Optimization model for sustainable food supply chains: An application to Norwegian salmon

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Optimization Model for Sustainable Food Supply Chains: An Application to Norwegian Salmon

Abstract

Food supply chains encompass multiple actors and simultaneously produce multiple products that require transportation using various modes or networks before arriving on consumers' tables. Transportation costs and related carbon emissions along a supply chain, however, can be high, prompting a search for efficient management solutions. This paper proposes a mathematical formulation in the form of a mixed-integer linear programming model, drawing on evidence from a Norwegian salmon supply chain network. The model addresses environmental aspects by aiming to minimize the fuel cost component from various transportation modes and considers carbon emissions related restrictions. Testing using various problem instances highlights the robustness of the proposed mathematical formulation and models. Moreover, a real-world case study of a Norwegian salmon exporter helps understand the applicability of the proposed model. The paper discusses the impact of different supply chain arrangements regarding their overall cost, including fuel cost, and carbon emissions to understand the need for holistic optimization of food supply chains. Sensitivity analysis regarding demand variability allows the proposed mathematical model to restructure the Norwegian salmon supply chain network to meet fluctuating retail demand. Transportation scenario analysis emphasizes the importance of shifting from road to maritime transportation for certain routes to achieve financial and environmental gains.

Keywords: Transportation; Food Supply Chains; Optimization; Carbon Emissions; Mixed-Integer Linear Programming; Salmon

1. Introduction

The transportation sector is the largest contributor to global carbon emissions, amounting to around 7.5 billion metric tonnes in 2015 (OECD/ITF, 2017) and logistics remains a critical financial cost for supply chains (Wu, Nie, Xu, & Yan, 2018). However, greening supply chain management practices, including transportation, is problematic, due to customer requirements, product specificities, cost pressures, supply chain complexity and regulation uncertainties (Ala-Harja & Helo, 2014; Shankar, Gupta, & Pathak, 2018). One supply chain entity acting alone may achieve very little and the minimisation of transportation and environmental costs requires co-operation between supply chain actors (Wang, Zhao, & Herty, 2019).

1.1. Sustainable Food Supply Chains

Food products provide typically additional challenges for logistics and transportation due to their perishability, limited storage capacity, safety and traceability requirements (An & Ouyang, 2016; Shankar et al., 2018; Wu et al., 2018). Food supply chains globally have become increasingly complex with a large number of actors involved and the average distance food travels from producers to final consumers rising sharply in the last two decades (European Commission, 2020; Shashi, Cerchione, Singh, Centobelli, & Shabani, 2018). With a high demand for increased food production, especially of meat, and an increase in logistics and transportation, global food systems are a major source of pollution, hence contributing to climate change. For example, the Joint Research Centre (2006) estimates that 29% of all consumption derived Greenhouse Gas (GHG) emissions are food related. Consequently, the attention from regulatory agencies to food systems' environmental performance, including logistics and transportation, has grown (Béné et al., 2020). Likewise, consumers generally have become more demanding regarding food system transparency and sustainability (European Parliament, 2019b; van der Vorst, Tromp, & van der Zee, 2009). These forces are leading to major changes in policy objectives. For instance, the proposed Climate Law of the European Union (EU) sets out the objective for a climate neutral EU in 2050 and its Green New Deal envisages a transition to sustainable food production systems that dramatically reduce GHG emissions (European Commission, 2020). In relation to transport, the EU seeks a 60% reduction in GHG emissions while maintaining a competitive and resource-efficient transport system (European Parliament, 2019a). Some of this reduction directly relates to optimizing the performance of multimodal logistics chains. For example, one target is for 30% of road freight over 300 km to shift to other modes (rail or inland waterways) by 2030, increasing to more than 50%, by 2050 (European Parliament, 2019a). Policy makers, supply chain actors and consumers thus demand greater transparency in mapping the financial and environmental impacts of food supply chains and seek strategies to minimize financial costs and GHG emissions (Ala-Harja & Helo, 2014; An & Ouyang, 2016).

1.2. Modelling approaches for Food Supply Chains

The management of food supply chains has received increased attention (Amorim, Curcio, Almada-Lobo, Barbosa-Póvoa, & Grossmann, 2016; Maiyar & Thakkar, 2019b; Mogale, Kumar, Kumar, & Tiwari, 2018). Prior research highlights the need for addressing issues related to integrating supply chain functions, sustainability aspects, and the development of decision support models (Esteso, Alemany, & Ortiz, 2018; Govindan, 2018; Zhu et al., 2018). The bulk of previous research focussing on modelling food supply chains are scenario specific and there is a lack of generic models (Mogale et al., 2018). Furthermore, recent papers utilise mixed-integer programming to optimize supply chains in fields such as liquid helium (Malinowski, Karwan, Pinto, & Sun, 2018) and the location of facilities (Liu, Kong, Wang, & Zhang, 2021). However, food supply chain specific requirements such as processing, residual aspects and environmental related constraints require a unique optimization model, which has been overlooked in the prior literature. To address this challenge, the paper develops a mathematical model for the transportation and logistics system of food supply chains. It undertakes this research through an illustrative case of the Norwegian salmon supply chain, which is an exemplary case for capturing the multiple stages that exist within a food supply chain which is international in nature, handling perishable products, and possesses limited storage capacity (Hjellnes, Rustad, & Falch, 2020). We developed multi-echelon, multi-period, supply chain models, informed by the literature (Govindan, Soleimani, & Kannan, 2015).

1.3. Research Gaps and Contribution to Theory and Practice

Extant research considering supply chain networks developed mathematical models incorporating multiple stakeholders and multiple products (Pasandideh, Niaki, & Asadi, 2015; Saberi, Cruz, Sarkis, & Nagurney, 2018). There is very limited work, however, focussing on mathematical modelling aspects, addressing supply chain complexities like those witnessed in the salmon supply chain, with few studies of the salmon case (Asche, Cojocaru, & Roth, 2018; Shepherd, Monroig, & Tocher, 2017). Furthermore, past literature highlights a need for more complex supply chain modelling, considering different kinds of products and multiple transportation modes (Maiyar & Thakkar, 2019a; Mogale et al., 2018). Within the current paper, we address the complexities of the salmon supply chain network while considering multiple transportation modes and processing activities and ensure that the model can be adapted to other food supply chains.

Furthermore, the paper contributes to the existing literature in several ways. Firstly, we present a conceptual framework (Figure 1) for understanding the salmon supply chain while considering the transportation linkages for product flows between different stakeholders. Secondly, we provide a mathematical model for the salmon supply chain, which can be applied to other food supply chains. Thirdly, we ensure that the mathematical model minimizes total supply chain costs, including transportation, inventory, fuel consumption, product processing and residual/waste, while mitigating carbon emissions. Finally, the paper provides policy makers with useful insights, evaluating the impacts of food supply chain reforms, with a focus on reducing carbon emissions.

Key contributions to practice are summarised as follows. The conceptual framework for the salmon supply chain helps understand the nature of the linkages and product flows between stakeholders. For developing a mathematical model relevant for practitioners, it is imperative to obtain an adequate conceptualisation of the supply chain network using expert interviews as typically the existing literature and available secondary data are inadequate. The mathematical model for the salmon supply chain is developed based on the conceptual framework presented in Figure 1. Restrictions associated with carbon emissions and wastage/residuals address sustainability aspects. Constraints related to supply, processing capacity, storage capacity, demand, carbon emissions, inventory balancing, transportation capacity, and modes of transportation between different facilities are incorporated. To aid managerial relevance, primary data collection occurred pertaining to the input parameters included in the mathematical model, supplied by industry stakeholders. The model is valuable for policy makers in terms of understanding the costs and emissions associated with different configurations of food supply chains, as well as the effects of particular policy interventions and market developments (e.g., variations in demand, fuel costs, emissions and waste constraints). In addition, the model can aid supply chain managers' decision making regarding the amount of inventory to be kept in different time periods and in selecting transport routes (e.g., whether maritime routes should be adopted in place of road/rail transportation, to address environmental concerns related to fuel consumption and carbon emissions).

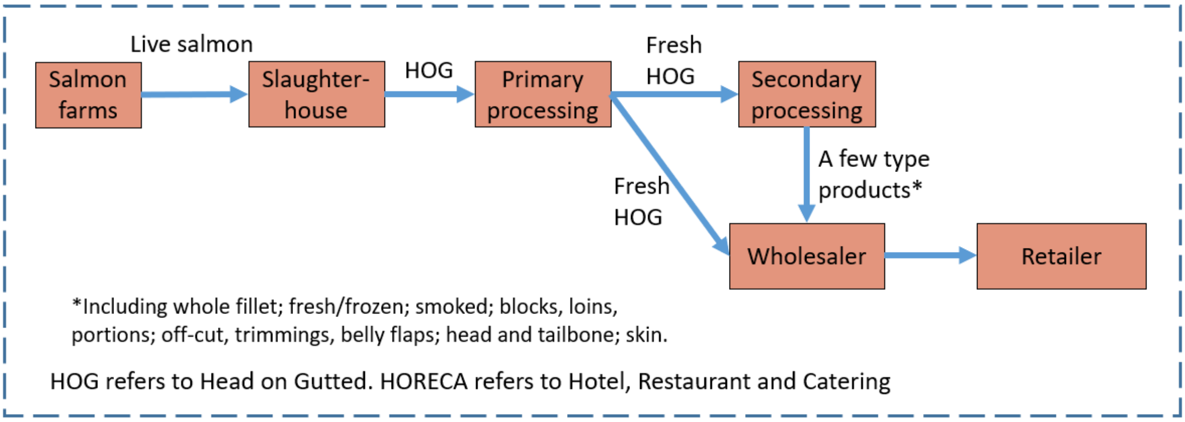

Figure 1: Conceptual framework for the Norwegian Salmon Supply Chain Network

2. Problem Description

The Norwegian salmon supply chain network comprises of six key actors, i.e. salmon farms, slaughterhouses, primary processing plants, secondary processing plants, wholesalers and retailers. Salmon farms supply live salmon to a slaughterhouse, where the live salmon product is processed and Head-on-Gutted (HOG) salmon is obtained. The HOG product is sent from the slaughterhouse to the primary processing plant, where the HOG product is processed to obtain fresh HOG salmon products. Some percentage of the fresh HOG salmon product obtained at the primary processing plant is sent to a secondary processing plant(s) and the remaining portion is sent to wholesalers. Similarly, a certain amount of fresh HOG salmon products received at the secondary processing plant is processed to obtain whole fillets and salmon by-products, which includes off-cuts, belly flaps, heads, tailbones, and skin. The retailers have a specific demand for fresh HOG salmon which is met from wholesalers; moreover, the retailers also have demand for whole fillets and salmon by-products provided by the secondary processing plants.

The shipment of various types of products depends on using different modes of transportation (e.g., road, maritime and air). Moreover, demand for various products varies significantly across the network and between actors. Processing different product types leads to certain residuals after processing. For example, processing of live salmon at the slaughterhouse, processing of HOG fish at the primary processing plant and processing of fresh HOG salmon products at the secondary processing plant ensure that residuals are also obtained from each of the processing activities. The demand for fresh HOG salmon products, whole fillets and salmon by-products at the retailer varies over time, which may have an adverse effect on inventory levels for various product types at different stakeholders. This might lead to an increase in inventory costs, which affect total costs. Therefore, in order to neutralize the impact of demand variability on various stakeholders, the proposed mathematical model (see Section 3) takes into consideration a multiple time period scenario, which aims to minimize the inventory cost component, which can vary significantly, while tackling demand variability.

The novelty of the research work lies in proposing a mathematical formulation (model M) presented in section 3, for addressing the Norwegian salmon supply chain network. Furthermore, owing due to the complex nature of this supply chain, the proposed mathematical model M is converted into two mathematical models – models N1 and N2, where the output of model N1 feeds into the input of model N2 (see Section 4). The development of models N1 and N2 is driven by the current operations of the Norwegian salmon exporter from which primary data were collected for validating the proposed model on a real-world problem. The main aim of the mathematical models is to help decision makers associated with the food supply chain to minimize total costs related to transportation, inventory holding, fuel consumption, product processing and residuals. The models also address several real-world restrictions related to transportation capacity, varying retail demand, inventory flow balance for various stakeholders while considering varying storage capacity and variability related to product supply. Moreover, the proposed mathematical models help to address the variability related to the cost components associated with transportation, inventory holding and processing.

