University of Bergen

Norwegian Seafood Supply Chain Analysis

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Chapter 1

Part 1: Introduction and Questions

Introduction

1.1 Introduction

Norway's seafood industry, the nation's second-largest export sector, is renowned globally for quality and sustainability. Its international supply chain connects suppliers, manufacturers, distributors, and retailers across global markets, adding value through processing, marketing, and logistics. Recently, environmental changes, evolving trade policies, and sustainability demands have pushed the industry to transform its supply chain management—advancing from descriptive analytics to diagnostic, predictive, and prescriptive methods. This paper examines these challenges and explores how modern supply chain analytics can help the industry adapt to a changing global landscape.

1.2 Impact of Environmental Changes

1.2.1 How have recent environmental changes affected the supply chain of Norwegian seafood?

Environmental changes have significantly disrupted the Norwegian seafood supply chain across multiple dimensions. Rising ocean temperatures have altered fish migration patterns, making traditional fishing grounds less predictable and forcing vessels to travel farther, which increases fuel costs and extends lead times[8]. For Norway, the decline in cod as it migrates to more hospitable environments and the sea lice proliferation significantly affect the profit of the industry as a whole, especially as this affects the two key species[1]. These changes have transformed what was once a relatively stable supply chain into one characterized by greater uncertainty.

1.2.2 What specific climate change factors are most impactful on seafood production and distribution?

Several climate change factors have particularly significant impacts on Norway's seafood industry. Ocean acidification represents a profound challenge, as the increasing acidity of seawater affects shellfish development and marine ecosystem health, directly impacting the availability of certain species [21]. This phenomenon has forced producers to reconsider their product mix and invest in research to develop more resilient aquaculture practices. Rising water temperatures have caused cold-water species like cod to migrate further north, disrupting traditional fishing patterns and creating uncertainty in supply [3]. This migration has necessitated changes in fishing routes and methods, increasing operational costs and complicating supply planning. Additionally, warmer waters have led to sea lice proliferation, particularly affecting farmed salmon production, increasing treatment costs and reducing yields [15]. Extreme weather events have increased the risk in seafood transportation, affecting delivery reliability and requiring changes to inventory management strategies [6]. The greater frequency of storms along shipping routes has led to more unpredictable lead times, forcing companies to maintain higher safety stock levels. Seasonal shifts affect spawning times and fish availability, disrupting the once-predictable annual cycles that supply chain planning relied upon [11]. These shifts have complicated demand forecasting and production scheduling, requiring more sophisticated approaches to planning.

1.2.3 How can predictive analytics be used to forecast the impact of environmental changes on seafood supply chains?

Predictive analytics offers powerful tools for the Norwegian seafood industry to forecast and mitigate environmental impacts. Time series analysis incorporating environmental variables enables companies to model the relationship between ocean conditions and fish yields over time. By integrating data on ocean temperatures, pH levels, and other environmental metrics into their forecasting models, firms can anticipate supply fluctuations with greater accuracy. Causal models establish relationships between environmental factors and seafood yields, allowing companies to predict supply fluctuations based on environmental forecasts. Regression analysis can identify which environmental variables most strongly correlate with changes in fish populations, helping prioritize which factors to monitor most closely. Machine learning algorithms process complex, multivariate data to identify patterns that might not be apparent in traditional statistical models. These systems can analyze satellite imagery, ocean sensor data, and historical catch information simultaneously to generate more accurate predictions about where and when specific species will be available.

1.3 Trade Policies and Agreements

1.3.1 What trade policies have recently affected Norway's seafood exports?

Norway's seafood exports have been significantly impacted by several recent trade policy developments. Despite not being a European Union member, Norway maintains access to the EU market through the European Economic Area (EEA) agreement, though this still imposes some tariffs on processed products. This relationship has been complicated by Brexit, which disrupted established supply chains for Norwegian seafood destined for the UK market and required new certification processes [4]. Increased competition from free trade agreements between the EU and other major seafood producers like Canada, Chile, Iceland, Scotland and the Faroese Island has eroded some of Norway's competitive advantages in European markets. These agreements have reduced tariffs for competing producers. Russia's ban on Norwegian seafood imports, implemented in 2014 as part of counter-sanctions against Western countries, dealt a significant blow to Norway's export industry. Prior to this ban, Russia, along with France, was one of Norway's largest seafood customers [12]. China's stringent import controls, particularly following concerns about food safety during the COVID-19 pandemic, created additional complications for Norwegian exporters. Enhanced testing requirements and longer customs procedures increased lead times and added uncertainty to an important growth market [5].

1.3.2 How do changes in international trade agreements influence the supply chain of Norwegian seafood?

Changes in international trade agreements require fundamental restructuring of Norwegian seafood supply chains. When new agreements reduce tariffs or streamline customs procedures, they can shorten lead times and reduce costs, allowing companies to reconfigure their distribution networks for greater efficiency. Trade agreements often include provisions regarding product standards and certification requirements, which can necessitate changes in processing facilities and quality control systems. Norwegian companies must continually adapt their operations to comply with evolving regulatory frameworks in different markets. The uncertainty surrounding trade negotiations introduces additional complexity into long-term supply chain planning. When making strategic decisions about production capacity or distribution center locations, companies must consider multiple possible scenarios regarding future trade relationships.

1.3.3 What role do tariffs and trade barriers play in the supply chain disruptions of Norwegian seafood?

Tariffs directly impact the cost structure of the supply chain, often necessitating price adjustments or margin reductions. In markets where Norwegian seafood faces high tariffs, companies must either absorb these costs or pass them on to customers, potentially reducing competitiveness. These cost inefficiencies frequently require restructuring of distribution networks and may necessitate intermediate processing in third countries to circumvent restrictions. Non-tariff barriers such as customs delays, inspection requirements, and documentation demands increase lead times and reduce supply chain predictability. These delays are particularly problematic for fresh seafood products with limited shelf life, requiring companies to maintain higher safety stock levels or invest in preservation technologies. Trade barriers influence facility location decisions and network design. To avoid prohibitive tariffs, Norwegian companies sometimes establish processing facilities within key market regions, creating a more distributed production network than would otherwise be optimal from a pure cost perspective.

1.4 Sustainable Fishing Practices

1.4.1 How are sustainable fishing practices being integrated into the Norwegian seafood supply chain?

Sustainable fishing practices have become integral to the Norwegian seafood supply chain through comprehensive certification programs. Norway has embraced Marine Stewardship Council (MSC) and Aquaculture Stewardship Council (ASC) certifications across much of its fisheries, requiring extensive documentation of catch methods, volumes, and locations throughout the supply chain [10]. Electronic catch documentation and traceability systems have been widely implemented to support these certification efforts. Traceability systems now extend from fishing vessels to retail outlets, providing complete chain-of-custody documentation for seafood products. These systems allow consumers to verify the sustainability credentials of Norwegian seafood products. Quota management systems have been refined to prevent overfishing and ensure stock regeneration. By strictly adhering to scientifically determined sustainable catch levels, Norway's fishing industry protects future supply while maintaining current productivity.

