Report on findings on transportation and logistics of selected food value chains

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REPORT ON FINDINGS ON TRANSPORTATION AND LOGISTICS OF SELECTED FOOD VALUE CHAINS

SALMON TO FILLET CASE STUDY

PROJECT REPORT
D7.1

VALUMICS – UNDERSTANDING FOOD VALUE CHAINS AND NETWORK DYNAMICS

SEPTEMBER 2019

VALUMICS
Food Systems Dynamics

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www.valumics.eu

ABOUT

VALUMICS stands for value chain dynamics and is a research project funded by the EU H2020 programme. VALUMICS will enable decision makers to evaluate policy impact on food value chains

AUTHORS

Paulus Aditjandra (UNEW), Arijit De (UNEW), Matthew Gorton (UNEW), Carmen Hubbard (UNEW), Gu Pang, Shraddha Mehta (SINTEF), Maitri Thakur (SINTEF), Roger Richardson (SINTEF), Sigurdur Bogasson (UoI), Gudrun Olafsdottir (UoI)

CONTRIBUTING PARTNERS

University of Newcastle (UNEW)
University of Iceland (UoI),
SINTEF Ocean, Norway

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FOR FURTHER INFORMATION

Paulus Aditjandra

Email: paulus.aditjandra@ncl.ac.uk

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VALUMICS

Understanding food value chains and network dynamics

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Report on findings on transportation and logistics of selected food value chains

Salmon to fillet case study

Food Systems Dynamics

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CO	Confidential, only for members of the consortium (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CI	Classified, information as referred to in Commission Decision 2001/844/EC.	

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Contact person responsible for this deliverable:	Paulus Aditjandra Email: paulus.aditjandra@ncl.ac.uk
Authors:	Paulus Aditjandra, Arijit De, Matthew Gorton, Carmen Hubbard, Gu Pang, Shraddha Mehta, Maitri Thakur, Roger Richardson, Sigurdur Bogasson, Gudrun Olafsdottir
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CONTENTS

EXECUTIVE SUMMARY

- Transportation has significant impact on food costs and the environment. It is a major contributor to carbon emissions, accounting for almost a quarter of the CO^2 emissions in the EU, of which 30% is attributed to the food sector.
- This deliverable addresses the modelling of food chains' transportation and logistics. It develops a robust model for policy support, which is applied to a specific case as a worked example. The approach can be used to model the transport and logistics of other food supply chains, given data availability.
- The mathematical modelling aims to optimise the cost and effectiveness of logistics operations. It also allows for the integration and consideration of environmental aspects within transportation, processing and distribution operations.
- Specifically, the deliverable focuses on the development of a logistics mathematical model using Atlantic salmon as an exemplary example of a globally integrated food supply chain. A Norwegian salmon exporter was engaged to supply data for validating the mathematical model.
- The model follows a multi-objective optimization approach that captures the trade-off between total logistics cost and the environment. It has two objectives. Firstly, to minimize total costs associated with transportation, fuel consumption, inventory holding, processing and residuals/waste. Secondly, to reduce CO_2 emissions incurred by production at plants, transportation from suppliers to plants, and transportation from plants to customers.
- Constraints related to supply, processing capacity, storage capacity, demand, carbon emissions, inventory balancing, transportation capacity, and different modes of transportation between different types of plants and facilities are also consider within the model.
- Model development, validation and policy recommendation occurred in four stages: (i) mapping supply chain linkages and product flows, (ii) designing the mathematical model, (iii) data collection for parameters of the model and (iv) model validation and deriving policy recommendation.
- Before modeling, consultation with salmon supply chain actors occurred as a first step to map the supply chain linkages. This involved expert interviews with VALUMICS partners.
- Based on the mapping of the supply chain, a mathematical model was developed. However, given the complexity of the supply chain and the limited information that can be drawn from a single company which completely covers both the supply and the demand ends of the value chains, the model was divided into two stages (Model N1 and N2)
- First it optimises the supply chain network from salmon farms, abattoirs, primary processing plants, secondary processing plants and wholesalers so to meet the demand of the Secondary Processing Plants and Wholesalers for Fresh HOG (Head-on-Gutted) product (Model N1) (farm to wholesaler).
- Second, it addresses the supply chain from the secondary processing plants and wholesalers to retailers. The secondary processing plants process HOG

into whole fillet, salmon by-products and some residual amount so to meet the demand of retailers (Model N2) (wholesaler to retailer).

- An additional model (Model M) allows for the optimisation of the overall supply chain network where, for example, a Company X tries to meet the demand of retailers in different time periods (farm to retailer).
- A transportation scenario analysis was also conducted by considering options for various maritime transportation routes from primary processing plant to secondary processing and primary processing plant to various wholesalers.
- The results from the three models highlight that it is essential for any company to optimise the overall supply chain network system (from salmon farms to retailers), as the total cost for model M is relatively much lower than the combined total cost of N1 and N2.
- Each model also shows that the supply chain network is sensitive to fuel cost and consequently fuel consumption and distances between actors across the supply chain.
- Environmental impact is generally measured by fuel consumption during operations and in the case of food chain, transportation and distribution are important contributors via the use of fuel-based vehicles, sea vessels and/or airplanes.
- The scenarios analysis highlights the importance of adopting maritime transportation routes in terms of significantly reducing the total cost, fuel cost and overall carbon emission. Hence shifting certain logistics operations from road to maritime transportation from the perspective of economic and environmental benefits is advocated.
- For short to medium distances (vans, trucks, rails and sea vessels) that covers transportation trips to reach airport hubs and big cities, lowering CO_2 emissions depends on the emissions ratio (the relative emissions impact of delivery vehicle when compared to personal vehicle – mostly applied in urban logistics) and customer density.
- For long distance transport (air), environmental improvement can be mainly achieved through technological development and this has been well supported by research dedicated specifically to address EU aviation industry challenges.
- The models are developed for a planning horizon consisting of discrete time periods, aiding the possibility of studying demand and supply uncertainty and its consequences in supply chain decision making. Hence, they help decision makers to identify the changes in a supply chain network when different transportation routes are adopted (for example whether maritime routes can be adopted or not in place of road/rail transportation, to address environmental concerns related to fuel consumption and carbon emissions).
- The models are valuable for policy makers in terms of understanding the costs and emissions associated with different food supply chains, as well as the effects of particular policy interventions and market developments (e.g. variation in demand, fuel costs, emission and waste constraints).

- They can aid supply chain managers to make decisions regarding the amount of inventory to be kept in different time periods.

1. INTRODUCTION

The H2020 VALUMICS project aims to provide decision makers throughout food value chains with a comprehensive suite of approaches and tools that will enable them to evaluate the impact of strategic and operational policies to enhance the resilience, integrity and sustainability of food value chains for European countries. A system dynamics methodology (Work Package 2/ WP2) was used to guide the overall project.

WP7 develops a transportation and logistics mathematical model of selected food chains – a computational model of food value networks – with particular focus on the impact of different regulatory scenarios, and network risk and resilience. The model is empirical verified using the case of the Norwegian salmon supply. In terms of logistics, this is an interesting case, being a global value chain, where about 95% of the products are exported to the European Union (EU) and other markets worldwide. The products are transported in a commodity format from Norway to secondary processors and retail markets. The analysis of the logistics and model development required access to company data.

This document (Deliverable 7.1) is the first task of WP7, which studies sustainability with a more focused environmental dimension in the development of a transportation model within the framework of the selected food chains. The aim is to examine different modes of transportation in food chains, and to assess which combination of transport modes provides the minimum transportation cost while taking into account opportunities to reduce CO_2 emissions.

The data collection process used to develop T71 was informed by activities in WP4, i.e. identification of case studies that focus on selected food systems, including the salmon to fillet case, where a set of primary and secondary data were defined and collected.

1.1. FOOD TRANSPORTATION ISSUES AND REDUCING CARBON EMISSIONS

The transportation sector is the largest contributor to carbon emissions, which at 7.5 billion metric tonnes in 2015, represented 23% of fuel-burn CO_2 emissions globally (OECD/ITF, 2017). While by sector, industry emissions in OECD countries have been decreasing since the 1990s, those from the transport sector increased constantly reaching a peak in 2006 (Figure 1). They slightly fell in 2007/8 when oil prices rose. In the EU, emissions from transport since 2013 are on an upwards trajectory, due to, perhaps, oil prices having been relatively low for several years and economies have recovered from the 2007/8 financial crisis. Similar trends are also evident in the US (EIA, 2018). Nevertheless, many companies generally have been reluctant to act towards curbing transport emissions (Golicic, Boerstler, & Ellram, 2010), and some governments, such as the US, also remain sceptical (Roberts, 2018). Green supply chain management (GSCM) practices, including transportation, are complex, due to customer requirements, cost pressures and regulation uncertainties, so that such initiatives are often considered a thankless task that increases overall product cost (Diabat & Govindan, 2011). However, government regulation and legislation and reverse logistics are identified as significant drivers towards reducing environmental impact (ibid).

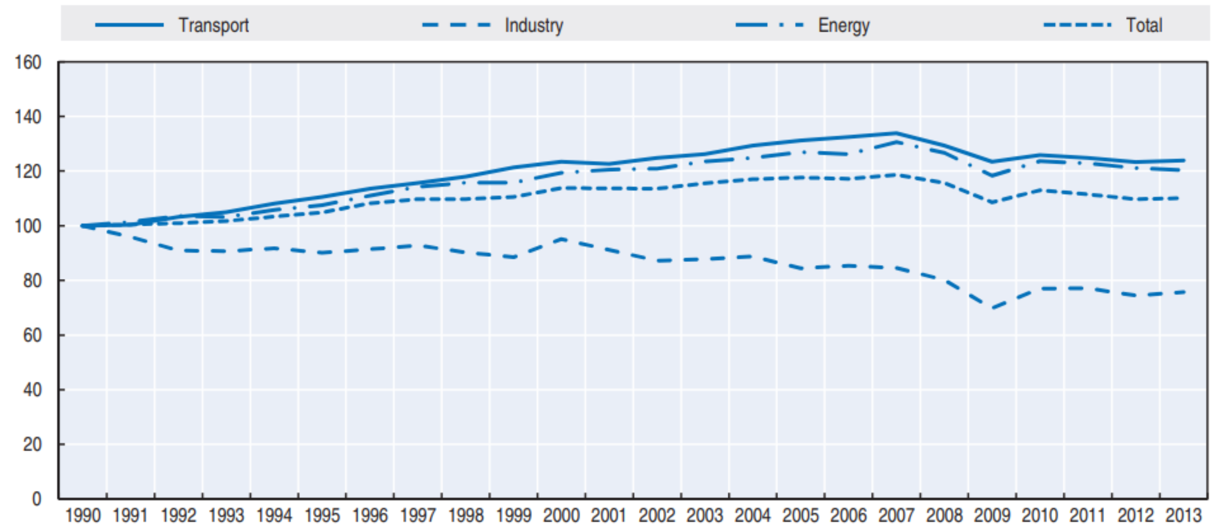


Figure 1 CO_2 emissions by sector in OECD countries (source: (OECD/ITF, 2017)

Transportation has significant impact on costs and emissions within the food and beverage sector because food is often shipped long distances and airfreight is used frequently (Wakeland, Cholette, & Venkat, 2012). This is especially the case for perishable food products such as the ones adopted within the VALUMICS case studies.

A US study shows that transportation represents 11% of GHG emissions of the food system (Weber & Matthews, 2008), with a similar figure of 12% estimated for the UK (Garnett, 2011). However, emissions vary by food type, for instance, red meat (such as beef), fruit/vegetable and cereals/carbohydrates are the most transport intensive GHG emitting products in the case of the USA (Weber & Matthews, 2008). While transportation is thus not the main cause of food system GHG emissions, ignoring it risks failing to create sustainable food systems. This is especially the case for long distance transport to reach global markets that allows for the transportation of livestock and refrigeration for various perishable food products such as fish and vegetables/fruits (Garnett, 2011).

The basic supply chain design for food system includes a number of agents: suppliers, manufacturers, distributors, warehouses, (processing) plants, retailers, and consumers. Those agents are connected with a transportation network and information flows. Figure 2 illustrates a three-stage multiple-product production-transportation network design that incorporates suppliers, plants and customers. The arrows in Figure 2 denote the flow of either product (blue lines) or information (dash red lines) between suppliers and customers. Supply capacity, plant capacity and lot size, demand capacity, and transportation capacity and time are key parameters to represent the physical flows of a commodity/product. These parameters are mapped in Figure 2 in light green boxes. There are also other components to inform the way in which a supply chain model is developed: the decision variables. Supplier selection, transportation quantities and modes, plant locations and production lot, product inventory are some of such variables, as shown in Figure 2 blue boxes.

The complexity of supply chains derive from the fact that few are completely controlled / governed by one firm or vertically integrated (Gereffi, Humphrey, & Sturgeon, 2005).

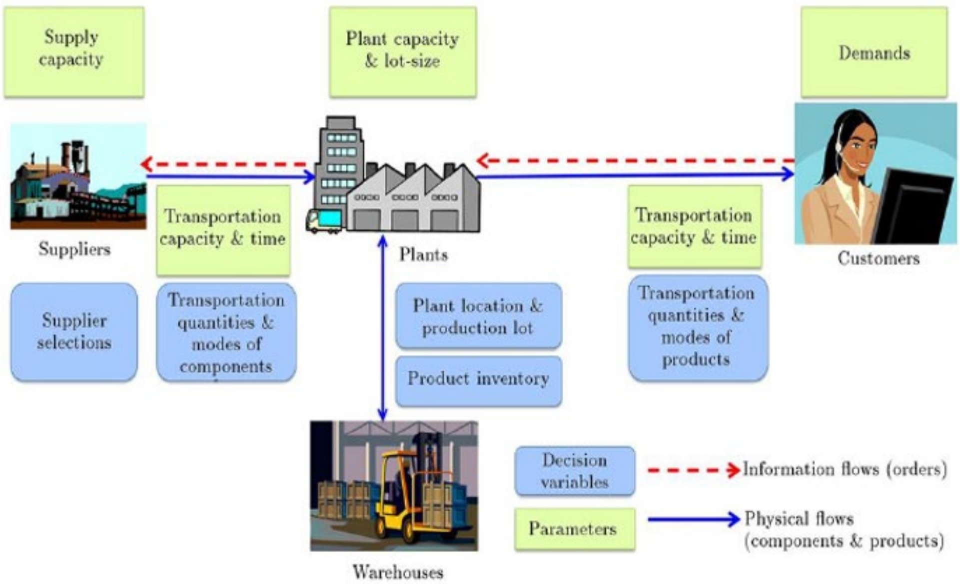


Figure 2 A three-stage multiple-product production-transportation network design that incorporates suppliers, plants and customers (presented at VALUMICS WP2 meeting in Reykjavik, 2018)

Food supply chains are characterised by ***time constraints*** due to spoilage, contamination, high weight-to-value ratios, fragility, packaging requirements, and potential impact of food being wasted rather than consumed (Wakeland et al., 2012). Furthermore, there are other challenges as well such as:

1. ***Nature dependent food production***, for example, long-distance supply chains, though energy intensive might yield the lowest overall emissions for providing out-of-season product to consumers;
2. ***Production methods for similar food commodities***, for example, energy-intensive production system between different countries;
3. ***Special handling requirements***, avoiding yield loss and potential health issues that consequently increase energy use and emissions;

4. ***Location of production and storage***, in countries where electricity is generated from renewable energy;
5. ***Limited choice of transport modes***, for example, highly perishable products such as berries or fresh salmon, and a location with no viable transport alternative available;
6. ***Safe and a high degree of sanitation food storage***, to be certified the food meets particular standards;
7. ***High cost extensive packaging and processing equipment***, which add weight and volume to the product, e.g. extensive packaging for gluten free.

All of the above can cause the transportation-related carbon emissions to rise from a few percent to more than half of the total emissions. Consequently it is important to study particular supply chains in detail and undertake relative comparisons (Wakeland et al., 2012).

For transportation policy in general, decarbonisation of freight (via, for instance road electrification and modal-shift) has featured as a key agenda for the EU, in plans to move to more sustainable development (Aditjandra, 2018). For inventory planning, responsible and sustainable cost optimisation (via, for instance controlling the mechanisms of logistics system) such as reviewed specifically for perishable products by Janssen, Claus, and Sauer (2016) has been the current and on-going political and industrial interest.

1.2. SUSTAINABLE FOOD SUPPLY CHAIN DESIGN

Food logistics has been mainly studied from the perspective of food research or logistics research and characterised with challenges due to perishability, traceability and highly inter-dependent actors in food supply chains (Fredrikson & Liljestrand, 2015).

Sustainable food supply chain management refers to all forward processes in the food chain from procurement of materials, production and distribution, as well as the reverse processes to collect and process returned unused products and/or parts of products in order to ensure a socioeconomically and ecologically sustainable recovery (Bloemhof & Soysal, 2017). Western-European consumers have become more demanding regarding food attributes such as quality, integrity, safety, diversity and sustainability (van der Vorst, Tromp, & van der Zee, 2009).

The Food and Agriculture Organization of the United Nations (FAO) acknowledges that substantial food losses takes place in the agri-food production processes (during post-harvesting, processing and distribution) while substantial food waste at the household / retail level also occurs (Bagherzadeh, Inamura, & Jeong, 2014). Addressing food loss / waste is one of the important aspects to creating a sustainable food future (Lipinski et al., 2013) and reducing environmental impacts (Heller & Keoleian, 2014).

Management of food supply chains traditionally focused on specific process and food product characteristics such as seasonality, process variability, quality maintenance, conditioned transportation and storage, and traceability (Bourlakis & Weightman, 2004). In addition, shelf-life constraints, suppliers' contracts, consumer preferences and retailers' strategies also shape management practices (Bloemhof & Soysal, 2017).

Over time, measurement and assessment of supply chains has become more complex, with a much wider set of key performance indicators as detailed in Table 1.

The many available options to deliver food to consumers via supply chain configurations create various energy and emissions profiles. Understanding the trade-offs and opportunities of different configurations is important and helps identify improvement strategies.

Table 1 illustrates the triple bottom line sustainability indicators of food chains and logistics. Key sustainability indicators are listed for each group (of the triple bottom line), and alongside that, food logistics policy tools are suggested. Table 1 can act as a toolkit to address food chain logistics sustainability. For instance, taking **environmental performance** for a particular food processing company it can be measured by key indicators such as energy use efficiency, GHG emissions, air pollutants, water quantity, land use, soil degradation, material cycle, waste (via weight and volume) and biodiversity. **Policies** that affect those indicators include food miles policy, environmental monitoring systems, hazard substance exposure monitoring systems, and environmental reporting.

Table 1 Sustainability indicators for food chains (adapted from (Bloemhof & Soysal, 2017)

Food chains and logistics of the triple bottom Line	Sustainability indicators	Food logistics policy tools
Environmental indicators	• Energy efficiency • GHG emissions • Air pollutants • Water quantity • Land use • Soil degradation • Material cycle • Waste (weight & volume) • Biodiversity •	• Food miles • Environmental monitoring system • Hazard substance exposure • Environmental reporting
Social indicators	• Human rights • Equity • Occupational health and safety • Food and nutrition security • Product quality	• Ethical report • Health and safety incidents • Distance between grower and distributor • Profit between farmer, processor, retailer • Quality of life and working satisfaction • Average wage
Economic indicators	• Profitability • Vulnerability • Local economy • Decent livelihood • Resilience to economic Risk	• % of food lost in mishandling • Type of distribution • Retail success • Labour productivity • Diversity of market • Transport efficiency • Imported vs domestic products

In the case of **social performance**, the key measures include a consideration of human rights, equity, occupational health and safety, food and nutrition security, and product quality. Those indicators can then be controlled with **policies** such as ethical reporting, health and safety incidents monitoring, distribution of profits between farmers, processors and retailers, quality of life and work satisfaction, and average wage.

For the **economic dimension**, key performance indicators include a company's profitability, vulnerability, contribution to the local economy, generation of decent livelihoods, resilience to economic risks, market. These can be influenced by the market structure of supply chains, trade openness, and **policy tools** such as competition policy.

At the VALUMICS partners' consortium meeting in Paris, November 2018, it was agreed to take a threefold agenda for addressing fairer and sustainable food supply chains in: consumer behaviour and 'diet', governance of the food supply chain, and food waste. These three pillars informed the development of the modelling work in WP7.

2. METHODS

This section covers the methods used to understand the food logistics system. It starts with a description of logistics planning and policies at EU level (section 2.1), followed by case study section (2.2) which describe the selected case study: salmon to fillet value chain. Section 2.3 describes the salmon supply chain logistics model conceptualisation which has been validated through VALUMICS partners and external (industry) stakeholder consultation. Section 2.4 describes the proposed mathematical model, taking into account all previous sections.

2.1 LOGISTICS PLANNING AND POLICIES

Recent analysis of the EU food supply chain identifies a number of actors (European Commission, 2017):

- 300,000 processors;
- 2.8 million distributors and retailers;
- 11 million farms;
- 500 million consumers.

The agri-food sector provides nearly 44 million jobs in the EU, with half of that number accounted for by primary agriculture. The rest lies within food processing, food retail and food services. The majority of over 15 million holdings/enterprises in the food chain are small and medium sized. Some 70% of all farms in the EU-28 were smaller than 5 ha and only 2.7% were over 100 ha in 2010; but concentration in the food processing industry and retail sectors is much higher (European Commission, 2017). The market share of the top five firms (or C5 concentration ratio) in the EU food industry was an average of 56% in 2012 in 14 of the EU's Member States, and over 60% of top five retailers in 13 Member States (ibid).

Figure 3 shows illustration of approximate representation of the food chain actors in the EU based on Eurostat. The small proportion of key actors, such as food processor, food service and food service (Figure 3), is of interest of policy scrutiny to ensure a fair trading practice.

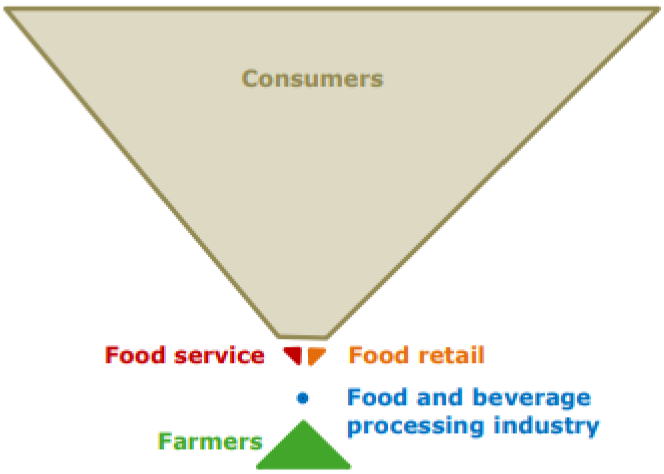


Figure 3 Approximate distribution of food chain actors in the EU, source: European Commission (2017)

Most EU logistics planning studies focus on the promotion of green transportation logistics. In EU White Paper on Transport, the European Commission (2011), targets a 60% reduction in Green House Gas (GHG) emissions while maintaining a competitive and resource-efficient transport system. Some of the goals have direct implications for optimizing the performance of multimodal logistics chains. For example, to achieve essentially CO_2-free city logistics in major urban centres, 30% of road freight over 300 km should shift to other modes (rail or inland waterways) by 2030, increasing to more than 50%, by 2050; and 'conventionally fueled' cars in urbans area should be halved by 2030, and phased out by 2050, (see Figure 4).