3. Mathematical Model (M)

This section presents the mathematical formulation pertaining to the food supply chain network. It is designed to specifically focus on salmon, but its key features are common across many other food supply chains. The notations associated with the mathematical model such as sets, indices, parameters, decision variables are provided in the Appendix A due to space limitations. The objective function and the constraints of the mathematical formulation are also presented.

Minimize

Total Cost = Transportation Cost + Fuel Cost + Inventory Cost + Processing Cost + Residual Cost

(1)

$$\left. \begin{aligned} C^{Tcost} = & \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} G^{a}_{ijt} X^{a}_{ijt} + \sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{t=1}^{T} G^{b}_{jpt} X^{b}_{jpt} + \sum_{p=1}^{P}\sum_{q=1}^{Q}\sum_{t=1}^{T} G^{c}_{pqt} X^{c}_{pqt} + \sum_{p=1}^{P}\sum_{u=1}^{U}\sum_{t=1}^{T} G^{c}_{put} X^{c}_{put} \\ & + \sum_{u=1}^{U}\sum_{r=1}^{R}\sum_{t=1}^{T} G^{c}_{urt} X^{c}_{urt} + \sum_{q=1}^{Q}\sum_{u=1}^{U}\sum_{t=1}^{T} \left[G^{e}_{qut} X^{e}_{qut} + G^{f}_{qut} X^{f}_{qut} \right] + \sum_{u=1}^{U}\sum_{r=1}^{R}\sum_{t=1}^{T} \left[G^{e}_{urt} X^{e}_{urt} + G^{f}_{urt} X^{f}_{urt} \right] \end{aligned} \right]$$

(2)

Equation (1) presents the objective function of the mathematical model which aims to minimize the total cost comprising of the transportation cost, fuel cost, inventory holding cost, processing cost and wastage cost. Equation (2) depicts the transportation cost, which comprises of seven terms, each dealing with the shipment of different types of salmon products.

The first term computes the transportation cost for the shipment of live salmon from the salmon farms to the slaughterhouses, whereas the second term aims to determine the transportation cost for the movement of HOG fish from slaughterhouses to the primary processing plants. The third term estimates the transportation cost for shipping fresh HOG salmon products from primary to secondary processing plants. The fourth and fifth terms compute the transportation cost related to the movement of fresh HOG salmon products from primary processing plants to wholesalers and also from wholesalers to retailers respectively. The sixth and seventh terms determine the transportation cost associated with the shipment of whole fillet products and salmon by-products from secondary processing plants to wholesalers and from wholesalers to retailers respectively.

$$\left.\begin{aligned}C^{Fcost} &= \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T}\alpha_t F_{ij}^{a} W_{ij} X_{ijt}^{a} + \sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{t=1}^{T}\alpha_t F_{jp}^{b} W_{jp} X_{jpt}^{b} + \sum_{p=1}^{P}\sum_{q=1}^{Q}\sum_{t=1}^{T}\alpha_t F_{pq}^{c} W_{pq} X_{pqt}^{c} \\ &+\sum_{q=1}^{Q}\sum_{u=1}^{U}\sum_{t=1}^{T}\alpha_t \left[F_{qu}^{e} X_{qut}^{e} + F_{qu}^{f} X_{qut}^{f} \right] W_{qu} + \sum_{u=1}^{U}\sum_{r=1}^{R}\sum_{t=1}^{T}\alpha_t \left[F_{ur}^{e} X_{urt}^{e} + F_{ur}^{f} X_{urt}^{f} \right] W_{ur} \\ &+\sum_{p=1}^{P}\sum_{u=1}^{U}\sum_{t=1}^{T}\alpha_t F_{pu}^{c} W_{pu} X_{put}^{c} + \sum_{u=1}^{U}\sum_{r=1}^{R}\sum_{t=1}^{T}\alpha_t F_{ur}^{c} W_{ur} X_{urt}^{c}\end{aligned}\right] \tag{3}$$

Equation (3) presents the fuel cost comprising of seven terms and it depicts the fuel cost associated with the total fuel consumed while transporting different types of salmon products while considering varying fuel prices. Each term relates to the fuel cost for the seven transportation stages described in the previous paragraph. For instance, the first term computes the fuel cost for the transportation of live salmon from the salmon farms to the slaughterhouses. The second term helps to estimate the fuel cost associated with the shipment of HOG fish from slaughterhouses to the primary processing plants. The third term determines the fuel cost associated with the transportation of fresh HOG product from primary to secondary processing plants. The fourth and fifth terms compute the fuel cost related to the shipment of whole fillets and salmon by-products from secondary processing plants to wholesalers and from wholesalers to retailers respectively. The sixth and seventh terms estimate the fuel cost for the transportation of fresh HOG fish from primary processing plants to wholesalers and then from wholesalers to retailers respectively.

$$\left.\begin{aligned}C^{Icost} &= \sum_{j=1}^{J}\sum_{t=1}^{T} H_{jt}^{b} IP_{jt}^{b} + \sum_{p=1}^{P}\sum_{t=1}^{T} H_{pt}^{c} IP_{pt}^{c} + \sum_{u=1}^{U}\sum_{t=1}^{T} H_{ut}^{c} IP_{ut}^{c} \\ &+\sum_{q=1}^{Q}\sum_{t=1}^{T}\left[H_{qt}^{e} IP_{qt}^{e} + H_{qt}^{f} IP_{qt}^{f} \right] + \sum_{u=1}^{U}\sum_{t=1}^{T}\left[H_{ut}^{e} IP_{ut}^{e} + H_{ut}^{f} IP_{ut}^{f} \right]\end{aligned}\right] \tag{4}$$

$$\left. C^{Pcost} = \sum_{j=1}^{J}\sum_{t=1}^{T} PC_{jt}^{b} TP_{jt}^{b} + \sum_{p=1}^{P}\sum_{t=1}^{T} PC_{pt}^{c} TP_{pt}^{c} + \sum_{q=1}^{Q}\sum_{t=1}^{T}\left[PC_{qt}^{e} TP_{qt}^{e} + PC_{qt}^{f} TP_{qt}^{f} \right] \right] \tag{5}$$

$$C^{Wcost} = \sum_{j=1}^{J}\sum_{t=1}^{T} PW_{jt}^{a} TW_{jt}^{a} + \sum_{p=1}^{P}\sum_{t=1}^{T} PW_{pt}^{b} TW_{pt}^{b} + \sum_{q=1}^{Q}\sum_{t=1}^{T} PW_{qt}^{c} TW_{qt}^{c} \tag{6}$$

Equation (4) represents the overall inventory holding cost and consists of five terms. The first term estimates the inventory holding cost for HOG salmon at slaughterhouses. The second and the third terms compute the inventory holding cost for fresh HOG salmon products at primary processing plants and wholesalers respectively. The fourth and fifth terms determine the inventory holding cost associated with whole fillet products and salmon by-products at secondary processing plants and wholesalers respectively. Equation (5) depicts processing costs and it is comprised of three terms. The first term estimates the processing cost incurred for obtaining the HOG fish at the slaughterhouses. The second term computes the processing cost incurred for obtaining fresh HOG salmon products at the primary processing plants. The third term estimates the processing cost associated with whole fillets and salmon by-products at secondary processing plants. Equation (6) gives the residual costs related to different types of products and this equation comprises of three terms. The first term depicts the residual cost incurred from live salmon products at slaughterhouses. The second term provides the residual cost incurred from the HOG salmon products at primary processing plants. The third term helps to estimate the residual cost incurred from fresh HOG salmon products at secondary processing plants.

$$\sum_{j=1}^{J} X_{ijt}^{a} \le AC_{it}^{a} \qquad \forall i \in I,\ \forall t \in T \tag{7}$$

Equation (7) is the supply constraint at salmon farms and it ensures that the number of live salmon shipped from a certain salmon farm to the slaughterhouses should be equal to the available capacity of live salmon products at the salmon farm. The following equations (8) to (13) represent the constraints associated with processing and residuals.

$$\sum_{i=1}^{I} X_{ijt}^{a} = TP_{jt}^{b} + TW_{jt}^{a} \qquad \forall j \in J,\ \forall t \in T \tag{8}$$

$$\sum_{j=1}^{J} X_{jpt}^{b} = TP_{pt}^{c} + TW_{pt}^{b} \qquad \forall p \in P,\ \forall t \in T \tag{9}$$

Equation (8) states that the total number of HOG salmon and the residual amount obtained after processing at the slaughterhouse depends on the total amount of live salmon received at the slaughterhouse from different salmon farms. Equation (9) ensures that the total amount of fresh HOG salmon products obtained after processing at the primary processing plant depends on the total amount of HOG fish received from various slaughterhouses.

$$\sum_{p=1}^{P} X_{pqt}^{c} = TP_{qt}^{e} + TP_{qt}^{f} + TW_{qt}^{c} \qquad \forall q \in Q,\ \forall t \in T \tag{10}$$

Equation (10) depicts that the total amount of whole fillets and salmon by-products obtained after processing at the secondary processing plant depends on the amount of fresh HOG salmon products received at the secondary processing plant from various primary processing plants.

$$0.05\sum_{i=1}^{I} X_{ijt}^{a} \leq TW_{jt}^{a} \leq 0.2\sum_{i=1}^{I} X_{ijt}^{a} \qquad \forall j \in J,\ \forall t \in T \tag{11}$$

$$0.05\sum_{j=1}^{J} X_{jpt}^{b} \leq TW_{pt}^{b} \leq 0.2\sum_{j=1}^{J} X_{jpt}^{b} \qquad \forall p \in P,\ \forall t \in T \tag{12}$$

$$0.05\sum_{p=1}^{P} X_{pqt}^{c} \leq TW_{qt}^{c} \leq 0.2\sum_{p=1}^{P} X_{pqt}^{c} \qquad \forall q \in Q,\ \forall t \in T \tag{13}$$

Equations (11), (12) and (13) present the range within which the residuals are obtained after processing live salmon, HOG fish and fresh HOG salmon products respectively. The value of the range was obtained after consultation with industry experts and a Norwegian Salmon exporter. The following equations from (14) – (20) present the storage capacity constraints.

$$TP_{jt}^{b} \leq \begin{cases} Cap_{jt}^{b} - IP_{j(t-1)}^{b}, & for\ t > 1 \\ Cap_{jt}^{b}, & for\ t = 1,\ IP_{j0}^{b} = 0 \end{cases} \qquad \forall j \in J,\ \forall t \in T \tag{14}$$

Equation (14) ensures that the sum of the available inventory of HOG salmon from the previous period and the total amount of HOG salmon processed should be less than or equal to the maximum storage capacity of HOG salmon at the slaughterhouse. The initial inventory of HOG fish at the slaughterhouse at start of the planning horizon is assumed to be zero.

$$TP_{pt}^{c} \leq \begin{cases} Cap_{pt}^{c} - IP_{p(t-1)}^{c}, & for\ t > 1 \\ Cap_{pt}^{c}, & for\ t = 1,\ IP_{p0}^{c} = 0 \end{cases} \qquad \forall p \in P,\ \forall t \in T \tag{15}$$

Equation (15) ensures that the sum of the available inventory of fresh HOG salmon products from the previous period and the total amount of fresh HOG salmon products processed should be less than or equal to the maximum storage capacity for fresh HOG salmon products at the primary processing plant. The initial inventory at the primary processing plant for the fresh HOG salmon product is assumed to be zero.

$$TP_{qt}^{\delta} \leq \begin{cases} Cap_{qt}^{\delta} - IP_{q(t-1)}^{\delta}, & for\ t > 1 \\ Cap_{qt}^{\delta}, & for\ t = 1,\ IP_{q0}^{\delta} = 0 \end{cases} \qquad \forall q \in Q,\ \forall t \in T,\ \delta = e, f \qquad (16) - (17)$$

