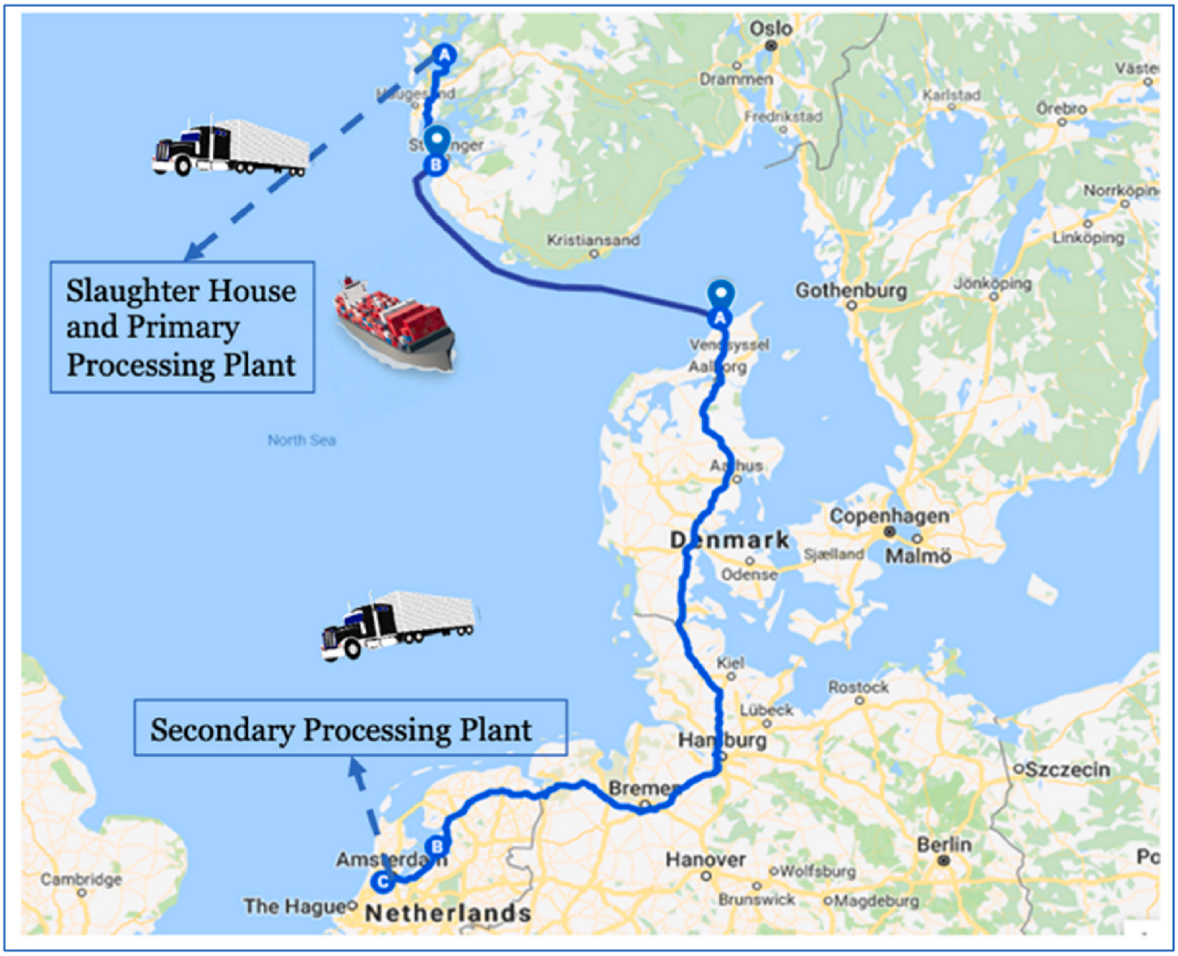

Figure (2). Transport route from Slaughterhouse and Primary Processing Plant to Secondary processing plant.

Figure (3). Supply chain logistics network from Secondary Processing Plant to Wholesalers.

respectively. Hence the linearized version of equation (36) is given within equations (59) and (60) and the linearized form for equation (37) is represented as equations (61) and (62).

$$\sum_{e\in E} Y^{ls}_{det} - IL^{ls}_{d(t-1)} - PA^{ls}_{dt} + IL^{ls}_{dt} + MC^{ls}_{d}V^{st}_{d} \le MC^{ls}_{d}, for\ t > 1\ \forall d \in D, s \in S, t \in T \quad (59)$$

$$\sum_{e\in E} Y^{ls}_{det} - IL^{ls}_{d(t-1)} - PA^{ls}_{dt} + IL^{ls}_{dt} - MC^{ls}_{d}V^{st}_{d} \ge -MC^{ls}_{d}, for\ t > 1\ \forall d \in D, s \in S, t \in T \quad (60)$$

$$\sum_{e\in E} Y^{ms}_{det} - IL^{ms}_{d(t-1)} - PA^{ms}_{dt} + IL^{ms}_{dt} + MC^{ms}_{d}V^{st}_{d} \le MC^{ms}_{d}, for\ t > 1\ \forall d \in D, s \in S, t \in T \quad (61)$$

$$\sum_{e\in E} Y^{ms}_{det} - IL^{ms}_{d(t-1)} - PA^{ms}_{dt} + IL^{ms}_{dt} - MC^{ms}_{d}V^{st}_{d} \ge -MC^{ms}_{d}, for\ t > 1\ \forall d \in D, s \in S, t \in T \quad (62)$$

During period $t = 1$, the linearized form of equation (36) is given as $\sum_{e\in E} Y^{ls}_{de(1)} - PA^{ls}_{d(1)} + IL^{ls}_{d(1)} + MC^{ls}_{d}V^{s(1)}_{d} \le MC^{ls}_{d}$ and $\sum_{e\in E} Y^{ls}_{de(1)} - PA^{ls}_{d(1)} + IL^{ls}_{d(1)} - MC^{ls}_{d}V^{s(1)}_{d} \ge -MC^{ls}_{d}$ as $IL^{ls}_{d(t=0)} = 0$ or the initial inventory level at the secondary processing plant is zero. Furthermore, during period $t = T$,

Table 1
Demand variations experiment performed on Problem Instance 1.

Demand Variations on Problem Instance 1											
Demand Variations	*Baseline Scenario*	*10% ↑*	*20% ↑*	*30% ↑*	*40% ↑*	*50% ↑*	*60% ↑*	*70% ↑*	*80% ↑*	*90% ↑*	*100% ↑*
Expected total cost (in Euro)	236,990	291,360	304,860	317,260	333,190	360,200	378,530	393,480	405,770	420,710	434,600
Expected number jobs created	7000	11,000	12,400	11,100	11,500	13,000	13,200	13,000	13,000	13,900	13,000
Expected carbon emissions Incurred (Kg CO_2)	42,077	47,923	51,337	53,538	59,246	61,299	65,291	71,265	75,278	79,389	82,619
Expected transport cost (in Euro)	27,923	31,803	34,069	35,529	39,317	40,679	43,329	47,293	49,956	52,684	54,828
Expected fuel cost (in Euro)	16,393	18,565	19,886	20,710	22,924	23,706	25,284	27,714	29,393	30,968	32,359
Expected inventory cost (in Euro)	13,800	13,232	14,256	15,480	16,520	12,500	13,720	17,387	16,448	18,196	19,666
Expected processing cost (in Euro)	72,900	80,190	87,480	94,770	102,060	109,350	116,640	123,930	131,220	138,510	145,800
Expected residual cost (in Euro)	15,975	17,573	19,170	20,768	22,365	23,963	25,560	27,158	28,755	30,353	31,950
Expected charging cost (in Euro)	0	0	0	0	0	0	0	0	0	0	0
Expected operating cost (in Euro)	90,000	130,000	130,000	130,000	130,000	150,000	154,000	150,000	150,000	150,000	150,000
Total demand quantity	72,000	79,200	86,400	93,600	100,800	108,000	115,200	122,400	129,600	136,800	144,000
Profit (in Euro)	1,779,010	1,926,240	2,114,340	2,303,540	2,489,210	2,663,800	2,847,070	3,033,720	3,223,030	3,409,690	3,597,400

Table 2
Average costs per level of customer demand - Demand Variations on Problem Instance 1.

