Seaweed logistics and supply chain design

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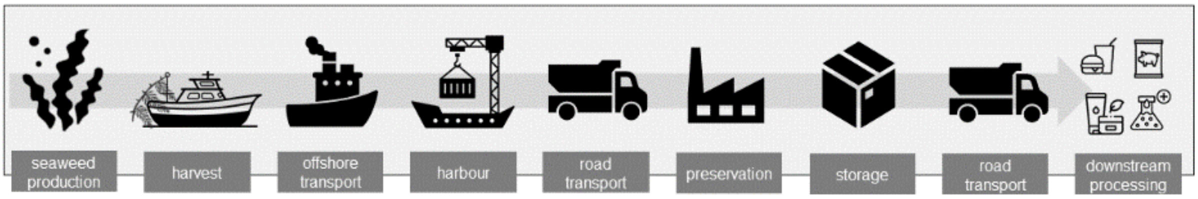
EXECUTIVE SUMMARY

The Qualisea model, developed by VITO/MooV, offers a solid **tool for optimizing seaweed logistics**. Developed and tested within the Qualisea project the model evaluated the impact of variety of scenarios on the logistics costs.

Context and Challenges in Seaweed Logistics

Seaweed aquaculture is increasingly recognised as a sustainable solution to meet the growing demand for high-quality biomass. Global seaweed production has tripled over the past two decades. However, Europe accounts for less than 1% of global production, primarily relying on wild harvesting. To achieve economically viable and larger-scale production, transitioning to aquaculture is imperative. High-value markets particularly require a stable, predictable, and quality-assured biomass supply. An efficient supply chain and well-coordinated logistics are fundamental to meeting these requirements.

The seaweed supply chain consists of numerous interconnected activities, including cultivation, harvesting, transportation and transhipment, preservation, storage and processing. At every stage, constraints related to location, capacity, cost, quality and planning must be addressed concurrently, creating complex logistical challenges.



The MooV Approach to Optimizing Seaweed Logistics

MooV is VITO's supply chain optimisation model and has been tailored to address Qualisea's seaweed logistics challenges. The following approach was implemented (cf. chapter 2, 3 and 4):

- **Define – The seaweed logistics context.** A needs assessment with identification of specific supply chain requirements and constraints.
- **Design – The seaweed logistics model.** Creating the logistics model tailored to the seaweed supply chain
- **Deliver – The seaweed logistics results.** Insights from multiple logistic scenarios varying by production, demand, preservation, and transportation strategy.

The model is tailored to seaweed production in Norway, but designed with flexibility, enabling its applicability across the EU and to different seaweed species. It integrates all supply chain activities detailing their characteristics, constraints and interconnections.

Seaweed Logistics Scenarios

The Qualisea-model evaluates the logistics costs for a variety of scenarios, starting with a prospected **baseline scenario.** Other future scenarios are compared with this baseline varying in **productivity rate, demand volumes**, **preservation techniques** and **offshore transportation strategies**.

In the evaluation of logistics costs differentiation is made between:

- **Mobilisation cost:** total cost of all associated seaweed supply chain activities; production/cultivation, harvesting, harbor infrastructure, preservation, storage, and transportation.
- **Transport cost:** a subset of the mobilisation cost, representing the aggregate cost of (offshore[1] and onshore[2]) transport as well as transshipment operations.
- **Logistics cost:** a subset of the mobilisation cost, representing the aggregate transport cost combined with costs for harbor activities.

Seaweed Logistics Results & Conclusions

Baseline scenario

- As a prospected baseline seario, a seaweed production yield of 20 WMT[3] per hectare is assumed to meet a market demand of 5,000 tons of frozen seaweed.
- In the baseline scenario, seaweed is harvested using a catamaran and then transferred to a barge for transport to the harbour. From there, it is transported by truck to a preservation facility, where it is frozen. After storage, the frozen seaweed is delivered by truck to a downstream processor, such as the feed industry.
- To meet the demand, approximately 8,000 fresh wet tons of seaweed must be harvested from around 40 cultivation sites, transported to 25 freezing facilities, and subsequently delivered to 17 downstream processors.
- The resulting mobilisation costs for this scenario is approximately €3.250 per WMT.
- The main contributor to this cost is cultivation, at €1.270 - around 40%. Logistics costs account for 21% of the total.
- The total mileage amounts to 99 km per frozen ton delivered, with an average offshore mileage of 9 km and an onshore mileage of 90 km.
- The loading rates are influenced by the interaction of production, demand, capacities, and planning. In the baseline scenario, the loading rates are as follows: barge – 88%, truck (harbor-to-preservation) – 63%, and truck (preservation-to-end processor) – 83%.