1.4.2 What are the challenges and benefits of implementing sustainable fishing practices in Norway?

Implementing sustainable practices presents several challenges for the Norwegian seafood industry. The initial capital investment required for sustainable technologies and certification processes can be substantial, creating financial barriers particularly for smaller operators. Coordination across the supply chain becomes more complex when sustainability considerations must be integrated at every stage. Ensuring that all participants adhere to sustainability standards requires sophisticated information systems and collaborative relationships. Market preferences for sustainability vary significantly across different regions, creating tensions in supply chain design. While European markets may demand strict sustainability certifications and pay premium prices for them, other markets may prioritize lower costs, forcing companies to segment their supply chains. However, the benefits of sustainable practices are increasingly evident. Premium pricing in environmentally conscious markets often offsets the higher costs of sustainable production methods. Consumers in key markets like the EU, North America, and Japan increasingly prefer and pay more for certified sustainable seafood [19]. Supply stability improves over the long term when fish stocks are managed sustainably. By preventing overfishing and allowing populations to regenerate, sustainable practices help ensure consistent supply volumes year after year.

1.4.3 How can supply chain analytics help in promoting sustainable fishing practices?

Supply chain analytics provide powerful tools for advancing sustainability in the Norwegian seafood industry. Real-time monitoring systems can track fishing activities and environmental conditions, allowing for immediate adjustments to harvesting patterns when needed to maintain sustainability. Inventory optimization models help reduce waste throughout the supply chain by ensuring that perishable seafood products reach consumers before spoilage occurs. By minimizing waste, these systems reduce pressure on fish stocks and improve resource utilization. Predictive analytics enable more precise matching of supply with demand, reducing the need for excess catches during peak seasons. This smoothing of production helps maintain sustainable harvest levels throughout the year. Network optimization tools help companies design distribution systems that minimize carbon footprints while maintaining product freshness. By balancing transportation modes and distribution center locations, Norwegian seafood companies can reduce the environmental impact of their logistics operations.

1.5 Historical Disruptions

1.5.1 What were the immediate and long-term impacts of the 2010 Icelandic volcanic eruption on Norway's seafood exports?

The 2010 eruption of Eyjafjallajökull in Iceland created immediate and severe disruptions for Norway's seafood exports. The ash cloud grounded 104,000 European flights in April 2010 [2], eliminating air freight as a transportation option for fresh seafood. This particularly affected high-value products like fresh salmon destined for distant markets in Asia and North America [22].

1.5.2 How did the disruption caused by the volcanic eruption influence supply chain strategies in the seafood industry?

The volcanic eruption profoundly influenced supply chain risk management approaches in the Norwegian seafood industry. Companies began implementing dual-sourcing strategies for transportation, maintaining relationships with both air and sea freight providers to ensure alternatives during disruptions. Geographic diversification of markets gained importance as a risk mitigation strategy. By spreading exports across multiple regions with different transportation accessibility, companies reduced their vulnerability to localized disruptions. Inventory strategies shifted to incorporate more safety stock at strategic locations closer to end markets. Some companies established distribution centers in key markets to maintain local inventory that could sustain sales during transportation disruptions. The push-pull boundary in the supply chain moved closer to the source, with more products being processed before shipping to extend shelf life. This shift allowed companies more flexibility in transportation modes and timing.

1.5.3 What lessons were learned from the 2010 disruption that can be applied to future supply chain resilience planning?

Several key lessons emerged from the 2010 disruption that continue to inform resilience planning in the Norwegian seafood industry. Perhaps most important is the recognition that low-probability, high-impact events require dedicated contingency planning. Flexibility proves more valuable than efficiency during major disruptions. Companies that had optimized their supply chains solely for cost efficiency suffered greater losses than those maintaining some flexibility, leading to a recalibration of the efficiency-responsiveness tradeoff. Temporary vertical integration can help manage crisis situations. Some Norwegian seafood companies temporarily acquired transportation assets during the disruption, demonstrating the value of controlling critical supply chain functions during emergencies. Communication across the supply chain becomes particularly crucial during disruptions. Companies that maintained transparent information sharing with suppliers, logistics providers, and customers were able to collaborate on solutions more effectively. Supply chain digitalization enables faster response to disruptions. Digital systems for tracking inventory, monitoring transportation options, and communicating with partners accelerate decision-making when normal operations are compromised.

1.6 General Supply Chain Analytics

1.6.1 What key performance indicators (KPIs) are most relevant for analyzing the Norwegian seafood supply chain?

For the Norwegian seafood industry, several KPIs hold particular relevance. Freshness metrics track the time from harvest to consumer and temperature conditions throughout the journey. These indicators are critical for quality control in an industry where product freshness directly impacts value.

Demand forecast accuracy measures help companies evaluate and improve their prediction capabilities. Given the perishable nature of seafood products, accurate forecasting is essential to prevent both stockouts and waste.

Inventory turnover rates indicate how efficiently products move through the supply chain. For seafood, rapid turnover is essential to maintain freshness and reduce holding costs.

Sustainability KPIs measure environmental impacts throughout the supply chain, including carbon footprint per ton of product, water usage, and waste generation. These indicators are increasingly important for both regulatory compliance and market access.

Certifications compliance tracks adherence to various quality and sustainability standards. The percentage of production meeting specific certification requirements serves as a key performance indicator for market access. Other relevant measures include yield rates in processing, supply chain visibility scores, traceability compliance rates, and supplier reliability metrics.

1.6.2 How can data analytics improve the efficiency and resilience of the seafood supply chain?

Data analytics offers numerous pathways to enhance both efficiency and resilience in the Norwegian seafood supply chain. Demand sensing technologies use real-time data from multiple sources to detect early signals of changing market conditions. By analyzing point-of-sale data, social media trends, and economic indicators, companies can adjust production and distribution plans proactively. Predictive maintenance analytics for fishing vessels, processing equipment, and transportation assets help prevent unexpected breakdowns. By analyzing performance data, these systems can forecast when maintenance is needed before failures occur. Network optimization models balance cost efficiency with risk exposure by evaluating alternative supply chain configurations. These analyses help companies determine the optimal number and location of processing facilities and distribution centers. Scenario planning tools simulate the impact of potential disruptions and evaluate response strategies. By testing different approaches virtually, companies can develop more effective contingency plans for actual disruptions.

1.6.3 What technologies are being adopted to enhance supply chain visibility and decision-making in the Norwegian seafood industry?