Demand Variations	Baseline Scenario	10% ↑	20% ↑	30% ↑	40% ↑	50% ↑	60% ↑	70% ↑	80% ↑	90% ↑	100% ↑
Avg. expected total cost per customer demand met (Euro)	3.29	3.68	3.53	3.39	3.31	3.34	3.29	3.21	3.13	3.08	3.02
Avg. expected number jobs created per customer demand	0.10	0.14	0.14	0.12	0.11	0.12	0.11	0.11	0.10	0.10	0.09
Avg. expected carbon emissions incurred per customer demand (Kg CO_2)	0.58	0.61	0.59	0.57	0.59	0.57	0.57	0.58	0.58	0.58	0.57
Avg. expected transport cost per customer demand (Euro)	0.39	0.40	0.39	0.38	0.39	0.38	0.38	0.39	0.39	0.39	0.38
Avg. expected fuel cost per customer demand (Euro)	0.23	0.23	0.23	0.22	0.23	0.22	0.22	0.23	0.23	0.23	0.22
Avg. expected inventory cost per customer demand (Euro)	0.19	0.17	0.17	0.17	0.16	0.12	0.12	0.14	0.13	0.13	0.14
Avg. expected processing cost per customer demand (Euro)	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01
Avg. expected residual cost per customer demand (Euro)	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
Avg. expected charging cost per customer demand (Euro)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Avg. expected operating cost per customer demand (Euro)	1.25	1.64	1.50	1.39	1.29	1.39	1.34	1.23	1.16	1.10	1.04
Total demand quantity	72,000	79,200	86,400	93,600	100,800	108,000	115,200	122,400	129,600	136,800	144,000

the inventory level is assumed to be zero, or $IL^{ls}_{d(t=T)} = 0$, hence the linearized version of equation (36) is given as $\sum_{e\in E} Y^{ls}_{de(T)} - IL^{ls}_{d(T-1)} - PA^{ls}_{d(T)} + MC^{ls}_d V^{s(T)}_d \le MC^{ls}_d$ and $\sum_{e\in E} Y^{ls}_{de(T)} - IL^{ls}_{d(T-1)} - PA^{ls}_{d(T)} - MC^{ls}_d V^{s(T)}_d \ge - MC^{ls}_d$. In a similar manner, at the start of the planning horizon $IL^{ms}_{d(t=0)} = 0$, hence for $t = 1$, linearized form of equation (37) is $\sum_{e\in E} Y^{ms}_{de(1)} - PA^{ms}_{d(1)} + IL^{ms}_{d(1)} + MC^{ms}_d V^{s(1)}_d \le MC^{ms}_d$ and $\sum_{e\in E} Y^{ms}_{de(1)} - PA^{ms}_{d(1)} + IL^{ms}_{d(1)} - MC^{ms}_d V^{s(1)}_d \ge - MC^{ms}_d$. Moreover, during $t = T$ (or last time period), the linearized version of equation (37) is represented in the following way, $\sum_{e\in E} Y^{ms}_{de(T)} - IL^{ms}_{d(T-1)} - PA^{ms}_{d(T)} + MC^{ms}_d V^{s(T)}_d \le MC^{ms}_d$ and $\sum_{e\in E} Y^{ms}_{de(T)} - IL^{ms}_{d(T-1)} - PA^{ms}_{d(T)} - MC^{ms}_d V^{s(T)}_d \ge - MC^{ms}_d$. This is because the inventory level of the secondary processing plant for salmon-by products at the end of the planning horizon is zero or, $IL^{ms}_{d(t=T)} = 0$. The next section highlights the computational experiment performed on the case study related to the salmon export organization based in Norway.

6. Results and discussions

This section presents the results and analyses obtained using the suggested mathematical model. The computational experiments were performed on IBM ILOG CPLEX optimization studio application version 22.1.0. The mathematical model was coded on OPL (Optimization Programming Language) modelling language and IBM CPLEX used for solving purposes. To solve the suggested model and demonstrate its applicability and reliability, we consider various problem instances and scenarios. Furthermore, a real life supply chain problem helps validate

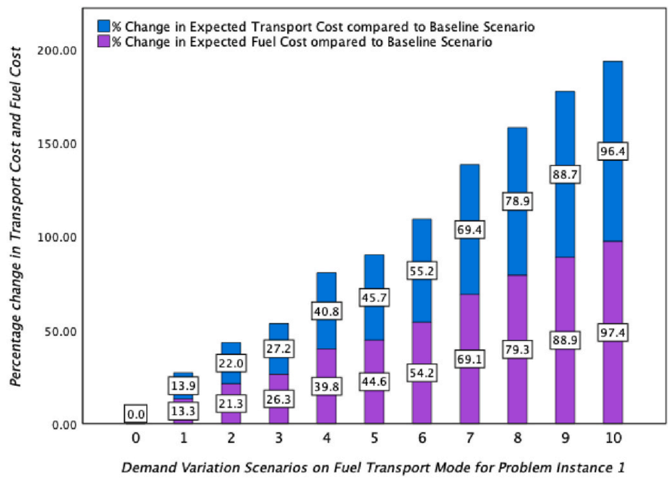

Fig. 4. Percentage change in fuel and transportation costs – demand variations.

the sensitivity analysis associated with demand uncertainties, electrification of transport modes, and fuel and charging cost variations.

6.1. Case study

A detailed real-world case study of Norway documented that the salmon supply chain network comprises salmon farms, slaughterhouse, primary processing plant, secondary processing plant, wholesalers, and retailers. Based on their average distance to the slaughterhouse, the salmon farms are classified into different clusters. Fig. 1 depicts the salmon farms located in the south of Norway which are part of the supply chain network. Fig. 2 presents a detailed illustration of the transportation route from slaughterhouse and primary processing plant to the secondary processing plant at The Hague. Fig. 3 highlights the supply chain logistics network from the secondary processing plant to some of the wholesalers located in Dusseldorf, Frankfurt, Munich, Copenhagen, Rotterdam, Brussels, Luxembourg.

The combined daily supply of live salmon to the slaughterhouse from various clusters is roughly 140 tonnes per day. A transportation cost of 0.39 euro/km for fuel-based vehicles and 0.25 euro/km for electric vehicles are considered within the research work. The payload for fuel vehicles is 2000 kg, and for electric vehicles is about 1015 kgs. The charging cost for electric vehicles is around 0.05 euro/km. Appendix B details the case study characteristics taken into consideration for the computational experiments. The case study contains information about the various stakeholders involved in the entire supply chain, the distances between facilities and distribution centres. Furthermore, Appendix B also includes the costs involved in the operations, the rates of fuel and electric transport mode charging costs, along with the varying capacities of transportation modalities. Certain modifications were made to the case study, for testing the model's robustness under various circumstances.

6.2. Experimentation and sensitivity analysis

We conducted numerous experiments considering multiple scenarios with variations in demand, job creation, varying fuel prices and the introduction of electric modes of transportation, based on the Norwegian case study. Additionally, a sensitivity analysis evaluates the impact of certain variables on the model's components. The remainder of this section discusses the results and findings of the experiments performed.

6.2.1. Experiments on demand variations

A sensitivity analysis assesses the impacts of variations in demand on cost components. Experiments were conducted on 11 unique scenarios, where each scenario is differentiated with an increment in aggregate customer demand by 10%. The proposed mathematical model was run on IBM CPLEX considering a time restriction of 600 s, and Table 1 documents the obtained results. Furthermore, to make the results obtained in Table 1 more understandable and to draw insights, a new Table 2 is created, displaying the average expected values (related to total cost, number of jobs created, carbon emissions incurred, fuel costs, inventory costs, processing costs, residual costs, charging costs and operating costs) per level of customer demand. From Tables 2 and it can be observed that with increases in demand, the average expected total cost gradually falls to Euro 3.02 compared to the baseline scenario of Euro 3.29 (a decrease in 8.31%). This is owing to the decline in the average expected inventory cost (equation (6)) and average expected operating cost (equation (7)). Therefore, the results highlight that profits can be maximized at higher levels of demand, since 100% of the

Table 3
Comparison of values with the baseline scenario - Demand Variations on Problem Instance 1.

Demand Variations	Baseline Scenario	10% ↑ Rise	20% ↑ Rise	30% ↑ Rise	40% ↑ Rise	50% ↑ Rise	60% ↑ Rise	70% ↑ Rise	80% ↑ Rise	90% ↑ Rise	100% ↑ Rise
Change in exp. total cost (%)	–	22.94%	28.64%	33.87%	40.59%	51.99%	59.72%	66.03%	71.22%	77.52%	83.38%
Change in exp. number jobs created (%)	–	57.14%	77.14%	58.57%	64.29%	85.71%	88.57%	85.71%	85.71%	98.57%	85.71%
Change exp. carbon emissions incurred (%)	–	13.89%	22.01%	27.24%	40.80%	45.68%	55.17%	69.37%	78.91%	88.68%	96.35%
Change in exp. transport cost (%)	–	13.90%	22.01%	27.24%	40.81%	45.68%	55.17%	69.37%	78.91%	88.68%	96.35%
Change in exp. fuel cost (%)	–	13.25%	21.31%	26.33%	39.84%	44.61%	54.24%	69.06%	79.30%	88.91%	97.40%
Change in exp. inventory cost (%)	–	−4.12%	3.30%	12.17%	19.71%	−9.42%	−0.58%	25.99%	19.19%	31.86%	42.51%
Change in exp. processing cost (%)	–	10.00%	20.00%	30.00%	40.00%	50.00%	60.00%	70.00%	80.00%	90.00%	100.00%
Change in exp. residual cost (%)	–	10.00%	20.00%	30.00%	40.00%	50.00%	60.00%	70.00%	80.00%	90.00%	100.00%
Change in exp. charging cost (%)	–	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Change in exp. operating cost (%)	–	44.44%	44.44%	44.44%	44.44%	66.67%	71.11%	66.67%	66.67%	66.67%	66.67%
Change in demand quantity (%)	–	10.00%	20.00%	30.00%	40.00%	50.00%	60.00%	70.00%	80.00%	90.00%	100.00%
Change in expected Profit (%)	–	8.28%	18.85%	29.48%	39.92%	49.73%	60.04%	70.53%	81.17%	91.66%	102.21%

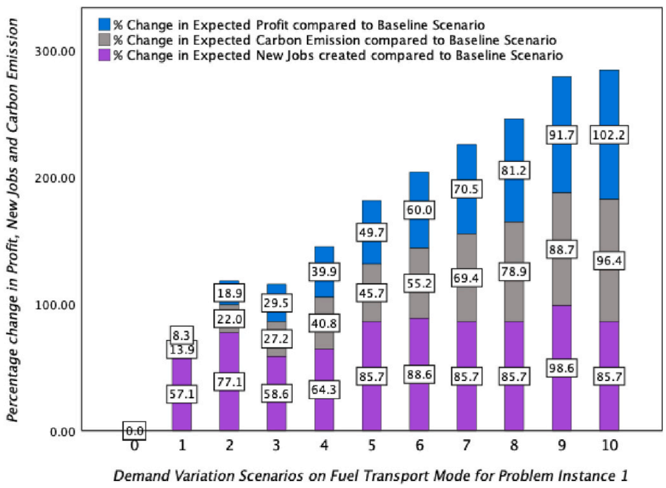

Fig. 5. Percentage Change in Profits, Jobs created and carbon emissions - Demand Variations.

increased demand can be met with decreased total costs (refer to Fig. 4), making the system more profitable as shown in Table 3. Additionally, from Table 3, an interesting insight can be observed, where the expected number of jobs created has almost doubled (85.71%) with a 100% increase in demand against the baseline scenario. Moreover, it can be attributed to operating new facilities to meet the rise in customer demand.