Equations (16) – (17) state that the storage capacity of the secondary processing plant needs to be maintained for both whole fillets and salmon by-products respectively while considering the available inventory from the previous period and the total number of each type of product transported from various primary processing plants. The initial inventory of whole fillets and salmon-by products at the secondary processing plant is assumed to be zero at the start of the planning horizon.

$$\sum_{p=1}^{P} X_{put}^{c} \leq \begin{cases} Cap_{ut}^{c} - IP_{u(t-1)}^{c}, & for\ t > 1 \\ Cap_{ut}^{c}, & for\ t = 1,\ IP_{u0}^{c} = 0 \end{cases} \qquad \forall u \in U,\ \forall t \in T \tag{18}$$

Equation (18) ensures that the sum of the total amount of fresh HOG salmon products shipped from various primary processing plants to a particular wholesaler and the available inventory of fresh HOG salmon products 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. The initial inventory of fresh HOG salmon products at the wholesaler is assumed to be zero at the start of the planning horizon.

$$\sum_{q=1}^{Q} X_{qut}^{\delta} \leq \begin{cases} Cap_{ut}^{\delta} - IP_{u(t-1)}^{\delta}, & for\ t > 1 \\ Cap_{ut}^{\delta}, & for\ t = 1,\ IP_{u0}^{\delta} = 0 \end{cases} \qquad \forall u \in U,\ \forall t \in T,\ \delta = e, f \qquad (19) - (20)$$

Equations (19) – (20) state that the storage capacity of the wholesaler need to be maintained for whole fillets and salmon by-products respectively while considering the available inventory of both products from the previous period and the total number of each type of product transported from various secondary processing plants. The initial inventory of whole fillet and salmon-by products at the wholesaler is assumed to be zero at the starting of the planning horizon. The following equations from (21) to (27) represent the inventory balancing constraints for the proposed mathematical formulation.

$$IP_{jt}^{b} = \begin{cases} TP_{jt}^{b} + IP_{j(t-1)}^{b} - \sum_{p=1}^{P} X_{jpt}^{b}, & for\ t > 1 \\ TP_{jt}^{b} - \sum_{p=1}^{P} X_{jpt}^{b}, & for\ t = 1,\ IP_{j0}^{b} = 0 \end{cases} \qquad \forall j \in J,\ \forall t \in T \tag{21}$$

Equation (21) depicts the inventory balancing constraint for HOG salmon at the slaughterhouse. The inventory of HOG salmon at the slaughterhouse at the end of each time period is computed while considering the inventory of HOG salmon from the previous time period, total processed amount of HOG salmon at the slaughterhouse at the end of the current time period and the total amount of HOG fish transported from the slaughterhouse to the primary processing plant.

$$IP_{pt}^{c} = \begin{cases} TP_{pt}^{c} + IP_{p(t-1)}^{c} - \sum_{q=1}^{Q} X_{pqt}^{c} - \sum_{u=1}^{U} X_{put}^{c}, & for\ t > 1 \\ TP_{pt}^{c} - \sum_{q=1}^{Q} X_{pqt}^{c} - \sum_{u=1}^{U} X_{put}^{c}, & for\ t = 1,\ IP_{p0}^{c} = 0 \end{cases} \qquad \forall p \in P,\ \forall t \in T \tag{22}$$

$$IP_{ut}^{c} = \begin{cases} \sum_{p=1}^{P} X_{put}^{c} + IP_{u(t-1)}^{c} - \sum_{r=1}^{R} X_{urt}^{c}, & for\ t > 1 \\ \sum_{p=1}^{P} X_{put}^{c} - \sum_{r=1}^{R} X_{urt}^{c}, & for\ t = 1,\ IP_{u0}^{c} = 0 \end{cases} \qquad \forall u \in U,\ \forall t \in T \qquad (23)$$

Equations (22) and (23) provide the inventory balancing constraints for fresh HOG salmon products at the primary processing plant and the wholesaler respectively. For determining the inventory level of the fresh HOG salmon product at the primary processing plant, equation (22) takes into account the total processed amount of fresh HOG salmon products at the primary processing plant, the inventory level from the previous time period and the total fresh HOG salmon products shipped from the primary to various secondary processing plants and wholesalers. Equation (23) aims to determine the inventory level of the fresh HOG salmon product at the wholesaler while considering the inventory level from the previous time period, total fresh HOG salmon products shipped from various primary processing plants to the wholesaler and total fresh HOG transported from the wholesaler to various retailers.

$$IP_{qt}^{\delta} = \begin{cases} TP_{qt}^{\delta} + IP_{q(t-1)}^{\delta} - \sum_{u=1}^{U} X_{qut}^{\delta}, & for\ t > 1 \\ TP_{qt}^{\delta} - \sum_{u=1}^{U} X_{qut}^{\delta}, & for\ t = 1 \end{cases} \qquad \forall q \in Q,\ \forall t \in T,\ \delta = e, f \qquad (24)-(25)$$

Equations (24) and (25) present the inventory balancing constraints at the secondary processing plant for whole fillets and salmon by-products respectively. Equations (24) and (25) compute the inventory level of whole fillets and salmon by-products at the secondary processing plant while considering the inventory level from the previous time periods, total processed amounts for whole fillets and salmon by-products at the secondary processing plant and the total amount of whole fillets and salmon by-products shipped from the secondary processing plant to various wholesalers.

$$IP_{ut}^{\delta} = \begin{cases} \sum_{q=1}^{Q} X_{qut}^{\delta} + IP_{u(t-1)}^{\delta} - \sum_{r=1}^{R} X_{urt}^{\delta}, & for\ t > 1 \\ \sum_{q=1}^{Q} X_{qut}^{\delta} - \sum_{r=1}^{R} X_{urt}^{\delta}, & for\ t = 1 \end{cases} \qquad \forall u \in U,\ \forall t \in T,\ \delta = e, f \qquad (26)-(27)$$

Equations (26) and (27) provide the inventory balancing constraints for whole fillets and salmon by-products respectively at the wholesaler. The inventory level of the two particular products at the wholesaler are computed using equations (26) and (27) while considering the inventory level from the previous time period, the total amount of whole fillets and salmon by-products shipped from various secondary processing plants to the wholesaler and also shipping of the same products from the wholesaler to various retailers.

$$\sum_{u=1}^{U} X_{urt}^{c} = D_{rt}^{c};\ \sum_{u=1}^{U} X_{urt}^{e} = D_{rt}^{e};\ \sum_{u=1}^{U} X_{urt}^{f} = D_{rt}^{f} \qquad \forall r \in R,\ \forall t \in T \qquad (28-30)$$

Equations (28), (29) and (30) present the demand constraints at the retail level for different types of products such as fresh HOG salmon products, whole salmon fillets and salmon by-products respectively, which are shipped from the wholesaler to the retailer.

$$E^{CO_2}\left[\begin{array}{l}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} F_{ij}^{a} W_{ij} X_{ijt}^{a} + \sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{t=1}^{T} F_{jp}^{b} W_{jp} X_{jpt}^{b} + \sum_{p=1}^{P}\sum_{q=1}^{Q}\sum_{t=1}^{T} F_{pq}^{c} W_{pq} X_{pqt}^{c} \\ + \sum_{q=1}^{Q}\sum_{u=1}^{U}\sum_{t=1}^{T}\left[F_{qu}^{e} X_{qut}^{e} + F_{qu}^{f} X_{qut}^{f}\right] W_{qu} + \sum_{p=1}^{P}\sum_{u=1}^{U}\sum_{t=1}^{T} F_{pu}^{c} W_{pu} X_{put}^{c} \\ + \sum_{u=1}^{U}\sum_{r=1}^{R}\sum_{t=1}^{T}\left[F_{ur}^{e} X_{urt}^{e} + F_{ur}^{f} X_{urt}^{f}\right] W_{ur} + \sum_{u=1}^{U}\sum_{r=1}^{R}\sum_{t=1}^{T} F_{ur}^{c} W_{ur} X_{urt}^{c}\end{array}\right] \le E^{Max} \qquad (31)$$

Equation (31) ensures that the overall carbon emissions emitted from transportation of various salmon products should be less than or equal to the maximum allowable carbon emission limit. Overall fuel consumed on all the transportation links and the carbon emission coefficient represented as E^{CO_2} are taken into consideration for computing the overall carbon emission emitted for the supply chain network. Constraints associated with the restriction on transportation capacity and non-negative integers are provided in Appendix B, where constraints (B1) – (B12) are presented.

The consideration of multiple product types, multiple stakeholders, and multiple periods for dealing with demand variability makes the mathematical model extremely complicated. Hence for solving purposes, we convert the mathematical model (M) into two models (N1 and N2) which also address the current operational policy of the organization (Norwegian Salmon Exporter), as discussed in section 4.

4. Reformulation of the Mathematical Model (M)

The mathematical model M presented in section 3 is complex given the involvement of different stakeholders such as salmon farms, slaughterhouses, primary processing plants, secondary processing plants, wholesalers and retailers. Therefore, to solve the mathematical model it is converted into two separate mathematical formulations – mathematical models N1 and N2.

4.1. Mathematical Model (N1)

The mathematical model N1 addresses the supply chain network comprising of salmon farms, slaughterhouses, primary processing plants, secondary processing plants and wholesaler. The main intention of the first mathematical model (N1) is to meet the demand of the secondary processing plants and wholesalers for fresh HOG salmon products. The objective function for the model N1 is given below.

Minimize

Total Cost = Transportation Cost + Fuel Cost + Inventory Cost + Processing Cost + Residual Cost

(32)

$$C^{Tcost} = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} G_{ijt}^{a} X_{ijt}^{a} + \sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{t=1}^{T} G_{jpt}^{b} X_{jpt}^{b} + \sum_{p=1}^{P}\sum_{q=1}^{Q}\sum_{t=1}^{T} G_{pqt}^{c} X_{pqt}^{c} + \sum_{p=1}^{P}\sum_{u=1}^{U}\sum_{t=1}^{T} G_{put}^{c} X_{put}^{c} \tag{33}$$

$$\begin{aligned} C^{Fcost} = {} & \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} \alpha_t F_{ij}^{a} W_{ij} X_{ijt}^{a} + \sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{t=1}^{T} \alpha_t F_{jp}^{b} W_{jp} X_{jpt}^{b} + \sum_{p=1}^{P}\sum_{q=1}^{Q}\sum_{t=1}^{T} \alpha_t F_{pq}^{c} W_{pq} X_{pqt}^{c} \\ & + \sum_{p=1}^{P}\sum_{u=1}^{U}\sum_{t=1}^{T} \alpha_t F_{pu}^{c} W_{pu} X_{put}^{c} \end{aligned} \tag{34}$$

Equation (32) presents the objective function for the model N1. It comprises the cost components associated with the transportation of salmon products, fuel cost incurred during transportation, costs related to holding inventory and the costs associated with processing and residuals. The transportation cost given in equation (33) is associated with the shipment of live salmon from salmon farms to slaughterhouses, shipment of HOG fish from slaughterhouses to primary processing plants, and shipment of fresh HOG salmon products from primary to a secondary processing plant and wholesalers. Equation (34) presents the fuel cost, depicting the costs incurred for fuel consumption associated with the transportation of different products from salmon farms to slaughterhouses to primary processing plants and finally to secondary processing plants and wholesalers.

$$C^{Icost} = \sum_{j=1}^{J}\sum_{t=1}^{T} H_{jt}^{b} IP_{jt}^{b} + \sum_{p=1}^{P}\sum_{t=1}^{T} H_{pt}^{c} IP_{pt}^{c} \tag{35}$$

$$C^{Pcost} = \sum_{j=1}^{J}\sum_{t=1}^{T} PC_{jt}^{b} TP_{jt}^{b} + \sum_{p=1}^{P}\sum_{t=1}^{T} PC_{pt}^{c} TP_{pt}^{c} \tag{36}$$

$$C^{Wcost} = \sum_{j=1}^{J}\sum_{t=1}^{T} PW_{jt}^{a} TW_{jt}^{a} + \sum_{p=1}^{P}\sum_{t=1}^{T} PW_{pt}^{b} TW_{pt}^{b} \tag{37}$$

Equation (35) presents the inventory holding costs associated with holding inventory at slaughterhouses and primary processing plants. Equations (36) and (37) provide the overall processing cost and residual costs incurred at slaughterhouses and primary processing plants.