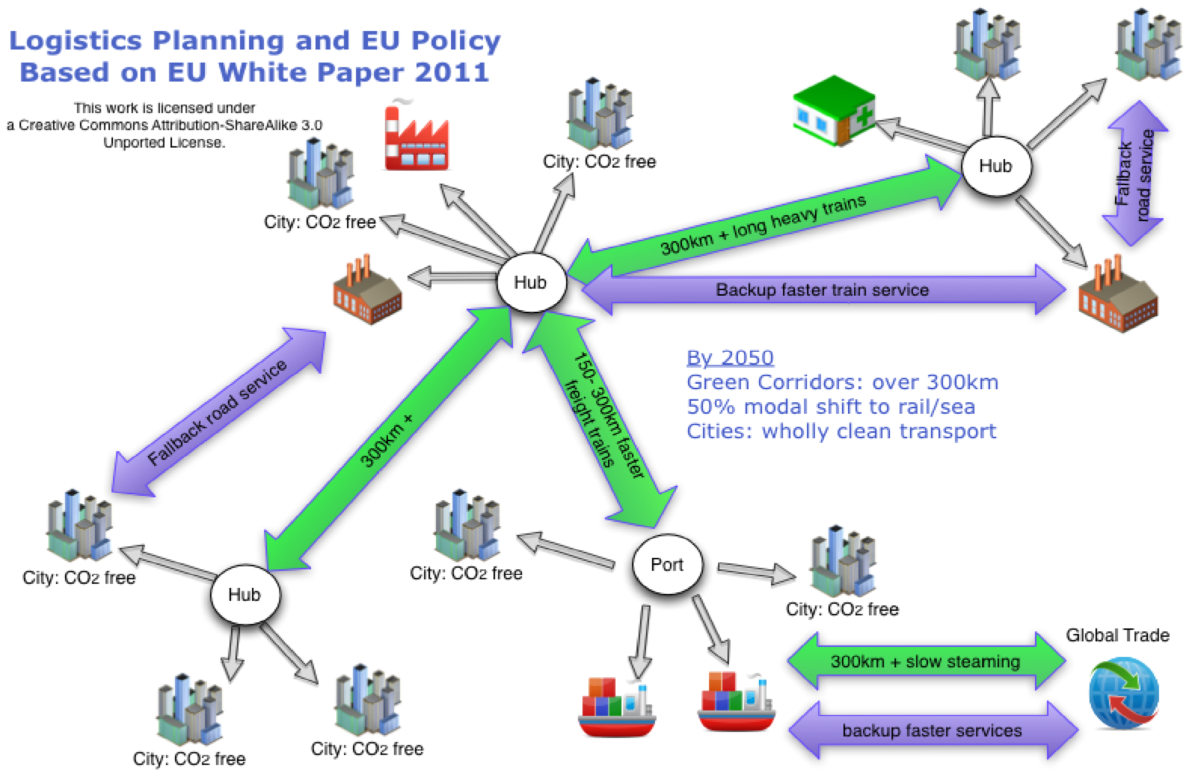
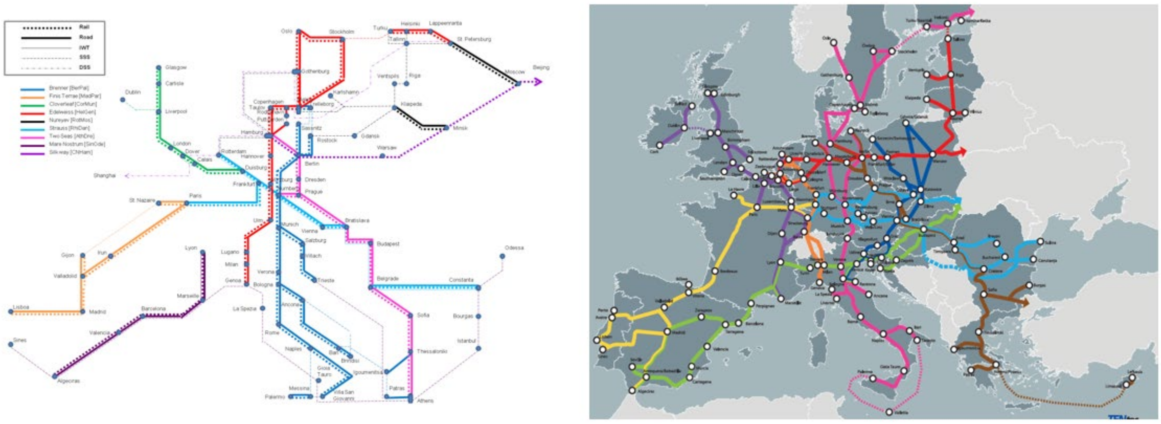


Figure 4 EU Logistics planning and policies, source: Aditjandra, Zunder, Islam, and Palacin (2016)

Additionally, a fully functioning EU-wide multimodal Trans-European Transport Network (TEN-T) – a 'core network' - is expected by 2030, with a high-quality and capacity network by 2050 and a corresponding set of information services. This particular goal lead to introduction of 'green corridor' concept as initially promoted by the Freight Transport Logistics Action Plan (2007) with aim to concentrating freight traffic between major hubs and over relatively long distances. Key characteristics of green corridors include the use of advanced technologies, cooperation between transport modes to improve quality and environmental performance, punctual, reliable and enabling collaborative business models (Panagakos, 2016). The ultimate benefit of adopting green corridor is to monitor the key performance indicators (KPI) of logistics operation, in such as cost, delivery time, emissions, reliability, frequency, ICT applications, cargo security and safety, and congestion and bottlenecks, as reported in FP7 funded coordination and support action research project and well documented in Psaraftis (2016). Figure 5 provides an illustration of a simplified freight transport priority corridor as developed by an FP7 EU funded project (2011) and the one endorsed by TEN-T (2013).



Green corridors as of FP7 SuperGreen project (2011)   Core Network corridors endorsed by TEN-T (2013)

Figure 5 Freight priority conceptual corridors, source: Psaraftis (2016, p. 97) and European Commission (2019)

In most developed countries, freight in cities constitutes between 10 and 20 percent of traffic (Zunder, Aditjandra, Islam, Tumasz, & Carnaby, 2016), and food related freight is one of the most common forms (Aditjandra & Zunder, 2018).

2.2 SALMON CASE STUDY

According to VALUMICS D2.4 (2019), the Atlantic salmon (mainly Norwegian sourced) supply chain can be divided into four stages: (1) feed, (2) farming, (3) primary and secondary processing and (4) distribution and markets.

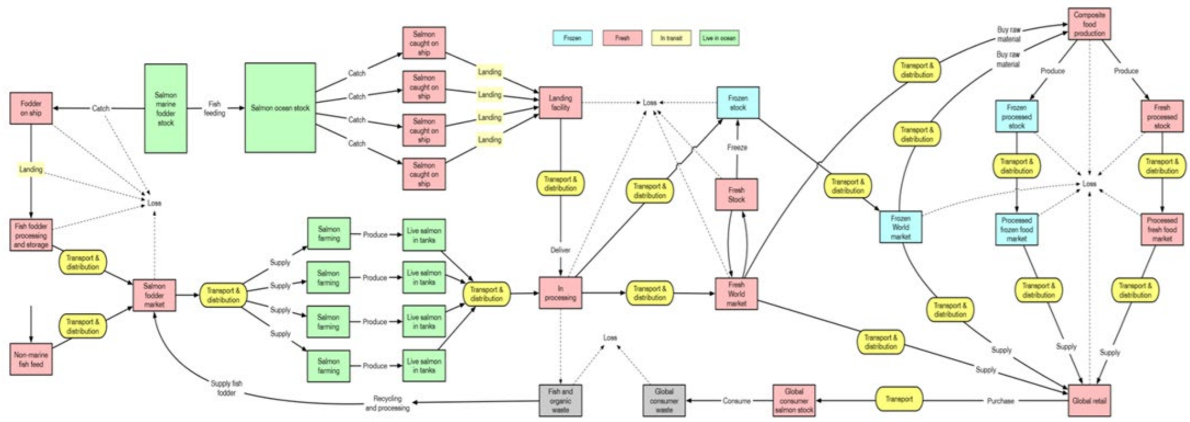


Figure 6 Salmon chain early-simulated dynamic system, source: VALUMICS WP2

Figure 6 illustrates an early-simulated salmon chain dynamic derived from one of the WP2 meetings, illustrating simplified material flows of fresh/live (red boxes) and frozen salmon (blue boxes) via many transport and distribution chains (yellow boxes). Grey boxes represent waste of the product. What is relevant to note in Figure 6 is the increasing density of transport and distribution chains along the downstream end of a global salmon supply chain.

The upstream Norwegian salmon supply chain is mainly characterized by logistics operations between fish farms, fish feed production factories with a number of ships owned by global salmon market key players, such as Marine Harvest, involved in the value chain from egg production to sales of finished salmon products (Agra, Christiansen, Ivarsøy, Solhaug, & Tomasgard, 2017). Salmon farmers are not traditionally involved in feed production, but *Marine Harvest*, presently known as *Mowi* – the largest seafood company in Norway (Norsk Fiskerinæring, 2019), aimed to integrate both feed production and delivery to optimize its operations.

Salmon farming production (aquaculture) has grown significantly in Europe in recent years. In Norway output grew by 115% within a decade (2005-2015) (Osmundsen, Almklov, & Tveterås, 2017).

In terms of salmon logistics, the modelling represents four main stages, from salmon farms in Norway producing the HOG (head on gutted) product and export to secondary processors mainly producing fresh fillets, smoked salmon and other value added products that are distributed further to retail markets as illustrated in Figure 7. Initially the main focus will be on the export from Norway to EU, but the global trade is also considered.

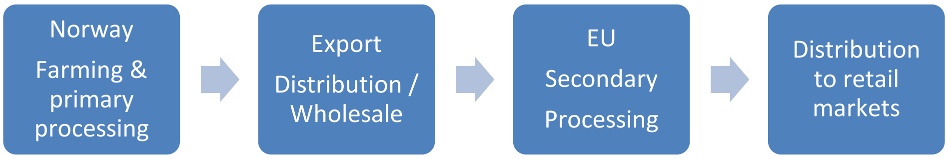


Figure 7 Logistics and Supply Chain focus for VALUMICS salmon case study

2.2.1 Process mapping

Significant volume of Norwegian salmon consumed in Europe is processed in Poland, Denmark and France (VALUMICS D2.4, 2019). Further information about the salmon chain has been compiled in D4.1 (2019) and WD4.4 (2019). Whole fish and value-added salmon products are transported in fresh or frozen form across the globe by land, air and sea routes. Looking into detail of Norway salmon production, in 2013, there were 991 fish farms (mainly for salmon and trout) that supplied 60 slaughterhouses, where 52 were active processing plants (Hanssen et al., 2014). In the same year, over 900k tonnes of fresh salmon and trout was exported with a value of NOK 37 billion (~ €3.71 billion), an increase of 73% from five years earlier (2009) (ibid).

Figure 8 illustrates the process of Norwegian salmon production with specific reference to primary processing and distribution. There are different categories of product quality but 90% of slaughtered Norwegian salmon is of superior quality that goes to export markets (Figure 8). The Norwegian salmon is mainly exported as fresh HOG (Head On Gutted) (80% of the total volume produced). The fresh chilled HOG salmon is transported in Styrofoam boxes by trucks from processing plants to secondary processors and wholesale/retail markets in Europe (80%), and to Asia (13%) as illustrated in Figure 8.

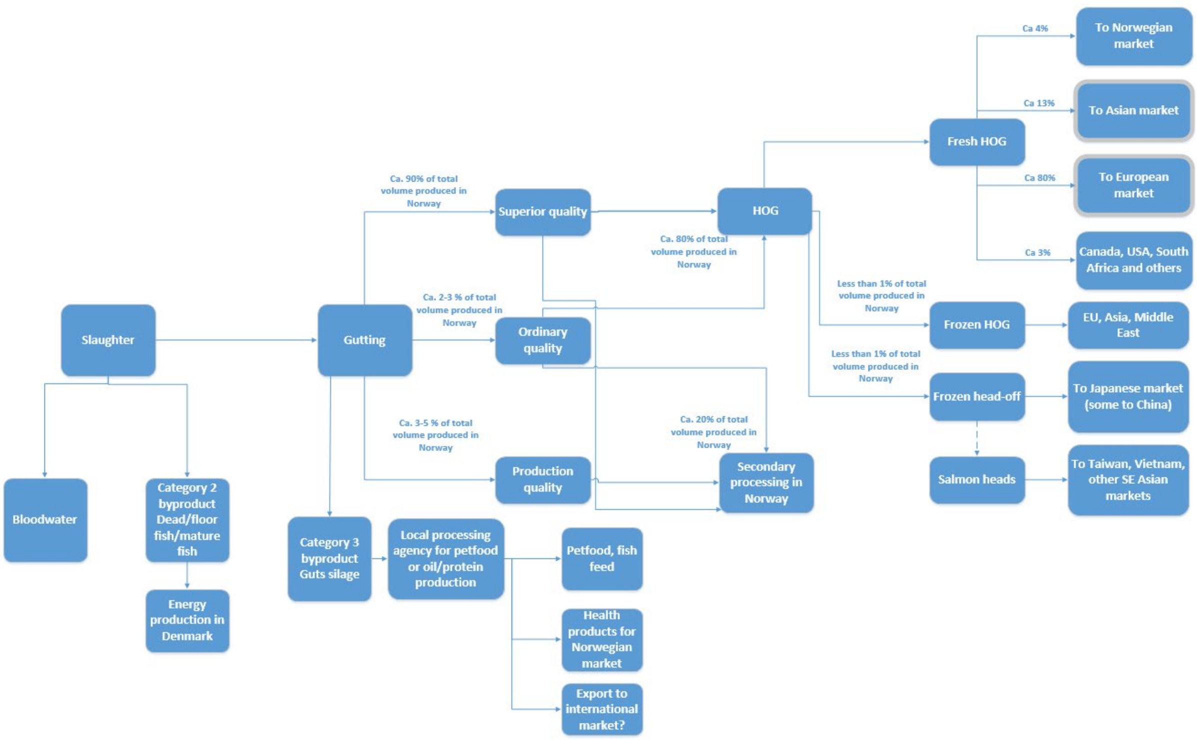


Figure 8 Norwegian salmon production process, source: SINTEF)

Figure 9 illustrates the secondary processing production process in Poland and Norway where filleting and smoking are the main value added processing activity among others (i.e. trimmings and skin for fish oil).

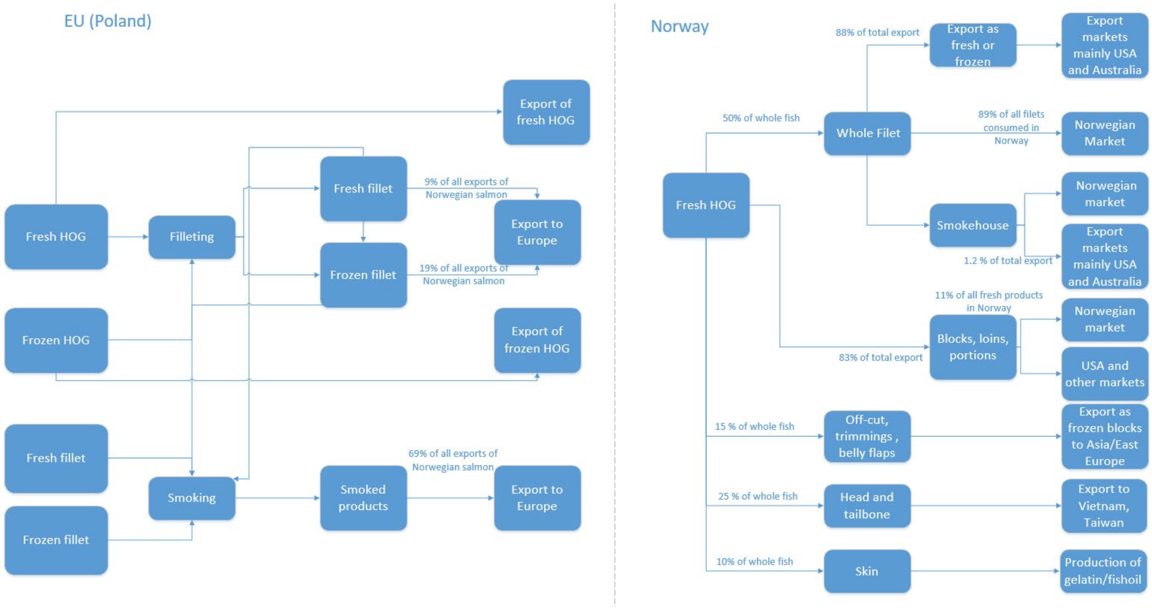


Figure 9 Norwegian salmon secondary processing production process (source: SINTEF)

Norwegian fresh HOG salmon export markets are illustrated in Figure 10 and Figure 11 details the transport operations.

Figure 10 demonstrates the distribution of Norwegian salmon fresh HOG to EU countries where Poland with 18%, France (13%) and Denmark (12%) are major markets followed by Spain (9%), Netherlands (8%), UK (8%) and Italy (7%).

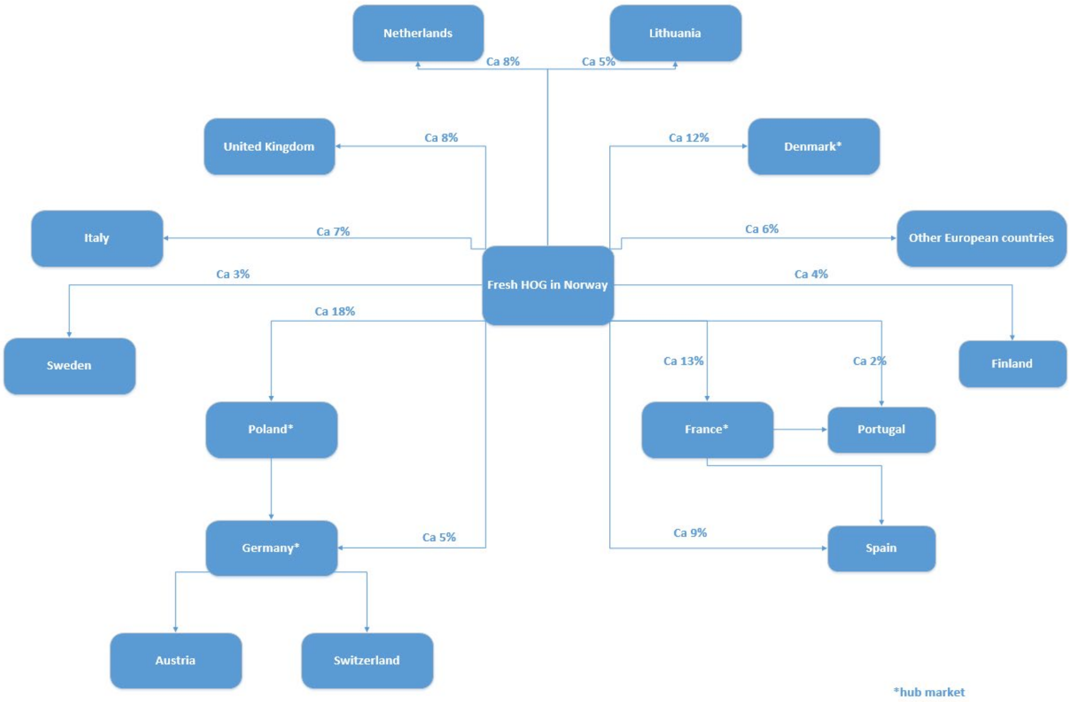


Figure 10 Norwegian salmon export to EU countries market (source: SINTEF)

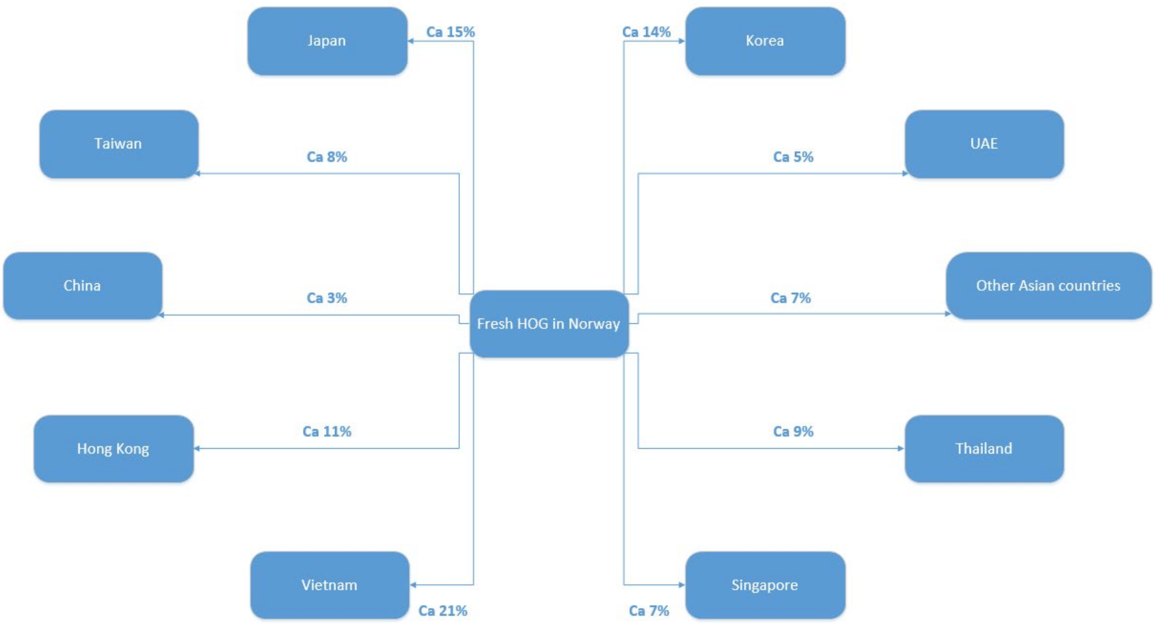


Figure 11 Norwegian salmon export to Asia countries market (source: SINTEF)

Figure 11 demonstrates the distribution of Norwegian salmon fresh HOG to Asia countries market where Vietnam (21%), Japan (15%), Korea (14%), Hong Kong (11%) and Thailand (9%) are major markets.