Through the experiments mentioned above, valuable insights can be generated for supply chain managers, highlighting two main aspects of sustainability, i.e., economic and social factors. Furthermore, the results demonstrate that the proposed model maximizes profitability (economic factor) while at the same time increasing employment (social factor) through increases in demand (demand variation) in an optimal way. However, from the results presented in Fig. 5, it can be noted that carbon emissions incurred drastically increase, almost doubling (96.35% for scenario 10) against the baseline scenario with increasing demand. This highlights that socio-economic development often has an adverse environmental impact. However, environmental obstacles must be addressed as they are critical to achieving holistic sustainability. Therefore, further experiments are conducted to mitigate the above-mentioned environmental issues, while simultaneously optimizing economic and social factors.

6.2.2. *Experiments on fuel price variations*

Insights from the experiments on increases in demand indicate that transportation costs (equation (2)), fuel costs (equation (3)) and carbon emissions (equations (10) and (11)) rise substantially, which should be addressed for sustainable development. We began addressing this by considering the impact of a rise in fuel prices, and this affects the fuel costs and transportation cost components. A sensitivity analysis helps understand the impact of changes in fuel prices on the cost components (equation (1)), carbon emissions and profitability. Based on current trends, assuming that fuel prices will increase (Bashir, 2022), experiments occurred relating to three problem instances, while considering 11 different fuel price scenarios, where each scenario is differentiated with a fuel price increment of 10%.

Furthermore, Tables 4–6 represent the results obtained after performing experiments on problem instances 1 to 3 respectively, for various fuel price scenarios. Further details about the problem instances are given in Tables 4–6. It can be observed that the results generated for all three instances indicate a similar gradual increase of fuel costs (equation (3)) with respect to the fuel price scenarios. In all three instances, there is a 100% increase in the expected fuel cost for scenario 10 compared to the baseline scenarios, which is graphically represented in Fig. 6. This increases the total costs (equation (1)) for the three problem instances by 6.97%, 7.51% and 9.27% respectively (Tables 4–6). Additionally, it is observed that the fuel cost (equation (3)) becomes higher

Table 4
Fuel price variations on problem instance 1 – comparison of values with the baseline scenario.

Problem Instance 1–3 clusters of salmon farms, 4 slaughterhouses, 3 primary processing plants, 2 secondary processing plants, 3 wholesalers, 4 retailers, 3 time periods and 4 disruption scenarios

	Baseline Scenario	*10% ↑ Rise*	*20% ↑ Rise*	*30% ↑ Rise*	*40% ↑ Rise*	*50% ↑ Rise*	*60% ↑ Rise*	*70% ↑ Rise*	*80% ↑ Rise*	*90% ↑ Rise*	*100% ↑ Rise*
Expected total cost (Euro)	237,020	238,630	240,570	242,510	243,620	245,240	246,830	248,540	250,310	251,860	253,550
Change in expected total cost when compared with baseline scenario (%)	–	0.68%	1.50%	2.32%	2.78%	3.47%	4.14%	4.86%	5.61%	6.26%	6.97%
Expected carbon Emissions incurred (Kg CO_2)	42,118	42,077	42,395	42,589	42,149	42,159	42,077	42,149	42,282	42,200	42,231
Expected transport cost (Euro)	27,951	27,923	28,134	28,263	27,971	27,978	27,923	27,971	28,059	28,005	28,025
Expected fuel cost (Euro)	16,393	18,032	19,761	21,567	22,976	24,589	26,228	27,895	29,574	31,182	32,851
Change in expected fuel cost compared to baseline scenario (%)	–	10.00%	20.55%	31.56%	40.16%	50.00%	60.00%	70.16%	80.41%	90.22%	100.40%
Expected Profit (revenue – expected total cost) (Euro)	1,778,980	1,777,370	1,775,430	1,773,490	1,772,380	1,770,760	1,769,170	1,767,460	1,765,690	1,764,140	1,762,450
Change in profit compared to baseline scenario (%)	–	−0.09%	−0.20%	−0.31%	−0.37%	−0.46%	−0.55%	−0.65%	−0.75%	−0.83%	−0.93%
Limit time (sec)	600	600	600	600	600	600	600	600	600	600	600
Execution time (sec)	2.58	24.7	18.19	18.42	16.08	12.06	20.39	14.17	15.05	29.74	18.36
Solution gap	0	0	0	0	0	0	0	0	0	0	0

Table 5
Fuel price variations on problem instance 2 – comparison of values with the baseline scenario.

Problem Instance 2–6 clusters of salmon farms, 8 slaughterhouses, 6 primary processing plants, 4 secondary processing plants, 6 wholesalers, 8 retailers, 3 time periods and 4 disruption scenarios

	Baseline Scenario	10% ↑ *Rise*	20% ↑ *Rise*	30% ↑ *Rise*	40% ↑ *Rise*	50% ↑ *Rise*	60% ↑ *Rise*	70% ↑ *Rise*	80% ↑ *Rise*	90% ↑ *Rise*	100% ↑ *Rise*
Expected total cost (Euro)	443,870	443,660	448,200	450,900	456,420	460,070	456,010	469,200	466,570	471,700	477,200
Change in expected total cost when compared with baseline scenario (%)	–	−0.05%	0.98%	1.58%	2.83%	3.65%	2.74%	5.71%	5.11%	6.27%	7.51%
Expected carbon Emissions incurred (Kg CO_2)	94,597	94,597	94,597	94,597	94,597	94,597	94,597	94,597	94,740	94,638	94,597
Expected transport cost (Euro)	62,777	62,777	62,777	62,777	62,777	62,777	62,777	62,777	62,872	62,804	62,777
Expected fuel cost (Euro)	36,175	39,792	43,410	47,027	50,645	54,262	57,880	61,497	65,200	68,750	72,350
Change in expected fuel cost compared to baseline scenario (%)	–	10.00%	20.00%	30.00%	40.00%	50.00%	60.00%	70.00%	80.23%	90.05%	100.00%
Expected profit (revenue – expected total cost) (Euro)	3,588,130	3,588,340	3,583,800	3,581,100	3,575,580	3,571,930	3,575,990	3,562,800	3,565,430	3,560,300	3,554,800
Change in expected profit compared to baseline scenario (%)	–	0.01%	−0.12%	−0.20%	−0.35%	−0.45%	−0.34%	−0.71%	−0.63%	−0.78%	−0.93%
Limit time (sec)	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600
Execution time (sec)	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600
Solution gap	2.94%	2.01%	3.00%	1.13%	1.92%	1.54%	2.14%	1.89%	2.18%	1.29%	1.86%

Table 6
Fuel price variations on problem instance 3 – comparison of values with the baseline scenario.

Problem Instance 3 – 12 clusters of salmon farms, 16 slaughterhouses, 12 primary processing plants, 8 secondary processing plants, 12 wholesalers, 16 retailers, 3 time periods and 4 disruption scenarios

	Baseline Scenario	10% ↑ Rise	20% ↑ Rise	30% ↑ Rise	40% ↑ Rise	50% ↑ Rise	60% ↑ Rise	70% ↑ Rise	80% ↑ Rise	90% ↑ Rise	100% ↑ Rise
Expected total cost (Euro)	778,190	785,050	792,500	800,350	807,230	813,980	821,320	828,650	835,830	842,980	850,300
Change in expected Total cost when compared with baseline scenario (%)	–	0.88%	1.84%	2.85%	3.73%	4.60%	5.54%	6.48%	7.41%	8.33%	9.27%
Expected carbon emissions Incurred (Kg CO_2)	189,720	189,320	189,540	189,920	189,700	189,330	189,440	189,550	189,440	189,430	189,500
Expected transport cost (Euro)	125,900	125,630	125,780	126,040	125,890	125,640	125,720	125,790	125,720	125,710	125,760
Change in expected fuel cost when compared with baseline scenario (%)	–	9.85%	20.00%	30.35%	40.10%	49.80%	59.84%	69.87%	79.79%	89.71%	99.77%
Expected fuel cost (Euro)	72,479	79,616	86,978	94,477	101,540	108,570	115,850	123,120	130,310	137,500	144,790
Expected profit (revenue – expected total cost) (Euro)	7,285,810	7,278,950	7,271,500	7,263,650	7,256,770	7,250,020	7,242,680	7,235,350	7,228,170	7,221,020	7,213,700
Change in expected profit when compared with baseline scenario (%)	–	−0.094%	−0.196%	−0.304%	−0.399%	−0.491%	−0.592%	−0.693%	−0.791%	−0.889%	−0.990%
Limit time (sec)	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600
Execution time (sec)	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600
Solution gap	1.95%	3.05%	2.52%	2.77%	1.78%	2.72%	2.95%	2.97%	2.40%	2.69%	2.65%