Constraints of the model N1 related to the supply constraints given in equation (7). Processing and residual constraints for the model N1 are given in equations (8), (9), (11) and (12). The following equations (38), (39), (40) and (41), given below, relate to processing and residuals and can be used in place of equations (8), (9), (11) and (12). The following constraints were obtained after discussions with industry experts regarding the percentage of salmon products and residuals obtained after performing the processing activities at the slaughterhouse and primary processing plant.

$$TP_{jt}^{b} = 0.9\sum_{i=1}^{I} X_{ijt}^{a};\ TW_{jt}^{a} = 0.1\sum_{i=1}^{I} X_{ijt}^{a} \qquad \forall j \in J,\ \forall t \in T \qquad (38)-(39)$$

$$TP_{pt}^{c} = 0.9\sum_{j=1}^{J} X_{jpt}^{b};\ TW_{pt}^{b} = 0.1\sum_{j=1}^{J} X_{jpt}^{b} \qquad \forall p \in P,\ \forall t \in T \qquad (40)-(41)$$

When the exact percentages of processed and residual amounts are known beforehand (e.g., after consultation with industry experts) then equations (38), (39), (40) and (41) can be employed in place of equations (8), (9), (11) and (12). The model N1 has storage capacity constraints for slaughterhouses and primary processing plants given in equations (14) and (15). Moreover, the model N1 also has inventory balancing constraints given in equations (21) and (22). The main aim of the model N1 is to meet the demand of secondary processing plants and wholesalers for fresh HOG salmon products. Therefore, the demand constraints for the model N1 are:

$$\sum_{p=1}^{P} X_{pqt}^{c} = D_{qt}^{c} \qquad \forall q \in Q,\ \forall t \in T \qquad (42)$$

$$\sum_{p=1}^{P} X_{put}^{c} = D_{ut}^{c} \qquad \forall u \in U,\ \forall t \in T \qquad (43)$$

Equations (42) and (43) provides the demand constraints of the model N1 for meeting the demand for fresh HOG salmon products at slaughterhouses and primary processing plants in different time periods. Here, D_{qt}^{c} is the demand for fresh HOG salmon products c at secondary processing plant q in time period t. Moreover, D_{ut}^{c} is the demand for fresh HOG salmon products c at wholesaler u in time period t. The carbon emissions constraint for the model N1 is:

$$E^{CO_2}\left[\begin{array}{l} \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} F_{ij}^{a} W_{ij} X_{ijt}^{a} + \sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{t=1}^{T} F_{jp}^{b} W_{jp} X_{jpt}^{b} + \sum_{p=1}^{P}\sum_{q=1}^{Q}\sum_{t=1}^{T} F_{pq}^{c} W_{pq} X_{pqt}^{c} \\ + \sum_{p=1}^{P}\sum_{u=1}^{U}\sum_{t=1}^{T} F_{pu}^{c} W_{pu} X_{put}^{c} \end{array}\right] \le E^{Max} \qquad (44)$$

Equation (44) aims to address the carbon emissions for the shipment of live salmon from salmon farms to slaughterhouses. It also estimates the carbon emissions related to the shipment of HOG fish from slaughterhouses to primary processing plants. Finally, equation (44) also determines the carbon emissions related to the transportation of fresh HOG salmon products from primary processing plants to secondary processing plants and wholesalers. The model N1 also has transportation capacity constraints (see Appendix B) given as equations (B1), (B2), (B3) and (B4). Therefore, the objective function of model N1 is given in equation (32). The constraints of model N1 are given in equations (7), (14), (15), (21), (22), (B1), (B2), (B3), (B4), (38), (39), (40), (41), (42), (43) and (44). The next sub-section provides detailed information about model N2.

4.2. Mathematical Model (N2)

The mathematical model N2 addresses the supply chain network starting from the secondary processing plants and wholesalers and ending at the retailers. The secondary processing plant aims to process fresh HOG salmon into whole fillets and salmon by-products, with some residuals. The total demand for fresh HOG salmon products received at the secondary processing plant is used for processing purposes and later the demand for whole fillets and salmon by products at the retailer is met via wholesalers. The objective function of the model N2 is given below,

Minimize

Total Cost = Transportation Cost + Fuel Cost + Inventory Cost + Processing Cost + Residual Cost (45)

$$C^{Tcost}=\sum_{q=1}^{Q}\sum_{u=1}^{U}\sum_{t=1}^{T}\left[G^{e}_{qut}X^{e}_{qut}+G^{f}_{qut}X^{f}_{qut}\right]+\sum_{u=1}^{U}\sum_{r=1}^{R}\sum_{t=1}^{T}\left[G^{e}_{urt}X^{e}_{urt}+G^{f}_{urt}X^{f}_{urt}\right]+\sum_{u=1}^{U}\sum_{r=1}^{R}\sum_{t=1}^{T}G^{c}_{urt}X^{c}_{urt} \tag{46}$$

$$C^{Fcost}=\left[\begin{aligned}&\sum_{q=1}^{Q}\sum_{u=1}^{U}\sum_{t=1}^{T}\alpha_t\left[F^{e}_{qu}X^{e}_{qut}+F^{f}_{qu}X^{f}_{qut}\right]W_{qu}+\sum_{u=1}^{U}\sum_{r=1}^{R}\sum_{t=1}^{T}\alpha_t\left[F^{e}_{ur}X^{e}_{urt}+F^{f}_{ur}X^{f}_{urt}\right]W_{ur}\\&+\sum_{u=1}^{U}\sum_{r=1}^{R}\sum_{t=1}^{T}\alpha_t F^{c}_{ur}W_{ur}X^{c}_{urt}\end{aligned}\right] \tag{47}$$

Equation (45) presents the objective function for the model N2 which comprises of the transportation cost, fuel cost, inventory holding cost, processing cost and residual cost. Equation (46) depicts the transportation cost for the shipment of whole fillets and salmon by-products from secondary processing plants to retailers via wholesalers. Equation (46) also estimates the transportation cost for the shipment of fresh HOG salmon products from wholesalers to retailers. Equation (47) provides the fuel cost associated with the total fuel consumed for transportation from secondary processing plants to wholesalers and product shipments from wholesalers to retailers.

$$C^{Icost}=\sum_{u=1}^{U}\sum_{t=1}^{T}H^{c}_{ut}IP^{c}_{ut}+\sum_{q=1}^{Q}\sum_{t=1}^{T}\left[H^{e}_{qt}IP^{e}_{qt}+H^{f}_{qt}IP^{f}_{qt}\right]+\sum_{u=1}^{U}\sum_{t=1}^{T}\left[H^{e}_{ut}IP^{e}_{ut}+H^{f}_{ut}IP^{f}_{ut}\right] \tag{48}$$

$$C^{Pcost}=\sum_{q=1}^{Q}\sum_{t=1}^{T}\left[PC^{e}_{qt}TP^{e}_{qt}+PC^{f}_{qt}TP^{f}_{qt}\right] \tag{49}$$

$$C^{Wcost}=\sum_{q=1}^{Q}\sum_{t=1}^{T}PW^{c}_{qt}TW^{c}_{qt} \tag{50}$$

Equation (48) estimates the inventory holding cost for holding whole fillets and salmon by-products at secondary processing plants and wholesalers and also holding inventory of fresh HOG salmon products at wholesalers. Equations (49) and (50) provide the processing and residual costs respectively at the secondary processing plants.

Constraints for the model N2 comprise of the processing and residual constraints given in equations (10) and (13). Although, the equations (51), (52) and (53) given below can be used in place of equations (10) and (13), when the exact percentages of whole fillet, salmon by-products and residual amounts obtained after processing fresh HOG salmon are known beforehand.

$$TP_{qt}^{e} = 0.7D_{qt}^{c};\ TP_{qt}^{f} = 0.2D_{qt}^{c};\ TW_{qt}^{c} = 0.1D_{qt}^{c} \qquad \forall q \in Q,\ \forall t \in T \qquad (51)-(53)$$

Equations (51) and (52) helps to estimate the total processed amount of whole fillets and salmon by-products obtained after processing fresh HOG salmon at the secondary processing plant. Equation (53) helps to determine the residual amount obtained after processing the total amount of fresh HOG salmon at the secondary processing plant. The model N2 also comprises the supply constraints for secondary processing plants and wholesalers as given below:

$$\sum_{u=1}^{U} X_{qut}^{\delta} \le TP_{qt}^{\delta} \qquad \forall q \in Q,\ \forall t \in T,\ \delta = e, f \qquad (54)-(55)$$

$$\sum_{r=1}^{R} X_{urt}^{c} \le D_{ut}^{c} \qquad \forall u \in U,\ \forall t \in T \qquad (56)$$

Equations (54) and (55) present the supply constraints for whole fillets and salmon by-products at the secondary processing plants. The equations state that the total amount of whole fillets and salmon by-products shipped from a specific secondary processing plant to several wholesalers should be less than or equal to the total processed amount of whole fillets and salmon by-products respectively at the secondary processing plant. Equation (56) states that the number of fresh HOG salmon flowing from a wholesaler to retailers should be less than or equal to the demand of the particular wholesaler for fresh HOG salmon which is met from several primary processing plants. The model N2 has storage capacity constraints given in equations (16), (17), (19) and (20) and these constraints ensure the restriction of storage capacity for whole fillets and salmon by-products at secondary processing plants and wholesalers. Moreover, the storage capacity constraint for fresh HOG salmon at the wholesaler can be expressed as follows:

$$D_{ut}^{c} \le \begin{cases} Cap_{ut}^{c} - IP_{u(t-1)}^{c}, & for\ t > 1 \\ Cap_{ut}^{c}, & for\ t = 1,\ IP_{u0}^{c} = 0 \end{cases} \qquad \forall u \in U,\ \forall t \in T \qquad (57)$$

Equation (57) presents the relationship between the inventory level for fresh HOG salmon at the wholesaler with the capacity of the wholesaler and demand of the wholesaler, which is met from the primary processing plants. The model N2 includes an inventory balancing constraint for fresh HOG salmon at the wholesaler, which can be expressed in the following way,

$$IP_{ut}^{c} = \begin{cases} D_{ut}^{c} + IP_{u(t-1)}^{c} - \sum_{r=1}^{R} X_{urt}^{c}, & for\ t > 1 \\ D_{ut}^{c} - \sum_{r=1}^{R} X_{urt}^{c}, & for\ t = 1 \end{cases} \qquad \forall u \in U,\ \forall t \in T \tag{58}$$

Equation (58) presents the inventory balancing constraint for fresh HOG salmon at the wholesaler considering the demand of the wholesaler which is met from various primary processing plants and the total fresh HOG salmon products shipped to several retailers from the wholesaler. Moreover, equation (58) also takes into consideration the inventory level for fresh HOG salmon products at the wholesaler in the previous time period. The model N2 has other inventory balancing constraints associated with whole fillets and salmon by-products at secondary processing plants and wholesalers. The inventory balancing constraints are given in equations (24), (25), (26) and (27). The model N2 also has demand constraints associated with the demand of retailers for products such as fresh HOG salmon, whole fillets and salmon by-products and these constraints are given in equations (28), (29) and (30). The carbon emissions constraint for the model N2 is expressed as:

$$E^{CO_2} \left[\begin{array}{l} \sum_{q=1}^{Q} \sum_{u=1}^{U} \sum_{t=1}^{T} \left[F_{qu}^{e} X_{qut}^{e} + F_{qu}^{f} X_{qut}^{f} \right] W_{qu} + \sum_{u=1}^{U} \sum_{r=1}^{R} \sum_{t=1}^{T} F_{ur}^{c} W_{ur} X_{urt}^{c} \\ + \sum_{u=1}^{U} \sum_{r=1}^{R} \sum_{t=1}^{T} \left[F_{ur}^{e} X_{urt}^{e} + F_{ur}^{f} X_{urt}^{f} \right] W_{ur} \end{array} \right] \le E^{Max} \tag{59}$$

Equation (59) helps to estimate the carbon emissions incurred for the shipment of whole fillets and salmon by-products from secondary processing plants to retailers via wholesalers. It also determines the carbon emissions incurred for the shipment of fresh HOG salmon from wholesalers to retailers. The model N2 also includes transportation capacity constraints (please refer to Appendix B), which are given in equations (B5), (B6), (B7), (B8) and (B9). Therefore, the objective function of the model N2 is given in equation (45). The constraints of the model N2 are given as equations (16), (17), (19), (20), (24), (25), (26), (27), (28), (29), (30), (B5), (B6), (B7), (B8), (B9), (51), (52), (53), (54), (55), (56), (57), (58) and (59). The validation of the proposed models is conducted by considering the real-world case study of the Norwegian salmon supply chain.