2.2.2 Logistics overview: transport Norway to France

A field study of the logistics of salmon from Norway to France was conducted as part of FP6 EC Project CHILL-ON[1] and reported as an internal document (CHILL-ON D5.5, 2011). This provides useful background for the initial development of the logistics model. The aim of the Salmon Field trial in August 2010 was to validate the functionality and performance of the various Chill-on technologies, including temperature monitoring (Hafliðason, Ólafsdóttir, Bogasson, & Stefánsson, 2012) in an entire supply chain of salmon, transported from Norway to a smokehouse in France. The field trial started at the processing company on the Norwegian island Aukra. The whole fresh fish was packed and transported by truck to Boulogne sur Mer. The salmon was delivered to the smokehouse for processing into cold smoked salmon products. The finished product was then shipped through distributors to a final retailer (restaurant or retailer).

Aukra – Vestby (Farms to slaughterhouse / primary processing): The first part of the journey includes collection of fish products on the island of Aukra, Norway, and then the truck heads to Molde (close to Aukra). Other trucks do the same in different areas around Molde. All the products were taken out of the truck and placed in a cooler. Products were then collected from all the trucks that were heading to the Oslo area (center/south part of Norway) and the products were placed in the order of the trucks. The truck stopped a few times on the way before arriving in the chilled warehouse in Vestby.

Table 2 Logistic overview of salmon transported from Norway to France

Way	Distance	Transport method	Estimated time
Aukra (Norway) – Vestby (Norway)	560 km	Truck / Ferry	(8h waiting for dispatch) 21 h transport
Vestby (Norway) – Boulogne sur Mer (France)	1730 km	Truck / short ferry	(storage 76 h) 117h transport (storage 119h)
Processor -> Distributor, Boulogne sur Mer (France)	>5 km	Small truck	Time varies
Primary distributor -> Secondary distributor	250 – 1000 km	Small truck	
Secondary distributor -> End customer (Retail / Restaurant)	>50 km	Small truck	
End customer (multiple stops)	250 – 1000 km	Small truck	

Vestby – Boulogne sur/Mer (Slaughterhouse / primary processing to secondary processing): The departure of trucks was scheduled depending on the collected amount of fish in the warehouse in Vestby. If the amount of fish was very small, it was likely that the truck stopped again and products from more locations were combined in one shipment in Padborg, Denmark. On the route to Padborg, the truck would take a ferry to Denmark, and depending on the time and traffic, the truck driver could select between a ferry from Oslo or from Gothenburg, Sweden.

[1] https://cordis.europa.eu/project/rcn/79819/factsheet/en

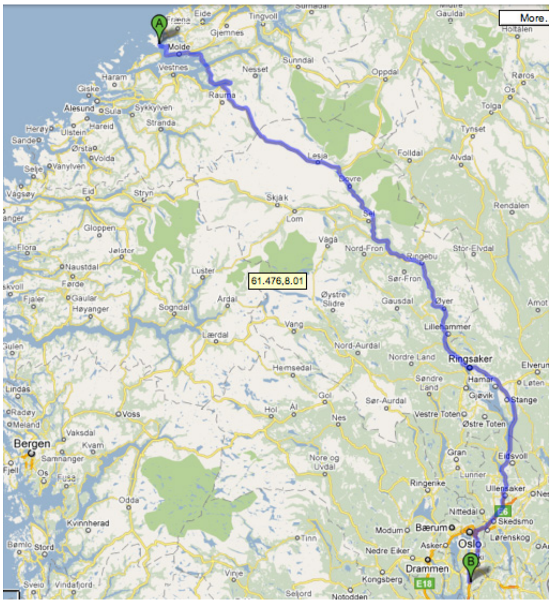


Figure 12- The route between Aukra (Norway) and Vestby (Norway).

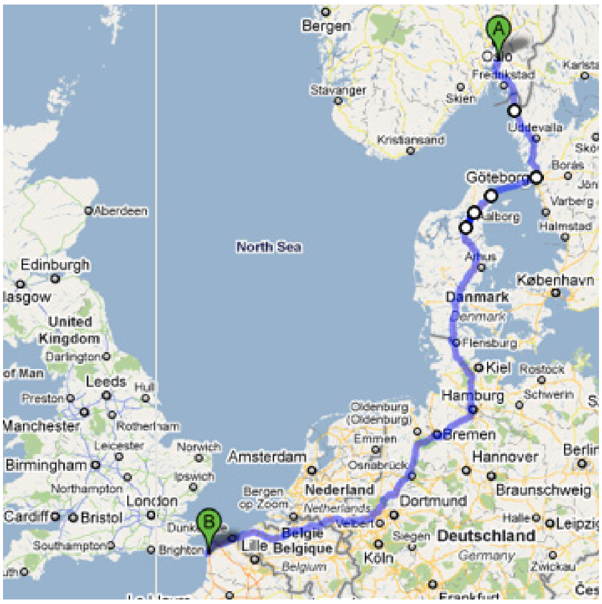


Figure 13- The route between Vestby (Norway) and Boulogne sur Mer (France)

Processor to distributor (Secondary processor to wholesaler): The distance was very short (less than 5 km) and was within the town of Boulogne sur Mer, France.

Primary distributor to secondary distributor (Wholesaler to food industry): During the mapping in June 2009, two different shipments were monitored. Both shipments had a secondary distributor in France.

Secondary distributor to final customer (Food industry to retailer/HORECA): The secondary business distributor shipped the products to either a restaurant or a retailer in the area close to the distributor. This was assumed to be less than 50 km.

Key aspects of the study drawn above for developing the logistics system:

- The logistics chain from farms to customers can go beyond simple 3 stages as illustrated in Figure 7 and goes up to 6 stages with 7 different stakeholders/agents along the chain as illustrated in Figure 14;

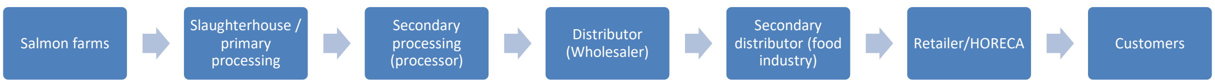


Figure 14 Salmon logistics chains from Norway to France based on FP6 CHILL-ON project

- The mode of fresh salmon transport from Norway to European market are mainly truck and ferry (with ro-ro, to carry truck with fish load);
- Truck almost always was full loaded otherwise the trip will be hold until the full load achieved;
- The total distance on ferry is between 560 – 1730 km;
- The total distance on truck (road driving) is within the range of 5 – 4290 km

2.2.3 Logistic systems

A review of the national Norwegian salmon and trout logistics system is reported in commissioned study using data from interviews with logistics managers and slaughterhouse managers supported with national statistics (Hanssen et al., 2014). Figure 15 shows the transportation logistics system from salmon and trout from farms to exports hubs.

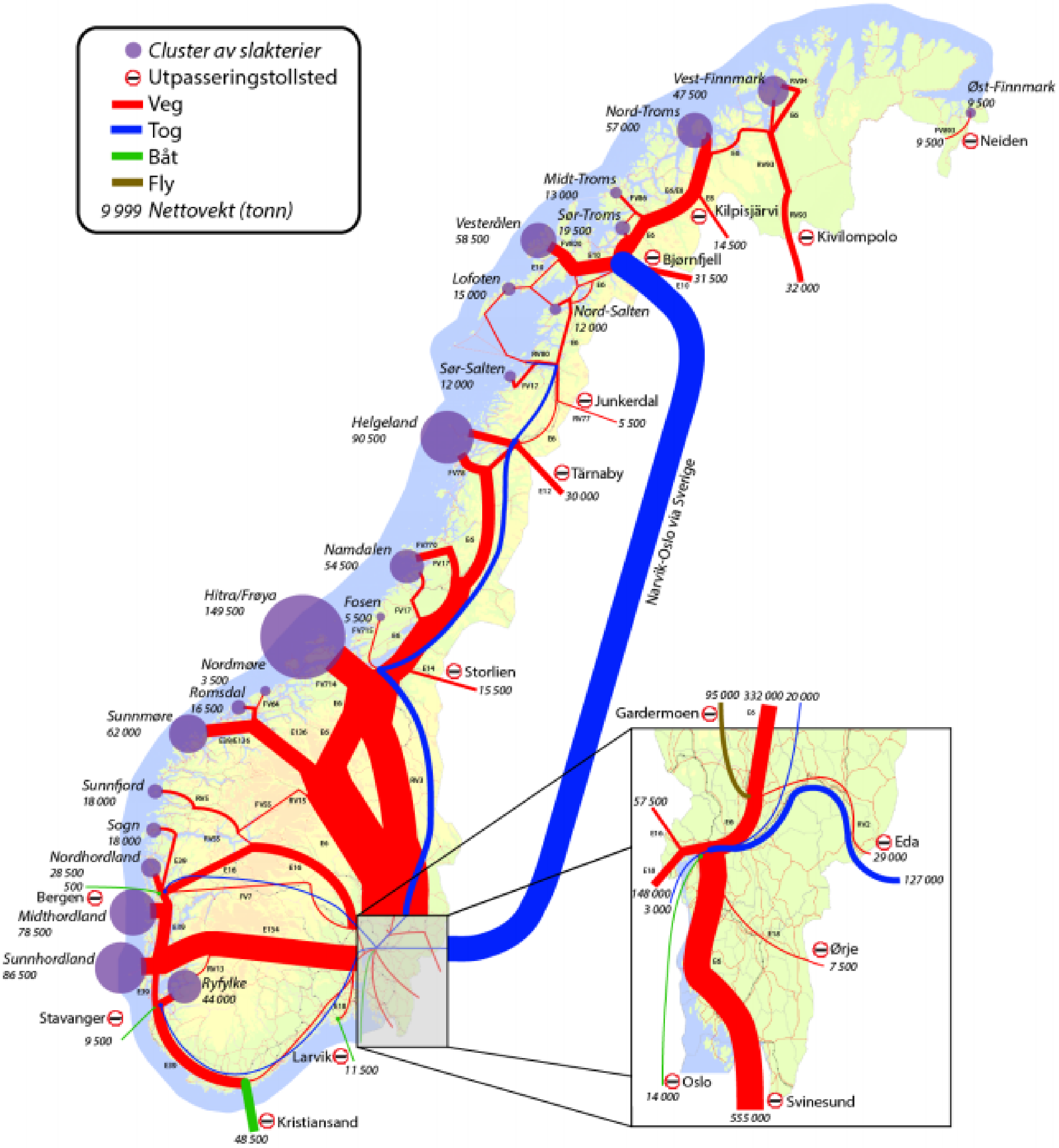


Figure 15 Salmon and trout transportation logistics flow in Norway, source: Hanssen et al. (2014)

Most of fresh fish from Norway's slaughterhouses end in Oslo by Alnabru rail freight terminal (Oslo's main cargo yard) before exported mainly via Svinesund (Figure 15 inset) and via Gardermoen (Oslo International Airport, OSL). From the 52 processing plants (= slaughterhouses) the report defined 22 slaughterhouse clusters, where 6 clusters (representing 18 slaughterhouses) produces 66% of the export volume (Hanssen et al., 2014).

Recently 1,000 tonnes of salmon went through one of the cold storage in Alnabru run by DB Schencker (Deutche Bahn rail freight operator) cold storage terminal every week with steady flow of lorries from Western Norway processing plants and the DB Schencker train from Northern Norway, 52 weeks a year (Witzøe, 2018a). Ninety percent (90%) of the salmon exported from here was transported to different locations in Europe, while 10% was shipped to Oslo International Airport (ibid). Salmon is stacked in boxes, on pallets as can be seen in Figure 16.

Figure 16 DB Schencker logistics hub at Alnabru, Oslo, source: Witzøe (2018a)

Every week about 70 semi-trailers leave the terminal to go to European countries. Each trailer could take 33 (Euro) pallets with each containing 27 boxes of fresh fish with 20 kg of salmon. Each truck can load up to 18 tonnes salmon, with Thursdays and Fridays the busiest days (Witzøe, 2018a).

On Tuesdays, at least 600 tonnes of seafood, mainly salmon, flew from Oslo International Airport for export (Witzøe, 2018b). The reason for Tuesdays was due to low demand that day for air cargo, and also adjusted for the seafood industry to reach customers before the weekend in Asia (ibid). Figure 17 and Figure 18 shows how the pallets arre lined in the airport before loading for export. In total, there were around 20 departures with on average 20 tonnes of seafood-loaded cargo onto planes directed

Figure 17 Pallets of salmon ready for loading on to cargo aircraft (Witzøe, 2018b)

weekly at the Asian seafood industry. In addition, there are the intercontinental passenger routes with up to 10 daily departures to North America, Africa and Asia (ibid).

Figure 18 Pallets with salmon cargo ready for scheduled aircraft (Witzøe, 2018b)

Table 3 shows the modal share of salmon/trout export distribution with export volume figures. The large transport modal share derived from truck shipment (81%) crossing the country border via Svinesund. The relatively low percentage of air shipment (11%) was due to the fact that large part of the fish was transported out of Norway to reach other major air hubs in Europe (e.g. London Heathrow, Amsterdam and Helsinki). In 2017, it was reported that around similar volume (~ 90k tonnes) of seafood dispatched from Gardermoen (OSL) but the total air cargo recorded amounted to around 220k tonnes, most of which left Norway by truck for other airports (Witzøe, 2018b). There has been on-going work to extend the International Airport to be able to handle 250k tonnes of seafood a year (Hjul, 2018) – more than doubling the current capacity.

Table 3 Distribution of product lines and net weight of salmon/trout for various means of transport at border crossing in 2013, source: Statistics Norway cited from Hanssen et al. (2014)

Transport	Items	Net weight (tonnes)	Proportion of product lines	Percentage of net weight
Car, road transport	114 294	731 626	65%	**81%**
Air freight	47 025	96,995	27%	**11%**
Boat (incl. Car / trailer on ferry)	13 197	72 962	8%	**8%**
Overall	**174 516**	**901 583**	100%	100%

The salmon logistics system in Norway (Hanssen et al., 2014) used Oslo as the main market hub because:

- Efficient rail freight traffic from Northern Norway to Oslo (as central hub of salmon before export);
- Investment made by market participants in ICT technologies (ITS) on vehicles as well as at terminals;

- The use of reverse logistics with imported fruit/green groceries (goes to wholesalers in Oslo) that fit in the temperature-controlled containers that ship export salmon;
- Much of the fish was not sold when loaded on the truck at the slaughterhouses. It was sold after the transport had started and Oslo was the most convenient market place for repackaging to suit different customers;
- Extra cost and material for long haul truck trip to continent Europe market hubs.

2.2.4 Alternative logistics scenarios and research agenda

Recently efforts have been made in Norway to address long-term salmon growth, transportation alternatives and environmental sustainability. An industrial initiative “Green Coastal Programme” (*Grønt Kystfartsprogram*) led by DNV (2018), occurred in response to the Norwegian government’s expert committee toward green competitiveness. The initiative studied the feasibility of switching fish transportation from road to sea, employing an intermodal logistics system instead of truck-based logistics system (Figure 19). The study also undertook a cost benefit analysis of the alternative scenario touching key sustainability issues such as money saving for society, reduced need for road development, reduced road wear, fewer accidents, less local air and noise pollution and reduction in GHG emissions by 70%.

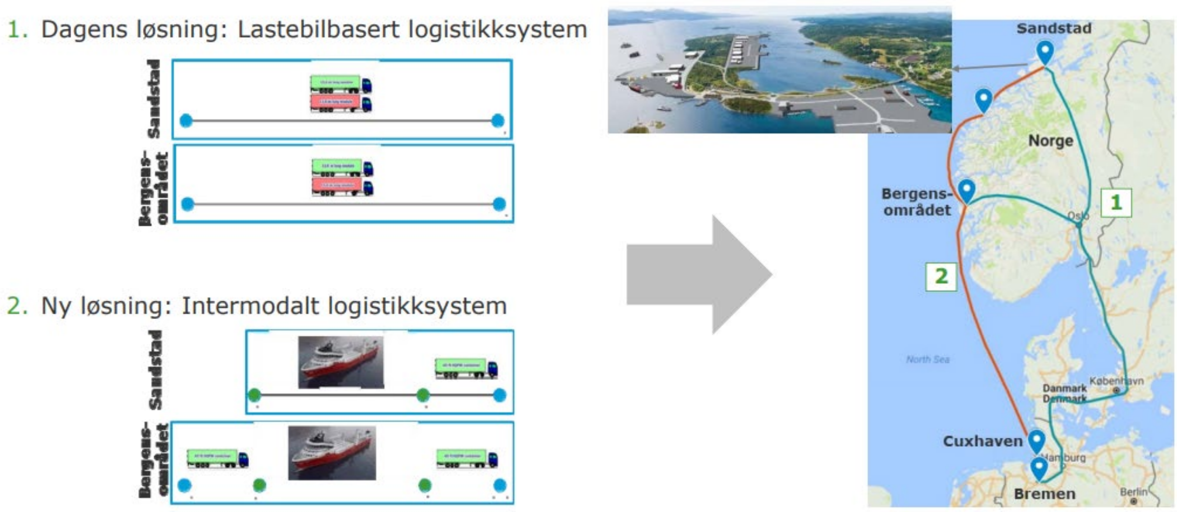


Figure 19 Salmon transport scenario truck based (1) vs intermodal based (2), source: DNV GL (2018)

Another recent study by LERØY (2019), also an industrial initiative toward cutting salmon transport emissions, shows the heavy reliance of salmon transportation distribution on trucks (steady at about 80% for the past 5 years to 2017). It also notes slight increases in the share of air transportation (from 9 to 10%) and a consequent decrease in the share accounted for by ocean vessel/boat transportation between year 2016 and year 2017 (Figure 20).

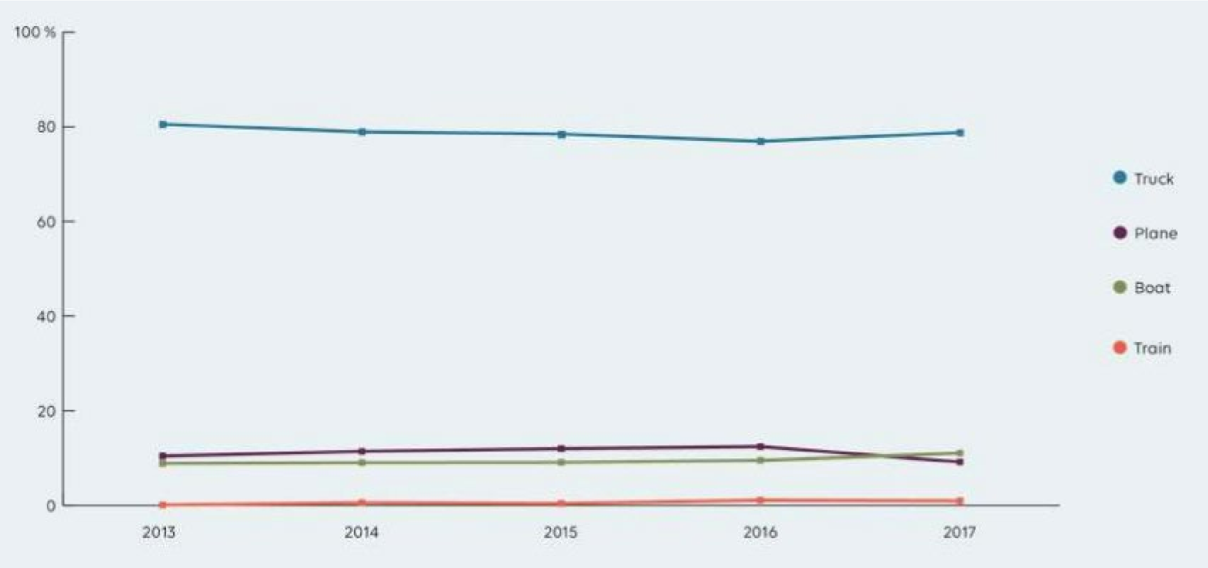


Figure 20 Lerøy transportation modes used distribution, source: LERØY (2019)

The study acknowledges improvement in air transport emissions,. The study also assessed the common three major transportation routes (from Tromsø) of global salmon chain, using a combination of truck and airplane, which can range from 27-29 hours (via Helsinki airport hub), 50-57 hours (via Oslo airport), and 71-79 hours (via other EU airport hubs, such as Paris, London and Amsterdam). In conclusion it was estimated that consuming Norwegian salmon, involves three times less CO_2 emissions compared with consuming local beef/lamb in Tokyo, Japan (LERØY, 2019).

2.3 SALMON TRANSPORT & LOGISTICS MODEL CONCEPTUALISATION

Using WP2 outputs as a starting point to illustrate the supply and demand model (Figure 21), the generic model of transportation and logistics operations can be mapped. The blue lines in Figure 21 show transportation (with direction indicated by an arrow) from node of processing plant 1 to nodes for three fresh world market destinations and three frozen world market destinations. The red lines show transportation from a node of the fresh world market 1 to nodes of three composite food production plants. The green lines show transportation from the node of composite food production plant 1 to nodes of two processed fresh markets and two processed frozen markets. The purple lines show transportation from the node of processed fresh food market 1 to the nodes of two global retailers. On each node of a processing plant, production rate capacity information is required and on each node of (fresh/frozen/processed markets) demand estimates are also required.

Following the above, the next stage was to draw on all chains of transportation from the other processing plants up to the two global retailers as illustrated in Figure 21, before model estimation. In each stage of the chain, information about the cost of transportation is required.