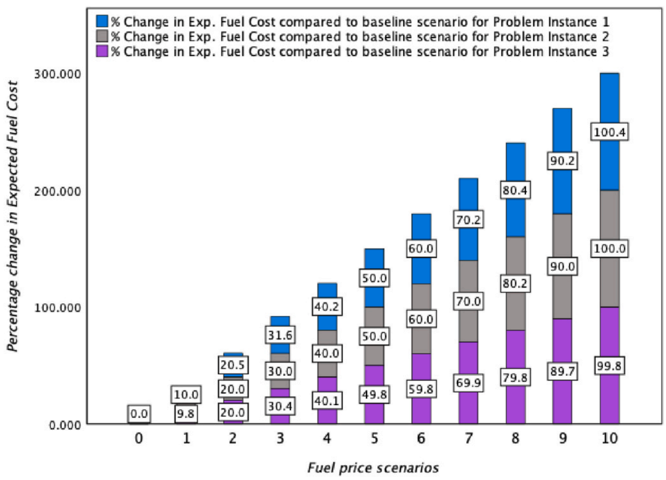

Fig. 6. Percentage change in fuel costs considering fuel price scenarios for three problem instances.

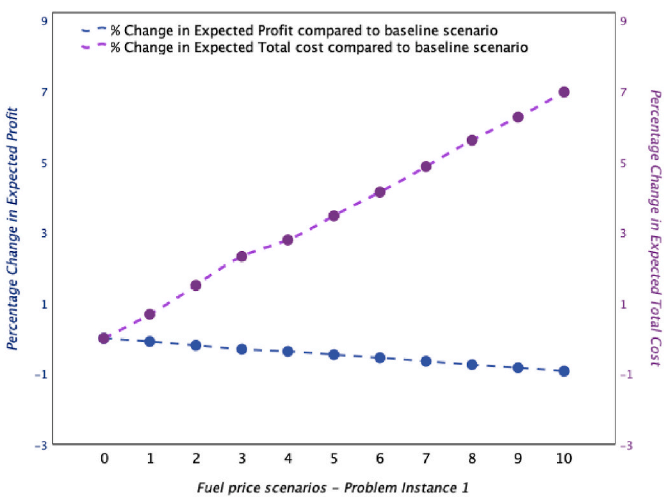

Fig. 7. Percentage change in profit and total costs for fuel price scenarios for problem instance 1.

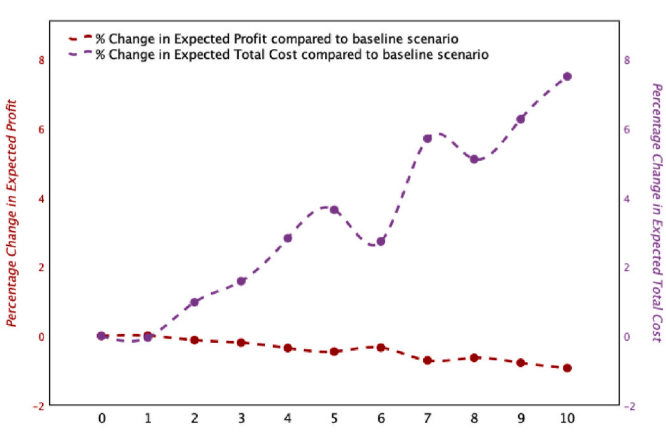

Fig. 8. Percentage change in profit and total costs for fuel price scenarios for problem instance 2.

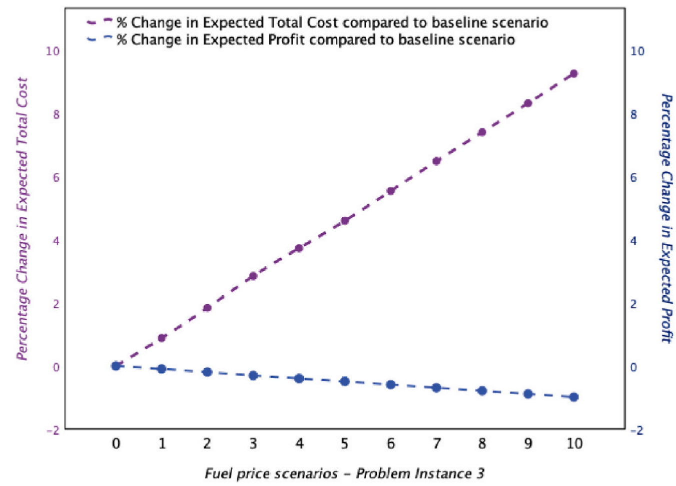

Fig. 9. Percentage change in profit and total costs for fuel price scenarios for problem instance 3.

than the transportation cost (equation (2)), from scenario 8 onwards for each instance, which is usually considered impractical by supply chain managers. Although the variations in fuel prices have less or no impact on carbon emissions and transportation costs, it can be noticed that the fuel cost has doubled for scenario 10 (refer to Tables 4–6), eventually increasing total costs.

Figs. 7–9 visually illustrate the slight decrease in expected profitability with the increase in the expected total costs (equation (1)). It can be interpreted, as expected, that profitability is inversely proportional to the rise in total costs. Consequently, given the current trend of high global fuel prices, it is evident that the continuation of a conventional, fuel-based transportation network may become increasingly unattractive in the future. Hence, the attained insights emphasize the need to consider implementing alternative greener transportation modes, such as electric vehicles within the supply chain logistics network, to help reduce carbon emissions, as well as transportation and fuel costs (Cunanan et al., 2021).

6.2.3. *Experiments on the electrification of transport modes on different routes*

The insights from the previous experiments on demand and fuel price variations indicate that the consideration of alternative greener transportation modes should be a priority, as the current logistical system may not in future be feasible economically and environmentally. Hence, the current experiment aims to gradually introduce electric vehicles within the supply chain logistics network in a step-by-step process on different transportation routes, and a sensitivity analysis is performed considering various scenarios. The results obtained after performing the experiments are recorded in Table 7 highlighting the actual values and percentage changes in values compared to the baseline scenario. Moreover, Table 8 provides useful information pertaining to average values per customer demand met. The expected transportation costs increased by 21.42% as observed in Fig. 10 for scenario 11, yet its impact is not reflected in total costs, owing to an exponential drop in fuel costs (equation (3)) due to adoption of the electrification of transport modes. From Fig. 11, it can be observed that the total costs (equation (1)) are slightly declining by gradually introducing electric transport into various shipment routes within the supply chain logistics network. Moreover, the average expected carbon emissions incurred per customer demand is reduced drastically for scenario 11 (see Fig. 11). This suggests for supply chain managers that the implementation of electric vehicles within the logistics network can be attractive moving forward in the future. Notably, the mathematical model highlights the potential level of job creation (equation (12)), creating and maintaining 7000 new jobs

Table 7
Experiments on various shipment links and percentage change in values compared to baseline scenario.

		Electric Vehicles adopted on shipment links – Problem Instance 1										
	Baseline Scenario (Only Fuel Transport)	SF to SH	SH to PP	PP to SP	PP to W	SP to W	W to R	SF to SH & SH to PP	SF to SH, SH to PP & PP to SP	SF to SH, SH to PP, PP to SP & PP to W	SF to SH, SH to PP, PP to SP, PP to W & SP to W	SF to SH, SH to PP, PP to SP, PP to W, SP to W & W to R
Expected total cost (Euro)	236,990	235,670	235,440	236,230	236,570	236,590	238,430	234,110	233,350	232,930	232,530	232,400
Percentage change in expected total cost (%)	–	−0.56%	−0.65%	−0.32%	−0.18%	−0.17%	0.61%	−1.22%	−1.54%	−1.71%	−1.88%	−1.94%
Expected carbon emissions incurred (Kg CO_2)	42,077	32,658	31,225	35,935	38,699	33,477	35,935	21,806	15,664	12,285	3686	0
Change in expected carbon emissions (%)	–	−22.4%	−25.79%	−14.60%	−8.03%	−20.44%	−14.60%	−48.18%	−62.77%	−70.80%	−91.24%	−100.00%
Expected transport costs (Euro)	27,923	29,373	29,570	28,952	28,489	28,797	30,608	31,019	32,048	32,613	33,487	33,904
Change in expected transport costs (%)	–	5.19%	5.90%	3.69%	2.03%	3.13%	9.62%	11.09%	14.77%	16.80%	19.93%	21.42%
Expected fuel cost (Euro)	16,393	12,061	11,402	13,568	14,839	14,834	14,529	7071	4246	2692	1134	0
Change in expected fuel cost (%)	–	−26.43%	−30.45%	−17.23%	−9.48%	−9.51%	−11.37%	−56.87%	−74.10%	−83.58%	−93.08%	−100.00%
Expected charging cost (Euro)	0	1557	1789	1032	568	286	620	3345	4377	4945	5231	5825

SF = Salmon Farms, SH = Slaughterhouses, PP = Primary Processing Plants, SP = Secondary Processing Plants, W = Wholesalers, R = Retailers.

across all scenarios, highlighting the impact on the social dimension. In conclusion, the experiment suggests that replacing traditional fuel-based transportation with electric transportation is not only an environmentally friendly measure but also highlights it as a cost-efficient practice, as there is a decline in the total and fuel costs. Furthermore, the optimality of these experiments in a larger case scenario, considering the economic (profit maximization and cost reduction) and social objective (maximizing job creation, which is equation (12)) would further assist in achieving the primary goal of holistic sustainability. Hence the following experiment aims to generate practical implications for the supply chain managers by optimizing the combination of objectives mentioned above.