Table 1: Problem instances solved for the validation of the proposed mathematical models

Problem Instances	Size of the Input Data	Number of Variables	Number of Constraints	Computational Time (Sec)	Total cost (Euro)	Fuel cost (Euro)	Residual Cost (Euro)	Inventory Cost (Euro)	Transportation cost (Euro)	Processing cost (Euro)	Carbon emission (Kg CO_2)
Instance 1: 2 SF, 1 SH, 1 PP, 1 SP, 1 W, 2 R, 3 TP; **Solving Model M**	191 data points	93	139	0.18 sec	232,596.77	11,062	10,985	557.77	65,422	144,570	18,866
Instance 2: 2 SF, 1 SH, 1 PP, 1 SP, 1 W, 3 TP; **Solving Model N1**	–	–	–	–	210,983.90	8,680.1	10,755	13.8	49,985	141,550	14,805
Instance 3: 1 SP, 1 W, 2 R, 3 TP; **Solving Model N2**	–	–	–	–	22,911.10	2,395.1	260	1,360	15,476	3,420	4,087
Instance 4: 4 SF, 3 SH, 2 PP, 2 SP, 4 W, 5 R, 3 TP; **Solving Model M**	1,036 data points	441	562	0.23 sec	220,997.70	11,691	10,172	8,302.7	56,922	133,910	19,992
Instance 5: 4 SF, 3 SH, 2 PP, 2 SP, 4 W, 3 TP; **Solving Model N1**	–	–	–	–	260,171.20	10,496	13,429	17.2	59,419	176,810	17,989
Instance 6: 2 SP, 4 W, 5 R, 3 TP; **Solving Model N2**	–	–	–	–	136,772.30	3,949.3	900	105,780	14,263	11,880	6,761.9
Instance 7: 10 SF, 9 SH, 2 PP, 2 SP, 4 W, 5 R, 14 TP; **Solving Model M**	7,346 data points	3,526	4,255	0.95 sec	1,108,618.50	51,102	47,545	125,540	258,580	625,850	88,047
Instance 8: 10 SF, 9 SH, 8 PP, 10 SP, 4 W, 5 R, 14 TP; **Solving Model M**	14,974 data points	7,390	8,427	2.05 sec	1,107,823.93	50,777	47,546	125,560	258,090	625,850	87,457
Instance 9: 10 SF, 9 SH, 8 PP, 10 SP, 8 W, 10 R, 14 TP; **Solving Model M**	24,120 data points	11,646	13,061	5.62 sec	2,205,731.95	96,936	95,091	251,040	510,980	1,251,700	167,000
Instance 10: 30 SF, 9 SH, 8 PP, 10 SP, 8 W, 30 R, 14 TP; **Solving Model M**	44,720 data points	20,886	23,455	254.36 sec	6,617,105.59	285,920	285,270	753,100	1,537,700	3,755,100	492,380
Instance 11: 60 SF, 9 SH, 8 PP, 10 SP, 24 W, 60 R, 14 TP; **Solving Model M**	174,724 data points	82,010	86,897	1246.22 sec	8,745,565.62	894,543	567,453	1,124,543	2,554,432	5,232,455	895,546

SF = Salmon Farms, SH = Slaughterhouse, PP = Primary Processing Plant, SP = Secondary Processing Plant, W = Wholesaler, R = Retailer, TP = Time Period

5. Results and Discussion

This section presents the comparative analysis of results obtained after solving the proposed mathematical models M, N1 and N2. Computational experiments are conducted on IBM ILOG CPLEX version 12.5 optimization studio software having 8GB RAM with Intel Core i7 1.8 GHz processor and 64-bit Windows 10 operating system. Problem instances are considered for solving the proposed model and establishing its validity and robustness. Moreover, a real-world supply chain problem of a Norwegian Salmon Exporter company, which specializes in the processing, and transportation of Norwegian Salmon products, is considered for validation and sensitivity analysis related to demand variation and transportation scenarios.

5.1. Model Validation for Various Problem Instances

For solving various problem instances, the simulated dataset related to the parameters of the mathematical models is based on primary data collected for the Norwegian salmon supply chain. Table 1 presents various problem instances and the cost components and overall carbon emissions incurred. Problem instances are solved using mathematical models M, N1 and N2 which highlight the validation of the proposed models in adapting to different supply chain networks. Figures C1, C2 and C3 (refer to Appendix C) give the visual illustration of the supply chain network for time periods 1, 2 and 3 respectively. Figures C1, C2 and C3 (refer to Appendix C) also provide the necessary information about the number of products shipped from one stakeholder to another. The figures present insights regarding processing and residuals amounts for various salmon products obtained in different time periods. Furthermore, the mathematical model M is tested on large problem instances such as instances 7, 8, 9 and 10. Moreover, their respective results are also presented in Table 1. The large input datasets considered for problem instances and moreover, the high number of constraints and decision variables highlight the computational complexity. This is typical, however, of contemporary food supply chains.

5.2. Real-World Case Study and Data Collection

The real-world problem considered in this research is the Norwegian salmon supply chain, drawing on evidence supplied by a large salmon processing and exporting organisation. The latter's supply chain network consists of several elements including 24 salmon farms, a packing station which performs the role of a slaughterhouse and primary processing plant, one secondary processing plant, 10 wholesalers and six retailers. The 24 salmon farms are categorised into five clusters based on their average distance to the slaughterhouse. Cluster 1 includes five salmon farms, cluster 2 comprises of seven salmon farms, cluster 3 consists of three salmon farms, cluster 4 includes two salmon farms and cluster 5 comprises of seven salmon farms. Average distances from cluster 1, cluster 2, cluster 3, cluster 4 and cluster 5 to the slaughterhouse are around 19.60 km, 25.30 km, 17.90 km, 58.30 km and 148.70 km respectively. The combined daily supply of live salmon from cluster 1, cluster 2, cluster 3, cluster 4 and cluster 5 to the slaughterhouse is around 140 tonnes per day. Cluster 1 tries to meet 50 percent of the daily supply of the packing station, which is around 70 tonnes per day, and cluster 2 meets around 40 percent of the daily supply of the packing station, which is around 56 tonnes per day. Clusters 3, 4 and 5 meet around 5%, 2.5% and 2.5% respectively of the overall daily supply for the packing station, equivalent to around 7 tonnes per day, 3.5 tonnes per day and 3.5 tonnes per day respectively. Only boats are used to transport live salmon from the salmon farms to the slaughterhouse and they have a capacity of between 150 and 300 tonnes per day. The transportation cost of per unit live salmon product from clusters to the slaughterhouse lies in the range of (0.05 – 0.1) Euro per kg.

Live salmon are processed at the slaughterhouse and HOG fish and residuals are obtained. After processing the live salmon, 87 – 90% is in the form a HOG product and the remaining 10 – 13% is residual. The processing cost for obtaining the HOG product lies within the range of €0.3 – 0.35 per kg. Moreover, the cost associated with obtaining the residual amount after processing the live salmon is €0.2 – 0.25 per kg. The daily maximum storage capacity of the slaughterhouse for HOG fish is 140 tonnes per day. As the primary processing plant is also located at the packing station alongside the slaughterhouse, HOG salmon obtained after processing are sent to the primary processing plant, which incurs a negligible transportation, and thus fuel, cost. The HOG processed at the primary processing plant results in 87-90% fresh HOG product, with the remainder a residual. Inventory holding at the slaughterhouse and primary processing plant is negligible. The maximum storage capacity of the primary processing plant for fresh HOG salmon is around 140 tonnes per day.

The fresh HOG products from the primary processing plant are shipped to a secondary processing plant in the Netherlands and wholesalers. A maximum of 90 to 95% is shipped to wholesalers on the European market and the remainder goes to the secondary processing plant. Fresh HOG salmon are shipped from the primary to secondary processing plants using multiple transportation modes. Frist they are transported by truck to Stavanger port in Norway (147km), where they go by ferry to Hirtshals in Denmark (350km) and then on to the Netherlands by truck (a further 906 km). The distance from the packing station to Stavanger port is around 147 km. The fresh hog products are then shipped from Stavanger in Norway to Hirtshals in Denmark via ferry (maritime transportation) and the distance from Stavanger port to Hirtshals is around 350 km. Then from Hirtshals in Denmark, the fresh HOG products are shipped to the secondary processing plant in the Netherlands by truck, a distance of around 906 km. The overall distance between the primary processing plant and the secondary processing plant is thus approximately 1403 km, with a transportation cost of between €0.1 and €0.2 per kg.

Fresh HOG salmon are transported via truck, boat and air freight from the primary processing plant to 10 wholesalers in various European cities such as Dusseldorf, Frankfurt, Munich, Copenhagen, The Hague, Rotterdam, Brussels, Luxembourg, Rome and Athens. Some European cities receive the fresh HOG products from Amsterdam airport after the products come from the primary processing plant to Amsterdam airport via the secondary processing plant and the distance from the primary processing plant to Schipol airport is around 1497 km. The distances from the primary processing plant to the 10 wholesalers in Dusseldorf, 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. Transportation costs for the shipment of fresh HOG product from the primary processing plant to the wholesalers in European cities is around €0.1 – €0.2 per kg. Moreover, some of the processed salmon products obtained at the secondary processing plant are also shipped to wholesalers in European cities. Whole fillets and salmon by-products are obtained after processing fresh HOG salmon at the secondary processing plants. After processing fresh HOG, 66% of the product is obtained as whole fillets, 33% of the product as salmon-by products and the remaining 1% as a residual. The processing and residual cost incurred at the secondary processing plant is €1.5 per kg for whole fillets, salmon by-products and residual. From the secondary processing plant, the whole fillets and salmon by-products are shipped to the various wholesalers in different European cites. The distance from the secondary processing plant to 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. Data on fuel consumption and carbon emissions derive in part from Soysal, Bloemhof-Ruwaard, and van der Vorst (2014). From the 10 wholesalers, salmon products are distributed to retailers. The fuel price is assumed to be between €1.1 and €1.5 per litre. The fuel consumption rate for a typical 12 tonne delivery truck is around 21.4 litres per 100 km (Delgado, Rodríguez, & Muncrief, 2017). The carbon emission coefficient is 2.392 kg CO_2 per litre.