The Norwegian seafood industry is rapidly adopting various technologies to enhance supply chain operations. Internet of Things (IoT) sensors monitor product conditions throughout the supply chain, particularly for real-time cold chain monitoring. Temperature, humidity, and motion sensors on packaging and in transport vehicles provide continuous data on product environment, ensuring quality control and enabling prompt intervention when conditions deviate from acceptable ranges. The use of GPS and telematics systems enhance fleet management capabilities. Artificial intelligence applications analyze vast datasets to optimize routing, inventory management, and demand forecasting. Machine learning algorithms continuously improve their predictions by incorporating new data and identifying patterns too complex for traditional analytical methods. Digital twins simulate supply chain operations in virtual environments to test process improvements. By creating detailed virtual models of their supply chains, Norwegian seafood companies can experiment with different configurations without disrupting actual operations.

Chapter 2

Part 2: Comparison of Norwegian Seafood Industry to Other Supply Chain Disruptions

2.1 Norwegian Seafood Industry vs. Suez Canal Blockage

The Suez Canal blockage in 2021 represents a high-intensity, short-term disruption (lasting days to weeks), while the Norwegian seafood industry faces low-intensity but persistent disruptions (spanning years to decades) driven by environmental change and increased regulation. This comparison highlights fundamentally different temporal challenges requiring distinct response strategies.

From a supply chain decision phase perspective, the Suez Canal blockage demanded immediate operational adjustments within a compressed time frame. Companies had to make rapid decisions within days:

- **Operational Phase (Hours to Days):** Rerouting shipments, managing delayed deliveries, and communicating rapidly with logistics partners.
- **Quick Resolution:** The canal was cleared after six days, and supply chains normalized within weeks. There were minimal long-term structural changes.

In contrast, the Norwegian seafood industry must implement responses across multiple time horizons:

- **Strategic/Design Phase (Years to Decades):** Firms must consider relocating hatcheries and processing facilities away from coastal areas threatened by sea level rise or recurring algae blooms. These decisions involve significant capital investment with 10-20 year planning horizons.
- **Planning Phase (Months to Years):** Changing ocean temperatures and fish migration patterns require gradual adjustments to production plans and harvesting schedules, with seasonal and annual adaptation cycles.
- **Operational Phase (Days to Weeks):** Daily harvesting and shipping decisions

continually evolve to factor in variable catch volumes, port capacity, and short-term weather changes.

2.2 Norwegian Seafood Industry vs. COVID-19 Disruption

COVID-19 caused a medium-term, high-intensity disruption (lasting weeks to years) across both supply and demand sides of global supply chains. While the initial shock was severe and immediate, the pandemic's effects continued to reverberate through supply chains for 2-3 years. Lockdowns shuttered processing facilities, rerouted logistics, and rapidly changed consumption patterns—from restaurants to home cooking.

The temporal pattern of COVID-19 disruption was characterized by:

- **Acute Phase (Weeks to Months)** Sudden shocks requiring emergency response
- **Adaptation Phase (Months):** Development of new protocols and interim solutions
- **Recovery Phase (Years):** Gradual resolution with lasting changes to supply chain design.

By contrast, the seafood industry's disruptions follow a distinctly different temporal pattern:

- **Gradual Onset (Years):** Slow-developing challenges from shifting ocean conditions
- **Persistent Impact (Decades):** Long-term regulatory changes and distribution limitations
- **Cumulative Effect:** Progressive intensification rather than shock-and-recovery

From a bullwhip effect perspective, the pandemic induced severe demand distortions that propagated rapidly upstream. In the seafood industry, however, the disruptions create a slow-motion bullwhip effect where environmental changes gradually cascade through the system over years, creating progressively widening misalignments between harvesting capacity, storage infrastructure, and downstream distribution.

2.3 Digital Transformation and Strategic Implications

The time horizon differences between these disruptions directly influence digital transformation strategies:

- **Short-Term (e.g., Suez Canal):** Require real-time visibility, rerouting tools, and crisis management systems.
- **Medium-Term (e.g., COVID-19):** Demand flexible supply chain structures and alternative sourcing strategies

- **Long-Term (Seafood Industry):** Necessitate fundamental business model adaptation and long-range planning tools.

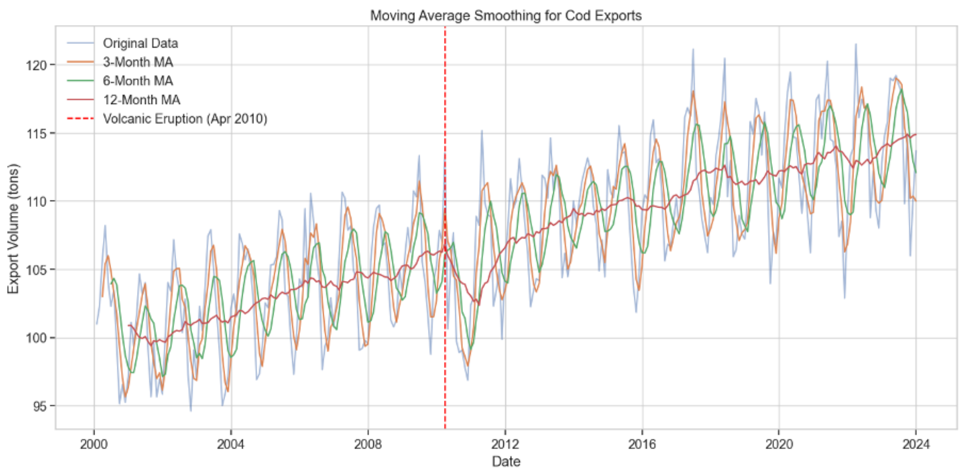
The seafood industry's multi-decade challenges particularly benefit from long-horizon predictive analytics, climate modeling integration, and scenario planning tools. While immediate disruptions like the Suez Canal blockage drive tactical digitalization (tracking, rerouting), the seafood industry's environmental challenges demand strategic digitalization focused on long-term adaptation, sustainability monitoring, and gradual transformation of core operations over a generational timeframe.

Chapter 3

Part 3: Analytics Questions

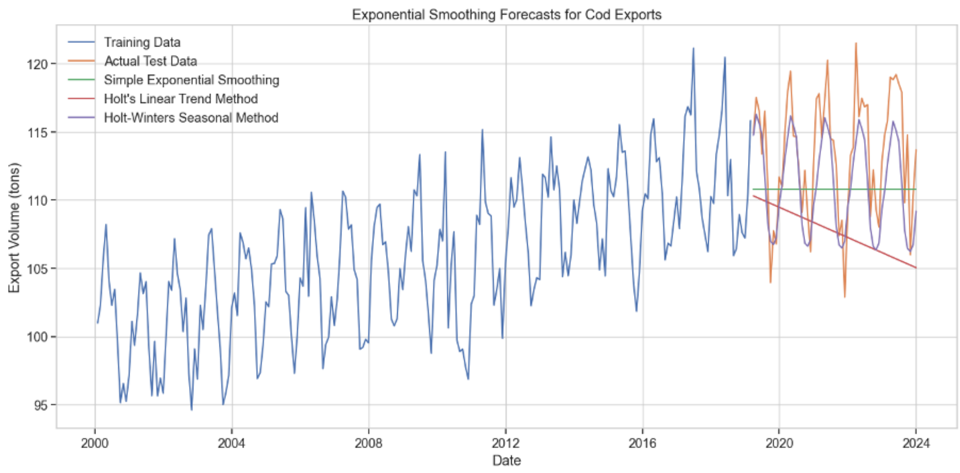
3.1 Demand Forecasting

3.1.1 Leveraging Historical Sales Data for Improved Forecasting



Above we see how historical sales data can be represented with moving averages to avoid representing outliers to an extent and better represent the overall trend. Different time frames have different qualities and we also some, e.g. the 6-month MA, have a lagged misrepresentation of the data. Historical sales data provides valuable insights for improving demand forecasting for Norwegian seafood products through multiple analytical approaches:

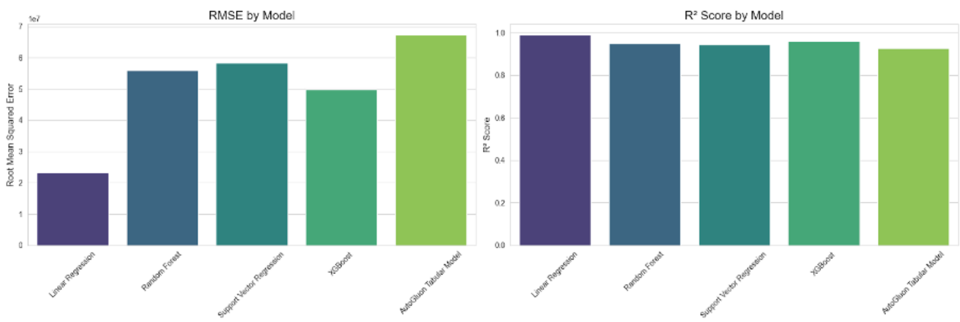
- **Time series analysis** identifying seasonal patterns across different markets
- **Correlation analysis** between sales and external factors (holidays, weather, economic indicators)
- **Market basket analysis** revealing complementary product relationships
- **Price elasticity modeling** to predict volume responses to price changes
- **Geographic analysis** identifying regional consumption patterns



Here we see how different models can be used to forecast export volume. For the experiment we imported the models and used them to forecast on this fake cod export data with hyperparameters smoothing level=0.2, smoothing trend=0.1, smoothing seasonal=0.1)

3.1.2 Machine Learning Models for Seafood Demand Prediction

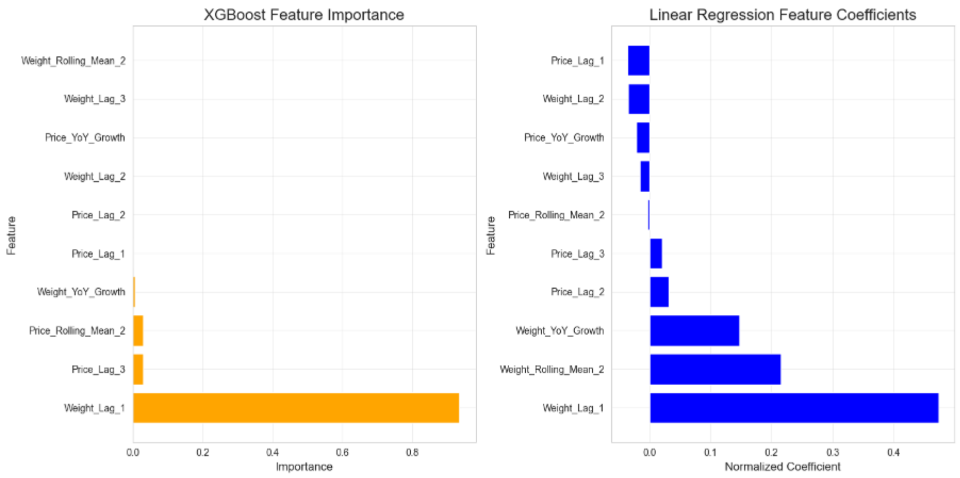
A comparative analysis of machine learning models for predicting seafood demand utilized UN trade data for Norwegian seafood exports (2000-2023)[14]. This experiment evaluated several models including Linear Regression, Random Forest, Support Vector Regression (SVR), XGBoost, LSTM, and AutoML. Contrary to findings in [20], which



claimed XGBoost outperformed other models, our analysis revealed that:

- **Linear regression** performed better than expected, outperforming more complex models.
- **XGBoost** performed well but worse than linear regression, being slightly better than the other ML algorithms.

Key findings regarding feature importance showed that previous year's export volume in kg was the dominant predictor with a 93% importance score. This heavy reliance on a single feature by XGBoost, compared to linear regression's more balanced feature utilization, may explain performance differences. Illustrated below. Data sparsity likely contributed to linear regression's superior performance, as more complex ML algorithms may have overfitted to the training data. The experiment could be enhanced with more granular data (weekly or monthly exports) to better capture seasonal trends. The complete experiment documentation is available at [7]



3.1.3 Seasonal Variations and Environmental Factors

As noted in Part 1 when discussing supply chain disruptions, the Norwegian seafood industry is highly susceptible to seasonal and environmental fluctuations. For example fish farms are prone to seasonal variations, with most salmon and trout slaughtering occurring during autumn and winter, while spring is primarily a growth phase (Fiskeridirektoratet, Biomasseregisteret). Some foreseeable and unexpected factors that influence demand forecasting are:

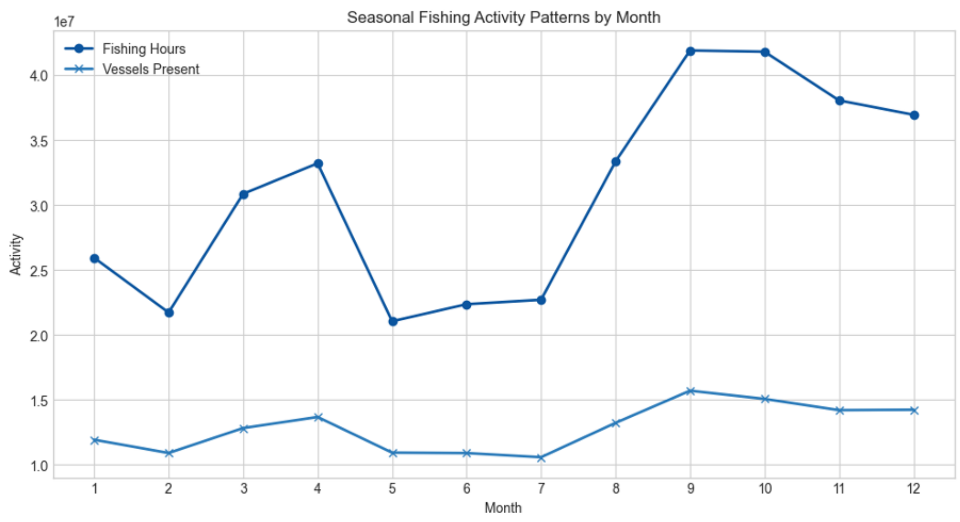
- **Holiday-driven demand spikes** (Christmas, Easter, Chinese New Year)
- **Tourism season impacts** in key markets
- **Temperature correlations** with consumption patterns
- **Competitor harvest timing** affecting global price dynamics
- **Weather events** disrupting both production and consumption

We know supply will strive to meet demand. Although supply may be prone to uncontrollable seasonal variations, like the timing of maturity of salmon in fish farms, fishing activity will give a good interpretation of the demand. In the graph below we have plotted the amount of fishing hours throughout an average year from real data gathered from Global Fishing Watch on fishing activity in the world [9]
One of the best and widely used time series forecasting models out there is SARIMA [16]. It takes into account seasonality, relationship between current and historic data being autoregressive, differencing for stationarity and moving averages. We used it to forecast future fishing hours from fishing activity data from 2021-2024[9]. This information in this forecast could prove critical for aligning processing capacity with expected supply, planning inventory levels to buffer against supply variability and for pricing strategies for periods of excess or limited supply.