6.2.4. *Experiments on demand variation when adopting electric vehicles (EVs)*

This experiment aims to generate insights by incorporating valuable results and addressing previous experiments' limitations. Specifically, a sensitivity analysis is performed, focusing on the effects of demand fluctuations while employing electric vehicles within the supply chain logistics network. Moreover, the model was run on a more extensive data set to evaluate the results while focusing on the economic aspects such as revenue and profitability with the intention to simulate real-world scenarios. A demand increment of 10% is considered, like the experiments on demand variations (refer to section 5.2.1). In addition, Table 9 highlights the percentage change in values when compared with those of the baseline scenarios, enabling a better understanding of the magnitude of change. Table 9 shows that with the rise in demand, the costs associated with transportation aspects grow, as electric vehicle charging increases. Therefore, the total costs incurred rise and almost double for scenario 10 when compared with the baseline scenario (refer to Fig. 12). However, insights from Fig. 13 reveal that, the revenue and profit generated also double with the rise in demand, compensating for the increase in total costs (equation (1)), making it more profitable. Moreover, the number of jobs (equation (12)) supported increases from 17,000 (baseline scenario) to 35,100 (scenario 10), a significant growth of 106.5%, which can directly impact societal aspects by improving the standards of living and wellbeing in rural and remote communities, which may lack many alternative employment opportunities. Additionally, the carbon emissions (equation (11)) and fuel costs (equation (3)) are completely nullified due to the 100% adoption of electric vehicles, hence contributing to net-zero objectives pertaining to CO_2 emissions. Given that the social (jobs created), environmental (carbon emissions), and the economic aspect (cost reduction and profit maximization) are addressed and optimized efficiently, it can be concluded that the mathematical model is robust and well-rounded, satisfying the core objective of holistic sustainability. While the first three experiments could not satisfy all three objectives established in the paper, the fourth experiment, however, amalgamates the favourable results of the previous experiments and succeeds in achieving the research's purpose.

Table 8
Average values per customer demand met while adopting electric vehicles for the shipment of products.

	Baseline Scenario -Only Fuel Transport	SF to SH	SH to PP	PP to SP	PP to W	SP to W	W to R	SF to SH & SH to PP	SF to SH, SH to PP & PP to SP	SF to SH, SH to PP, PP to SP & PP to W	SF to SH, SH to PP, PP to SP, PP to W & SP to W	SF to SH, SH to PP, PP to SP, PP to W, SP to W & W to R
		Electric Vehicles adopted on shipment links – Problem Instance 1										
Average expected total cost per customer demand (Euro)	3.29	3.27	3.27	3.28	3.29	3.29	3.31	3.25	3.24	3.24	3.23	3.23
Change in avg. total cost per demand compared to Baseline Scenario (Euro)	0.00	−0.02	−0.02	−0.01	0.00	0.00	0.02	−0.04	−0.05	−0.05	−0.06	−0.06
Average expected carbon emissions per customer demand (Kg CO_2)	0.58	0.45	0.43	0.50	0.54	0.46	0.50	0.30	0.22	0.17	0.05	0.00
Change in avg. carbon emissions per demand compared to baseline Scenario (Kg CO_2)	0.00	−0.13	−0.15	−0.08	−0.04	−0.12	−0.08	−0.28	−0.36	−0.41	−0.53	−0.58
Average expected transport cost per customer demand (Euro)	0.39	0.41	0.41	0.40	0.40	0.40	0.43	0.43	0.45	0.45	0.47	0.47
Change in avg. transport cost per demand compared to baseline Scenarios (Euro)	0.00	0.02	0.02	0.01	0.01	0.01	0.04	0.04	0.06	0.06	0.07	0.07
Average expected fuel cost per customer demand (Euro)	0.23	0.17	0.16	0.19	0.21	0.21	0.20	0.10	0.06	0.04	0.02	0.00
Change in avg. fuel cost value per demand compared to baseline Scenario (Euro)	0.00	−0.06	−0.07	−0.04	−0.02	−0.02	−0.03	−0.13	−0.17	−0.19	−0.21	−0.23
Average expected charging cost per customer demand (Euro)	0.00	0.02	0.02	0.01	0.01	0.00	0.01	0.05	0.06	0.07	0.07	0.08

SF = Salmon Farms, SH = Slaughterhouses, PP = Primary Processing Plants, SP = Secondary Processing Plants, W = Wholesalers, R = Retailers.

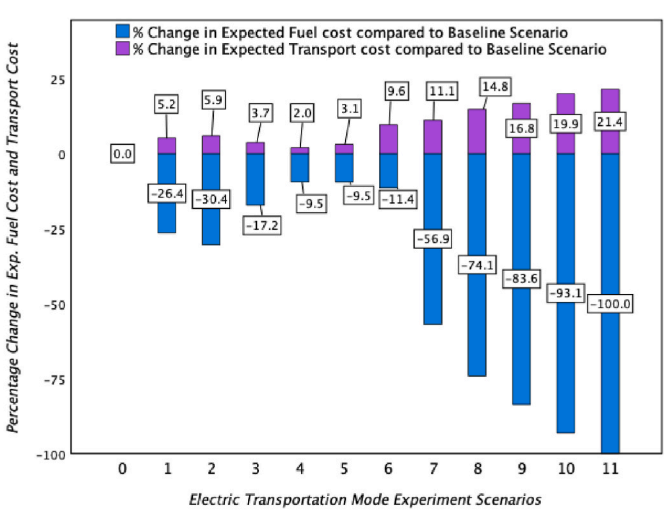

Fig. 10. Percentage change in fuel and transportation costs for partial electric vehicle adoption scenarios.

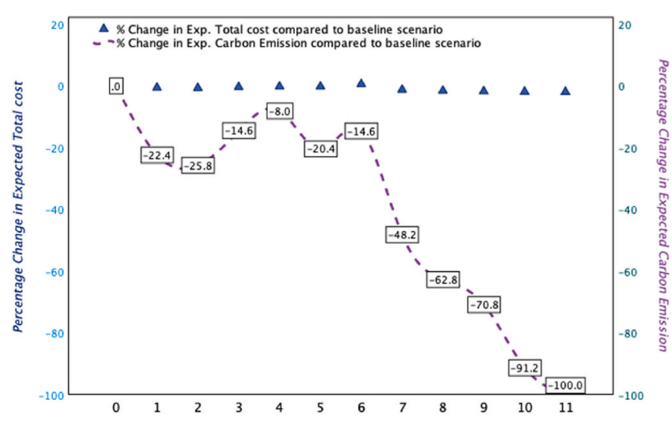

Fig. 11. Percentage change in expected total costs for partial electric vehicle adoption scenarios.

Table 9
Comparison of values with the baseline scenario for demand variations experiment considering full adoption of EVs.

Change in values compared to baseline scenario	Baseline Scenario Values	10% ↑ Rise in demand	20% ↑ Rise in demand	30% ↑ Rise in demand	40% ↑ Rise in demand	50% ↑ Rise in demand	60% ↑ Rise in demand	70% ↑ Rise in demand	80% ↑ Rise in demand	90% ↑ Rise in demand	100% ↑ Rise in demand
Change in expected total cost (%)	751,400	12.69%	22.49%	31.63%	42.12%	47.63%	57.59%	73.86%	80.38%	88.93%	98.59%
Change in expected number of jobs created (%)	17,000	17.06%	21.18%	24.71%	41.76%	27.65%	37.65%	84.71%	58.82%	97.06%	106.47%
Change in expected carbon emissions incurred (%)	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Change in expected transport cost (%)	146,710	18.64%	25.68%	34.98%	47.26%	54.11%	67.73%	80.76%	88.21%	96.65%	103.63%
Change in expected fuel cost (%)	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Change in expected inventory cost (%)	34,249	6.14%	17.76%	32.42%	38.97%	62.22%	67.95%	56.99%	99.59%	64.92%	73.62%
Change in expected processing cost (%)	291,600	10.00%	20.00%	30.00%	40.00%	50.00%	60.00%	70.00%	80.00%	90.00%	100.00%
Change in expected residual cost (%)	63,900	10.00%	20.00%	30.00%	40.00%	50.00%	60.00%	70.00%	80.00%	90.00%	100.00%
Change in expected charging cost (%)	24,941	17.33%	24.53%	34.49%	46.63%	53.75%	67.26%	80.58%	88.34%	97.18%	104.42%
Change in expected operating cost (%)	190,000	13.68%	25.26%	31.58%	42.11%	34.74%	42.11%	77.89%	70.53%	84.21%	95.79%
Change in expected unutilised space (%)	12,473	938.33%	715.44%	477.89%	659.43%	417.82%	587.15%	762.18%	523.01%	325.34%	99.19%
Change in total demand quantity (%)	288,000	10.00%	20.00%	30.00%	40.00%	50.00%	60.00%	70.00%	80.00%	90.00%	100.00%
Change in revenue (%)	8,064,000	10.00%	20.00%	30.00%	40.00%	50.00%	60.00%	70.00%	80.00%	90.00%	100.00%
Change in profit incurred (%)	7,312,600	9.72%	19.74%	29.83%	39.78%	50.24%	60.25%	69.60%	79.96%	90.11%	100.14%
Limit time	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600
Execution time	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600
Gap	4.66%	6.32%	6.61%	6.45%	6.45%	4.47%	4.18%	6.97%	6.00%	4.44%	4.53%

6.3. Managerial implications

The experiments generate actionable insights, which can assist supply chain managers in achieving their goals and objectives. The results indicate that the proposed mathematical model assists supply chain managers comprehend the interactions and trade-offs between economic, social, and environmental dimensions. The analysis indicates that a successful market expansion strategy results in an increase in the total revenue generated and employment. While costs also rise, they do not do so at the rate of revenues, so that market expansion leads to higher profits. However, market expansion using existing transport modes generates substantially higher carbon emissions. Consequently, without technological change, socio-economic development comes at the expense of environmental objectives.