Impact of Demand

- This scenario examines the impact of varying demand while keeping other key parameters constant. Three alternative scenarios with respective yearly demands; low (3.000 tons), high (10.000 tons), and very high (13.300 tons) are compared to the medium baseline (5.000 tons).
- In comparison to the baseline scenario, meeting a demand of 13.300 tons of frozen seaweed maintains the mobilization cost at approximately €3.250 per ton.
- Focusing on logistics costs reveals an approximate 35% increase, driven by higher offshore transport costs (+71%) and increased road transport as the cultivation area and the number of cultivation sites expand. However, this rise is offset by reduced harvesting costs enabled by a more efficient harvesting strategy. As a result, the total mobilization cost remains nearly unchanged.
- The total mileage per per frozen ton deliverd for the 13.300 ton-scenario is 147 km. The offshore mileage is 18 km, while the onshore mileage is 129 km.

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[1] Offshore transport: sea transport - cultivation site to harbour

[2] Onshore transport: road transport - harbour to conservation site + conservation site to downstream processor

[3] Wet metric ton

- The 13,300-ton scenario demonstrates the following loading rates: barge – 100%, truck (harbor-to-preservation) – 98%, and truck (preservation-to-end processor) – 83%. The increased loading rates result from improved alignment between the throughput capacity at the harbor and the loading capacity of the trucks.

Impact of Seaweed Production/Cultivation

- This scenario examines the impact of a projected increase in seaweed productivity over time, driven by upscaling, technological advancements, and efficiency improvements. The analysis considers a gradual increase in productivity from 14 to 20, 24, 30, 50, 75, and 100 WMT/ha, while maintaining other baseline key parameters, including a demand of 5.000 WMT.
- Compared to the baseline scenario (€3.250/WMT), increasing productivity to 30 WMT/ha reduces mobilization costs by approximately 10%, bringing them down to €2.955/WMT. In the extreme scenario of 100 WMT/ha, a 25% reduction is observed, lowering costs to €2.416/WMT. These cost reductions are primarily attributed to anticipated decreases in cultivation expenses.
- Focusing on logistics costs reveals an approximate 8% decrease at 30 WMT/ha and an 18% decrease at 100 WMT/ha. This reduction is primarily attributed to lower offshore transport costs, as fewer cultivation sites need to be visited to harvest the same volume.
- The total mileage is 93 km for 30 WMT, consisting of 6 km offshore and 87 km onshore. For 100 WMT, the total mileage decreases to 83 km, with 4 km offshore and 79 km onshore.
- The barge loading rate increases from 88% in the baseline scenario to over 95% in the high productivity scenarios of 30 WMT and 100 WMT.

Impact of Preservation Methods

- This scenario examines the impact of four different seaweed preservation methods: freezing (baseline), acid preservation, blanching, and fermentation.
- Compared to the baseline scenario (€3,250/WMT), mobilisation costs decrease by approximately 8% for both acid and fermentation preservation methods. However, blanching results in a steep cost increase of 84%, primarily due to higher energy costs. Additionally, blanching requires 25% more input material, further driving up expenses.
- Focusing on logistics costs, a 20% decrease is observed for acid and fermentation preservation methods, primarily due to the ability to store and transport the processed seaweed at room temperature. In contrast, blanching results in a 7% increase in logistics costs, as it requires 25% more input material.
- The total mileage remains largely unaffected by the preservation method. However, for blanching, offshore mileage increases by 16% due to the need for more input material.

Impact of Offshore Transport Strategies

- This scenario examines the impact of an alternative offshore transport strategy. The baseline involves a small barge with a 10-box capacity shuttling between cultivation sites and the harbor. Alternatively, the impact of a barge conducting a pickup round across multiple sites is tested. Additionally, the barge capacity is varied, with scenarios ranging from 10 to 25, 50, 75, and 100 boxes.
- The results indicate that the round-trip strategy is ineffective at low barge capacities (10 boxes). However, with higher capacities (25 to 100 boxes), mobilization costs decrease by 4% to 10%. This reduction is primarily due to lower harvesting costs, achieved through more efficient utilization of the harvesting catamaran.