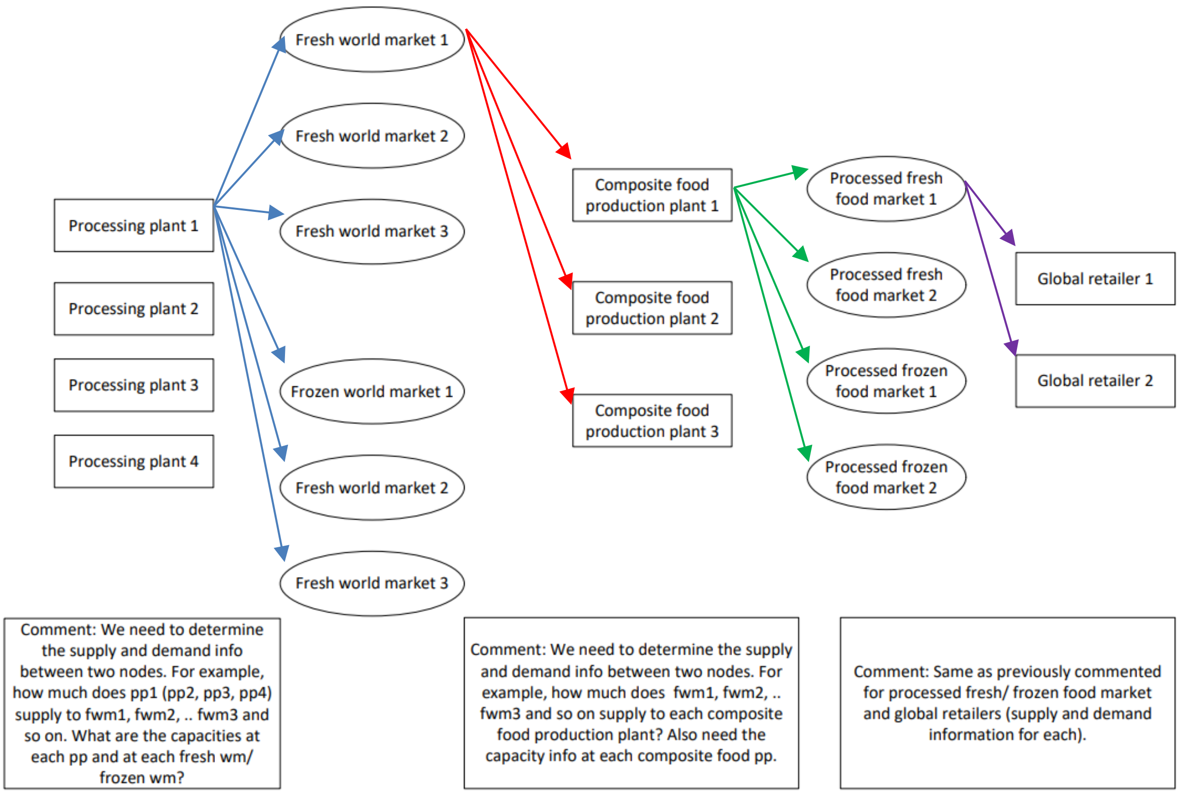


Figure 21 Supply and Demand Model of Salmon to fillet based on WP2

The development of the model follows a multi-objective optimization approach. The multi-objective optimization model captures the trade-off between the total cost and the environment impact (Chen & Wang, 2017; Wang, Lai, & Shi, 2011).

Objective 1 aims to minimise total cost. This consists of transportation cost of components and products, ordering cost charged by suppliers, setup cost at plants, production cost at plants and investment on environmental activities.

Objective 2 aims to minimize CO_2 emissions, incurred by production at plants, transportation from suppliers to plants, and transportation from plants to customers.

Before any modelling, consultation with salmon supply chain actors occurred as a first step to map supply chain linkages. Expert interviews with VALUMICS partners responsible for the salmon case study were held to refine the conceptual Norwegian logistics system framework. Figure 22 presents the supply chain networks for Norwegian salmon following consultation with salmon case study VALUMICS partners. Food supply chain consultations are uncommon (Govindan, 2018), and the consultation process held in VALUMICS was required for adequate mapping and model development.

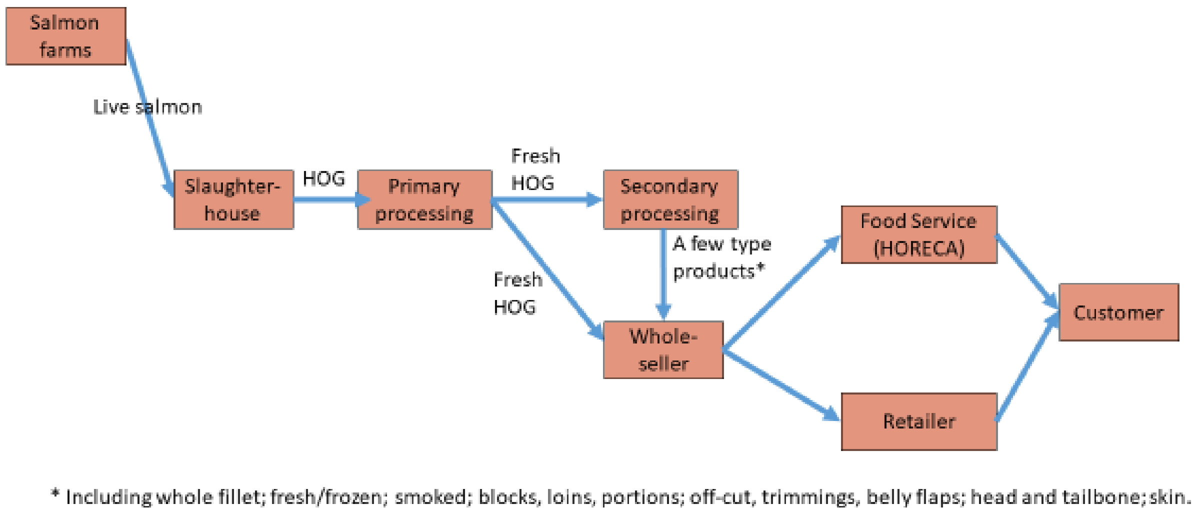


Figure 22 Conceptual framework for the Norwegian Salmon Supply Chain Network (Source: this study)

There are seven major agents/stakeholders (red boxes) (Figure 22) identified. The products considered are fresh salmon whole fillets and salmon by-products.

2.4 TRANSPORT & LOGISTICS MATHEMATICAL MODEL

Following the validation of the Norwegian salmon supply chain conceptual framework through consultation, the next step is to develop a mathematical model representing cost minimisation. The cost model comprises of transportation cost, fuel consumption, inventory holding, processing and residual/waste costs. Figure 23 illustrates the mathematical model function with input and output parameters.

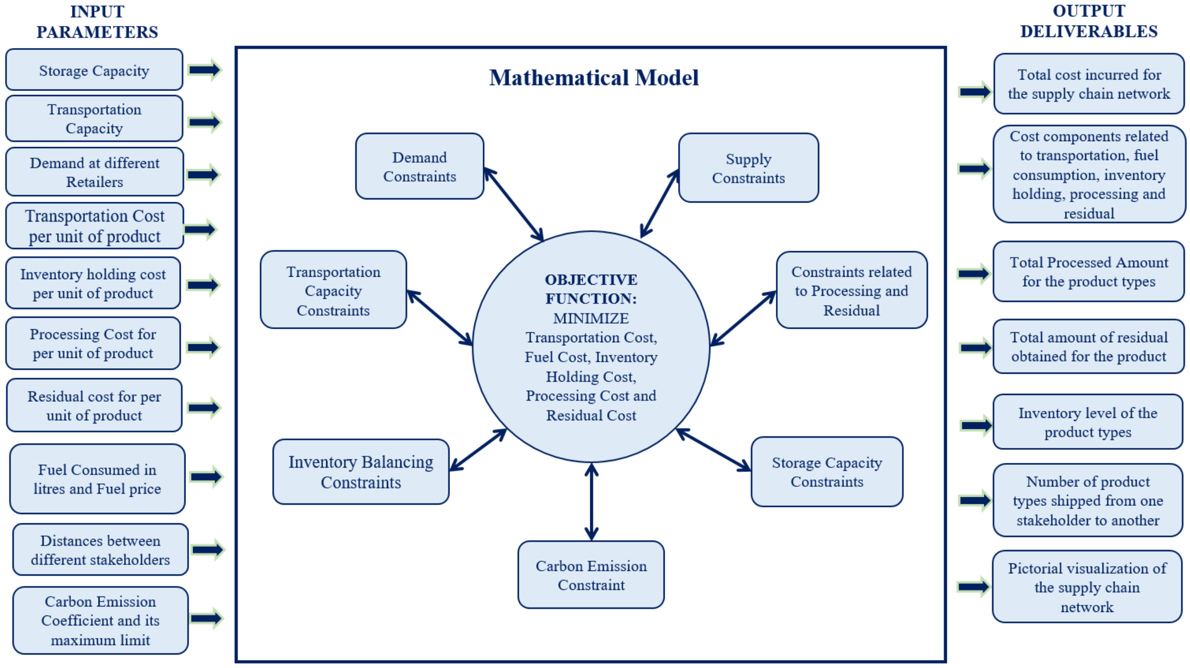


Figure 23 Framework for the logistics model (Source: this study)

The objective function of the mathematical model aims to minimize total cost, comprising of the costs associated with transportation, fuel consumption, inventory holding, processing and residuals/waste. Restrictions associated with carbon emission and waste are considered for addressing the sustainability aspects. Constraints related to supply, processing capacity, storage capacity, demand, carbon emissions, inventory balancing, transportation capacity, and different modes of transportation between different types of plants and facilities are taken into consideration for the model.

2.4.1 MATHEMATICAL MODEL

This section presents the mathematical formulation pertaining to the Norwegian salmon supply chain network. The notation associated with the mathematical model such as sets, indices, parameters, decision variables are presented below. The objective function and the constraints of the mathematical formulation are also presented.

Indices and Sets

i, I Index and Set of Salmon Farm respectively, $i \in I$

j, J Index and Set of Slaughter House respectively, $j \in J$

p, P Index and Set of Primary Processing Plant respectively, $p \in P$

q, Q Index and Set of Secondary Processing Plant respectively, $q \in Q$

u, U Index and Set of Wholesaler respectively, $u \in U$

r, R Index and Set of Retailer respectively, $r \in R$

t, T Index and Set of Time Period respectively, $t \in T$

a Index of Live Salmon product

b Index of HOG (Head on Gutted) product

c Index of Fresh HOG (Fresh Head on Gutted) product

e Index of Whole Fillet product

f Index of Salmon by-product (it includes blocks, loins and portions, off-cut trimming belly flaps, head, tailbone, and skin)

Parameters – Related to Storage Capacity and Transportation Capacity

AC_{it}^{a} Available capacity of Live Salmon product a at Salmon Farm i in period t

Cap_{jt}^{b} Maximum storage capacity of HOG product b at Slaughter House j in period t

Cap_{pt}^{c} Maximum storage capacity of Fresh HOG product c at Primary Processing Plant p in period t

Cap_{qt}^{e} Maximum storage capacity of Whole Fillet product e at Secondary Processing Plant q in period t

Cap_{qt}^{f} Maximum storage capacity of By-product of salmon f at Secondary Processing Plant q in period t

Cap_{ut}^{c} Maximum storage capacity of Fresh HOG product c at Wholesaler u in period t

Cap_{ut}^{e} Maximum storage capacity of Whole Fillet product e at Wholesaler u in period t

Cap_{ut}^{f} Maximum storage capacity of Salmon by-product f at Wholesaler u in period t

TC^{a}_{ijt} Capacity of the transportation mode for the shipment of Live Salmon product a from Salmon Farm i to Slaughter House j in period t

TC^{b}_{jpt} Capacity of the transportation mode for the shipment of HOG product b from Slaughter House j to Primary Processing Plant p in period t

TC^{c}_{pqt} Capacity of the transportation mode for the shipment of Fresh HOG product c from Primary Processing Plant p to Secondary Processing Plant q in period t

TC^{c}_{put} Capacity of the transportation mode for the shipment of Fresh HOG product c from Primary Processing Plant p to Wholesaler u in period t

TC^{c}_{urt} Capacity of the transportation mode for the shipment of Fresh HOG product c from Wholesaler u to Retailer r in period t

TC^{e}_{qut} Capacity of the transportation mode for the shipment of Whole Fillet product e from Secondary Processing Plant q to Wholesaler u in period t

TC^{f}_{qut} Capacity of the transportation mode for the shipment of Salmon by-product f from Secondary Processing Plant q to Wholesaler u in period t

TC^{e}_{urt} Capacity of the transportation mode for the shipment of Whole Fillet product e from Wholesaler u to Retailer r in period t

TC^{f}_{urt} Capacity of the transportation mode for the shipment of Salmon by-product f from Wholesaler u to Retailer r in period t

Parameters – Related to Demand and Cost Components

D^{c}_{rt} Demand of Fresh HOG product c at Retailer r in period t

D^{e}_{rt} Demand of Whole Fillet product e at Retailer r in period t

D^{f}_{rt} Demand of Salmon by-product f at Retailer r in period t

G^{a}_{ijt} Transportation cost for the shipment of per unit Live Salmon a from Salmon Farm i to Slaughter House j in period t

G^{b}_{jpt} Transportation cost for the shipment of per unit HOG Product b from Slaughter House j to Primary Processing Plant p in period t

G^{c}_{pqt} Transportation cost for the shipment of per unit Fresh HOG Product c from Primary Processing Plant p to Secondary Processing Plant q in period t

G^{c}_{put} Transportation cost for the shipment of per unit Fresh HOG Product c from Primary Processing Plant p to Wholesaler u in period t

G^{c}_{urt} Transportation cost for the shipment of per unit Fresh HOG Product c from Wholesaler u to Retailer r in period t

G^{e}_{qut} Transportation cost for the shipment of per unit Whole Fillet product e from Secondary Processing Plant q to Wholesaler u in period t

G^{f}_{qut} Transportation cost for the shipment of per unit Salmon by-product f from Secondary Processing Plant q to Wholesaler u in period t

G^{e}_{urt} Transportation cost for the shipment of per unit Whole Fillet product e from Wholesaler u to Retailer r in period t

G^{f}_{urt} Transportation cost for the shipment of per unit Salmon by-product f from Wholesaler u to Retailer r in period t

H^{b}_{jt} Inventory holding cost per unit of HOG product b at Slaughter House j in period t

H^{c}_{pt} Inventory holding cost per unit of Fresh HOG product c at Primary Processing Plant p in period t

H^{c}_{ut} Inventory holding cost per unit of Fresh HOG product c at Wholesaler u in period t

H^{e}_{qt} Inventory holding cost per unit of Whole Fillet product e at Secondary Processing Plant q in period t

H^{f}_{qt} Inventory holding cost per unit of Salmon by-product f at Secondary Processing Plant q in period t

H^{e}_{ut} Inventory holding cost per unit of Whole Fillet product e at Wholesaler u in period t

H^{f}_{ut} Inventory holding cost per unit of Salmon by-product f Wholesaler u in period t

PC^{b}_{jt} Processing cost for per unit of HOG product b at Slaughter House j in period t

PC_{pt}^{c} Processing cost for per unit of Fresh HOG product c at Primary Processing Plant p in period t

PC_{qt}^{e} Processing cost for per unit of Whole Fillet product e at Secondary Processing Plant q in period t

PC_{qt}^{f} Processing cost for per unit of Salmon by-product f at Secondary Processing Plant q in period t

PW_{jt}^{a} Residual cost for per unit of residual amount obtained after processing Live Salmon product a at Slaughter House j in period t

PW_{pt}^{b} Residual cost for per unit of residual amount obtained after processing HOG product b at Primary Processing Plant p in period t

PW_{qt}^{c} Residual cost associated with per unit of residual amount obtained after processing Fresh HOG product c at Secondary Processing Plant q in period t

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

F_{ij}^{a} Fuel consumed (in litres per unit distance per unit product) in shipping Live Salmon a via certain mode of transport from Salmon Farm i to Slaughter House j

F_{jp}^{b} Fuel consumed (in litres per unit distance per unit product) in shipping HOG product b via certain transport mode from Slaughter House j to Primary Processing Plant p

F_{pq}^{c} Fuel consumed (in litres per unit distance per unit product) in shipping Fresh HOG product c via certain transport mode from Primary Processing Plant p to Secondary Processing Plant q

F_{pu}^{c} Fuel consumed (in litres per unit distance per unit product) while shipping Fresh HOG product c via certain mode of transportation from Primary Processing Plant p to Wholesaler u

F_{qu}^{e} Fuel consumed (in litres per unit distance per unit product) while shipping Whole Fillet product e via certain mode of transportation from Secondary Processing Plant q to Wholesaler u

F_{qu}^{f} Fuel consumed (in litres per unit distance per unit product) while shipping Salmon by-product f via certain mode of transportation from Secondary Processing Plant q to Wholesaler u

F_{ur}^{c} Fuel consumed (in litres per unit distance per unit product) while shipping Fresh HOG product c via certain mode of transportation from Wholesaler u to Retailer r

F_{ur}^{e} Fuel consumed (in litres per unit distance per unit product) while shipping Whole Fillet product e via certain mode of transportation from Wholesaler u to Retailer r

F_{ur}^{f} Fuel consumed (in litres per unit distance per unit product) while shipping Salmon by-product f via certain mode of transportation from Wholesaler u to Retailer r

α_t Fuel price (Euro per litre) in period t

E^{CO_2} Carbon emission coefficient associated with the fuel

E^{Max} Maximum allowable carbon emission limit

$W_{ij}, W_{jp}, W_{pq}, W_{pu}, W_{qu}, W_{ur}$ Distance from Salmon Farm i to Slaughter House j; Distance from Slaughter House j to Primary Processing Plant p; Distance from Primary Processing Plant p to Secondary Processing Plant q; Distance from Primary Processing Plant p to Wholesaler u; Distance from Secondary Processing Plant q to Wholesaler u; Distance from Wholesaler u to Retailer r respectively

Continuous Variables – Related to the Processed Amount and Wastage / Residual Amount

TP_{jt}^{b} Total processed amount of HOG product b at Slaughter House j in period t

TP_{pt}^{c} Total processed amount of Fresh HOG product c at Primary Processing Plant p in period t

TP_{qt}^{e} Total processed amount of Whole Fillet product e at Secondary Processing Plant q in period t

TP_{qt}^{f} Total processed amount of Salmon by-product f at Secondary Processing Plant q in period t

TW^{a}_{jt} Total amount of residual obtained after processing Live Salmon product a at Slaughter House j in period t

TW^{b}_{pt} Total amount of residual obtained after processing HOG product b at Primary Processing Plant p in period t

TW^{c}_{qt} Total amount of residual obtained after processing Fresh HOG product c at Secondary Processing Plant q in period t

Continuous Variables – Related to the Inventory Level

IP^{b}_{jt} Inventory of HOG product b at Slaughter House j in period t

IP^{c}_{pt} Inventory of Fresh HOG product c at Primary Processing Plant p in period t

IP^{c}_{ut} Inventory of Fresh HOG product c at Wholesaler u in period t

IP^{e}_{qt} Inventory of Whole Fillet product e at Secondary Processing Plant q in period t

IP^{f}_{qt} Inventory of Salmon by-product f at Secondary Processing Plant q in period t

IP^{e}_{ut} Inventory of Whole Fillet product e at Wholesaler u in period t

IP^{f}_{ut} Inventory of Salmon by-product f at Wholesaler u in period t

Integer Variables – Related to Amount Transported

X^{a}_{ijt} Total amount of Live Salmon a transported from Salmon Farm i to Slaughter House j in period t

X^{b}_{jpt} Total amount of HOG product b transported from Slaughter House j to Primary Processing Plant p in period t

X^{c}_{pqt} Total amount of Fresh HOG product c transported from Primary Processing Plant p to Secondary Processing Plant q in period t

X^{c}_{put} Total amount of Fresh HOG product c transported from Primary Processing Plant p to Wholesaler u in period t

X^{e}_{qut} Total amount of Whole Fillet product e transported from Secondary Processing Plant q to Wholesaler u in period t

X^{f}_{qut} Total amount of Salmon by-product f transported from Secondary Processing Plant q to Wholesaler u in period t

X^{c}_{urt} Total amount of Fresh HOG product c transported from Wholesaler u to Retailer r in period t

X^{e}_{urt} Total amount of Whole Fillet product e from Wholesaler u to Retailer r in period t

X^{f}_{urt} Total amount of Salmon by-product f transported from Wholesaler u to Retailer r in period t

Objective Function of Model M

Minimize
Total Cost = Transportation Cost + Fuel Cost + Inventory Holding Cost + Processing Cost + Wastage/Residual Cost (1)

Transportation Cost,

$$C^{Tcost} = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} G^{a}_{ijt}X^{a}_{ijt} + \sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{t=1}^{T} G^{b}_{jpt}X^{b}_{jpt} + \sum_{p=1}^{P}\sum_{q=1}^{Q}\sum_{t=1}^{T} G^{c}_{pqt}X^{c}_{pqt} + \sum_{q=1}^{Q}\sum_{u=1}^{U}\sum_{t=1}^{T}\left[G^{e}_{qut}X^{e}_{qut} + G^{f}_{qut}X^{f}_{qut}\right] + \sum_{u=1}^{U}\sum_{r=1}^{R}\sum_{t=1}^{T}\left[G^{e}_{urt}X^{e}_{urt} + G^{f}_{urt}X^{f}_{urt}\right] + \sum_{p=1}^{P}\sum_{u=1}^{U}\sum_{t=1}^{T} G^{c}_{put}X^{c}_{put} + \sum_{u=1}^{U}\sum_{r=1}^{R}\sum_{t=1}^{T} G^{c}_{urt}X^{c}_{urt} \quad (2)$$

Fuel Cost,

$$C^{Fcost} = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} \alpha_t F^{a}_{ij}W_{ij}X^{a}_{ijt} + \sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{t=1}^{T} \alpha_t F^{b}_{jp}W_{jp}X^{b}_{jpt} + \sum_{p=1}^{P}\sum_{q=1}^{Q}\sum_{t=1}^{T} \alpha_t F^{c}_{pq}W_{pq}X^{c}_{pqt} + \sum_{q=1}^{Q}\sum_{u=1}^{U}\sum_{t=1}^{T} \alpha_t\left[F^{e}_{qu}X^{e}_{qut} + F^{f}_{qu}X^{f}_{qut}\right]W_{qu} + \sum_{u=1}^{U}\sum_{r=1}^{R}\sum_{t=1}^{T} \alpha_t\left[F^{e}_{ur}X^{e}_{urt} + F^{f}_{ur}X^{f}_{urt}\right]W_{ur} + \sum_{p=1}^{P}\sum_{u=1}^{U}\sum_{t=1}^{T} \alpha_t F^{c}_{pu}W_{pu}X^{c}_{put} + \sum_{u=1}^{U}\sum_{r=1}^{R}\sum_{t=1}^{T} \alpha_t F^{c}_{ur}W_{ur}X^{c}_{urt} \quad (3)$$

Inventory Holding Cost,

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

Processing Cost,

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

Wastage/Residual Cost,

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

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/residual cost.

Equation (2) depicts the transportation cost and comprises of seven terms and each deals with the shipment of different types of salmon products. The first term computes the transportation cost for the shipment of live salmon product from the salmon farms to the slaughterhouses. The second term aims to determine the transportation cost for the movement of HOG (head on gutted) product from slaughterhouses to the primary processing plants. The third term estimates the transportation cost for the shipping fresh HOG product from primary processing plants to the secondary processing plants. The fourth and fifth terms determine the transportation cost associated with shipment of whole fillet product and salmon by-product from secondary processing plants to the wholesalers and from wholesalers to the retailers respectively. The sixth and seventh terms compute the transportation cost related to the movement of fresh HOG product from primary processing plants to the wholesalers and also from the wholesalers to the retailers respectively.