However, reconfiguring transport modes allows for a market expansion strategy to achieve socio-economic objectives without increased carbon emissions. Specifically, incorporating alternative, greener transportation modes, like electric vehicles, within the supply chain network, mitigates not only carbon emissions, but also transportation, and fuel costs. A trajectory that is more sustainable economically, socially, and environmentally is thus possible. The sensitivity analysis also emphasizes the mathematical model's adaptability in responding to demand variations, which can be valuable for supply chain managers when optimizing and mitigating demand

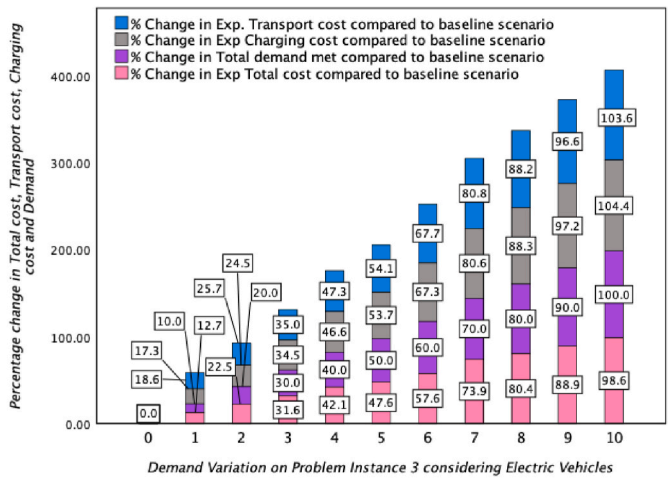

Fig. 12. Percentage change in cost components during demand variations with full adoption of electric vehicles.

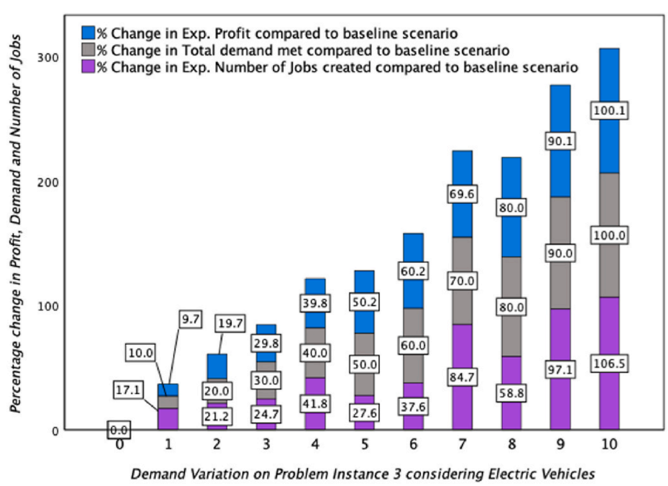

Fig. 13. Percentage change in profit and jobs created during demand variation with full adoption of electric vehicles.

fluctuations in uncertain circumstances like pandemics and wars. In addition, the model responds to changes in demand by restructuring the supply chain and arriving at the best feasible solution by optimizing the cost component, thus demonstrating the current model's efficacy in coping with unexpected fluctuations in demand.

7. Conclusions

The paper develops an optimization model to enhance the Norwegian salmon supply chain network's ability to achieve holistic sustainability, incorporating social, economic, and environmental dimensions (Senyo and Osabutey, 2021). The paper introduces and validates a MILP model containing all three dimensions of sustainability to aid in tactical and strategic food supply chain decision-making. The model aims to adapt to fluctuations in consumer demand while considering the incorporation of electrical vehicles, to reduce costs and increase profits. Additionally, the model considers real-world constraints such as varying supply and demand, carbon emissions constraints, fuel consumption, various operational costs associated with transportation, product processing, inventory holding, etc. The suggested model's efficiency in dealing with complex situations is demonstrated by examining it under various scenarios based on a case study and real-world data. Furthermore, the model assists in understanding how logistical operations can be reconfigured to streamline the whole supply chain to maximize the profits, save costs, and create jobs while complying with carbon emission regulations. Notably, the inclusion of the social aspect of employment generation, is one of the distinctive features of the model. The sensitivity analysis demonstrates the model's resilience in coping with varying customer demand and its consequences for the overall supply chain. The model thus offers an appropriate tool that practitioners and decision-makers can employ to optimize and evaluate food supply chain networks' sustainability.

The limitations of this research can guide future research. The current research focuses on optimizing logistical aspects; however, optimizing operational activities is also critical, as the nature of the latter is an important determinant of how well a supply chain copes with unexpected disruptions and the generation of carbon emissions (Dolgui & Ivanov, 2021). Therefore, implementing Industry 4.0 technologies to optimize facility-level operations warrants further research. Additionally, the research focuses on the food supply chain of a developed nation (Norway). However, the model could be adapted to the contexts of developing countries and different supply chain networks. Finally, the study investigations one alternative transport mode, namely electric vehicles. However, various renewable fuels, such as biofuels and bioenergy, and green modes of transportation, such as green trains and hybrid vehicles (Andersson et al., 2014) could be evaluated in future studies. Future studies can also explore the role of initial acquisition costs associated with electric vehicles and capacity considerations emanating from grids which impact truck productivity, and affect the three dimensions of sustainability considered in the research. Moreover, by considering an extended life cycle perspective (involving activities such as mining for battery production and transportation over long distances), future studies can augment this research. Finally, the current optimization model could be extended to integrate factors such as lead times, service levels and customer satisfaction, increasing its utility as a business management tool.

CRediT authorship contribution statement

Arijit De: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Akhil Kalavagunta:** Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation. **Matthew Gorton:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization. **Mohit Goswami:** Writing – review & editing, Writing – original draft, Validation, Supervision.

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.

Data availability

Data will be made available on request.

Appendix A – Notations of Mathematical Model

Indices and Sets

$a,\ A$	Index and Set of Salmon Farm respectively, $a \in A$
b, B	Index and Set of Slaughterhouse respectively, $b \in B$
c, C	Index and Set of Primary Processing Plant respectively, $c \in C$
d, D	Index and Set of Secondary Processing Plant respectively, $d \in D$
e, E	Index and Set of Wholesaler respectively, $e \in E$
f, F	Index and Set of Retailer respectively, $f \in F$
t, T	Index and Set of Time Period respectively, $t \in T$
s, S	Index and Set of Disruption Scenario respectively, $s \in S$
i	Index of Live Salmon product
j	Index of HOG product
k	Index of fresh HOG product
l	Index of Whole Fillet product
m	Index of Salmon by-product (it includes blocks, loins and portions, off-cut trimming belly flaps, head, tailbone, and skin)

Parameters – Related to Storage Capacity and Transportation Capacity

π^s	Probability of occurrence of disruption scenario S
CA_{at}^{is}	Supply available for Live Salmon product i at Salmon Farm a in time period t during disruption scenario s
MC_b^{js}	Maximum storage capacity of HOG product j at Slaughterhouse b during disruption scenario s
MC_c^{ks}	Maximum storage capacity of fresh HOG salmon products k at Primary Processing Plant c during disruption scenario s
MC_d^{ls}	Maximum storage capacity of Whole Fillet product l at Secondary Processing Plant d during disruption scenario s
MC_d^{ms}	Maximum storage capacity of By-product of salmon m at Secondary Processing Plant d during disruption scenario s
MC_e^{ks}	Maximum storage capacity of fresh HOG salmon products k at Wholesaler e during disruption scenario s
MC_e^{ls}	Maximum storage capacity of Whole Fillet product l at Wholesaler e during disruption scenario s
MC_e^{ms}	Maximum storage capacity of Salmon by-product m at Wholesaler e during disruption scenario s
CT_{ab}^{is}	Capacity of the transportation mode for the shipment of Live Salmon product i from Salmon Farm a to Slaughterhouse b during disruption scenario s
CT_{bc}^{js}	Capacity of the transportation mode for the shipment of Hog product j from Slaughterhouse b to Primary Processing Plant c during disruption scenario s
CT_{cd}^{ks}	Capacity of the transportation mode for the shipment of fresh HOG salmon products k from Primary Processing Plant c to Secondary Processing Plant d during disruption scenario s
CT_{ce}^{ks}	Capacity of the transportation mode for the shipment of fresh HOG salmon products k from Primary Processing Plant c to Wholesaler e during disruption scenario s
CT_{ef}^{ks}	Capacity of the transportation mode for the shipment of fresh HOG salmon products k from Wholesaler e to Retailer f during disruption scenario s
CT_{de}^{ls}	Capacity of the transportation mode for the shipment of Whole Fillet product l from Secondary Processing Plant d to Wholesaler e during disruption scenario s
CT_{de}^{ms}	Capacity of the transportation mode for the shipment of Salmon by-product m from Secondary Processing Plant d to Wholesaler e during disruption scenario s
CT_{ef}^{ls}	Capacity of the transportation mode for the shipment of Whole Fillet product l from Wholesaler e to Retailer f during disruption scenario s
CT_{ef}^{ms}	Capacity of the transportation mode for the shipment of Salmon by-product m from Wholesaler e to Retailer f during disruption scenario s