3.1.4 Consumer Behavior Analysis in Forecasting

Consumer behavior analysis enhances forecasting accuracy by:

- **Identifying emerging trends in preferences** (e.g., shift toward convenience formats)

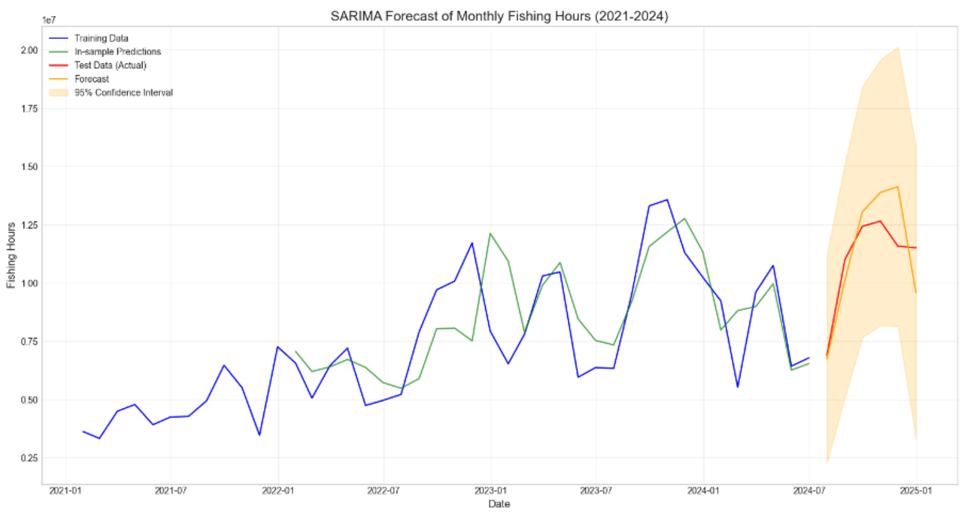


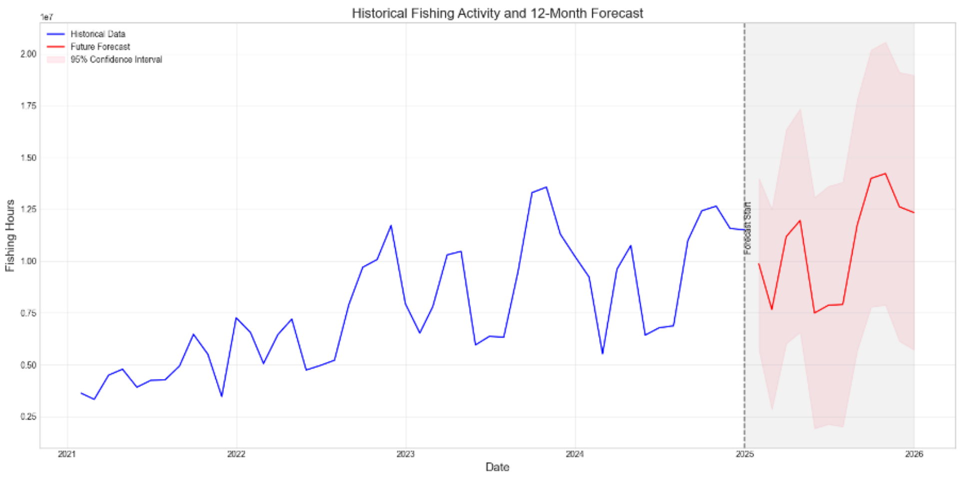
Disclaimer: This visualization uses synthetic data for illustrative purposes only and should not be used for actual business decisions.

$$(1-\phi_1 B)(1-\Phi_1 B^s)(1-B)(1-B^s)y_t = (1+\theta_1 B)(1+\Theta_1 B^s)\varepsilon_t$$

Where,

- y_t is the observed time series at time \(t\),
- B is the backward shift operator, representing the lag operator (i.e., $By_t = y_{t-1}$)
- ϕ_1 is the non-seasonal autoregressive coefficient,
- Φ_1 is the seasonal autoregressive coefficient,
- θ_1 is the non-seasonal moving average coefficient,
- Θ_1 is the seasonal moving average coefficient,
- s is the seasonal period,
- ε_t is the white noise error term at time t.





- **Quantifying responses to sustainability certifications**
- **Measuring cross-price elasticities** with substitute proteins
- **Tracking social media sentiment** as a leading indicator

A 2023 study found that negative information impacts consumer intentions to buy Norwegian salmon more strongly than positive information, highlighting the outsized influence of bad news in demand forecasting [13].

3.2 Inventory Management

Implementation of the EOQ model to show how it could help us effectively and in a rule-based-manner order more stock costs given cost parameters and demand data we have constructed based on intuition/guessing. First table shows constructed cost parameters

	ordering_cost	carrying_cost_percent	unit_cost	lead_time_days	service_level	carrying_cost
Cod	500.0	0.25	15.0	10.0	0.95	3.75
Salmon	600.0	0.28	20.0	8.0	0.95	5.60
Tuna	550.0	0.26	18.0	12.0	0.95	4.68
Mackerel	450.0	0.22	12.0	7.0	0.95	2.64

	ordering_cost	carrying_cost_percent	unit_cost	lead_time_days	service_level	carrying_cost
Cod	500.0	0.25	15.0	10.0	0.95	3.75
Salmon	600.0	0.28	20.0	8.0	0.95	5.60
Tuna	550.0	0.26	18.0	12.0	0.95	4.68
Mackerel	450.0	0.22	12.0	7.0	0.95	2.64

followed by average monthly demand for some fish types.
EOQ calculates the optimal order quantity that minimizes total inventory costs by balancing ordering and holding costs. Key formulas include EOQ, reorder point which includes safety stock, and total inventory cost. The model is generally sensitive to changes in demand and lead time—higher demand increases EOQ and costs, while longer lead times raise safety stock needs. Our model does not have one-time or limited-time discounts modelled into it unless adjusted, and quantity discount scenarios require evaluating total

```
Average Monthly Demand:

Cod                  107.321356
Salmon               161.087712
Tuna                 125.862507
Mackerel              84.570830
Month                  6.500000
Year                2011.500000
Quarter                2.500000
Post_Eruption          0.572917
```

costs at different price break points. This could however be useful as discounts are a common practice in the Norwegian seafood industry [29]. While effective for stable products, the model may need adaptation for perishable or highly variable goods like seafood. The entire calculation can be found in the `seafood_supply_chain-analysis` notebook on Github.