5.3. Computational Experimental Setting for the Real-World Case Study

The real-world problem instance associated with the Norwegian salmon supply chain network is solved using the mathematical model N1. The first and second experiments aim to solve the model N1 for the real-world problem instance of Norwegian salmon supply chain networks comprising the following stakeholders – salmon farms, slaughterhouse, primary processing plant, secondary processing plant and wholesaler. The primary intention for using model N1 is to address the operational tendency of the organization where it only aims to meet the demand of wholesalers and the secondary processing plant. The first experiment tries to solve model N1 for the revised Norwegian salmon supply chain network without considering the fuel cost component of the objective function given in equation (34) and the carbon emissions constraint presented in equation (44). The output of the first experiment is used in equation (34) for obtaining the overall fuel cost and it is also used in equation (60) given below for obtaining the overall carbon emissions for the revised Norwegian salmon supply chain network comprising of salmon farms, slaughterhouse, primary processing plant, secondary processing plant and wholesaler. The second experiment considers the fuel cost component in the objective function given in equation (34) and integrates the carbon emissions constraint presented in equation (44) while solving the model N1 for the revised Norwegian salmon supply chain network. The output of the second experiment is used to obtain carbon emissions, using equation (60). The total cost, fuel cost and carbon emissions obtained for the fourth experiment is compared with that of the third experiment.

$$CE = E^{CO_2}\left[\begin{array}{l}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T}F_{ij}^{a}W_{ij}X_{ijt}^{a}+\sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{t=1}^{T}F_{jp}^{b}W_{jp}X_{jpt}^{b}+\sum_{p=1}^{P}\sum_{q=1}^{Q}\sum_{t=1}^{T}F_{pq}^{c}W_{pq}X_{pqt}^{c}\\+\sum_{p=1}^{P}\sum_{u=1}^{U}\sum_{t=1}^{T}F_{pu}^{c}W_{pu}X_{put}^{c}\end{array}\right] \tag{60}$$

The third and fourth experiments aim to solve the model N2 for the real-world problem instance of the Norwegian salmon supply chain network where the organization only aims to meet the demand of retailers from the wholesalers and secondary processing plants. The third experiment aims to solve model N2 without considering the fuel cost equation (47) in the objective function and also without considering the carbon emissions constraint (59). The output of the third experiment obtained after solving the model N2 is used to determine the fuel cost using equation (47) and the overall carbon emissions using equation (61) given below. The fourth experiment aims to solve model N2 while considering the fuel cost component within the objective function and the carbon emissions constraint. The output obtained from the fourth experiment is used to obtain carbon emissions using equation (61). The total cost, fuel cost and carbon emissions incurred for the fourth experiment are compared with that of the third experiment. Table 2 provides in-depth information about each experiment and also the values of the cost components obtained after performing the experiments.

$$CE = E^{CO_2}\left[\begin{array}{l}\sum_{q=1}^{Q}\sum_{u=1}^{U}\sum_{t=1}^{T}\left[F_{qu}^{e}X_{qut}^{e}+F_{qu}^{f}X_{qut}^{f}\right]W_{qu}+\sum_{u=1}^{U}\sum_{r=1}^{R}\sum_{t=1}^{T}F_{ur}^{c}W_{ur}X_{urt}^{c}\\+\sum_{u=1}^{U}\sum_{r=1}^{R}\sum_{t=1}^{T}\left[F_{ur}^{e}X_{urt}^{e}+F_{ur}^{f}X_{urt}^{f}\right]W_{ur}\end{array}\right] \tag{61}$$

Finally, the real-world problem instance related to Norwegian salmon supply chain network is solved using the mathematical model M presented in section 4. Solving the real-world problem instance using model M highlights the ways the Norwegian salmon supply chain network reacts when different stakeholders collaborate with each other and aim to reduce optimally overall operational and transportation costs. The fifth experiment aims to optimize the overall Norwegian salmon supply chain network comprising of all the stakeholders including salmon farms, slaughterhouse, primary processing plant, secondary processing plant, wholesaler and retailer. The fifth experiment solves the Model M without considering the fuel cost component given in equation (3) in the objective function and carbon emissions constraint given in equation (31). The output obtained from the fifth experiment is used to obtain the fuel cost by employing equation (3). Moreover, the output of the fifth experiment is also used to obtain the overall carbon emissions (where CE denotes carbon emissions) by using equation (62) given below. The sixth experiment considers the fuel cost equation (3) in the objective function and carbon emissions constraint (31) while optimizing model M related to the salmon supply chain network comprised of all stakeholders. The output of the sixth experiment is used to obtain the carbon emissions from equation (62). The overall cost, fuel cost and carbon emissions obtained for the second experiment is compared with that of the first experiment.

$$CE = E^{CO_2}\left[\begin{array}{l} \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} F_{ij}^{a} W_{ij} X_{ijt}^{a} + \sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{t=1}^{T} F_{jp}^{b} W_{jp} X_{jpt}^{b} + \sum_{p=1}^{P}\sum_{q=1}^{Q}\sum_{t=1}^{T} F_{pq}^{c} W_{pq} X_{pqt}^{c} \\ + \sum_{q=1}^{Q}\sum_{u=1}^{U}\sum_{t=1}^{T}\left[F_{qu}^{e} X_{qut}^{e} + F_{qu}^{f} X_{qut}^{f}\right] W_{qu} + \sum_{p=1}^{P}\sum_{u=1}^{U}\sum_{t=1}^{T} F_{pu}^{c} W_{pu} X_{put}^{c} \\ + \sum_{u=1}^{U}\sum_{r=1}^{R}\sum_{t=1}^{T}\left[F_{ur}^{e} X_{urt}^{e} + F_{ur}^{f} X_{urt}^{f}\right] W_{ur} + \sum_{u=1}^{U}\sum_{r=1}^{R}\sum_{t=1}^{T} F_{ur}^{c} W_{ur} X_{urt}^{c} \end{array}\right] \tag{62}$$

Table 2: Cost components for different experiments performed considering various models

Experiment	Solving procedure	Total cost (Euro)	Fuel cost (Euro)	Residual Cost (Euro)	Inventory Cost (Euro)	Transportation cost (Euro)	Processing cost (Euro)
Experiment 1	Solving Model N1 (without Fuel cost parameter and Carbon emissions constraint)	334,356.00	17,668	16,689	–	80,129	219,870
Experiment 2	Solving Model N1 (considering Fuel cost parameter and Carbon emissions constraint)	334,353.00	17,665	16,689	–	80,129	219,870
Experiment 3	Solving Model N2 (without Fuel cost parameter and Carbon emissions constraint)	111,388.60	8,200.6	640	72,585	21,503	8,460
Experiment 4	Solving Model N2 (with Fuel cost parameter and Carbon emissions constraint)	107,423.90	4,235.9	640	72,585	21,503	8,460
Experiment 5	Solving Model M (without Fuel cost parameter and Carbon emissions constraint)	315,569.18	22,434	14,318	755.18	88,322	189,740
Experiment 6	Solving Model M (with fuel cost parameter and Carbon emissions constraint)	310,351.18	17,216	14,318	755.18	88,322	189,740

5.4. Carbon Emissions along the Supply Chain Network

The real-world problem instance is considered for three time periods where each period is equivalent to a day. The demand associated with the six retailers considered for solving model M and N2 are generated within the range of (10 – 16) tonnes for fresh HOG salmon, (0.8 – 1.4) tonnes for whole fillets and (0.2 – 0.4) tonnes of salmon by-products. For solving model N1, the demand related to the secondary processing plants for fresh HOG salmon is considered in the range of 8 to 12 tonnes and the demand associated with 10 wholesalers for fresh HOG salmon are also considered within the range of (8 to 12 tonnes. After performing experiments 1 and 2 related to model N1, Table 2 presents the transportation, fuel, residual, and processing costs obtained. It must be noted that when the fuel cost component and carbon emissions constraints are not considered while solving model N1, then the total cost incurred for experiment 1 is higher when compared against experiment 2. Moreover, from Tables 2 and 3, it is evident that the fuel cost and carbon emissions incurred for experiment 1 is slightly more than that of experiment 2. The carbon emissions and fuel cost incurred in experiment 1 are 30,147.46

Kg CO_2 and €17,668 respectively and the carbon emissions and fuel cost incurred for experiment 2 are 30,142.53 Kg CO_2 and €17,665 respectively. The carbon emissions incurred for the shipment of live salmon from salmon farms to the slaughterhouse for experiments 1 and 2 are around 452.06 Kg CO_2 and 447.13 Kg CO_2 respectively.

The results thus provide actionable insights for food supply chain managers regarding how to reduce fuel costs and carbon emissions, which are important financial and sustainability related aspects relating to logistics management. Food supply chain managers should embrace monitoring and decision-making procedures that allow for the joint optimization of fuel costs, carbon emissions and total costs, as the model gives superior results when performing experiment 2. Table 3 presents the carbon emissions incurred while solving model N1 for experiments 1 and 2. The carbon emissions obtained after performing experiment 2 include 447.13 Kg CO_2 incurred from the shipment of live salmon from twenty-four salmon farms to the slaughterhouse. Moreover, the carbon emissions incurred for the shipment fresh HOG salmon from the primary to the secondary processing plant is around 1,795.4 Kg CO_2. Finally, transportation of fresh HOG salmon products from primary processing plants to wholesalers located in 10 European cities also incurs substantial carbon emissions (27,900 Kg CO_2).

Experiments 3 and 4 are performed on the real-world problem instance using the mathematical model N2. Table 2 details the transportation, inventory, fuel, processing and residual costs. As evident from Table 2, the total and fuel costs incurred for experiment 3 are higher than that for experiment 4. Table 4 provides useful information for food supply chain managers regarding the carbon emissions incurred for the shipment of products from one stakeholder to another, with the level of carbon emissions incurred in experiment 3 higher than that of experiment 4. This reflects that when performing experiment 3, fuel cost components and the carbon emissions constraint are not considered within the mathematical model N2. Therefore, for experiment 3, the model parameters related to the distances between stakeholders (which helps to estimate fuel consumption, fuel cost and carbon emissions) are not taken into consideration when obtaining an optimal result related to total cost. Only transportation cost per unit product, inventory cost per unit product and processing and residual cost per unit product are considered for obtaining optimal results in experiment 3. Although, for experiment 4, the optimal result is obtained while considering the distances between stakeholders, which plays a significant role in reducing the fuel cost as well as carbon emissions. Fuel costs and carbon emissions incurred for experiment 3 are €8,200.6 and 13,877.28 Kg CO_2 respectively, whereas for experiment 4, the fuel cost and carbon emission incurred are much less and they are around €4,235.9 and 7,189.37 Kg CO_2 respectively. It is also observed in Table 4 that, for experiment 4 the carbon emissions incurred for the shipment of fresh HOG salmon products from ten wholesalers to six retailers is around 6,234.8 Kg CO_2 and it is significantly less when compared to that of the carbon emissions incurred for experiment 3 which is around 12,191 Kg CO_2. Optimizing model N2, while considering the fuel cost and carbon emissions constraints reduces total carbon emissions incurred for the shipment of whole fillets, salmon by-products and fresh HOG salmon products from wholesalers and retailers from 13,430 Kg CO_2 to

6,855.3 Kg CO_2. Comparing the results of experiments 3 and 4 highlights that it is important to consider sustainability aspects related to fuel cost and carbon emissions while optimizing overall supply chain network.

Experiments 5 and 6 relate to solving model M, which considers the scenario where all the stakeholders such as salmon farms, slaughterhouse, primary processing plants, secondary processing plants, wholesalers and retailers collaborate with each other to optimize total cost. Experiment 5 aims to solve the model M without considering the fuel cost parameters and carbon emissions constraint. In contrast, experiment 6 accounts for the latter two considerations. Table 2 presents the value of the cost components obtained after performing experiments 5 and 6. Table 2 details that the fuel and total costs incurred for experiment 5 are much higher than that for experiment 6. Table 5 provides the necessary information regarding the carbon emissions incurred for the shipment of salmon products from one stakeholder to another. Total carbon emissions, fuel costs and total costs are much higher in the case of experiment 5 compared to experiment 6, reflecting that fuel cost parameters and carbon emissions constraints are taken into consideration, in the latter case, for solving model M. For experiment 6, the optimal decisions depend on some important parameters such as fuel cost, distances between stakeholders, and transportation costs.