Parameters – Related to Demand and Cost Components

DM_{ft}^{k}	Demand for fresh HOG salmon product k at Retailer f in period t
DM_{et}^{l}	Demand of Whole Fillet product l at Retailer f in period t
DM_{et}^{m}	Demand of Salmon by-product m at Retailer f in period t
TQ_{ab}^{i}	Fixed transport cost (Euro per km) for shipping Live Salmon i from Salmon Farm a to Slaughterhouse b
TQ_{bc}^{j}	Fixed transport cost (Euro per km) for shipping Hog Product j from Slaughterhouse b to Primary Processing Plant c
TQ_{cd}^{k}	Fixed transport cost (Euro per km) for shipping fresh HOG salmon product k from Primary Processing Plant c to Secondary Processing Plant d
TQ_{ce}^{k}	Fixed transport cost (Euro per km) for shipping fresh HOG salmon product k from Primary Processing Plant c to Wholesaler
TQ_{ef}^{k}	Fixed transport cost (Euro per km) for shipping fresh HOG salmon product k from Wholesaler e to Retailer f
TQ_{de}^{l}	Fixed transport cost (Euro per km) for shipping Whole Fillet product l from Secondary Processing Plant d to Wholesaler e
TQ_{de}^{m}	Fixed transport cost (Euro per km) for shipping Salmon by-product m from Secondary Processing Plant d to Wholesaler e
TQ_{ef}^{l}	Fixed transportation cost (Euro per km) for shipping Whole Fillet product l from Wholesaler e to Retailer f
TQ_{ef}^{m}	Fixed transportation cost (Euro per km) for shipping Salmon by-product m from Wholesaler e to Retailer f
O_b^t	Number of job opportunities created if Slaughterhouse j operates in period t
O_c^t	Number of job opportunities created if Primary Processing Plant c operates in period t

O_d^t Number of job opportunities created if Secondary Processing Plant d operates in period t
OQ_b^t Fixed operating cost for operating Slaughterhouse j in period t
OQ_c^t Fixed operating cost for operating Primary Processing Plant c in period t
OQ_d^t Fixed operating cost for operating Secondary Processing Plant d in period t
IQ_{bt}^j Inventory holding cost (Euro per unit) of Hog product j at Slaughterhouse b in period t
IQ_{ct}^k Inventory holding cost (Euro per unit) of fresh HOG salmon product k at Primary Processing Plant c in period t
IQ_{et}^k Inventory holding cost (Euro per unit) of fresh HOG salmon product k at Wholesaler e in period t
IQ_{dt}^l Inventory holding cost (Euro per unit) of Whole Fillet product l at Secondary Processing Plant d in period t
IQ_{dt}^m Inventory holding cost (Euro per unit) of Salmon by-product m at Secondary Processing Plant d in period t
IQ_{et}^l Inventory holding cost (Euro per unit) of Whole Fillet product l at Wholesaler e in period t
IQ_{et}^m Inventory holding cost (Euro per unit) of Salmon by-product m Wholesaler e in period t
PQ_{bt}^j Processing cost (Euro per unit) of Hog product j at Slaughterhouse b in period t
PQ_{ct}^k Processing cost (Euro per unit) of fresh HOG salmon product k at Primary Processing Plant c in period t
PQ_{dt}^l Processing cost (Euro per unit) of Whole Fillet product l at Secondary Processing Plant d in period t
PQ_{dt}^m Processing cost (Euro per unit) of Salmon by-product m at Secondary Processing Plant d in period t
RQ_{bt}^i Residual cost (Euro per unit) of residual amount obtained after processing Live Salmon product i at Slaughterhouse b in period t
RQ_{ct}^j Residual cost (Euro per unit) of residual amount obtained after processing Hog product j at Primary Processing Plant c in period t
RQ_{dt}^k Residual cost (Euro per unit) of residual amount obtained after processing fresh HOG salmon product k at Secondary Processing Plant d in period t

Parameters - Fuel Consumption, Distance, Fuel Price and Carbon Emission Coefficient

FC_{ab}^i Fuel consumed (in litres per km) in shipping Live Salmon i via certain mode of transport from Salmon Farm a to Slaughterhouse b
FC_{bc}^j Fuel consumed (in litres per km) in shipping Hog product j via certain transport mode from Slaughterhouse b to Primary Processing Plant c
FC_{cd}^k Fuel consumed (in litres per km) in shipping fresh HOG salmon product k via certain transport mode from Primary Processing Plant c to Secondary Processing Plant d
FC_{ce}^k Fuel consumed (in litres per km) while shipping fresh HOG salmon product k via certain mode of transport from Primary Processing Plant c to Wholesaler e
FC_{de}^l Fuel consumed (in litres per km) while shipping Whole Fillet product l via certain mode of transport from Secondary Processing Plant d to Wholesaler e
FC_{de}^m Fuel consumed (in litres per km) while shipping Salmon by-product m via certain mode of transport from Secondary Processing Plant d to Wholesaler e
FC_{ef}^k Fuel consumed (in litres per km) while shipping fresh HOG salmon product k via certain mode of transport from Wholesaler e to Retailer f
FC_{ef}^l Fuel consumed (in litres per km) while shipping Whole Fillet product l via certain mode of transport from Wholesaler e to Retailer f
FC_{ef}^m Fuel consumed (in litres per km) while shipping Salmon by-product m via certain mode of transport from Wholesaler e to Retailer f
α_t Fuel price (Euro per litre) in period t
β_t Charging price (Euro per km) of electric transportation mode in period t
E^{CO_2} Carbon emission coefficient associated with the fuel (Kg CO_2 per litre)
Z_{ab},Z_{bc},Z_{cd},Z_{ce},Z_{de},Z_{ef} Distance from Salmon Farm a to Slaughterhouse b; Distance from Slaughterhouse b to Primary Processing Plant c; Distance from Primary Processing Plant c to Secondary Processing Plant d; Distance from Primary Processing Plant c to Wholesaler e; Distance from Secondary Processing Plant d to Wholesaler e; Distance from Wholesaler e to Retailer f
IE^{CO_2} Carbon emission incurred for maintaining inventory level of one unit of Salmon product at the facility (Kg CO_2 per unit product)
PE^{CO_2} Carbon emission incurred while processing one unit of Salmon product at the facilities (Kg CO_2 per unit product)
RE^{CO_2} Carbon emission incurred while obtaining residual of one unit of Salmon product at the facilities (Kg CO_2 per unit product)

Parameters – Electric and Fuel Transportation

X_{ab} 1, if electric transportation mode is deployed from Salmon farm a to Slaughterhouse b, 0 otherwise
X_{bc} 1, if electric transportation mode is deployed from Slaughterhouse b to Primary Processing Plant c, 0 Otherwise
X_{cd} 1, if electric transportation mode is deployed from Primary Processing Plant c to Secondary Processing Plant d, 0 otherwise
X_{ce} 1, if electric transportation mode is deployed from Primary Processing Plant c to Wholesaler e, 0 Otherwise
X_{de} 1, if electric transportation mode is deployed from Secondary Processing Plant d to Wholesaler e, 0 otherwise
X_{ef} 1, if electric transportation mode is deployed from Wholesaler e to Retailer f, 0 otherwise
U_{ab} 1, if fuel transportation mode is deployed from Salmon farm a to Slaughterhouse b, 0 otherwise
U_{bc} 1, if fuel transportation mode is deployed from Slaughterhouse b to Primary Processing Plant c, 0 Otherwise
U_{cd} 1, if fuel transportation mode is deployed from Primary Processing Plant c to Secondary Processing Plant d, 0 otherwise
U_{ce} 1, if fuel transportation mode is deployed from Primary Processing Plant c to Wholesaler e, 0 Otherwise
U_{de} 1, if fuel transportation mode is deployed from Secondary Processing Plant d to Wholesaler e, 0 otherwise
U_{ef} 1, if fuel transportation mode is deployed from Wholesaler e to Retailer f, 0 otherwise

Continuous Variables – Related to the Processed Amount and Wastage Amount

PA_{bt}^{js} Processed amount of HOG product j obtained at Slaughterhouse b in period t during disruption scenario s