Equation (3) comprises of seven terms and it depicts the fuel cost associated with the total fuel consumed while transporting different types of salmon products while considering the varying fuel prices. The first term computes the fuel cost for the transportation of the live salmon product from the salmon farms to the slaughterhouses. The second term helps to estimate the fuel cost associated with the shipment of HOG (head on gutted) product from slaughterhouses to the primary processing plants. The third term determines the fuel cost associated with the transportation of fresh HOG product from primary processing plants to the secondary processing plants. The fourth and fifth terms aim to compute the fuel cost related to the shipment of whole fillet product and salmon by-product 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 product from primary processing plants to wholesalers and then from wholesalers to retailers respectively.

Equation (4) presents the overall inventory holding cost and it comprises of five terms. The first term estimates the inventory holding cost for the HOG (head on gutted) product at the slaughterhouses. The second and the third terms compute the inventory holding cost for the fresh HOG product at primary processing plants and wholesalers respectively. The fourth and fifth terms determine the inventory holding cost associated with whole fillet product and salmon by-product at secondary processing plants and wholesalers respectively.

Equation (5) depicts the processing cost and it comprises of three terms. The first term estimates the processing cost incurred for obtaining HOG (head on gutted) product at the slaughterhouses. The second term computes the processing cost incurred for obtaining fresh HOG product at the primary processing plants. The third term estimates the processing cost associated with whole fillet product and salmon by-product at secondary processing plants.

Equation (6) gives the wastage/residual cost related to different types of products and this equation comprises of three terms. The first term depicts the residual cost incurred from the live salmon products at the slaughterhouses. The second term provides the residual cost incurred from the HOG (head on gutted) product at the primary processing plants. The third term helps to estimate the residual cost incurred from the fresh HOG product at the secondary processing plants.

Supply Constraints,

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

Constraints related to Processing and Wastage/Residual,

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

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

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

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

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

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

Equation (7) ensures that the number of live salmon products shipped from a certain salmon farm to the slaughterhouses should be equal to the available capacity of live salmon products at the salmon farm.

Equation (8) states that the total number of HOG (head on gutted) product and the residual amount obtained after processing at the slaughter house is depended on the total amount of live salmon received at the slaughter house from different salmon farms.

Equation (9) ensures that the total amount of fresh HOG (head on gutted) product obtained after processing at the primary processing plant is depended on the total amount of HOG product received from various slaughter houses.

Equation (10) depicts that the total amount of whole fillet product and salmon by-product obtained after processing at the secondary processing plant are depended on the amount of fresh HOG (head on gutted) product received at the secondary processing plant from various primary processing plants.

Equations (11), (12) and (13) present the range within which the residuals are obtained after processing live salmon product, hog product and fresh hog product respectively.

Storage Capacity Constraints,

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

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

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

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

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

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

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

Equations (14) – (20) present the storage capacity constraints.

Equation (14) ensures that the sum of the available inventory of the HOG (head on gutted) product from previous period and the total amount of HOG product processed should be less than or equal to the maximum storage capacity of HOG product at the slaughterhouse.

Equation (15) ensures that the sum of the available inventory of fresh HOG (head on gutted) product from the previous period and the total amount of fresh HOG product processed should be less than or equal to the maximum storage capacity of the fresh HOG product at the primary processing plant.

Equations (16) – (17) state that the storage capacity of the secondary processing plant need to be maintained for both whole fillet product and salmon by-product respectively while considering the available inventory from the previous period and total number of each type of product transported from various primary processing plants.

Equation (18) ensures that the sum of the total amount of fresh HOG (head on gutted) product shipped from various primary processing plants to the particular wholesaler and the available inventory of fresh HOG product from the previous period at the wholesaler should be less than or equal to the maximum storage capacity of the fresh HOG product at the wholesaler.

Equations (19) – (20) state that the storage capacity of the wholesaler need to be maintained for whole fillet product and salmon by-product respectively while considering the available inventory of both the products from the previous period and the total number of each type of product transported from various secondary processing plants.

Inventory Balancing Constraints,

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

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

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

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

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

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

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

Equation (21) depicts the inventory balancing constraint for the HOG (head on gutted) product at the slaughterhouse.

Equations (22) and (23) provide the inventory balancing constraints for the fresh HOG (head on gutted) product at the primary processing plant and the wholesaler respectively.

Equations (24) and (25) present the inventory balancing constraints at the secondary processing plant for the whole fillet product and salmon by-product respectively.

Equations (26) and (27) provide the inventory balancing constraints for the whole fillet product and salmon by-product respectively at the wholesaler.

Demand Constraints and Carbon Emission Constraint,

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

$$\sum_{u=1}^{U} X_{urt}^{e} = D_{rt}^{e} \qquad \forall r \in R,\ \forall t \in T \qquad (29)$$

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

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

Equations (28), (29) and (30) present the demand constraints at the retailer for different types of products such as fresh HOG (head on gutted) product, whole salmon fillet product and salmon by-product respectively which are being shipped from the wholesaler to the retailer.

Equation (31) ensures that the overall carbon emission emitted from transportation of various salmon products should be less than or equal to the maximum allowable carbon emission limit.

Transportation Capacity Constraints,

$$\begin{cases} X_{ijt}^{a} \leq TC_{ijt}^{a} & For\ TC_{ijt}^{a} > 0 \\ X_{ijt}^{a} = 0 & For\ TC_{ijt}^{a} = 0 \end{cases} \qquad \forall i \in I,\ \forall j \in J,\ \forall t \in T \qquad (32)$$

$$\begin{cases} X_{jpt}^{b} \leq TC_{jpt}^{b} & For\ TC_{jpt}^{b} > 0 \\ X_{jpt}^{b} = 0 & For\ TC_{jpt}^{b} = 0 \end{cases} \qquad \forall j \in J,\ \forall p \in P,\ \forall t \in T \qquad (33)$$

$$\begin{cases} X_{pqt}^{c} \leq TC_{pqt}^{c} & For\ TC_{pqt}^{c} > 0 \\ X_{pqt}^{c} = 0 & For\ TC_{pqt}^{c} = 0 \end{cases} \qquad \forall p \in P,\ \forall q \in Q,\ \forall t \in T \qquad (34)$$

$$\begin{cases} X^c_{put} \leq TC^c_{put} & For\ TC^c_{put} > 0 \\ X^c_{put} = 0 & For\ TC^c_{put} = 0 \end{cases} \qquad \forall p \in P,\ \forall u \in U,\ \forall t \in T \qquad (35)$$

$$\begin{cases} X^e_{qut} \leq TC^e_{qut} & For\ TC^e_{qut} > 0 \\ X^e_{qut} = 0 & For\ TC^e_{qut} = 0 \end{cases} \qquad \forall q \in Q,\ \forall u \in U,\ \forall t \in T \qquad (36)$$

$$\begin{cases} X^f_{qut} \leq TC^f_{qut} & For\ TC^f_{qut} > 0 \\ X^f_{qut} = 0 & For\ TC^f_{qut} = 0 \end{cases} \qquad \forall q \in Q,\ \forall u \in U,\ \forall t \in T \qquad (37)$$

$$\begin{cases} X^c_{urt} \leq TC^c_{urt} & For\ TC^c_{urt} > 0 \\ X^c_{urt} = 0 & For\ TC^c_{urt} = 0 \end{cases} \qquad \forall u \in U,\ \forall r \in R,\ \forall t \in T \qquad (38)$$

$$\begin{cases} X^e_{urt} \leq TC^e_{urt} & For\ TC^e_{urt} > 0 \\ X^e_{urt} = 0 & For\ TC^e_{urt} = 0 \end{cases} \qquad \forall u \in U,\ \forall r \in R,\ \forall t \in T \qquad (39)$$

$$\begin{cases} X^f_{urt} \leq TC^f_{urt} & For\ TC^f_{urt} > 0 \\ X^f_{urt} = 0 & For\ TC^f_{urt} = 0 \end{cases} \qquad \forall u \in U,\ \forall r \in R,\ \forall t \in T \qquad (40)$$

Non-Negative Integers,

$$TP^b_{jt}, TP^c_{pt}, TP^e_{qt}, TP^f_{qt}, TW^a_{jt}, TW^b_{pt}, TW^c_{qt} \geq 0 \qquad \forall j \in J,\ \forall p \in P,\ \forall q \in Q,\ \forall t \in T \qquad (41)$$

$$IP^b_{jt}, IP^c_{pt}, IP^c_{ut}, IP^e_{qt}, IP^f_{qt}, IP^e_{ut}, IP^f_{ut} \geq 0 \quad \forall j \in J,\ \forall p \in P,\ \forall u \in U,\ \forall q \in Q,\ \forall t \in T \qquad (42)$$

$$X^a_{ijt}, X^b_{jpt}, X^c_{pqt}, X^c_{put}, X^e_{qut}, X^f_{qut}, X^c_{urt}, X^e_{urt}, X^f_{urt} \geq 0$$

$$\forall i \in I,\ \forall j \in J,\ \forall p \in P,\ \forall q \in Q,\ \forall u \in U,\ \forall r \in R,\ \forall t \in T \qquad (43)$$

Equations (32) – (40) state that the number of products flowing on each transportation link should be less than or equal to the maximum transportation capacity. Moreover, equations (32) – (40) also state that there would be no transportation of products between any two stakeholders if there is no possible transportation capacity available on the route.

Equations (41) – (43) presents the non-negative integers.

2.4.2. Two – Stage Reformulation of the Mathematical Model

The mathematical model presented in the previous section (2.4.1) is complex given the involvement of a variety of stakeholders such as salmon farms, slaughterhouses, primary processing plants, secondary processing plants, wholesalers and retailers.

There is limited information that can be drawn from a single company, as few completely cover both the supply and the demand ends of the value chain. In addition, the processing of raw material into a number of different products also complicates the analysis. Therefore, the aforementioned mathematical model is decomposed into two separate mathematical formulations for solving purpose.

2.4.2.1. First Stage of the Salmon Model

The first stage of the mathematical model N1 addresses the supply chain network comprising of Salmon Farms, Slaughter Houses, Primary Processing Plants, Secondary Processing Plants and Wholesaler. The main intention of this first mathematical model is to meet the demand of the Secondary Processing Plants and Wholesalers for Fresh HOG (Head on Gutted) product. The objective function for the first stage of the Salmon Model N1 is given below.

Objective function of Model N1

Minimize

Total Cost = Transportation Cost + Fuel Cost + Inventory Holding Cost + Processing Cost + Wastage/Residual Cost (44)

Transportation Cost,

$$C^{Tcost} = \left. \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} G_{ijt}^{a} X_{ijt}^{a} + \sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{t=1}^{T} G_{jpt}^{b} X_{jpt}^{b} + \sum_{p=1}^{P}\sum_{q=1}^{Q}\sum_{t=1}^{T} G_{pqt}^{c} X_{pqt}^{c} + \sum_{p=1}^{P}\sum_{u=1}^{U}\sum_{t=1}^{T} G_{put}^{c} X_{put}^{c} \right] \quad (45)$$

Fuel Cost,

$$C^{Fcost} = \left. \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} \alpha_t F_{ij}^{a} W_{ij} X_{ijt}^{a} + \sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{t=1}^{T} \alpha_t F_{jp}^{b} W_{jp} X_{jpt}^{b} + \sum_{p=1}^{P}\sum_{q=1}^{Q}\sum_{t=1}^{T} \alpha_t F_{pq}^{c} W_{pq} X_{pqt}^{c} + \sum_{p=1}^{P}\sum_{u=1}^{U}\sum_{t=1}^{T} \alpha_t F_{pu}^{c} W_{pu} X_{put}^{c} \right] \quad (46)$$

Inventory Holding Cost,

$$C^{Icost} = \left. \sum_{j=1}^{J}\sum_{t=1}^{T} H_{jt}^{b} IP_{jt}^{b} + \sum_{p=1}^{P}\sum_{t=1}^{T} H_{pt}^{c} IP_{pt}^{c} \right] \quad (47)$$

Processing Cost,

$$C^{Pcost} = \sum_{j=1}^{J}\sum_{t=1}^{T} PC_{jt}^{b} TP_{jt}^{b} + \sum_{p=1}^{P}\sum_{t=1}^{T} PC_{pt}^{c} TP_{pt}^{c} \Bigg] \tag{48}$$

Wastage/Residual Cost,

$$C^{Wcost} = \sum_{j=1}^{J}\sum_{t=1}^{T} PW_{jt}^{a} TW_{jt}^{a} + \sum_{p=1}^{P}\sum_{t=1}^{T} PW_{pt}^{b} TW_{pt}^{b} \tag{49}$$

Equation (44) presents the objective function for the first stage of the salmon model comprises of the cost components associated with the transportation of salmon products, fuel cost incurred during shipment process, cost related to holding inventory and cost associated with processing and residual.

The transportation cost given in equation (45) is associated with the shipment of live salmon products from salmon farms to slaughter houses, shipment of HOG product from slaughterhouses to primary processing plants, shipment of fresh HOG product from primary processing plants to secondary processing plant and wholesalers.

Equation (46) presents the fuel cost depicting the cost incurred for the fuel consumption associated with the transportation of different varieties of products from salmon farms to slaughter houses to primary processing plants and finally to secondary processing plants and wholesalers.

Equation (47) presents the inventory holding cost associated with holding inventory at slaughterhouses and primary processing plants.

Equations (48) and (49) provide the overall processing cost and residual cost incurred at the slaughterhouses and primary processing plants.

Constraints of the first stage of the salmon model comprises of the supply constraints given in equation (7). Processing and residual constraints for the first stage salmon model are given in equations (8), (9), (11) and (12). Although, the following equations (50), (51), (52) and (53) given below related to the processing and residual can be used in place of the equations (8), (9), (11) and (12).

$$TP_{jt}^{b} = 0.9\sum_{i=1}^{I} X_{ijt}^{a} \qquad \forall j \in J,\ \forall t \in T \tag{50}$$

$$TW_{jt}^{a} = 0.1\sum_{i=1}^{I} X_{ijt}^{a} \qquad \forall j \in J,\ \forall t \in T \tag{51}$$

$$TP_{pt}^{c} = 0.9\sum_{j=1}^{J} X_{jpt}^{b} \qquad \forall p \in P,\ \forall t \in T \tag{52}$$

$$TW_{pt}^{b} = 0.1\sum_{j=1}^{J} X_{jpt}^{b} \qquad \forall p \in P,\ \forall t \in T \qquad (53)$$

When the exact percentages of processed and wastage/residual amounts is known beforehand then the equations (50), (51), (52) and (53) can be employed in place of equations (8), (9), (11) and (12). The first stage salmon model has storage capacity constraints for slaughterhouses and primary processing plants given in equations (14) and (15). Moreover, the first stage salmon model also has inventory balancing constraints given in equations (21) and (22). The main aim of the first stage Norwegian salmon model is to meet the demand of secondary processing plants and wholesalers for fresh HOG (head on gutted) product. Therefore, the demand constraints for first stage model is given as,

$$\sum_{p=1}^{P} X_{pqt}^{c} = D_{qt}^{c} \qquad \forall q \in Q,\ \forall t \in T \qquad (54)$$

$$\sum_{p=1}^{P} X_{put}^{c} = D_{ut}^{c} \qquad \forall u \in U,\ \forall t \in T \qquad (55)$$

Equations (54) and (55) provides the demand constraint of the first stage salmon supply model for meeting the demand of fresh HOG product at slaughter houses and primary processing plants in different time periods. Here, D_{qt}^{c} is the demand of fresh HOG c at secondary processing plant q in time period t. Moreover, D_{ut}^{c} is the demand of fresh HOG c at wholesaler u in time period t. The carbon emission constraint for the first stage salmon model is given by the following equation,

$$E^{CO_2}\left[\begin{array}{l}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} F_{ij}^{a} W_{ij} X_{ijt}^{a} + \sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{t=1}^{T} F_{jp}^{b} W_{jp} X_{jpt}^{b} + \sum_{p=1}^{P}\sum_{q=1}^{Q}\sum_{t=1}^{T} F_{pq}^{c} W_{pq} X_{pqt}^{c} \\ + \sum_{p=1}^{P}\sum_{u=1}^{U}\sum_{t=1}^{T} F_{pu}^{c} W_{pu} X_{put}^{c}\end{array}\right] \le E^{Max} \qquad (56)$$

Equation (56) aims to address the carbon emission for the shipment of live salmon products from salmon farms to slaughter houses. It also estimates the carbon emission related to the shipment of HOG (head on gutted) product from slaughterhouses to primary processing plants.

Finally, equation (56) determines the carbon emission related to the transportation of fresh HOG product from primary processing plants to secondary processing plants and wholesalers. The first stage salmon model also has certain transportation capacity constraints provided in equations (32), (33), (34) and (35). Therefore, the objective function of the first stage salmon model is given in equation (44). The constraints of the first stage salmon model are given in equations (7), (14), (15), (21), (22), (32), (33), (34), (35), (50), (51), (52), (53), (54), (55) and (56). The next sub-section provides detailed information about the second stage salmon model.

2.4.2.1. Second Stage of the Salmon Model

The second stage of the salmon 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 the fresh HOG (head on gutted) product into whole fillet, salmon by-product and some residual amount. The total demand of fresh HOG received at secondary processing plant is used for processing purpose and later the demand of whole fillet and salmon-by product at retailer is met via wholesalers. The objective function of the second stage salmon model N2 is given below,

Objective function of Model N2

Minimize
Total Cost = Transportation Cost + Fuel Cost + Inventory Holding Cost
+ Processing Cost + Wastage/Residual Cost (57)

Transportation Cost,

$$C^{Tcost} = \sum_{q=1}^{Q}\sum_{u=1}^{U}\sum_{t=1}^{T}\left[G^{e}_{qut}X^{e}_{qut} + G^{f}_{qut}X^{f}_{qut}\right] + \sum_{u=1}^{U}\sum_{r=1}^{R}\sum_{t=1}^{T}\left[G^{e}_{urt}X^{e}_{urt} + G^{f}_{urt}X^{f}_{urt}\right] + \sum_{u=1}^{U}\sum_{r=1}^{R}\sum_{t=1}^{T}G^{c}_{urt}X^{c}_{urt} \quad (58)$$

Fuel Cost,

$$C^{Fcost} = \sum_{q=1}^{Q}\sum_{u=1}^{U}\sum_{t=1}^{T}\alpha_t\left[F^{e}_{qu}X^{e}_{qut} + F^{f}_{qu}X^{f}_{qut}\right]W_{qu} + \sum_{u=1}^{U}\sum_{r=1}^{R}\sum_{t=1}^{T}\alpha_t\left[F^{e}_{ur}X^{e}_{urt} + F^{f}_{ur}X^{f}_{urt}\right]W_{ur} + \sum_{u=1}^{U}\sum_{r=1}^{R}\sum_{t=1}^{T}\alpha_t F^{c}_{ur}W_{ur}X^{c}_{urt} \quad (59)$$

Inventory Holding Cost,

$$C^{Icost} = \sum_{u=1}^{U}\sum_{t=1}^{T} H_{ut}^{c} IP_{ut}^{c} + \sum_{q=1}^{Q}\sum_{t=1}^{T}\left[H_{qt}^{e} IP_{qt}^{e} + H_{qt}^{f} IP_{qt}^{f} \right] + \sum_{u=1}^{U}\sum_{t=1}^{T}\left[H_{ut}^{e} IP_{ut}^{e} + H_{ut}^{f} IP_{ut}^{f} \right]\Bigg] \tag{60}$$

Processing Cost,

$$C^{Pcost} = \sum_{q=1}^{Q}\sum_{t=1}^{T}\left[PC_{qt}^{e} TP_{qt}^{e} + PC_{qt}^{f} TP_{qt}^{f} \right]\Bigg] \tag{61}$$

Wastage/Residual Cost,

$$C^{Wcost} = \sum_{q=1}^{Q}\sum_{t=1}^{T} PW_{qt}^{c} TW_{qt}^{c} \tag{62}$$

Equation (57) presents the objective function for the second stage of the salmon supply model, which comprises of the transportation cost, fuel cost, inventory holding cost, processing cost and residual cost.

Equation (58) depicts the transportation cost for the shipment of whole fillet and salmon by-product from secondary processing plants to retailers via wholesalers. Equation (58) also estimates the transportation cost for the shipment of fresh HOG from wholesalers to retailers.

Equation (59) provides the fuel cost associated with the total fuel consumed for the product transportation from secondary processing plants to wholesalers and product shipment from wholesalers to retailers.

Equation (60) estimates the inventory holding cost for holding inventory of whole fillet and salmon by-product at secondary processing plants and wholesalers and also holding inventory of fresh HOG (head on gutted) at wholesalers.

Equations (61) and (62) provide the processing cost and wastage/residual cost respectively at the secondary processing plants.

Constraints for the second stage salmon model comprises of the processing and wastage/residual constraint given in equations (10) and (13). Although, the equations (63), (64) and (65) given below can be used in place of equations (10) and (13), when the exact percentages of whole fillet, salmon by-product and residual amount obtained after processing fresh HOG (head on gutted) product are known beforehand.

$$TP_{qt}^{e} = 0.7 D_{qt}^{c} \qquad \forall q \in Q,\ \forall t \in T \tag{63}$$

$$TP_{qt}^{f} = 0.2 D_{qt}^{c} \qquad \forall q \in Q,\ \forall t \in T \tag{64}$$

$$TW_{qt}^{c} = 0.1 D_{qt}^{c} \qquad \forall q \in Q,\ \forall t \in T \tag{65}$$

Equations (63) and (64) helps to estimate the total processed amount of whole fillet and salmon by-product obtained after processing the fresh hog at the secondary processing plant.

Equation (65) helps to determine the residual amount obtained after processing the total amount of fresh HOG at the secondary processing plant. The second stage salmon model also comprises of the supply constraints for secondary processing plants and wholesalers as given below,

$$\sum_{u=1}^{U} X_{qut}^{e} \leq TP_{qt}^{e} \qquad \forall q \in Q,\ \forall t \in T \qquad (66)$$

$$\sum_{u=1}^{U} X_{qut}^{f} \leq TP_{qt}^{f} \qquad \forall q \in Q,\ \forall t \in T \qquad (67)$$

$$\sum_{r=1}^{R} X_{urt}^{c} \leq D_{ut}^{c} \qquad \forall u \in U,\ \forall t \in T \qquad (68)$$

Equations (66) and (67) present the supply constraints for whole fillet and salmon by-product at the secondary processing plants. The equations state that the total amount of whole fillet and salmon by-product shipped from a specific secondary processing plant to several wholesalers should be less than or equal to the total processed amount of whole fillet and salmon by-product respectively at the secondary processing plant.