Table 3: Carbon emission incurred after solving model N1 for the real-world problem instance

Experiment	Solving procedure	Carbon emission (Kg CO_2)	Carbon Emission from SF to SH (Kg CO_2)	Carbon Emission from PPP to SPP (Kg CO_2)	Carbon Emission from PPP to W (Kg CO_2)
Experiment 1	Solving Model N1 (without Fuel cost parameter and Carbon emission constraint)	30,147.46	452.06	1,795.4	27,900
Experiment 2	Solving Model N1 (considering Fuel cost parameter and Carbon emission constraint)	30,142.53	447.13	1,795.4	27,900
SF = Salmon Farms, SH = Slaughterhouse, PPP = Primary Processing Plant, SPP = Secondary Processing Plant, W = Wholesaler					

5.5. Results associated with the Real-World Problem

The results related to experiment 6 are presented in this sub-section which also provides an insight into the various types of salmon products shipped from one stakeholder to another in different time periods. Table 6 presents the values associated with the shipment of live salmon (in kg) from 24 salmon farms which are categorised into five clusters to the slaughterhouse at the packing station. Tables 6 and 7 provide useful information for food supply chain managers regarding the product amount shipped via various transportation links during different time periods. The total amount of HOG salmon obtained in different time periods after processing live salmon at the slaughterhouse is detailed in Table 6. Table 7 provides valuable information for managers regarding the amount of fresh HOG salmon and residuals obtained after processing at the primary processing plant and shipped amounts to wholesalers in different time periods. Furthermore, Table 7 informs food supply chain managers about the amount of whole fillets and salmon by-products transported from the secondary processing plant to different wholesalers in various time periods. Moreover, Tables 8 and 9 provide information for managers about the shipped amount of fresh HOG, whole fillets, and salmon by-products from ten wholesalers to six retailers. Maximum shipment capacity related to fresh HOG salmon, whole fillets and salmon by-products for the transportation links from secondary processing plants to wholesalers and from wholesalers to retailers is considered as 3 metric tonnes. Tables 8 and 9 also provide useful information to food supply chain managers relating to the specific wholesalers, which are responsible for meeting the demand of each retailer in different time periods. For example, food supply chain managers need to be mindful of the fact that the demand for fresh HOG salmon in different time periods for retailer 6 is met by wholesalers 2, 6, 7, 8 and 9, while the demand for fresh HOG salmon in different time periods for retailer 2 is met by wholesalers 1, 2, 3, 4 and 5. The results also provide useful managerial implications pertaining to the model parameters, such as the distance between stakeholders and transportation costs from wholesalers and retailers, which determine which wholesalers should meet the demand of the retailers. Furthermore, Table 9 highlights useful information for food supply chain managers such as the majority of whole fillets and salmon by-products being sent from the secondary processing plant to wholesalers 1, 3, 4, 5, 6 and 8. This reflects that these wholesalers are nearest in terms of distance to the secondary processing plant. These wholesalers meet most of the demand for whole fillets and salmon by-products for the six retailers in different time periods.

Table 4: Carbon emission incurred after solving model N2 for the real-world problem instance

Experiment	Solving procedure	Carbon emissions (Kg CO_2)	Carbon Emissions from SPP to W (Kg CO_2)	Carbon Emissions from W to R for FH (Kg CO_2)	Carbon Emissions from W to R for WF and SB (Kg CO_2)	Total Carbon Emissions from W to R (Kg CO_2)
Experiment 3	Model N2 (without Fuel cost parameter and Carbon emissions constraint)	13,877.28	447.38	12,191	1,238.9	13,430
Experiment 4	Model N2 (with Fuel cost parameter and Carbon emissions constraint)	7,189.37	334.12	6,234.8	620.45	6,855.3
SPP = Secondary Processing Plant, W = Wholesaler, R = Retailer, FH = Fresh Hog, WF = Whole Fillet, SB = Salmon By-product						

Table 5: Carbon emissions incurred after solving model M for the real-world problem instance

Experiment	Solving procedure	Carbon emissions (Kg CO_2)	Carbon Emissions from SF to SH (Kg CO_2)	Carbon Emissions from PPP to SPP (Kg CO_2)	Carbon Emissions from PPP to W (Kg CO_2)	Carbon Emissions from SPP to W (Kg CO_2)	Carbon Emissions from W to R (Kg CO_2)
Experiment 5	Model M (without Fuel cost parameter and Carbon emissions constraint)	38,104.45	376.04	1,692.9	22,665	427.51	12,943
Experiment 6	Model M (with fuel cost parameter and Carbon emissions constraint)	29,265.25	365.13	1,692.9	19,034	334.12	7,839.1
SF = Salmon Farms, SH = Slaughterhouse, PPP = Primary Processing Plant, SPP = Secondary Processing Plant, W = Wholesaler, R = Retailer							

Table 6: Transported amount of Live Salmon (in Kg) from Salmon Farms to Slaughterhouse and transported amount of Fresh HOG (in Kg) from Primary Processing Plant to Secondary Processing Plant

	Slaughterhouse at Packing Station		
	Time period 1	Time period 2	Time period 3
Salmon Farm 1	70,000	70,000	70,000
Salmon Farm 2	56,000	–	38,576
Salmon Farm 3	7,000	7,000	7,000
Salmon Farm 4	3,500	–	3,500
Salmon Farm 5	3,500	1,519	3,500
Processed amount of Hog	126,000	70,667.1	110,318.4
Residual amount	14,000	7,851.9	12,257.6

	Secondary Processing Plant (Netherlands)		
	Time period 1	Time period 2	Time period 3
Primary Processing Plant at Packing Station	9,000	9,000	10,286
Processed amount of Whole Fillet	6,300	6,300	7,200.2
Processed amount of Salmon By-product	1,800	1,800	2057.2
Residual amount	900	900	1028.6

Table 7: Transported amount of Fresh HOG salmon (in Kg) from Primary Processing Plant to Wholesalers and shipment of Whole fillet and Salmon by-product from Secondary processing plant to Wholesalers

	Primary Processing Plant at Packing Station		
	Time period 1	Time period 2	Time period 3
Processed amount of Fresh HOG	113,400	63,600.3	99,286.2
Residual amount	12,600	7,066.7	11,031.8
Wholesaler 1	13,500	13,500	13,500
Wholesaler 2	11,500	11,500	13,500
Wholesaler 3	5,000	8,000	9,000
Wholesaler 4	–	6,000	5,500
Wholesaler 5	13,500	13,500	13,500
Wholesaler 6	9,000	9,000	9,000
Wholesaler 7	6,500	9,000	10,000
Wholesaler 8	12,000	12,000	12,000
Wholesaler 9	3,000	3,000	3,000
Wholesaler 10	–	–	–

	Secondary Processing Plant (Netherlands)					
	Whole Fillet			Salmon by-product		
	Time period 1	Time period 2	Time period 3	Time period 1	Time period 2	Time period 3
Wholesaler 1	800	1,200	–	–	–	–
Wholesaler 2	–	–	–	–	–	–
Wholesaler 3	–	–	3,000	–	–	450
Wholesaler 4	–	–	1,200	–	–	–
Wholesaler 5	3,000	3,000	–	1,350	1,000	–
Wholesaler 6	2,500	2,100	–	450	450	–
Wholesaler 7	–	–	–	–	–	–
Wholesaler 8	–	–	3,000	–	–	1250
Wholesaler 9	–	–	–	–	–	–
Wholesaler 10	–	–	–	–	–	–

Table 8: Shipped amount of Fresh HOG product from wholesalers to retailers in different time periods

	Retailer 1			Retailer 2			Retailer 3			Retailer 4			Retailer 5			Retailer 6		
	Time Period 1	Time Period 2	Time Period 3	Time Period 1	Time Period 2	Time Period 3	Time Period 1	Time Period 2	Time Period 3	Time Period 1	Time Period 2	Time Period 3	Time Period 1	Time Period 2	Time Period 3	Time Period 1	Time Period 2	Time Period 3
Wholesaler 1	3,000	3,000	3,000	3,000	3,000	1,500	3,000	3,000	3,000	1,500	1,500	3,000	3,000	3,000	3,000	–	–	–
Wholesaler 2	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	–	2,500	–	500	–	1,500	2,000	–	3,000
Wholesaler 3	2,000	3,000	3,000	3,000	3,000	3,000	–	2,000	3,000	–	–	–	–	–	–	–	–	–
Wholesaler 4	0	3,000	3,000	0	3,000	2,500	–	–	–	–	–	–	–	–	–	–	–	–
Wholesaler 5	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	1,500	1,000	1,500	–	–	–
Wholesaler 6	–	–	–	–	–	–	–	–	–	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000
Wholesaler 7	–	–	1,000	–	–	–	–	–	–	500	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000
Wholesaler 8	–	–	–	–	–	–	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000
Wholesaler 9	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	3,000	3,000	3,000
Wholesaler 10	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–

Table 9: Shipped amount of Whole fillets (WB) and Salmon by-products (SB) from wholesalers to retailers in different time periods

WF = Whole Fillet SB = Salmon By-product		Retailer 1			Retailer 2			Retailer 3			Retailer 4			Retailer 5			Retailer 6		
		Time Period 1	Time Period 2	Time Period 3	Time Period 1	Time Period 2	Time Period 3	Time Period 1	Time Period 2	Time Period 3	Time Period 1	Time Period 2	Time Period 3	Time Period 1	Time Period 2	Time Period 3	Time Period 1	Time Period 2	Time Period 3
Wholesaler 1	WF	800	1,200	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	SB	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Wholesaler 2	WF	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	SB	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Wholesaler 3	WF	–	–	600	–	–	1,100	–	–	1,300	–	–	–	–	–	–	–	–	–
	SB	–	–	200	–	–	250	–	–	–	–	–	–	–	–	–	–	–	–
Wholesaler 4	WF	–	–	700	–	–	–	–	–	–	–	–	500	–	–	–	–	–	–
	SB	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Wholesaler 5	WF	–	–	–	1,000	1,200	–	1,100	900	–	800	1000	–	–	–	–	–	–	–
	SB	400	300	–	200	300	–	400	200	–	350	200	–	–	–	–	–	–	–
Wholesaler 6	WF	–	–	–	–	–	–	–	–	–	400	–	–	900	1,300	–	1,200	800	–
	SB	–	–	–	–	–	–	–	–	–	–	–	–	200	250	–	250	200	–
Wholesaler 7	WF	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	SB	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Wholesaler 8	WF	–	–	–	–	–	–	–	–	–	–	–	600	–	–	1,100	–	–	1,300
	SB	–	–	–	–	–	–	–	–	250	–	–	300	–	–	300	–	–	400
Wholesaler 9	WF	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	SB	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Wholesaler 10	WF	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	SB	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–

5.6. Sensitivity Analysis relating to Variations in Demand

Sensitivity analysis is performed on experiment 6 by varying the demand of retailers in various time periods and tracking the effects on the supply chain network. Table 10 presents four different demand scenarios, their respective cost components, and the percentage change in the cost component when compared with the results of the baseline scenario (values also mentioned in Table 2). Demand scenario 1 entails the demand for fresh HOG salmon for retailers 1, 2, 3 and 4 decreasing by 50% in time period 3 (equivalent to day 3). For demand scenario 2, the demand for fresh HOG salmon from retailers 1, 2, 3 and 4 increases by 50% in time period 3. Demand scenario 3 involves a 75% increase in the demand for fresh HOG salmon for retailers 1, 2 and 3 in time period 2 and a 50% decrease in demand for fresh HOG salmon products for retailers 4, 5 and 6 in time period 1. For demand scenario 4, the demand for fresh HOG salmon for retailers 1, 2 and 3 decreases by 75% in time period 2 and the demand for the same product from retailers 4, 5 and 6 increases by 50% in time period 1. Table 10 provides the results associated with the demand variations and presents the cost components and carbon emissions incurred for various demand scenarios. The table also presents information about the change in cost components when compared against the baseline scenario (expressed as % increase or decrease).