PA_{ct}^{ks} Processed amount of fresh HOG salmon product k obtained at Primary Processing Plant c in period t during disruption scenario s
PA_{dt}^{ls} Processed amount of Whole Fillet product l obtained at Secondary Processing Plant d in period t during disruption scenario s
PA_{dt}^{ms} Processed amount of Salmon by-product m obtained at Secondary Processing Plant d in period t during disruption scenario s
RO_{bt}^{is} Amount of residual obtained after processing Live Salmon product i at Slaughterhouse b in period t during disruption scenario s
RO_{ct}^{js} Amount of residual obtained after processing HOG product j at Primary Processing Plant c in period t during disruption scenario s
RO_{dt}^{ks} Amount of residual obtained after processing fresh HOG salmon product k at Secondary Processing Plant d in period t during disruption scenario s

Continuous Variables – Related to the Inventory Level

IL_{bt}^{js} Inventory level available for HOG product j in Slaughterhouse b at the end of period t during disruption scenario s
IL_{ct}^{ks} Inventory level available for fresh HOG product k in Primary Processing Plant c at the end of period t during disruption scenario s
IL_{et}^{ks} Inventory level available for fresh HOG product k in Wholesaler e at the end of period t during disruption scenario s
IL_{dt}^{ls} Inventory level available for Whole Fillet product l in Secondary Processing Plant d at the end of period t during disruption scenario s
IL_{dt}^{ms} Inventory level available for Salmon by-product m in Secondary Processing Plant d at the end of period t during disruption scenario s
IL_{et}^{ls} Inventory level available for Whole Fillet product l in Wholesaler e at the end period t during disruption scenario s
IL_{et}^{ms} Inventory level available for Salmon by-product m in Wholesaler e at the end of period t during disruption scenario s

Integer Variables – Related to Amount Transported

Y_{abt}^{is} Total amount of Live Salmon i transported from Salmon Farm a to Slaughterhouse b in period t during disruption scenario s
Y_{bct}^{js} Total amount of HOG product j transported from Slaughterhouse b to Primary Processing Plant c in period t during disruption scenario s
Y_{cdt}^{ks} Total amount of fresh HOG salmon product k transported from Primary Processing Plant c to Secondary Processing Plant d in period t during disruption scenario s
Y_{cet}^{ks} Total amount of fresh HOG salmon product k transported from Primary Processing Plant c to Wholesaler e in period t during disruption scenario s
Y_{det}^{ls} Total amount of Whole Fillet product l transported from Secondary Processing Plant d to Wholesaler e in period t during disruption scenario s
Y_{det}^{ms} Total amount of Salmon by-product m transported from Secondary Processing Plant d to Wholesaler e in period t during disruption scenario s
Y_{eft}^{ks} Total amount of fresh HOG salmon product k transported from Wholesaler e to Retailer f in period t during disruption scenario s
Y_{eft}^{ls} Total amount of Whole Fillet product l from Wholesaler e to Retailer f in period t during disruption scenario s
Y_{eft}^{ms} Total amount of Salmon by-product m transported from Wholesaler e to Retailer f in period t during disruption scenario s
N_{abt}^{is} Number of trips made by the transport mode in shipping Live Salmon i from Salmon Farm a to Slaughterhouse b in period t during disruption scenario s
N_{bct}^{js} Number of trips made by the transport mode in shipping HOG product j from Slaughterhouse b to Primary Processing Plant c in period t during disruption scenario s
N_{cdt}^{ks} Number of trips made by the transport mode in shipping fresh HOG product k from Primary Processing Plant c to Secondary Processing Plant d in period t during disruption scenario s
N_{cet}^{ks} Number of trips made by the transport mode in shipping fresh HOG product k from Primary Processing Plant c to Wholesaler e in period t during disruption scenario s
N_{det}^{ls} Number of trips made by the transport mode in shipping Whole Fillet product l from Secondary Processing Plant d to Wholesaler e in period t during disruption scenario s
N_{det}^{ms} Number of trips made by the transport mode in shipping Salmon by-product m from Secondary Processing Plant d to Wholesaler e in period t during disruption scenario s
N_{eft}^{ks} Number of trips made by the transport mode in shipping fresh HOG product k from Wholesaler e to Retailer f in period t during disruption scenario s
N_{eft}^{ls} Number of trips made by the transport mode in shipping Whole Fillet product l from Wholesaler e to Retailer f in period t during disruption scenario s
N_{eft}^{ms} Number of trips made by the transport mode in shipping Salmon by-product m from Wholesaler e to Retailer f in period t during disruption scenario s

Binary Variables – Related to Operating Facility

V_{b}^{st} 1, if Slaughterhouse b is operating in period t during disruption scenario s, 0 otherwise
V_{c}^{st} 1, if Primary Processing Plant c is operating in period t during disruption scenario s, 0 otherwise
V_{d}^{st} 1, if Secondary Processing Plant d is operating in period t during disruption scenario s, 0 otherwise

Appendix B

Case Study

The Norway's salmon supply chain network (NSSCN) consists of salmon farms, slaughterhouses, primary processing plants, secondary processing plants, wholesalers, and retailers. Based on their average distance to the slaughterhouse, the salmon farms are classified into different clusters. In this paper, various permutations and combinations of the elements of NSSCN were considered, and 3 unique data instances were developed with varying complexities and sizes of variables. The following are the characteristics of each instance. Problem instance 1–3 clusters of salmon farms, 4 slaughterhouses, 3 primary processing plants, 2 secondary processing plants, 3 wholesalers, 4 retailers, 3 time periods and 4 disruption scenarios. Problem instance 2–6 clusters of salmon farms, 8 slaughterhouses, 6 primary processing plants, 4 secondary processing plants, 6 wholesalers, 8 retailers, 3 time periods and 4 disruption scenarios. Problem instance 3–12 clusters of salmon farms, 16 slaughterhouses, 12 primary processing plants, 8 secondary processing plants, 12 wholesalers, 16 retailers, 3 time periods and 4 disruption scenarios.

The combined daily supply of live salmon to the slaughterhouse from various clusters of salmon farms is roughly 140 tonnes per day. Only boats with a capacity of 150–300 tonnes per day are utilized to transport live salmon from salmon farms to the slaughterhouse, with a transportation cost of 0.39 euro/km for the fuel-based vehicles and 0.25 euro/km for electric vehicles. For the electric vehicles, the charging cost is 0.05 euro/km. The payload for fuel vehicles is 2000 kg, and payload for electric vehicles is about 1015 kgs. The slaughterhouse processes live salmon and obtains Head on Gutted (HOG fish and residuals. After processing the live salmon, 87–90% is in the form of a HOG product, with the remaining 10–13% residual. The processing cost for producing the HOG product is between €0.3 and 0.35 per kg. Furthermore, the cost of acquiring the residual amount after processing live salmon is €0.2–0.25 per kg. The slaughterhouse's maximum storage capacity for HOG fish is 140 tons daily and inventory costs are 0.12 per kg. Since the primary processing plant is also located at the packing station near the slaughterhouse, HOG salmon obtained after processing are conveyed to the primary processing plant, incurring low transit and consequently low fuel costs. Consequently, the inventory in the slaughterhouse and primary processing plant is minimal. The primary processing plant's maximum storage capacity for fresh HOG salmon is roughly 140 tonnes daily. Fresh HOG products are transported from the primary processing plant to a secondary processing plant in the Netherlands and wholesalers. A maximum of 90–95% is supplied to European wholesalers, with the remainder going to the secondary processing plant. Multiple modes of transportation transport fresh HOG salmon from primary to secondary processing plants. Fresh HOG salmon is transported by truck, and boat, from the primary processing plant to ten wholesalers around Europe, including cities such as Düsseldorf, Frankfurt, Munich, Copenhagen, The Hague, Rotterdam, Brussels, Luxembourg, Rome, and Athens. The distances between the primary processing plant and the ten wholesalers in Düsseldorf, Frankfurt, Munich, Copenhagen, The Hague, Rotterdam, Brussels, Luxembourg, Rome, and Athens are 1603 km, 1857 km, 2203 km, 2204 km, 1540 km, 1553 km, 1703 km, 1813 km, 3053 km, and 4273 km, respectively. The transportation costs for fresh HOG product from the primary processing plant to wholesalers in European cities are around €0.1 - €0.2 per kg. Furthermore, some processed salmon products from the secondary processing plant are shipped to wholesalers in European cities. After processing fresh HOG salmon at secondary processing plants, whole fillets and salmon by-products are obtained. Following the processing of fresh HOG, 66% of the product obtained is whole fillets, 33% as salmon by-products, and the remaining 1% as a residual. For whole fillets, salmon by-products, and residual, the processing and residual cost at the secondary processing plant is €1.5 per kg. The whole fillets and salmon by-products are sent from the secondary processing plant to wholesalers in various European cities. The distances between the secondary processing plant and wholesalers in Dusseldorf, Frankfurt, Munich, Copenhagen, The Hague, Rotterdam, Brussels, Luxembourg, Rome, and Athens are 200 km, 454 km, 800 km, 801 km, 137 km, 150 km, 300 km, 410 km, 1650 km, and 2870 km, respectively. Consumption of fuel and carbon emissions data are partly derived from the research work of Soysal et al. (2014). Salmon products are distributed to retailers through the ten wholesalers. The fuel price is between €1.1 and €1.5 per litre. A typical 12 tonne delivery truck consumes around 21.4 L per 100 km (Delgado et al., 2017). The coefficient of carbon emissions is 2.392 kg CO_2 per litre. The market price of salmon per kg is €28 (Svanidze et al., 2022).

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