Equation (68) states that the number of fresh HOG (head on gutted) products flowing from a wholesaler to several retailers should be less than or equal to the demand of the particular wholesaler for the fresh HOG product which is met from several primary processing plants. The second stage salmon model has storage capacity constraints given in equations (16), (17), (19) and (20) and these constraints ensure the restriction of storage capacity for whole fillet and salmon by-product at secondary processing plants and wholesalers. Moreover, the storage capacity constraint for fresh HOG at the wholesaler can be expressed in the following way,

$$D_{ut}^{c} \leq \begin{cases} Cap_{ut}^{c} - IP_{u(t-1)}^{c}, & for\ t > 1 \\ Cap_{ut}^{c}, & for\ t = 1,\ IP_{u0}^{c} = 0 \end{cases} \qquad \forall u \in U,\ \forall t \in T \qquad (69)$$

Equation (69) presents the relationship between inventory level of fresh HOG at the wholesaler with the capacity of the wholesaler and demand of the wholesaler, which is met from the primary processing plants. The second stage of salmon model comprises of inventory balancing constraint for fresh HOG at the wholesaler, which can be expressed in the following way,

$$IP_{ut}^{c} = \begin{cases} D_{ut}^{c} + IP_{u(t-1)}^{c} - \sum_{r=1}^{R} X_{urt}^{c}, & for\ t > 1 \\ D_{ut}^{c} - \sum_{r=1}^{R} X_{urt}^{c}, & for\ t = 1 \end{cases} \qquad \forall u \in U,\ \forall t \in T \qquad (70)$$

Equations (70) presents the inventory balancing constraint for fresh HOG at the wholesaler considering the demand of the wholesaler which is met from various primary processing plants and the total fresh HOG product shipped to several retailers from the wholesaler. Moreover, the equation (70) also takes into consideration the inventory level of fresh HOG at the wholesaler in the previous time period.

The second stage of salmon model has other inventory balancing constraints associated with whole fillet and salmon by-product at secondary processing plants and wholesalers. The inventory balancing constraints are given in equations (24), (25), (26) and (27). The second stage of salmon model also has demand constraints associated with the demand of retailers for products such as fresh HOG, whole fillet and salmon by-product and these constraints are given in equations (28), (29) and (30). The carbon emission constraint for the second stage of salmon model is expressed in the following way,

$$E^{CO_2}\left[\begin{array}{l}\sum_{q=1}^{Q}\sum_{u=1}^{U}\sum_{t=1}^{T}\left[F^{e}_{qu}X^{e}_{qut}+F^{f}_{qu}X^{f}_{qut}\right]W_{qu}+\sum_{u=1}^{U}\sum_{r=1}^{R}\sum_{t=1}^{T}F^{c}_{ur}W_{ur}X^{c}_{urt}\\+\sum_{u=1}^{U}\sum_{r=1}^{R}\sum_{t=1}^{T}\left[F^{e}_{ur}X^{e}_{urt}+F^{f}_{ur}X^{f}_{urt}\right]W_{ur}\end{array}\right]\leq E^{Max} \qquad (71)$$

Equation (71) helps to estimate the carbon emission incurred for the shipment of whole fillet and salmon by-product from secondary processing plants to retailers via wholesalers. It also determines the carbon emission incurred for the shipment of fresh HOG from wholesalers to retailers. The second stage of the salmon model also comprises of transportation capacity constraints, which are given in equations (36), (37), (38), (39) and (40). Therefore, the objective function of the second stage salmon model is given in equation (57). The constraints of the second stage salmon model are given as equations (16), (17), (19), (20), (24), (25), (26), (27), (28), (29), (30), (36), (37), (38), (39), (40), (63), (64), (65), (66), (67), (68), (69), (70) and (71). The validation of the proposed mathematical formulation and two – stage formulation are carried out by considering the real-world case study of Norwegian salmon supply chain organization. Section 3 provides the result and discussion associated with the real-world case study.

2.4.3. DATA COLLECTION FRAMEWORK

Conceptualisation of the supply chain network constitutes the first step of logistics system modelling. Following that is the development of a mathematical modelling framework as described in the previous sections (2.4.1 and 2.4.2). Before any result can be estimated and discussed, a data collection framework is required to enable simulation of logistics operations that will allow scenario testing. A data collection brief introducing the purpose of VALUMICS T71 study was used to invite potential company respondents. Information about the benefits for an individual company to join the study was also elaborated in the brief, which include opportunities for the company to embed environmental and social credentials into the company's logistics systems. The full brief is appended in Annex I. VALUMICS partners helped identify potential company informants.

A data collection framework in a questionnaire form (based on the mathematical model formulation) to collect information about company's supply chain operation was developed and used to complete the data set, to test the model developed (Annex II). The data was collated via a workshop as reported in VALUMICS D4.5 (2019) and a series of interviews with a company.

An excel-based data framework was developed to ease capture of the figures required to run the mathematical model drawn from the interviews. For the logistics system case study (i.e. Norwegian salmon), six key questions were posed toward a selected company respondent (Table 4). The selected company is well-known (e.g. Norwegian salmon) logistics expert and esteemed global market player. Company level information is supplemented by data from the literature (Hanssen & Mathisen, 2011).

Table 4 Key questions posed to interviewee to complete logistics system data

	Interview questions
Q1	Can you confirm the illustrated figure of the logistics system is typical of the supply chain network?
Q2	Please identify your supply chain network that you use to reach your market (i.e. from farms, processors, distributors and retailers/customers)
Q3	Please describe your basic supply chain network (i.e. how many farms, processors, distributors, and retailers)
Q4	Please provide detailed logistics information from farms to processors (i.e. daily capacity, transportation link, fuel consumption rate.)
Q5	Please provide detailed logistics information from processors to distributors (i.e. percentage of different products, processing costs, daily storage capacity, inventory cost, waste cost, distances between agents, and fuel consumption rate)
Q6	Please provide detailed logistics information from distributors to retailers/customers (i.e. similar as above and daily demand of products)

The Norwegian salmon key figures, as gathered from the literature and interviews with the selected company, are appended in Annex III (excel-based completed data entry). The selected company is a medium size Norwegian salmon exporter with access to over 100 global customers. The company is listed among the 30 biggest seafood companies in Norway with an annual turnover of over 1.2 billion Norwegian Krone (NOK) (equal to about €120 million) (Norsk Fiskerinæring, 2019). The company is supplied by 10 salmon farmers who have access to over 100 sites across the Norwegian coastline.

A key feature of the Norwegian salmon supply chain is the distinction between the presence of primary and secondary processing plants (Figure 22). The transportation of salmon starts from salmon farms. The slaughterhouse processes customer orders within 2 hours, with whole salmon head on gutted (HOG) is packaged and ready for delivery. Secondary processing plants process the whole salmon HOG into other valued added products such as smoked salmon, fillet and sliced. Fresh salmon is highly perishable and so, time is very important and after leaving the primary or secondary processing plants, salmon products need to reach their customers (i.e. wholesalers, retailers) within 24-48 hours.

3. RESULTS AND DISCUSSIONS

This section presents a comparative analysis of the results obtained after solving the mathematical model (section 2.4.1) and the two – stage reformulation (section 2.4.2) of the model. All the computational experiments were 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. Various problem instances were considered for solving the proposed model and highlighting the validation and robustness of the model. Moreover, a real-world supply chain problem of an organization, which specializes in the processing, and transportation of (exporting) Norwegian Salmon products, was considered for validation purposes. Sensitivity analysis related to demand variation and transportation scenarios were also executed.

3.1. Model Validation for Various Problem Instances

The proposed mathematical models M (described in section 2.4.1), N1 (section 2.4.2.1) and N2 (section 2.4.2.2) presented in previous sections are validated by considering various problem instances. Solving the simulated problem instances highlights the robustness of the models in adapting to various supply chain scenarios where the number of different types of stakeholder changes. For solving the problem instances, the simulated data set related to the parameters of the mathematical models are generated based on the primary data collected for the real-world problem instance associated with the Norwegian salmon supply chain, which is presented in the next section. The data collection process is conducted via workshops and key stakeholders' interviews related to the selected food chain case study. The data collected then used to feed the proposed mathematical models, to then generate a number of key parameters of the food logistics system.

Table 5 presents the various problem instances and the cost components and overall carbon emission incurred after solving the problem instances. 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. Figure 24, Figure 25, and Figure 26 give the visual illustration of the supply chain network for time periods 1, 2 and 3 respectively. Each time period equals to a day (24 hour). Those figures also provide the necessary information about the number of products shipped from one stakeholder to another. The figures present useful insights about the processing amount and wastage/residual amount for various salmon products obtained at different time periods. The next section explores in further detail about the real-world problem instances and the data collection.

Table 5 Problem instances solved for the validation of the proposed mathematical models

Problem Instances	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 PPP, 1 SPP, 1 W, 2 R, 3 TP; Solving Model M	232,596.77	11,062	10,985	557.77	65,422	144,570	18,866
Instance 2: 2 SF, 1 SH, 1 PPP, 1 SPP, 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 SPP, 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 PPP, 2 SPP, 4 W, 5 R, 3 TP; Solving Model M	220,997.70	11,691	10,172	8,302.7	56,922	133,910	19,992
Instance 5: 4 SF, 3 SH, 2 PPP, 2 SPP, 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 SPP, 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
SF = Salmon Farms, SH = Slaughterhouse, PPP = Primary Processing Plant, SPP = Secondary Processing Plant, W = Wholesaler, R = Retailer, TP – Time Period							

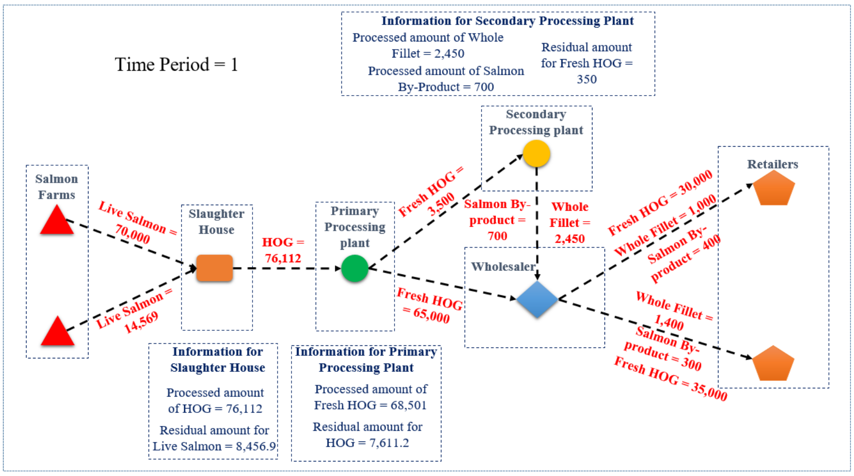


Figure 24 Solution obtained for problem instance 1 related to time period 1

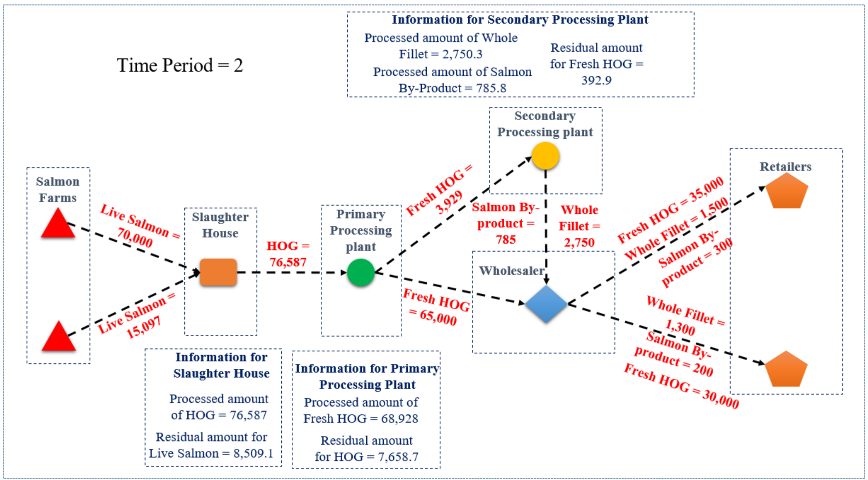


Figure 25 Solution obtained for problem instance 1 related to time period 2

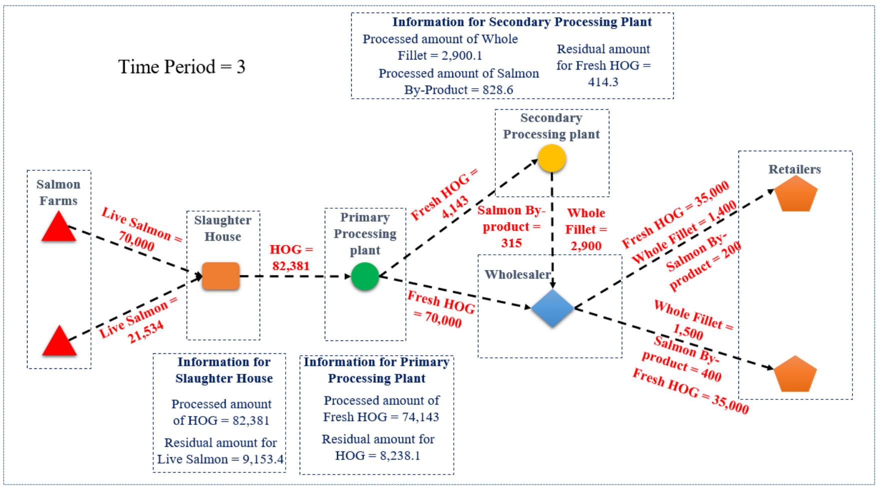


Figure 26 Solution obtained for problem instance 1 related to time period 3

3.2. The Norwegian salmon case study

The real-world problem instance considered in this research is related to the Norwegian salmon supply chain network of an organization named Company X. The Norwegian salmon key figures are appended in Annex III (excel-based completed data entry). The selected company is a salmon exporter with access to over 100 global customers. Ten salmon farmers with access of over 100 sites across the Norwegian coastline supplied Company X. The flow of salmon logistics starts from salmon farms, where live fish was held at holding cages instead as of an inventory storage. The slaughterhouse was used once the order placed by customer where within 2 hours; whole salmon heads on gutted (HOG) was packaged and ready to be delivered to final customers all over the world. Secondary processing was used to process the whole salmon HOG product into other valued added products such as smoked salmon, fillet, sliced, etc. Since fresh salmon is highly perishable, salmon products reach their customers (i.e. wholesalers/retailers) within the next 24-48 hours' time after leaving the primary processing plants.

The supply chain network for the organization considered in this study comprises of several stakeholders including twenty four salmon farms; packing station A – a major packing station used by Company X and listed as one of major salmon slaughterhouses with relatively large capacity with over 100 tonne per day (Norsk Fiskerinæring, 2016). Packing station A performs the role of a slaughterhouse and primary processing plant for Company X. Company X supply chain network also comprises one major secondary processing plant, ten wholesalers and six retailers.

The twenty-four salmon farms are categorised into five clusters (mainly based on distance proximity relative to a 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 (Packing Station A) 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 (Packing Station A) is around 140 tonnes per day.

Hypothetical demand scenario was developed to assign volume on each cluster. Cluster 1 tries to meet 50 percent of the daily supply of the Packing Station A, which is around 70 tonnes per day, and cluster 2 meets around 40 percent of the daily supply of the Packing Station A, 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 A and it is around 7 tonnes per day, 3.5 tonnes per day and 3.5 tonnes per day respectively. Wellboats are used to transport live salmon products from the salmon farms to the slaughterhouse at Packing Station A. Therefore, the transportation mode for shipping live salmon to slaughterhouse comprises of only wellboats and the capacity of the transportation mode lies within the range of 150 – 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. Alongside information collected to supply the mathematical model required figures, geographical distance information about where each of the agents/key stakeholders along the supply chain located were collected. Figure 27 depicts the locations of salmon farm sites with links to a slaughterhouse / primary processing. The slaughterhouse is a regular supplier of live salmon to the selected salmon exporter interviewed in this study. The distance of salmon farms to the slaughterhouse is ranging between 2 and 150 nautical miles (1 and 10 hours distance by wellboat).

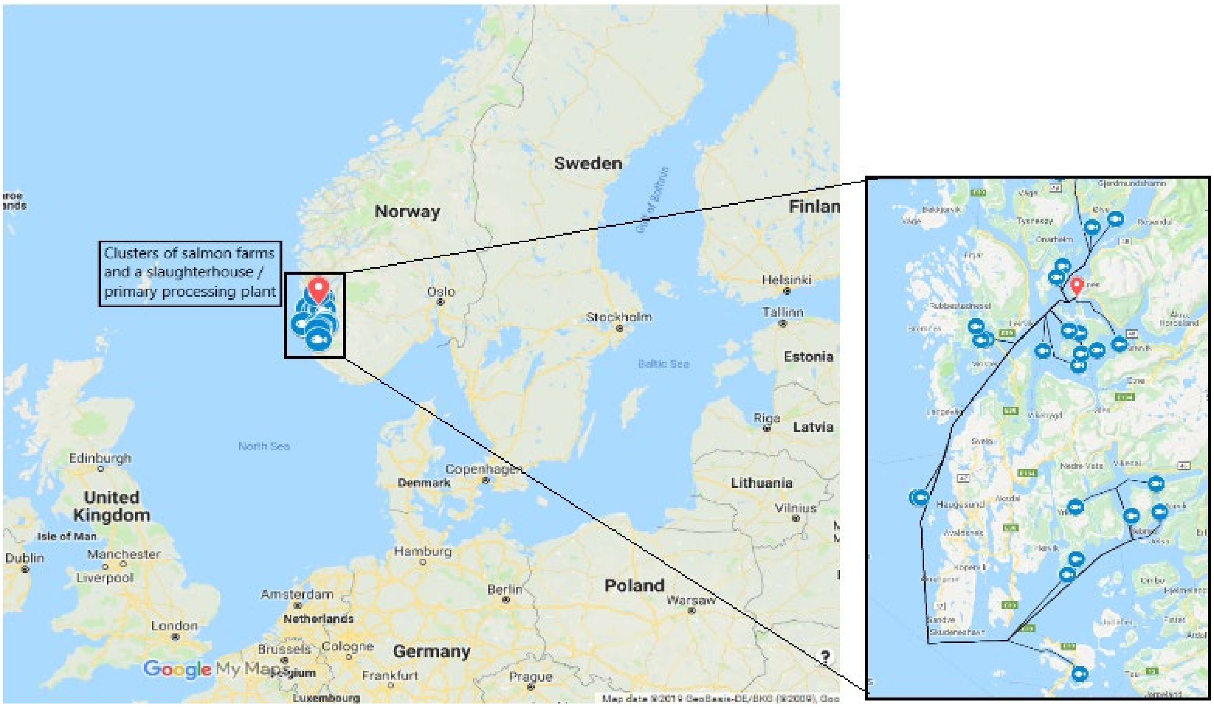


Figure 27 Salmon farms locations and links to a slaughterhouse as a selected supply chain

Live salmon is processed at the slaughterhouse (Packing Station A) and HOG (Head on Gutted) product and certain amount of wastage/residual are obtained. After processing the live salmon, (87 – 90%) of the products are obtained as HOG and the remaining (10 – 13%) of the live salmon are processed as wastage/residual amount. The processing cost for obtaining the HOG product lies within the range of (0.3 – 0.35) Euro per kg. The cost associated with obtaining the residual amount after processing the live salmon is (0.2 – 0.25) Euro per kg.

The daily maximum storage capacity of the slaughterhouse at Packing Station A for HOG product is 140 tonnes per day. As the primary processing plant also located in the Packing Station A, the HOG product obtained after processing incurs negligible transportation cost and fuel cost. The HOG product is processed at the primary processing plant to obtain (87 – 90%) as fresh HOG product and the remaining as wastage/residual amount. The amount of inventory holding for HOG product at the slaughterhouse and fresh HOG product at primary processing plant is negligible as the main tendency of the exporter is to transport the maximum quantity of the product obtained after processing without keeping any inventory.

The fresh HOG product obtained at the primary processing plant (Packing Station A) are shipped to the secondary processing plant at Urk (in the Netherlands) and wholesalers. From the primary processing plant, maximum of (90 – 95%) of the total capacity of primary processing plant for fresh HOG are shipped to the wholesalers in European market. The remaining portion (5 – 10%) of the fresh HOG is shipped from primary processing plant (Packing Station A) to the secondary processing plant at Urk. The transportation modes from primary processing plant at Packing Station A to secondary processing plant at Urk include truck mode of transport from Packing Station A to Stavanger port in Norway. The distance from Packing Station A to Stavanger port is around 147 km. The fresh HOG products are then shipped from

Stavanger port in Norway to Hirtshals in Denmark via ferry (maritime transportation) and the distance from Stavanger port to Hirtshals is around 350 km.

From Hirtshals in Denmark, the fresh HOG products are shipped to secondary processing plant at Urk (Netherlands) via truck mode of transportation and the distance between Hirtshals to Urk is around 906 km. In short, the fresh HOG products shipped from primary processing plant (Packing Station A) to secondary processing plant (Urk) are using multiple transportation modes. The overall distance between the primary processing plant and the secondary processing plant is around 1403 km.

Transportation cost related to the shipment of fresh hog from primary processing plant to secondary processing plant is around (0.1 – 0.2) Euro per kg. From primary processing plant, the fresh HOG salmon product delivered to either secondary processing plants (in liaison with the exporter) or international airport hubs to reach global wholesalers/retailers. Figure 28 (left box) illustrates links from the primary processing plant to a ferry hub (in Stavanger) to deliver salmon products (using mainly trucks) to cross the North Sea to reach EU port hub (Hirtshals in Denmark), to continue journey to the secondary processing plant in Urk, the Netherlands. For fresh HOG salmon product destined to meet global wholesalers demand would directly go straight to airport hub (in Amsterdam Schipol) to reach the global market places (Figure 28 right box).