Table 10: Effect of demand variation on cost components and carbon emissions

	Baseline Scenario	Demand Scenario 1	Demand Scenario 2	Demand Scenario 3	Demand Scenario 4
Total cost (Euro)	310,351.18	276,157.18	345,910.18	328,121.18	295,205.18
Change in Total cost (%)	–	– 11.01%	11.45%	5.72%	– 4.88%
Fuel cost (Euro)	17,216	15,068	20,028	19,040	16,763
Change in Fuel cost (%)	–	– 12.47%	16.33%	10.59%	– 2.63%
Transportation cost (Euro)	88,322	76,350	99,894	93,506	83,602
Change in Transportation cost (%)	–	– 13.55%	13.10%	5.86%	– 5.34%
Inventory cost (Euro)	755.18	755.18	755.18	755.18	755.18
Change in Inventory cost (%)	–	–	–	–	–
Processing cost (Euro)	189,740	171,050	209,420	199,710	180,500
Change in Processing cost (%)	–	– 9.85%	10.37%	5.25%	– 4.86%
Residual Cost (Euro)	14,318	12,934	15,813	15,110	13,585
Change in Residual cost (%)	–	– 9.66%	10.44%	5.53%	– 5.11%
Total Carbon Emission (Kg CO_2)	29,265.25	25,840.54	33,751.87	32,212.26	28,700.98
Change in Carbon Emission (%)	–	– 11.70%	15.33%	10.08%	– 1.92%

The results presented in Table 10 generate useful insights for managers, highlighting that the inventory costs remain the same for all demand scenarios, as when demand decreases, the organization procures less from salmon farms. Food supply chain managers should be mindful of the fact that when demand for fresh HOG salmon increases, processing and residual costs rise as more salmon need to be processed at the slaughterhouse and the primary processing plant. Moreover, the per unit processing cost is greater. Furthermore, the modelling helps food supply chain managers understand how increases in demand relate to rises in transportation costs, including increased fuel costs and carbon emissions. The sensitivity analysis also highlights the robustness of the mathematical model in dealing with demand variations during different time periods, which can be useful for food supply chain managers for modelling and addressing demand fluctuations. The mathematical formulation adapts to changes in demand and accordingly designs the supply chain network, optimizes the cost component and obtains the best possible solution in terms of the values of the decision variables related to shipments between various stakeholders. For certain scenarios, when demand reduces or increases significantly in particular time periods, the mathematical model quickly adjusts itself to obtain the optimal solution. This also highlights the effectiveness of the proposed model in dealing with multiple variations in demand.

5.7. Transportation Scenario Analysis

Transportation scenario analysis is performed by considering various maritime routes for the shipment of salmon products. The routes considered in this study include the truck transportation route from the primary processing plant to Stavanger port for the shipment of live salmon and maritime transportation from Stavanger to Amsterdam port. The distance between Stavanger and Amsterdam ports is around 391 nautical miles or approximately 724 km. Moreover, the distance from the port of Amsterdam to the secondary processing plant is around 83 km. So, the total distance from the primary to secondary processing plant is 954 km.

Additionally, other maritime routes are taken into consideration for transportation from the primary processing plant to 10 wholesalers in different European cities. The shipment of fresh HOG fish from the primary processing plant to Dusseldorf includes truck transportation from the primary processing plant to Stavanger and then maritime transportation from Stavanger to Dusseldorf ports (distance between two ports of 554 nautical miles or 1,026 km). Therefore, the distance from the primary processing plant to the wholesaler in Dusseldorf is 1,173 km. The movement of fresh HOG salmon from the primary processing plant to wholesalers in Munich, The Hague and Luxembourg includes road transportation from the primary processing plant to Stavanger, maritime transportation from Stavanger to Amsterdam port and finally road transportation from Amsterdam to wholesalers in Munich, The Hague and Luxembourg via the secondary processing plant. Therefore, the total distance from the primary processing plant to wholesalers in Munich, The Hague and Luxembourg are 1,754 km 1091 km and 1364 km. Now, the shipment of fresh HOG salmon from the primary processing plant to wholesalers in Copenhagen, Rotterdam and Brussels includes the maritime transportation routes from

Stavanger to Copenhagen, Rotterdam Brussels ports respectively and their distances are 444 nautical miles, 490 nautical miles and 574 nautical miles respectively. Therefore, the total distance from the primary processing plant to wholesalers in Copenhagen, Rotterdam and Brussels are 969 km, 1054 km and 1210 km respectively. The shipment of fresh HOG salmon from the primary processing plant to wholesalers in Rome and Athens includes road and maritime transportation from the primary processing plant to Amsterdam via Stavanger and finally air transportation from Amsterdam to wholesalers in Rome and Athens. Therefore, the distance from the primary processing plant to wholesalers in Rome and Athens are 2604 km and 3824 km respectively. For performing the transportation scenario analysis, the total distances considered from the primary processing plant to ten wholesalers in Dusseldorf, Frankfurt, Munich, Copenhagen, The Hague, Rotterdam, Brussels, Luxembourg, Rome and Athens are: 1,173 km, 1,545 km, 1,754 km, 969 km, 1,091 km, 1054 km, 1210 km, 1364 km, 2604 km and 3824 km respectively. The distances from the secondary processing plant to the ten wholesalers remains the same and moreover, the distances from the ten wholesalers to six retailers also remain unchanged.

Table 11: Analysis of transportation scenarios on cost components and carbon emission

	Baseline Scenario	Transportation Scenario 1	Transportation Scenario 2	Transportation Scenario 3
Total cost (Euro)	310,351.18	310,033.18	306,990.18	306,672.18
Change in Total cost (%)	–	0.10% (decrease)	1.08% (decrease)	1.18% (decrease)
Fuel cost (Euro)	17,216	16,898	13,855	13,537
Change in Fuel cost (%)	–	1.84% (decrease)	19.52% (decrease)	21.36% (decrease)
Transportation cost (Euro)	88,322	88,322	88,322	88,322
Change in Transportation cost (%)	–	–	–	–
Processing cost (Euro)	189,740	189,740	189,740	189,740
Change in Processing cost (%)	–	–	–	–
Total Carbon Emissions (Kg CO_2)	29,265.25	28,723.45	23,546.55	23,004.75
Change in Carbon Emissions (%)	–	1.85% (decrease)	19.54% (decrease)	21.39% (decrease)

Three transportation scenarios consider the impact of maritime transportation routes on total costs and fuel costs as well as carbon emissions. Transportation scenario 1 considers the maritime transportation route from Stavanger to Amsterdam ports, while shipping fresh HOG salmon from the primary to the secondary processing plant. Transportation scenario 2 considers several maritime transportation routes while shipping fresh HOG salmon from the primary processing plant to ten wholesalers at various European cities. Transportation scenario 3 takes into account the maritime transportation route while shipping products from the primary to the secondary processing plant. It also considers the other maritime transportation routes from the primary processing plant to various wholesalers. Tables 11 and 12 provide the detailed results related to the cost components and the total carbon emissions incurred for various transportation scenarios. The results of the three transportation scenarios are compared with that of the baseline scenario and the percentage changes in the value of cost components and carbon emissions detailed.

Table 12 presents useful information for food supply chain managers regarding the carbon emissions generated from transportation between various stakeholders. Of particular importance for managers are the lessons of Tables 11 and 12 regarding how the adoption of maritime routes reduces overall costs as well as fuel costs. A substantial decrease in fuel costs and carbon emissions for transportation scenarios 2 and 3, which adopt maritime routes, is apparent, for the shipment of fresh HOG salmon from the primary processing plant to wholesalers. Specifically, adopting maritime transportation routes (transportation scenario 3) leads to a decrease in fuel costs and carbon emissions by 21.36% and 21.30% respectively. These results thus provide valuable managerial insights for food supply chain managers regarding the importance of considering maritime routes when making logistics decisions as they can cut costs and carbon emissions substantially.

Table 12: Carbon emissions results for different transportation scenarios

Transportation Scenarios	Carbon emissions (Kg CO_2)	Carbon Emissions from SF to SH (Kg CO_2)	Carbon Emissions from PPP to SPP (Kg CO_2)	Carbon Emissions from PPP to W (Kg CO_2)	Carbon Emissions from SPP to W (Kg CO_2)	Carbon Emissions from W to R (Kg CO_2)
Baseline Scenario	29,265.25	365.13	1,692.9	19,034	334.12	7,839.1
Transportation Scenario 1	28,723.45	365.13	1,151.1	19,034	334.12	7,839.1
Transportation Scenario 2	23,546.55	365.13	1,692.9	13,125	334.12	8029.4
Transportation Scenario 3	23,004.75	365.13	1151.1	13,125	334.12	8029.4

5.8. Managerial Implications

Low margins and considerable cost pressures characterise the food industry globally (ECSIP Consortium, 2016), with managers typically having to identify ways of reducing costs and minimise inventory while ensuring retailers' demands and sustainability objectives, particularly relating to carbon emissions, are met (OECD, 2019). The models presented here are designed to aid managers in meeting these challenges. Model N1 optimizes the supply chain network comprised of salmon farms, slaughterhouse, primary processing plant, secondary processing plant and wholesalers, while aiming to meet the demand of the secondary processing plant and wholesalers. Model N2 optimizes the network comprised of the secondary processing plant, wholesalers, and retailers, while aiming to meet the demand of the retailers. When the demand of the wholesaler is not accurately predicted and is higher than retail demand, inventory costs incurred in model N2 become substantially higher, as observed in Tables 1 and 2. Consequently, the proposed mathematical model M provides useful managerial insights for managers with the option of optimizing the overall supply chain network where the organization tries to meet the fluctuating demand of retailers while incorporating necessary information regarding supply capacity at the secondary processing plants and wholesalers. The results further emphasize the importance of optimizing the overall supply chain network, helping food supply chain managers to regulate inventory costs as all decisions are made based on retail demand. The results obtained after solving the proposed mathematical models M, N1 and N2, provide useful managerial implications regarding the desirability of optimizing the overall supply chain network system from salmon farms to retailers, as the total cost for model M is much less than the combined total costs for models N1 and N2. While a whole supply chain perspective is often recommended, this paper provides managers with supporting evidence to justify the cost savings that can be realised.

The real-world problem case of Norwegian Salmon is solved by considering fuel cost parameters and constraints relating to carbon emissions, generating a substantial decrease in total costs, fuel costs and carbon emissions. From the models, managers can understand how sensitive is the supply chain network to fuel costs, which in turn depend on fuel consumption and the distance between stakeholders.

The findings from the transportation scenario analysis generate actionable insights for managers regarding the adoption of maritime transportation routes within the supply chain network to substantially cut total costs, fuel costs and carbon emissions. The transportation scenario analysis thus also supports policy initiatives (European Commission, 2011) to shift logistics operations from road to maritime transportation to yield both economic and environmental benefits. The results highlight how sustainability aspects can be integrated into corporate strategy, as envisaged in recent proposed policies (European Commission, 2020). Increasingly, food supply chain must monitor and limit carbon emissions as part of corporate governance requirements (European Commission, 2019) while also maintaining a supply chain network yielding long-term economic as well as environmental benefits. The models presented here provide a framework for achieving this task, and the current model can be adapted for other food supply chain organizations.

The demand scenario analysis helps verify the robustness of the proposed mathematical model in dealing with demand fluctuations and accordingly optimizes the supply chain network. In practice, the demand for salmon may suddenly decrease due to various reasons such as food safety scares and public health disruptions such as witnessed with the recent Coronavirus crisis. For food supply chain managers it is important to react appropriately to demand variability, for example by adequately lowering inventory costs when demand decreases. Furthermore, when demand increases the model aims to procure more products for meeting the demand. Therefore, the proposed model is useful for supply chain managers as it quickly adapts to significant fluctuations in demand within the supply chain network and accordingly reschedule logistics, procurement, and inventory related decisions.

6. Conclusion and Future Research

Food supply chains are increasingly complex with transportation and logistics a significant source of costs and carbon emissions (Ala-Harja & Helo, 2014; Wu et al., 2018). Recent policy frameworks call for mapping the financial and environmental performance of food supply chains (European Commission, 2020). This is addressed through consideration of an archetypal multi-stage, multiple output, international case, namely the Norwegian salmon supply chain network. A mathematical formulation is proposed in the form of a mixed integer linear programming model. The model aims to meet time-varying retail demand while accommodating various product types. The proposed mathematical model captures the real-world constraints related to demand and supply variability, carbon emission restrictions, fuel consumption and time-varying cost components associated with inventory holding, transportation and product processing. Testing the model with various scenarios highlights its applicability in dealing with complex problems and it is validated through consideration of a real-world case study.

The models help study the current operational tendencies of the organization and also understand the wider importance of optimizing the overall supply chain network to reduce costs while addressing carbon emissions restrictions. Sensitivity analysis validates the robustness of the model in dealing with the fluctuating nature of retail demand and its impact on the overall supply chain structure. Furthermore, transportation scenario analysis captures the impact of adopting maritime, in place of road, transportation for lowering the overall cost, fuel cost and reducing carbon emissions. The model thus provides a flexible tool for the analysis of food supply chains, for use by practitioners and policymakers. The current study could be extended by incorporating stochastic aspects related to retailer demand. Moreover, it could also incorporate delivery times within the model for addressing service levels.

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