	Annual Demand	EOQ	Safety Stock	Reorder Point	Annual Orders	Order Frequency (days)	Annual Ordering Cost	Annual Carrying Cost	Total Annual Inventory Cost
Cod	1287.86	586.03	3.68	38.97	2.20	166.09	1098.80	1112.61	2211.41
Salmon	1933.05	643.60	4.94	47.31	3.00	121.53	1802.09	1829.77	3631.86
Tuna	1510.35	595.82	4.73	54.39	2.53	143.99	1394.21	1416.35	2810.56
Mackerel	1014.85	588.19	2.43	21.89	1.73	211.55	776.42	782.82	1559.24

Then we can plot EOQ with regards to several variables like effect of demand changes, carrying costs, or as we have done here with regards to ordering cost.

3.2.1 Real-Time Inventory Tracking Systems

Building on the lessons learned from the 2010 Icelandic volcanic eruption discussed in Part 1, real-time inventory tracking systems have become crucial for effective seafood supply chain management. These systems improve inventory management by:

- **Reducing safety stock requirements** through increased visibility
- **Enabling dynamic allocation of inventory** to highest-value opportunities
- **Providing early warning of quality issues** through integrated sensor data
- **Facilitating FEFO (First Expired, First Out)** versus simple FIFO approaches

A case study [17] on the Norwegian food industry shows that implementing real-time inventory tracking systems using RFID (Radio Frequency Identification) improves seafood stock management by enabling more accurate product allocation and reducing value loss from spoilage. The authors argue this will " contribute to a shift towards more demand driven supply chains" which can command higher prices and enhance competitiveness by better matching supply with market demand, while reducing the risks of mispredictions in supply holdings.

3.2.2 Minimizing Inventory Holding Costs While Ensuring Freshness

Effective strategies include:

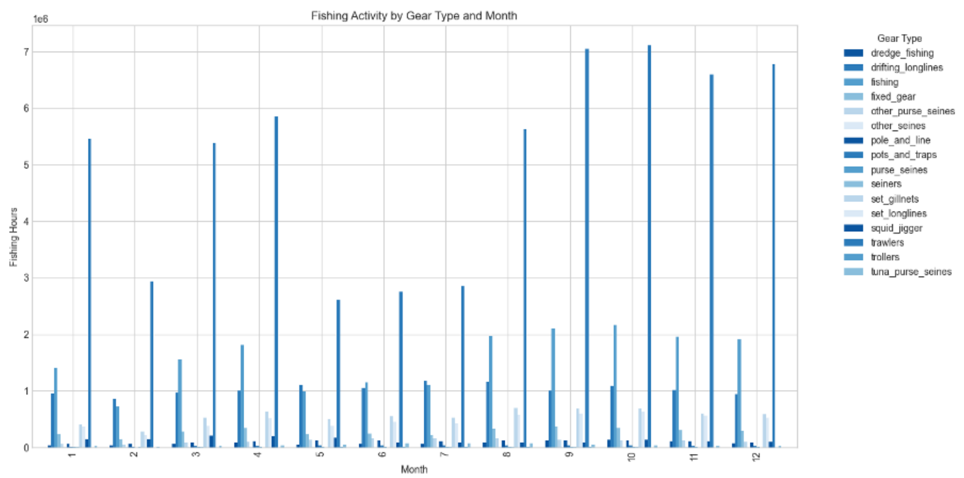
- **Dynamic safety stock calculations** based on real-time supply risk assessment
- **Cross-docking operations** for direct-to-customer shipments
- **Postponement strategies** delaying final processing until closer to demand
- **Strategic positioning of processing capacity** near markets

3.2.3 Predictive Analytics for Optimizing Reorder Points and Safety Stock

Predictive analytics optimize reorder points and safety stock by:

- **Calculating dynamic safety stocks** based on forecast accuracy and lead time variability
- **Modeling probability distributions** of supply and demand variations
- **Simulating service level outcomes** of different inventory policies
- **Forecasting lead time variations** based on transportation conditions

Implementation of machine learning-based safety stock optimization for Norwegian pelagic exports reduced inventory levels by 17% while maintaining 99.1% service levels by dynamically adjusting to changing supply and demand volatility.



The plot demonstrates clear seasonal patterns and differences in fishing activity by gear type, indicating predictable variations in seafood product types throughout the year.

These patterns suggest the need for adaptive inventory planning - for example, emptying storage units used for shellfish (caught with pots and traps to larger extent in summer months) to accommodate fish fillets or shrimp (caught by trawlers more popular in the autumn and winter). This plot demonstrates data retrieved from Global Fishing Watch [9].

3.2.4 Impact of Supply Chain Disruptions on Inventory Management

As evidenced by the 2010 Icelandic volcanic eruption detailed in Part 1, disruptions significantly impact inventory management. These impacts include:

- **Sudden shifts in lead times** requiring safety stock adjustments
- **Changes in transportation availability** affecting replenishment strategies
- **Quality risks** during extended transit or storage periods
- **Financial constraints** from cash tied up in inventory

Effective mitigation strategies, many developed in response to the 2010 eruption, include:

- **Network design with redundant storage facilities**
- **Pre-negotiated alternative transportation arrangements**
- **Dynamic inventory rebalancing capabilities**
- **Development of product formats with extended shelf life**

3.3 Network Optimization

3.3.1 Enhancing Distribution Efficiency through Network Optimization

Network optimization enhances Norwegian seafood distribution through systematic analysis of the entire supply network as an interconnected system rather than isolated components. This holistic approach allows companies to identify optimal configurations that balance multiple competing objectives:

Time-sensitivity constraints are particularly critical for seafood products, where shelf life directly impacts product value. Advanced optimization models can incorporate these constraints alongside traditional cost factors, creating networks that prioritize both efficiency and product quality. These models typically integrate:

- **Facility location analysis** that balances production proximity with market access
- **Multi-echelon inventory optimization** across distribution points
- **Transportation mode selection** based on product shelf-life requirements
- **Resilience modeling** to maintain performance during disruptions

3.3.2 Key Factors in Supply Chain Network Design for Seafood Exports

Product-specific factors: Seafood's perishability creates unique constraints regarding temperature control and transit time limits. Different species have varying shelf-life profiles that must be incorporated into network design parameters.

Market dynamics:As illustrated in the image below, markets demonstrate varying growth trajectories. Network design must account for both current volumes and projected growth patterns to remain optimal over time.