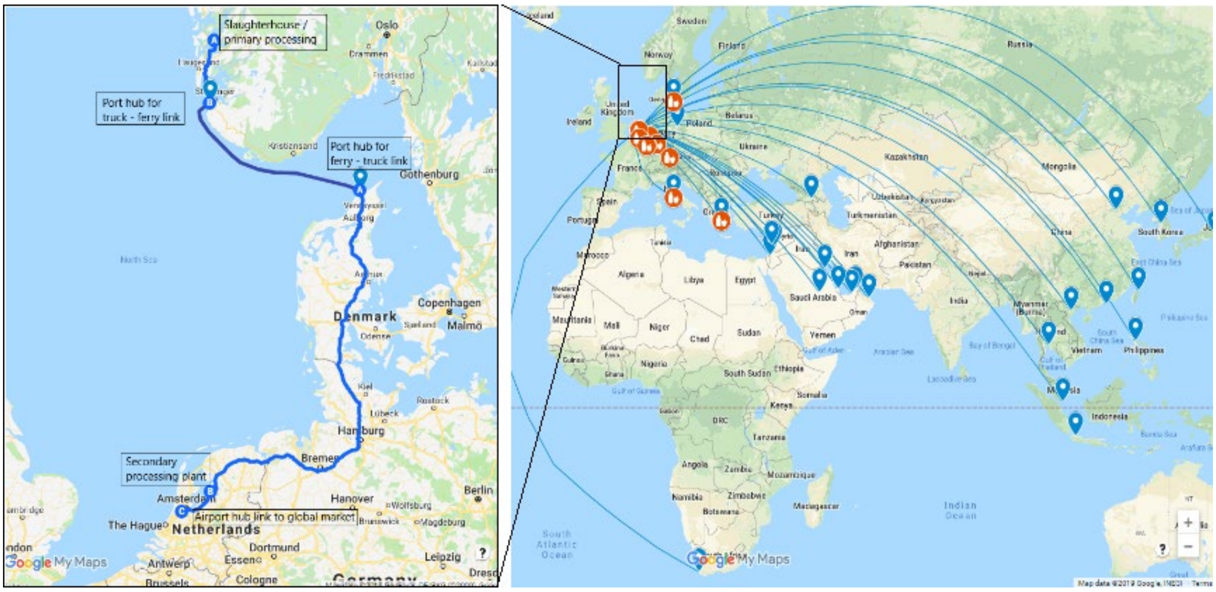


Figure 28 salmon slaughterhouse links to secondary processing before reaching the EU and global market places

The fresh HOG products are transported via truck, inland waterways and air freight from the primary processing plant to ten wholesalers in various European cities such as Dusseldorf, Frankfurt, Munich (in Western and Southern Germany), Copenhagen (Denmark), The Hague, Rotterdam, Brussels, Luxembourg (BENELUX), Rome (Italy) and Athens (Greece). Please note that these cities were picked for illustration purpose to represent land-based distances' market catchment of a realistic transportation logistics operation.

Some of the European cities receives the fresh HOG products from Amsterdam airport after the products comes from primary processing plant to Amsterdam airport via Urk and the distance from primary processing plant to Schipol airport is around 1497 km. The distances from the primary processing plant to ten wholesalers at 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 cost for the shipment of fresh HOG product from the primary processing plant to the wholesalers in European cities is around (0.1 – 0.2) Euro per kg. Moreover, some of the processed salmon products obtained at the secondary processing plant at Urk are also shipped to the wholesalers in the European cities. Whole fillet product and salmon by-products are obtained after processing fresh HOG at the secondary processing plants. After processing fresh HOG, 66% of the products are obtained as whole fillet, 33% of the product as salmon-by product and rest 1% as residual.

The processing and residual cost incurred at the secondary processing plant is 1.5 Euro per kg for whole fillet, salmon by-product and residual amount. From the secondary processing plant, the whole fillet and salmon by-product are shipped to the various wholesalers in different European cites. The distance from secondary processing plant to various wholesalers at 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.

Majority of the data associated with fuel consumption and carbon emission are borrowed from the research work of Soysal, Bloemhof-Ruwaard, and van der Vorst (2014). From ten wholesalers, different salmon products such as fresh HOG, whole fillet and salmon by-product are shipped to six retailers in different European cities. Fuel price in Europe is assumed to be (1.1 – 1.5) Euro per litre. The fuel consumption rate for a typical 12 tonne delivery truck consumes around 21.4 litres per 100 km (Delgado, Rodriguez, & Muncrief, 2017). The value of the carbon emission coefficient is considered as 2.392 kg CO_2 per litre.

In summary, for EU markets, the main transport links served mainly by refrigerated standard container (TEU) trucks covering distances between 1 000 to 4 000 kms. Example given for this particular processing plant (in Urk) to serve BENELUX and German salmon markets (mainly in big cities). For global market place, the main transport links were airplanes and to cover distance between 4 000 – 10 000 kms. The next section presents the experiment settings for the real – world case study.

3.3. Computational Experimental Setting

The real-world problem instance associated with the Norwegian salmon supply chain network is solved using the mathematical model N1 (described in section 2.4.2.1). The first and second experiments aim to solve the model N1 for real-world problem instance of Norwegian salmon supply chain networks comprising of the following stakeholders – salmon farms, slaughter house, primary processing plant, secondary processing plant and wholesaler. The primary intention for using model N1 is to address the behavioural tendency of the organization where it only aims to meet the demand of wholesalers and 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 (46) and the carbon emission constraint presented in equation (56). The output of the first experiment is used in equation (46) for obtaining the overall fuel cost and it is also used in equation (72) given below for obtaining the overall carbon emission for the revised Norwegian salmon supply chain network comprising of salmon farms, slaughter house, primary processing plant, secondary processing plant and wholesaler.

The second experiment considers the fuel cost component in the objective function given in equation (46) and integrates the carbon emission constraint presented in equation (56) while solving the optimization model N1 for the revised Norwegian salmon supply chain network. The output of the second experiment is used to obtain the carbon emission using equation (72). The total cost, fuel cost and carbon emission obtained for the fourth experiment is compared with that of the third experiment.

$$CE = E^{CO_2}\left[\begin{array}{l}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T}F_{ij}^{a}W_{ij}X_{ijt}^{a}+\sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{t=1}^{T}F_{jp}^{b}W_{jp}X_{jpt}^{b}+\sum_{p=1}^{P}\sum_{q=1}^{Q}\sum_{t=1}^{T}F_{pq}^{c}W_{pq}X_{pqt}^{c}\\+\sum_{p=1}^{P}\sum_{u=1}^{U}\sum_{t=1}^{T}F_{pu}^{c}W_{pu}X_{put}^{c}\end{array}\right] \quad (72)$$

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 fuel cost equation (59) in objective function and also without considering the carbon emission constraint (71). The output of the third experiment obtained after solving the optimization model N2 is used to determine the fuel cost using equation (59) and the overall carbon emission using the equation (73) given below.

$$CE = E^{CO_2}\left[\begin{array}{l}\sum_{q=1}^{Q}\sum_{u=1}^{U}\sum_{t=1}^{T}\left[F_{qu}^{e}X_{qut}^{e}+F_{qu}^{f}X_{qut}^{f}\right]W_{qu}+\sum_{u=1}^{U}\sum_{r=1}^{R}\sum_{t=1}^{T}F_{ur}^{c}W_{ur}X_{urt}^{c}\\+\sum_{u=1}^{U}\sum_{r=1}^{R}\sum_{t=1}^{T}\left[F_{ur}^{e}X_{urt}^{e}+F_{ur}^{f}X_{urt}^{f}\right]W_{ur}\end{array}\right] \quad (73)$$

The fourth experiment aims to solve the model N2 while considering the fuel cost component within the objective function and the carbon emission constraint. The output obtained from the fourth experiment is used to obtain the carbon emission using equation (73). The total cost, fuel cost and carbon emission incurred for the fourth experiment are compared with that of the third experiment. Table 6 provides in-depth information about each experiments and also values of the cost components obtained after performing the experiments.

Table 6 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 emission constraint)	334,356	17,668	16,689	–	80,129	219,870
Experiment 2	Solving Model N1 (considering Fuel cost parameter and Carbon emission constraint)	334,353	17,665	16,689	–	80,129	219,870
Experiment 3	Solving Model N2 (without Fuel cost parameter and Carbon emission 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 emission 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 emission 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 emission constraint)	310,351.18	17,216	14,318	755.18	88,322	189,740

Finally, the real-world problem instance related to Norwegian salmon supply chain network is solved using the mathematical model M (described in section 2.4.1). Solving the real-world problem using model M highlights the ways the Norwegian salmon supply chain network reacts when different stakeholders collaborate with each other and aim to reduce the overall operational and transportation cost optimally. The fifth experiment (see Table 6) 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 optimization Model M without considering the fuel cost component given in equation (3) in the objective function and carbon emission 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 emission (denotes as CE in the equation formula) by the using the equation (74) given below.

$$CE = E^{CO_2} \left[\begin{array}{l} \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} F_{ij}^{a} W_{ij} X_{ijt}^{a} + \sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{t=1}^{T} F_{jp}^{b} W_{jp} X_{jpt}^{b} + \sum_{p=1}^{P}\sum_{q=1}^{Q}\sum_{t=1}^{T} F_{pq}^{c} W_{pq} X_{pqt}^{c} \\ + \sum_{q=1}^{Q}\sum_{u=1}^{U}\sum_{t=1}^{T} \left[F_{qu}^{e} X_{qut}^{e} + F_{qu}^{f} X_{qut}^{f} \right] W_{qu} + \sum_{p=1}^{P}\sum_{u=1}^{U}\sum_{t=1}^{T} F_{pu}^{c} W_{pu} X_{put}^{c} \\ + \sum_{u=1}^{U}\sum_{r=1}^{R}\sum_{t=1}^{T} \left[F_{ur}^{e} X_{urt}^{e} + F_{ur}^{f} X_{urt}^{f} \right] W_{ur} + \sum_{u=1}^{U}\sum_{r=1}^{R}\sum_{t=1}^{T} F_{ur}^{c} W_{ur} X_{urt}^{c} \end{array} \right] \quad (74)$$

The sixth experiment aims to considering the fuel cost equation (3) in the objective function and carbon emission constraint (31) while optimizing the model M related to the Norwegian salmon supply chain network comprising of all the stakeholders. The output of the sixth experiment is used to obtain the carbon emission from equation (74). The overall cost, fuel cost and carbon emission obtained for the second experiment is compared with that of the first experiment.

All estimations from each experiments are presented and discussed in the next section.

3.4. Carbon emission along the supply chain

The real-world problem instance is considered for three time periods where each period is equivalent to a day. The demand associated with six (hypothetical) retailers considered for solving model M and N2 and are generated within the range of (10 – 16) tonnes for fresh HOG, (0.8 – 1.4) tonnes for whole fillet and (0.2 – 0.4) tonnes for salmon by-product.

For solving model N1, the demand data related to the secondary processing plants for fresh HOG is considered in the range of (8 – 12) tonnes and the demand data associated with ten (hypothetical) wholesalers for fresh HOG product are also considered within the range of (8 – 12) tonnes.

After performing experiments 1 and 2 related to model N1, the transportation cost, fuel cost, residual cost and processing cost obtained are presented in Table 6. It must be noted that when fuel cost component and carbon emission constraint are not considered while solving model N1, then the total cost incurred for experiment 1 is more compared to experiment 2. Moreover, from Table 6 and Table 7, it can be seen that the fuel cost and carbon emission incurred for experiment 1 is slightly more than that of experiment 2.

Table 7 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					

The carbon emission and fuel cost incurred for the experiment 1 are around 30,147.46 Kg CO_2 (Table 6) and 17,668 Euro (Table 7) respectively and the carbon emission and fuel cost incurred for the experiment 2 are 30,142.53 Kg CO_2 (Table 6) and 17,665 Euro (Table 7) respectively. The slight increase in carbon emission and fuel cost for experiment 1 when compared with that of experiment 2 is primarily due to the fact that the carbon emission incurred for the shipment of live salmon products from salmon farms to slaughter house for experiment 1 is slightly more than that of experiment 2.

The carbon emission incurred for the shipment of live salmon products from salmon farms to slaughter house for experiments 1 and 2 (Table 7) are around 452.06 Kg CO_2 and 447.13 Kg CO_2 respectively. This highlights the fact that it is essential to consider the fuel cost component and carbon emission constraint within the model for addressing the sustainability aspect while dealing with the processing and transportation aspect within supply chain network. While jointly optimizing the fuel cost, carbon emission and total cost, the model gives superior results while performing experiment 2.

Table 7 presents the carbon emission incurred while solving model N1 for experiments 1 and 2. The carbon emission results obtained after performing experiment 2 mainly includes 447.13 Kg CO_2 incurring from the shipment of live salmon products from twenty-four salmon farms to slaughterhouse at Packing Station A. Moreover, the carbon emission incurred for the shipment of Fresh HOG product from primary processing plant at Packing Station A to secondary processing plant at Urk is around 1,795.4 Kg CO_2. Finally, transportation of fresh HOG product from primary processing plants to wholesalers at ten European cities also incurred a significant amount of carbon emission and it is computed as 27,900 Kg CO_2.

Experiments 3 and 4 are performed on the real-world problem instance using the mathematical model N2. The transportation cost, inventory cost, fuel cost, processing cost and residual cost are given in Table 6. It can be seen from Table 6, that the total cost and fuel cost incurred for experiment 3 is higher than that of experiment 4. Table 8 provides information about the carbon emission incurred for the shipment of products from one stakeholder to another. It can be also be noted that carbon emission incurred for experiment 3 is higher than that of experiment 4. This due to the fact that while performing experiment 3 fuel cost components and carbon emission constraint are not considered within the mathematical model N2. Therefore, for experiment 3, the model parameters related to distances between stakeholders (which helps to estimate the fuel consumption, fuel cost and carbon emission) are not taken into consideration while 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 taken into account for obtaining optimal results for experiment 3.

For experiment 4, the optimal result is obtained while considering the distances value between the stakeholders, which plays a significant role in reducing the fuel cost as well as the carbon emission. Fuel cost and carbon emission incurred for experiment 3 are 8,200.6 Euro (Table 6) and 13,877.28 Kg CO_2 (Table 8) respectively, whereas for experiment 4, the fuel cost and carbon emission incurred are much less and they are around 4,235.9 Euro (Table 6) and 7,189.37 Kg CO_2 (Table 8) respectively.

Table 8 Carbon emission incurred after solving model N2 for the rea-world problem instance

Experiment	Solving procedure	Carbon emission (Kg CO_2)	Carbon Emission from SPP to W (Kg CO_2)	Carbon Emission from W to R for FH (Kg CO_2)	Carbon Emission from W to R for WF and SB (Kg CO_2)	Total Carbon Emission from W to R (Kg CO_2)
Experiment 3	Solving Model N2 (without Fuel cost parameter and Carbon emission constraint)	13,877.28	447.38	12,191	1,238.9	13,430
Experiment 4	Solving Model N2 (with Fuel cost parameter and Carbon emission 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						

For experiment 4 (as seen in Table 8) the carbon emission incurred for the shipment of fresh HOG product 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 emission incurred for experiment 3 which is around 12,191 Kg CO_2. Optimizing model N2 while considering the fuel cost and carbon emission constraint helps the total carbon emission incurred for the shipment of whole fillet, salmon by-product and fresh hog from wholesalers and retailers to decrease from 13,430 Kg CO_2 to 6,855.3 Kg CO_2. Therefore, comparing the results of experiments 3 and 4 highlight the fact that it is essential to consider the sustainability aspects related to fuel cost and carbon emission while optimizing overall supply chain network.

Experiments 5 and 6 are performed by solving model M that 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 the total cost. Experiment 5 aims to solve the optimization model M without considering the fuel cost parameters and carbon emission constraint. Experiment 6 optimizes the model M while considering the fuel cost parameter and carbon emission constraint.

Table 6 presents the value of the cost components obtained after performing experiments 5 and 6. It can be interpreted from Table 6 that, the fuel cost and total cost incurred for experiment 5 are much higher than that of experiment 6.

Table 9 provides the necessary information regarding the carbon emission incurred for the shipment of salmon products from one stakeholder to another. It can be depicted from the Table 9 that total carbon emission incurred for experiment 5 is much higher than that of experiment 6. Moreover, carbon emission incurred for the shipment of salmon products from primary processing plants to ten wholesalers and also the shipment of salmon products from ten wholesalers to six retailers are much higher for experiment 5 when compared with that of experiment 6.

Table 9 Carbon emission incurred after solving model M 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)	Carbon Emission from SPP to W (Kg CO_2)	Carbon Emission from W to R (Kg CO_2)
Experiment 5	Solving Model M (without Fuel cost parameter and Carbon emission constraint)	38,104.45	376.04	1,692.9	22,665	427.51	12,943
Experiment 6	Solving Model M (with fuel cost parameter and Carbon emission 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							

Total cost, fuel cost and carbon emission incurred for experiment 5 are 315,569.18 Euro, 22,434 Euro (Table 6) and 38,104.45 Kg CO_2 (Table 9) respectively. Whereas the total cost, fuel cost and carbon emission incurred for experiment 6 are around 310,351.18 Euro, 17,216 Euro (Table 6) and 29,265.25 Kg CO_2 (Table 9) respectively.

The main reason for obtaining better results from experiment 6 is due to the fact that fuel cost parameters and carbon emission constraints are taken into consideration for solving model M. For experiment 6, the optimal decisions are made based on some of the important parameters such as fuel cost, distances between stakeholders and transportation cost. Therefore, the results obtained from experiments 5 and 6 highlights the importance of considering fuel cost parameters and carbon emission constraints within the mathematical model for obtaining superior results.

3.5. Results associated with the Real-World Problem

The results related to experiment 6 are presented in this section which also gives an idea about the various types of salmon products shipped from one stakeholder to another in different time periods. Table 10 presents the values associated with the shipment of live salmon (in kg) from twenty-four salmon farms which are categorised into five clusters to slaughterhouse at Packing Station A.

Table 10 Transported amount of live salmon (in kg) from salmon farms to slaughterhouse and processed and wastage/residual amount at slaughterhouse

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

Total amount of HOG product obtained in different time periods after processing live salmon product at the slaughterhouse is shown in Table 10. Table 10 also presents information about the wastage/residual amount obtained on various time period. The information about the shipped amount of fresh HOG from primary processing plant at Packing Station A to secondary processing plant at Urk is presented in Table 11.

Table 11 Transported amount of Fresh HOG (in Kg) from Primary Processing Plant to Secondary Processing Plant and processed and residual amount obtained at Secondary Processing Plant

	Secondary Processing Plant at Urk (Netherlands)		
	Time period 1	Time period 2	Time period 3
Primary Processing Plant at Packing Station A	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
Wastage/Residual amount	900	900	1028.6

The processed amount of whole fillet and salmon by-product and also the wastage/residual amount obtained after processing fresh HOG at the secondary processing plant are also presented in Table 11. Table 12 provides information about the amount of the fresh HOG product and wastage/residual amount obtained after processing HOG product at primary processing plant. Moreover, Table 12 also presents the amount of fresh HOG shipped from primary processing plant to ten wholesalers in different time periods.

Table 12 Transported amount of Fresh HOG (in Kg) from Primary Processing Plant to Wholesalers and processed and residual amount obtained at Primary Processing Plant

	Primary Processing Plant at Packing Station A		
	Time period 1	Time period 2	Time period 3
Processed amount of Fresh HOG	113,400	63,600.3	99,286.2
Wastage/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	–	–	–

The amount of whole fillet and salmon by-product transported from secondary processing plant to different wholesalers in various time periods are presented in Table 13.

Table 13 Transported amount of Whole fillet and Salmon by-product from Secondary processing plant to Wholesalers for different time periods

	Secondary Processing Plant at Urk (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 14 and Table 15 gives detailed information about the shipped amount of fresh HOG, whole fillet and salmon by-product from ten wholesalers to six retailers.

Maximum shipment capacity related to fresh HOG, whole fillet and salmon by-product for the transportation links from secondary processing plants to wholesalers and from wholesalers to retailers is considered as 3000 Kg.

Table 14 and Table 15 also gives the necessary information about the specific wholesalers, which are responsible for meeting the demand of each retailers in different time periods. For example, the demand of fresh HOG in different time periods for retailer 6 is met by wholesalers 2, 6, 7, 8 and 9. Moreover, the demand of fresh HOG in different time periods for retailer 2 is met by wholesalers 1, 2, 3, 4 and 5. Insights obtained from Table 13 highlight that the majority of the whole fillet product and salmon by-product are sent from secondary processing plant at Urk to wholesalers 1, 3, 4, 5, 6 and 8. This is because these wholesalers are nearest in terms of distance for the secondary processing plant at Urk and the rest of the wholesalers are farthest from the secondary processing plant. Moreover, these wholesalers meet the majority of the demand of whole fillet and salmon by-product for the six retailers in different time periods.

Table 14 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	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–

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Table 15 Shipped amount of Whole fillet (WB) and Salmon by-product (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	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–

3.6. Sensitivity Analysis based on Demand Variation

Sensitivity analysis is performed on experiment 6 (Model M – with fuel cost parameter and carbon emission constraint) by changing the demand of the retailers in various time period to study the Norwegian salmon supply chain network. Different demand scenarios are generated randomly by depicting a realistic scenario for validating performance of the mathematical model. Table 16 presents four different demand scenarios, its respective cost components, and the percentage change in the cost component when compared with the results of the Base Case scenario (values of the sixth experiment in Table 6).

Table 16 Effect of demand variation on cost components and carbon emission

	Base Case 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% (decrease)	11.45% (increase)	5.72% (increase)	4.88% (decrease)
Fuel cost (Euro)	17,216	15, 068	20,028	19,040	16,763
Change in Fuel cost (%)	–	12.47% (decrease)	16.33% (increase)	10.59% (increase)	2.63% (decrease)
Transportation cost (Euro)	88,322	76,350	99,894	93,506	83,602
Change in Transportation cost (%)	–	13.55% (decrease)	13.10% (increase)	5.86% (increase)	5.34% (decrease)
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% (decrease)	10.37% (increase)	5.25% (increase)	4.86% (decrease)
Residual Cost (Euro)	14,318	12,934	15,813	15,110	13,585
Change in Wastage/Residual cost (%)	–	9.66% (decrease)	10.44% (increase)	5.53% (increase)	5.11% (decrease)
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% (decrease)	15.33% (increase)	10.08% (increase)	1.92% (decrease)

The demand scenario 1 depicts a scenario where the demand of fresh HOG for retailers 1, 2, 3 and 4 decrease by 50% in time period 3 (equivalent to day 3).

For demand scenario 2, the demand of fresh HOG for retailers 1, 2, 3 and 4 increase by 50% in time period 3.

Demand scenario 3 ensures 75% increase in the demand of fresh HOG for retailers 1, 2 and 3 in time period 2 and 50% decrease in the demand of fresh HOG for retailers 4, 5 and 6 in time period 1.

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For demand scenario 4, the demand of fresh HOG product for retailers 1, 2 and 3 decrease by 75% in time period 2 and the demand of fresh HOG product for retailers 4, 5 and 6 increase by 50% in time period 1.