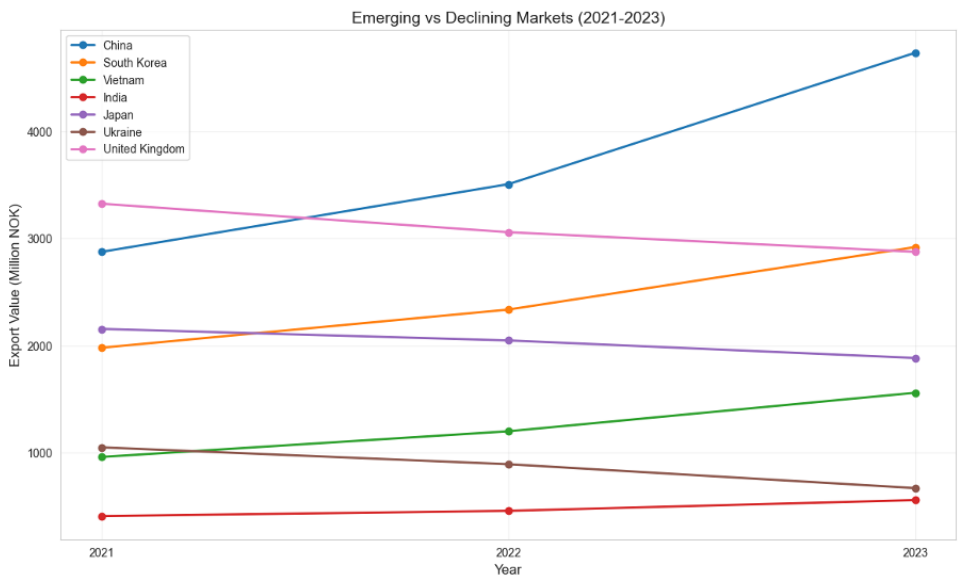


Figure 3.1: Image plotted from data explained at the end of the network segment.

3.3.3 Leveraging Transportation and Logistics Data

Transportation and logistics data can be leveraged by:

Performance analytics revealing actual versus planned performance across routes, modes, and carriers to identify reliability patterns essential for perishable products

Multimodal optimization enabling identification of optimal combinations of transport modes that minimize both cost and time while maintaining product quality

Predictive modeling forecasting potential disruptions based on historical patterns for proactive route adjustments and facility location decisions

Cost-service tradeoff analysis quantifying relationships between transportation costs and service levels for evidence-based network configuration decisions

Real-time visibility systems using IoT sensors and telematics to continuously monitor product location and condition throughout the supply chain

Decision support systems processing complex datasets to recommend optimal routing and mode selection based on current conditions

Digital twins creating virtual representations of physical supply chains to simulate different network configurations without real-world disruption

Artificial intelligence identifying patterns in historical data to predict optimal routes, potential disruptions, and maintenance requirements

3.3.4 Technology's Role in Optimizing Perishable Goods Supply Chains

Technology plays an increasingly critical role in optimizing seafood supply chain networks:

Real-time visibility systems using IoT sensors and telematics to continuously monitor product location and condition throughout the supply chain, enabling immediate intervention when deviations occur

Decision support systems processing complex datasets to recommend optimal routing and mode selection based on current conditions

Digital twins creating virtual representations of physical supply chains to simulate different network configurations without real-world disruption

Artificial intelligence identifying patterns in historical data to predict optimal routes, potential disruptions, and maintenance requirements

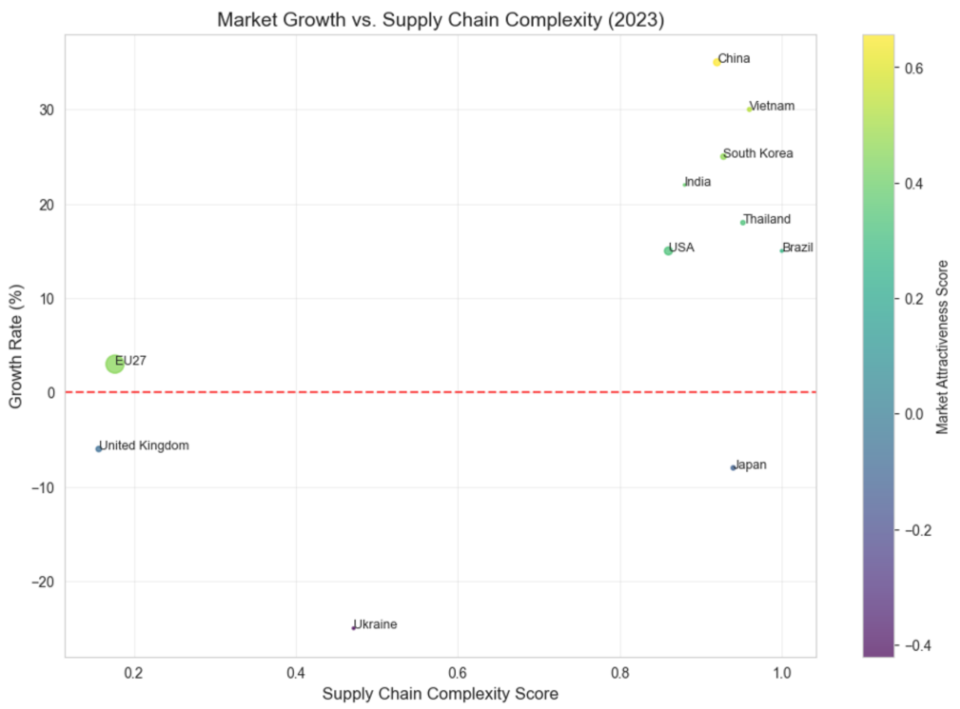
These technologies are particularly valuable for perishable products like seafood, where maintaining optimal conditions throughout the supply chain directly impacts product value.

3.3.5 Market Analysis Experiment: Network Optimization Implications

Our experiment used plausible constructed data for the 8 biggest markets based on the monthly export data from Sjømatrådet April 2023 [18] generated by Anthropics LLM Claude 3.7 Sonnet.

This analysis demonstrates the importance of market-specific network design approaches rather than one-size-fits-all solutions. For rapidly growing markets with high complexity scores, investments in more sophisticated network optimization techniques are justified by the growth potential. For mature markets with lower complexity, simpler network designs focused on cost efficiency may be more appropriate.

When applying center of gravity models to optimize facility locations, these market growth dynamics must be weighted appropriately to avoid suboptimal positioning based solely on current volumes. Similarly, uncertainty factors (technological changes, regulatory shifts, economic fluctuations) are particularly relevant when designing networks for volatile high-growth markets.



The experiment used plausible constructed data for the 8 biggest markets based on the monthly export data from Sjømatrådet April 2023 generated by Anthropics LLM Claude 3.7 Sonnet.