Table 16 provides the results associated with the demand variations and accordingly presents the cost components and carbon emission incurred for various demand scenarios. The table presents necessary information about the change in cost components when compared with the base case scenario and it is represented in percentage increase or decrease.

It can be seen from Table 16 that inventory cost remains the same for all demand scenarios as the Company X adopts a policy of nearly holding of inventory related to any salmon products. When the demand of the product decreases, then the organization procures less products (live salmon) from the salmon farms and majority of the capacity of the live salmon are kept in cages pulled by wellboats. Table 16 shows that with increase in demand for fresh HOG, the processing cost and wastage/residual cost increases as more products need to be processed at the slaughterhouse and primary processing plant in Packing Station A. Moreover, the per unit processing cost is more when compared with that of the transportation cost and thereby more processing cost is incurred.

With increase in product demand, the transportation cost increases which in turn increases fuel cost and carbon emission. The sensitivity analysis on the demand also highlights the robustness of the mathematical model in dealing with the variation associated with demand of products in different time periods. The mathematical formulation adapts to the change in demand patterns and accordingly designs the Norwegian salmon supply chain network, optimizes the cost components and obtains the best possible solution in terms of the values of the decision variables related to the shipment amount between various stakeholders. For certain demand scenarios, when the demand reduces significantly for certain time periods and the demand increases abruptly in other 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 variation in the demand patterns.

3.7. 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 primary processing plant at Packing Station A to Stavanger port for the shipment of live salmon and maritime transportation route from Stavanger port to Amsterdam port. The distance between Stavanger port and Amsterdam port is around 391 nautical miles or approximately 724 km. Moreover, the distance from Amsterdam port to Urk (secondary processing plant) is around 83 km. So, the total distance from primary processing plant at Packing Station A to secondary processing plant at Urk is 954 km.

Moreover, other maritime routes are taken into consideration for the transportation from primary processing plant to ten wholesalers in different European cities. The shipment of fresh HOG from primary processing plant to Dusseldorf includes truck transportation from primary processing plant to Stavanger port and then maritime transportation from Stavanger port to port of Dusseldorf and the distance between two ports is 554 nautical miles or 1,026 km. Therefore, the distance from primary processing plant to the wholesaler at Dusseldorf is 1,173 km. The transportation route from primary processing plant to Frankfurt includes the maritime route from Stavanger port to Frankfurt port and its distance is 755 nautical miles or 1,398 km. Therefore, the total distance form primary processing plant to the wholesaler at Frankfurt is 1,545 km. The movement of fresh HOG from primary processing plant to wholesalers at Munich, The Hague and Luxembourg include road transportation from primary processing plant to Stavanger port, maritime transportation from Stavanger port to Amsterdam port and finally road transportation from Amsterdam port to various wholesaler Munich, The Hague and Luxembourg via Urk. Therefore, the total distance from primary processing plant to wholesalers at Munich, The Hague and Luxembourg are 1,754 km 1091 km and 1364 km. Now, the shipment of fresh HOG from primary processing plant to wholesalers at Copenhagen, Rotterdam and Brussels include the maritime transportation routes from Stavanger port to Copenhagen port, Stavanger port to Rotterdam port and Stavanger port to Brussels port and their distances are 444 nautical miles, 490 nautical miles and 574 nautical miles respectively. Therefore, the total distance from primary processing plant to wholesalers at Copenhagen, Rotterdam and Brussels are 969 km, 1054 km and 1210 km respectively. The shipment of fresh HOG from primary processing plant to wholesalers at Rome and Athens include the road and maritime transportation from primary processing plant to Amsterdam port via Stavanger port and finally air transportation from Amsterdam to different wholesalers at Rome and Athens. Therefore, the distance from primary processing plant to wholesalers at Rome and Athens are 2604 km and 3824 km respectively. For performing the transportation scenario analysis, the distances value considered from the primary processing plant at Packing Station A to ten wholesalers at 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 value from the secondary processing plants at Urk to the ten wholesalers remains same and moreover, the distances value from ten wholesalers to six retailers also remain unchanged.

Three transportation scenarios are considered for analysing the impact of considering maritime transportation routes on the total cost, fuel cost and carbon emission. Transportation scenario 1 considers the maritime transportation route Stavanger port and Amsterdam port, while shipping fresh HOG from primary processing plant at Packing Station A to secondary processing plant at Urk. Transportation scenario 2 considers several maritime transportation routes while shipping fresh HOG from primary processing plant at Packing Station A to ten wholesalers at various European cities. Transportation scenario 3 takes into account the maritime transportation route while shipping products from primary processing plant to secondary processing plant. It also considers the other maritime transportation routes from primary processing plant to various wholesalers.

Table 17 and Table 18 provide detail results related to the cost components and the total carbon emission incurred for various transportation scenarios. The results of the three transportation scenarios are compared with that of the base case scenario and the percentage changes in the value of cost component and carbon emission is presented. Moreover, Table 18 presents the in-depth results associated with the carbon emission incurred during the shipment between various stakeholders. It can be depicted from Table 17 and Table 18 that adopting maritime routes helps to reduce the overall cost as the fuel cost decreases. Moreover, it is noted that there is a significant decrease in the fuel cost and carbon emission for transportation scenarios 2 and 3 which adopt the maritime routes during the shipment of fresh HOG from primary processing plant to wholesalers at various European cities. Considering the maritime transportation routes for transportation scenario 3 leads to a decrease in fuel cost and carbon emission by 21.36% and 21.30% respectively. The significant reduction in carbon emission is due to the fact that the carbon emission incurred for the shipment of fresh HOG from primary processing plant to various wholesalers decreased substantially due to the adoption of maritime transportation routes. This also highlights the impact of considering maritime routes while making logistics decisions related to the Norwegian salmon supply chain.

Table 17 Analysis of transportation scenarios on cost components and carbon emission

	Base Case 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 Emission (Kg CO_2)	29,265.25	28,723.45	23,546.55	23,004.75
Change in Carbon Emission (%)	–	1.85% (decrease)	19.54% (decrease)	21.39% (decrease)

Table 18 Carbon emission results for different transportation scenarios

Transportation Scenarios	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)	Carbon Emission from SPP to W (Kg CO_2)	Carbon Emission from W to R (Kg CO_2)
Base Case 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

3.8. INSIGHTS FROM THE RESULTS

The proposed mathematical models N1 and N2 are developed for addressing the behavioural tendencies of the organization. **Model N1** aims to optimize the supply chain network comprising of salmon farms, slaughterhouse, primary processing plant, secondary processing plant and wholesalers. The intention of model N1 is to address the behavioural tendency of the organization for meeting **the demand of secondary processing plant and wholesalers** in various time periods (equivalent to days) while aiming to optimize the supply chain network from salmon farms to wholesalers.

Model N2 aims to optimize the network comprising of secondary processing plant, wholesalers and retailers. The objective of model N2 is to address the behavioural intention of the organization related to meeting **the demand of the retailers** while considering the supply capacity of the wholesalers and secondary processing plants. Although, when the demand of the wholesaler is not accurately predicted and tend to be higher than the demand at the retailer side, then the inventory cost incurred for the model N2 becomes higher and this can be observed in Table 5 and Table 6.

The proposed mathematical **model M** gives the option of optimizing the overall supply chain network where the organization (Seafood Company X) tries to meet **demand of retailers in different time periods** while having necessary information about supply capacity at the secondary processing plants and wholesalers. Optimization of the overall supply chain network helps Company X to regulate the inventory cost (when applicable) as all decisions are made based on demand at retailer side.

The results obtained after solving the proposed mathematical models M, N1 and N2 highlight the fact that it is essential for Company X to optimize 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 cost for models N1 and N2. Moreover, optimizing the overall supply chain network related to model M helps Company X to reduce the overall cost to a significant level when compared with the results of model N1 and N2.

The real-world problem instance has been solved by optimizing the proposed models without considering the fuel cost parameters and carbon emission constraints and outputs of the models are used to obtain fuel cost and carbon emission incurred separately. Although, when the real-world problem instance is solved by optimizing the models while considering fuel cost parameters and carbon emission constraints, it has been observed that there is significant decrease in the total cost, fuel cost and carbon emission. Insights obtained from the results highlight the fact that **supply chain network is sensitive to fuel cost**, which in turn **depends on** the **fuel consumption** and **distances** between stakeholders. Moreover, the results makes it imperative for the supply chain managers to understand the need for the consideration of sustainability aspects associated with fuel cost and carbon emission while solving a supply chain network for obtaining long term economic as well as environmental benefits.

Analysis related to various demand scenarios are performed which helps to validate a robust proposed mathematical model dealing with demand changes while optimizes the supply chain network. In practical scenario, demand of the salmon product may decrease due to various reasons such as, for example, decrease in product quality, rise in purchasing price, disruptions at retailer side etc. Although the supply chain network needs to be modelled in a certain way that it can quickly adapt to the significant changes in the demand and accordingly reschedule its logistics, processing, and inventory related decisions.

The transportation scenario analysis is conducted by consider options of various maritime transportation routes from primary processing plant to secondary processing and primary processing plant to various wholesalers. The results obtained from the analysis highlights the importance of adopting maritime transportation route in terms of significantly reducing the total cost, fuel cost and overall carbon emission. Therefore, the transportation scenario analysis highlights the importance of shifting certain logistics operations from road transportation to maritime transportation from the perspective of the economic and environmental benefits associated with the adoption of maritime routes.

4. CONCLUSIONS

The goal of developing a logistics model is traditionally to the optimise cost of operations. However more recently models seek to capture environmental considerations (Kasarda, 2016). A transport and logistics mathematical model was developed, applied to a real world case of Atlantic salmon. A Norwegian salmon exporter supplied data for validating the mathematical model. The model developed minimizes total cost, taking into account transportation, fuel consumption, inventory holding, processing and residuals/waste. Restrictions associated with carbon emissions and waste are specifically considered. Three developed models informed by the available data were validated, simulated and compared. Each model with different demand scenarios shows that the supply chain network is sensitive to fuel cost and consequently fuel consumption and distances.

Environmental impact is generally measured by fuel consumption during operations and in the case of food chain, transportation and distribution are important contributors via the use of fuel-based vehicles, sea vessels and/or airplanes. The scenarios analysis highlights the importance of adopting maritime transportation routes in terms of significantly reducing the total cost, fuel cost and overall carbon emission. Hence shifting certain logistics operations from road to maritime transportation from the perspective of economic and environmental benefits is advocated. For short to medium distances (vans, trucks, rails and sea vessels) that covers transportation trips to reach airport hubs and big cities, lowering CO_2 emissions depends on the emissions ratio (the relative emissions impact of delivery vehicle when compared to personal vehicle – mostly applied in urban logistics) and customer density. For long distance transport (air), environmental improvement can be mainly achieved through technological advancement.

The models are developed for a planning horizon consisting of discrete time periods, aiding the possibility of studying demand and supply uncertainty and its consequences in supply chain decision making. Hence, they help decision makers to identify the changes in a supply chain network when different transportation routes are adopted (for example whether maritime routes can be adopted or not in place of road/rail transportation, to address environmental concerns related to fuel consumption and carbon emissions).

The deliverable provides a framework for modelling the transport and logistics of other food supply chains given suitable data.

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ANNEX I

VALUMICS T71 DATA COLLECTION BRIEF

Type: Brief abstract and description of study

VALUMICS T71 Data Collection brief

H2020 VALUMICS project aims to provide decision makers throughout food value chains with a comprehensive suite of approaches and tools that will enable them to evaluate the impact of strategic and operational policies to enhance the resilience, integrity and sustainability of food value chains for European countries.

The aim of T71 is to study sustainability with a more focused environmental dimension. The task is to model transport and logistics of selected food chains. VALUMICS 18 months on – the consortium has decided to focus on four food chains' case studies including 'salmon to fillet'. The case is one of the most important as the demand forecast for the food will increase significantly which require more slaughterhouses and process plants[2]. This is not only due to the demand for more mouth to feed but also due to the preference of consumer of healthier food choices (i.e. high in Omega 3). It is evidenced that fishmeal such as salmon fillet has attracted the higher socio-economic group who are up to 4 times more likely to consume oily fish than that of the lower socio-economic groups[3]. Additionally, higher incomes make people more concerned about the natural environment with implication to the willingness to pay[4]. For all these reasons, it is envisaged that VALUMICS T71 could be the catalyst to develop logistics system that is environmental and socially savvy, so new added value of the supply chains can be appraised and elaborated as decision making tools for addressing the sustainability agenda.

Why do we need company data?

Logistics system design traditionally is developed to minimise the total (weighted) distances or 'costs' for supplying customer demands[5]. The recent challenges is when this 'costs' have to take into account factors beyond economic efficiency namely environmental and social. This is especially the case for most, if not all firms, which become progressively tightly coupled in global supply chains, and consequently require monitoring and management proactively on orchestrating triple bottom line concept within their businesses[6]. Notwithstanding the importance of the agenda, there is very little that we know with the real implications in the real business environment. For example, we do not know how much the impact of the salmon fillet production on CO_2emission in monetary unit. And if this unit can be used as catalyst to increase value

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to the salmon fillet product because of the demand of higher socio-economic groups who are willing to pay for the sustainable product. We do not know where and how much in the supply chains, the value added activities have been absorbed as well as distributed – thus benefitting certain socio-demographic sustainably – to the exchange points where a product eventually consumed. All of this information would help us understand better to not only prescript inefficiencies in food transportation and logistics operation but also to address wider issue of the sustainability within the business environment.

Concrete benefit for individual companies:

1) Access to the expertise to improve their logistics system

2) Open opportunities to have choices in embedding environmental and social credential (to add 'sustainability' value) into the companies' logistics system

3) Be one of the first companies to promote their products targeting selected market with informed environmental and social (where possible) - forming sustainability - credential as part of their business model.

4) To be the green champion in the business environment which consequently attracts public attention at global level, and wider marketing campaign in fighting against the climate change.

5) Allow documentation of valuable scientific evidence which will be useful to inform policy decision makers and future generation on how to address the sustainability agenda within the framework of the 'food value chain'.

ANNEX II

DATA FOR SALMON SUPPLY CHAIN LOGISTICS MODEL

Type: Interview survey form

Data for salmon supply chain logistics model (by Arijit De and Paulus Aditjandra)

Should be collected from one company (e.g. Company X) to demonstrate a unique supply chain.

Salmon Farms – Slaughterhouses – 1st Processing – 2nd Processing – Wholesaler – Retailer

Scenario 1 – Data for the Norwegian Salmon Supply Chain Network

Number of salmon farms of your supply chain network: 5

Number of slaughterhouses of your supply chain network: 3

Number of primary processing plants of your supply chain network: 4

Number of secondary processing plants of your supply chain network: 6

Number of wholesalers associated with your supply chain network: (8 – 12)

Number of retailers associated with your supply chain network: (10 – 14)

We also then need to collect information about: (Numbers given are hypothetical and for understanding purpose)

Salmon farms to Slaughterhouses

1. Daily supply of raw salmon from each Salmon Farm: (100 – 300) Units of raw salmon
2. From salmon farms to slaughterhouses – what mode of transportation being used and what is the daily shipment capacity on each transportation links? (10 - 40) Units of raw salmon
3. Are all the salmon farms connected via transportation links to all slaughterhouses?
4. If not all connected, please then kindly let us know which salmon farms are not connected to which slaughterhouses? (For example - 50% of the transportation links being used daily – exactly which 50% transportation links – is the decision of choosing transportation links made on the basis of transportation cost or distances)
5. Transportation cost for per unit raw salmon shipped from salmon farms to slaughter houses £(4-8) per product
6. Distances between salmon farms and slaughter houses (200 – 300) km
7. Fuel consumption in litres per unit distance per unit product (vehicle travels 10km, carries 50 units of raw salmon products, 10litres of fuel)

Slaughterhouses to Primary processing plant

1. What percentage of HOG product and residuals being obtained after processing the raw salmon at slaughterhouses? (Example - 70 HOG products and 30 Residual products are obtained after processing 100 raw salmon)

2. Processing cost of HOG product and residual at slaughterhouse (Example - £2.1 per unit HOG product and also £2.1 per unit residual or processing cost of 70 HOG product and 30 Residual is £210)

3. Daily maximum storage capacity of HOG at each Slaughter House – (100 – 300) units of products

4. From slaughterhouse(s) to primary processing plants – what mode of transportation being used and what is the daily shipment capacity on each transportation links? (10 - 40) Units of HOG

5. Are all slaughterhouses connected via transportation links to all primary processing plants?

6. If not all connected, please then kindly let us know which slaughter houses are not connected to which primary processing plants? (For example - 50% of the transportation links being used daily – exactly which 50% transportation links – is the decision of choosing transportation links made on the basis of transportation cost or distances)

7. Inventory holding cost of HOG product at slaughterhouse (Example - £2 per unit HOG product or inventory cost of 100 HOG product is £200)

8. Transportation cost for per unit HOG shipped from slaughter houses to primary processing plants £(4-8) per product

9. Distances between slaughter houses to primary processing plants (200 – 300) km

10. Fuel consumption in litres per unit distance per unit HOG product (vehicle travels 10km, carries 50 units of HOG products, 10litres of fuel)

Primary processing plant to Secondary Processing Plant

1. What percentage of Fresh HOG product and residuals being obtained after processing the HOG product at primary processing plant? (Example - 70 Fresh HOG products and 30 Residual products are obtained after processing 100 HOG product)

2. Processing cost of Fresh HOG product and residual at primary processing plant (Example - £2.1 per unit HOG product and also £2.1 per unit residual or processing cost of 70 HOG product and 30 Residual is £210)

3. Daily maximum storage capacity of Fresh HOG at each primary processing plant – (100 – 300) units of products

4. From primary processing plants to secondary processing plants – what mode of transportation being used and what is the daily shipment capacity on each transportation links? (10 - 40) Units of Fresh HOG

5. Are all primary processing plant connected via transportation links to all secondary processing plants?

6. If not all connected, please then kindly let us know which primary processing plant are not connected to which secondary processing plants? (For example - 50% of the transportation links being used daily – exactly which 50% transportation links – is the decision of choosing transportation links made on the basis of transportation cost or distances)

7. Inventory holding cost of Fresh HOG product at primary processing plant (Example - £2 per unit Fresh HOG product or inventory cost of 100 Fresh HOG product is £200)

8. Transportation cost for per unit Fresh HOG shipped from primary processing plants to secondary processing plants £(4-8) per product

9. Distances between primary processing plants to secondary processing plant (200 – 300) km

10. Fuel consumption in litres per unit distance per unit Fresh HOG product (vehicle travels 10km, carries 50 units of Fresh HOG products, 10 litres of fuel)

Primary processing plant to Wholesaler

1. From primary processing plants to wholesaler – what mode of transportation being used and what is the daily shipment capacity on each transportation links? (10 - 40) Units of Fresh HOG

2. Are all primary processing plant connected via transportation links to all wholesaler?

3. If not all connected, please then kindly let us know which primary processing plant are not connected to which wholesaler? (For example - 50% of the transportation links being used daily – exactly which 50% transportation links – is the decision of choosing transportation links made on the basis of transportation cost or distances)

4. Transportation cost for per unit Fresh HOG shipped from primary processing plants to wholesaler £(4-8) per product

5. Distances between primary processing plants to wholesaler (200 – 300) km

6. Fuel consumption in litres per unit distance per unit Fresh HOG product (vehicle travels 10km, carries 50 units of Fresh HOG products, 10 litres of fuel)

7. What percentage of total Fresh HOG transported from primary processing plant to secondary processing plant? (70% of that total Fresh HOG at the primary processing plant)

8. What percentage of total Fresh HOG transported from primary processing plant to wholesaler? (30% of that total Fresh HOG at the primary processing plant)

Secondary Processing Plant to Wholesaler

1. What percentage of Whole Fillet product and Salmon by-products being obtained after processing the Fresh HOG product at secondary processing plant? (Example - 70 whole fillet products and 30 Salmon by-products are obtained after processing 100 Fresh HOG product)

2. Processing cost of Whole Fillet product and Salmon by-products at secondary processing plant (Example - £2.1 per unit whole fillet product and also £2.1 per unit salmon by-product or processing cost of 70 whole fillet product and 30 salmon by-product is £210)

3. Daily maximum storage capacity of Whole fillet product and salmon by-product at each secondary processing plant – (100 – 300) units of products

4. From secondary processing plants to wholesaler – what mode of transportation being used and what is the daily shipment capacity on each transportation links? (10 - 40) Units of whole fillet product and salmon by-products

5. Are all secondary processing plant connected via transportation links to all wholesalers?

6. If not all connected, please then kindly let us know which secondary processing plant are not connected to which wholesalers? (For example - 50% of the transportation links being used daily – exactly which 50% transportation links – is the decision of choosing transportation links made on the basis of transportation cost or distances)

7. Inventory holding cost of whole fillet product and salmon by-product at secondary processing plant (Example - £1.5 per unit whole fillet product and £0.5 per unit salmon by-product or inventory cost of 100 whole fillet product and salmon by-product is £200)

8. Transportation cost for per unit whole fillet product and salmon-by product shipped from secondary processing plants to wholesalers (Example - £(4-8) per product)

9. Distances between secondary processing plants to wholesalers (200 – 300) km

10. Fuel consumption in litres per unit distance per unit whole fillet product and salmon by-product (vehicle travels 10km, carries 50 units of whole fillet products, 10 litres of fuel)

Wholesaler to Retailer

1. Daily maximum storage capacity of Whole fillet product and salmon by-product at each wholesaler – (100 – 300) units of products

2. From wholesaler to retailer – what mode of transportation being used and what is the daily shipment capacity on each transportation links? (10 - 40) Units of whole fillet product and salmon by-products

3. Are all wholesalers connected via transportation links to all retailers?

4. If not all connected, please then kindly let us know which wholesalers are not connected to which retailers? (For example - 50% of the transportation links being used daily – exactly which 50% transportation links – is the decision of choosing transportation links made on the basis of transportation cost or distances)

5. Inventory holding cost of whole fillet and salmon by-product at wholesalers (Example - £1.5 per unit whole fillet product and £0.5 per unit salmon by-product or inventory cost of 100 whole fillet product and salmon by-product is £200)

6. Transportation cost for per unit whole fillet product and salmon by-product shipped from wholesalers to retailers (Example - £(4-8) per product)

7. Distances between wholesalers to retailers (200 – 300) km

8. Fuel consumption in litres per unit distance per unit whole fillet product and salmon by-product (vehicle travels 10km, carries 50 units of whole fillet products, 10 litres of fuel)

9. Daily demand of Whole fillet, Salmon by-product, Fresh Hog at the Retailer (100 - 300)

ANNEX III

DATA COLLECTED FOR SALMON SUPPLY CHAIN LOGISTICS MODEL

Type: Excel form