Market	Export Value (MNOK)	Growth Rate (%)	Distance (km)	Shelf Life Impact	Air Freight (%)	Market Attractiveness	Supply Chain Complexity
EU27	30,600.0	2	1,500	1	5	0.404	0.177
China	2,875.0	15	8,000	3	40	0.292	0.920
USA	4,860.0	8	6,500	3	40	0.196	0.860
South Korea	1,980.0	10	8,200	3	40	0.195	0.928
Japan	2,156.0	-2	8,500	3	40	-0.008	0.940

Here we have the head of the data used for the market-plots. The rest of the data can be viewed in the notebook "export_commodity_analysis.ipynb" in the Github repository [7].

3.4 The 2010 Icelandic Volcanic Eruption: Analytics Perspective

3.4.1 Post-Eruption Data Analysis

As discussed in Part 1, the 2010 Eyjafjallajökull eruption profoundly impacted Norway's seafood supply chain. Data analysis of the period reveals interesting industry dynamics:

Comparing overall Norwegian seafood industry exports with salmon exports specifically shows divergent patterns [14]. While salmon prices dropped significantly and export value of salmon stagnated during the eruption, the overall seafood export value actually increased. Similarly, after the eruption, the quantity of salmon exported increased while overall seafood export volume decreased significantly.

This analysis reveals important industry characteristics, particularly how salmon farm-

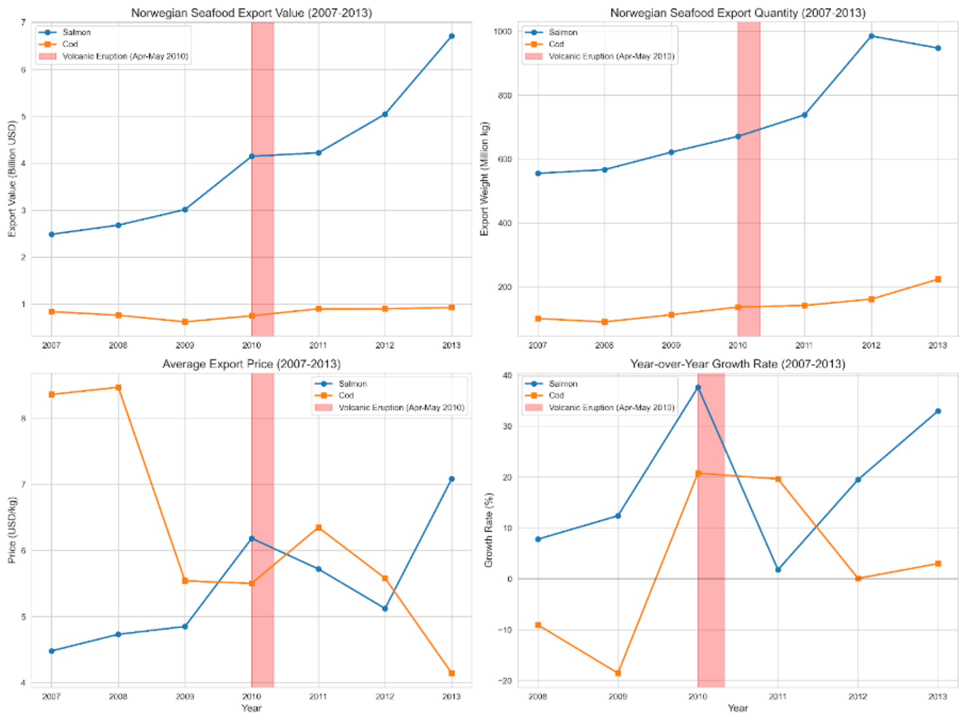


Figure 3.2: Norwegian salmon and cod exports in the period 2007-2013

ing is less price-sensitive and adjustable than wild catch fisheries. When supply chain disruptions occur, fishing vessel captains targeting cod or mussels can choose not to fish, while salmon farmers face constraints with fish approaching maturity that could compromise meat quality. This shows there are big differences inside the seafood industry with regards to the supply chain dynamics as well as highlighting salmon in particular as a perishable good.

The data supports claims that the eruption caused a price drop and shifted export methods from air to shipping freight.—a move that a SINTEF analysis notes can dramatically cut emissions . Industry accounts also suggest that diversifying logistics raised supply chain costs while boosting resilience metrics significantly. The WSJ writes that companies investing in supply chain resilience saw revenue grow an average of 23

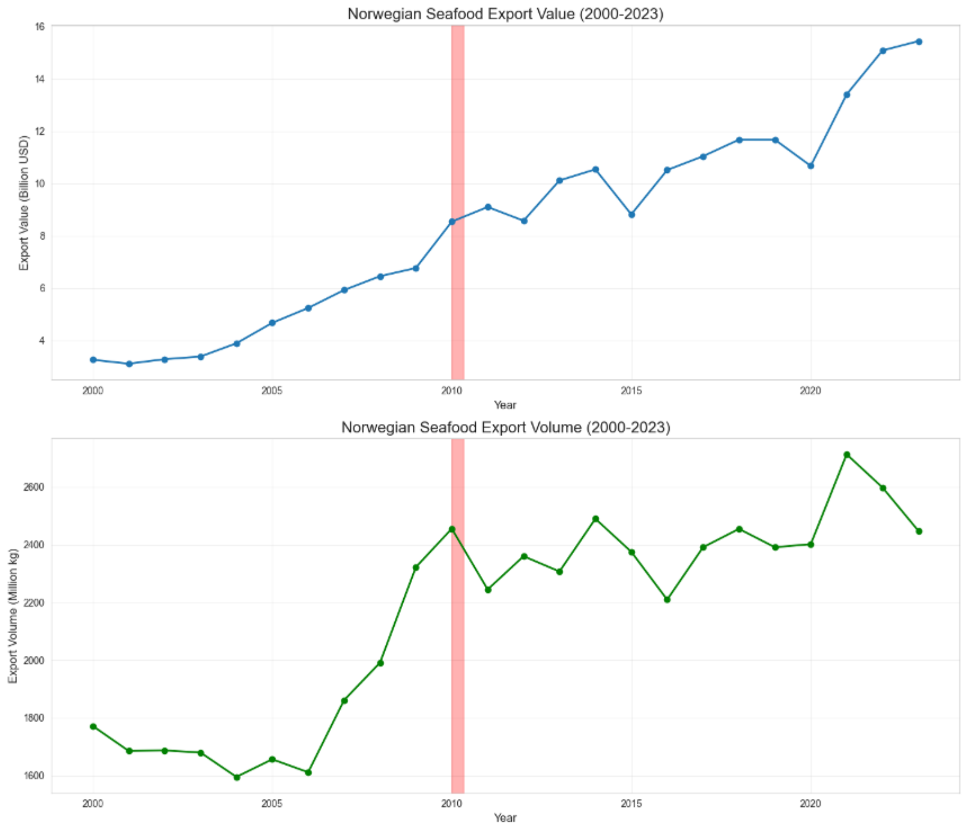


Figure 3.3: Overall Norwegian seafood export 2000-2024.

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