The comprehensive analysis of various scenarios offers valuable insights for optimizing the seaweed logistics supply chain. As the seaweed industry continues to scale up, the importance and complexity of logistics will grow accordingly. By evaluating the impacts of different parameters and decisions, stakeholders can make well-informed choices to improve the efficiency and competitiveness of their supply chains. The refined and tested Qualisea model is now prepared for application across EU regions as the seaweed industry advances.

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INTRODUCTION

1 INTRODUCTION

The Qualisea model by VITO/MooV enhances seaweed supply chain logistics by optimizing mobilisation costs while meeting quality and demand requirements. It covers all costs from sea-to-harbour and harbour-to-processor for current and future production scenario's.

Seaweed cultivation in Europe remains in its early stages, with relatively low production volumes. Currently, the primary applications of seaweed are in food and feed, typically involving minimal processing. For the industry to grow, it is essential to expand the market, which requires a consistent and dependable biomass supply with predictable, stable, and traceable quality—a goal that the Qualisea project aims to support.

At present, European seaweed aquaculture is limited to a small number of farms, and the harvested seaweed is processed, or frozen and packaged, near the harvesting locations. The ambition to increase production will necessitate larger and/or more numerous farms, leading to more complex supply chain logistics.

To improve the efficiency of existing and future seaweed supply chain logistics, VITO/MooV has developed an advanced logistics model, referred to as the Qualisea model. The primary goal of this model is to optimise seaweed logistic or mobilisation costs while satisfying both quality standards and demand requirements from various downstream processors across different scenarios. The total mobilisation cost in scope encompasses all expenses from sea-to-harbour as well as harbour-to-downstream processor.

1.1 ERA-net BlueBio

This report files as deliverable D4.2 within the Qualisea-project[4] which is funded by ERA-NET Cofund[5] on Blue Bioeconomy[6] and by Flanders Innovation and Entrepreneurship (VLAIO)[7]

The ERA-NET Cofund is an instrument under Horizon 2020 designed to support public-public partnerships between Member States and associated countries.

The Blue Bioeconomy Call, as part of the ERA-NET Cofund, focuses on unlocking the potential of aquatic bioresources by advancing the supply systems. More specifically focus rests on facilitating the transfer - i.e. logistics, preservation and transportation - of bio-resources from harvest to processing to ensure e.g. traceability, quality, sustainability, and the necessary quantity or pre-processing of the bio-resources for conversion into products for the market.

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[4] https://bluebioeconomy.eu/enhancing-and-controlling-the-quality-of-cultivated-seaweeds-for-large-scale-production-and-a-sustainable-supply-chain-to-food-and-feed-markets/

[5] https://www.era-learn.eu/support-for-partnerships/cofunded-p2p/era-net-cofund

[6] https://bluebioeconomy.eu/about-2/

[7] https://www.vlaio.be/en

1.2 The Qualisea-project

The Qualisea-project in broad aims to solve bottlenecks for further growth in European seaweed or marine macroalgae farming, and for the implementation of seaweed biomass as a raw material for food, feed, materials, and higher-value products. Project focus is on supply chain challenges related to maintaining biomass quality from harvesting to processing.

An important challenge is this regard is to define the optimal supply chain configuration which facilitates efficient logistics while maintaining quality levels. In response to this challenge VITO[8] customised its supply chain optimisation model – MooV[9] - to a model that addresses logistic challenges in seaweed supply chain design. This report details the conceptualisation, design, and testing of this logistics model.

[8] https://vito.be/en

[9] https://moov.vito.be/en

1.3 The seaweed landscape

Seaweed aquaculture is a promising solution for meeting the growing demand for high-quality, traceable biomass, with global production tripling in 20 years, led by Asia. Europe, contributing just 0.8% of global output, relies on wild harvesting, needing a transition to aquaculture to avoid resource overexploitation and address scalability challenges. Ensuring stable, predictable biomass supply and quality is critical for expanding applications into high-value markets.

Current socio-economic policies do not sufficiently address the ecological overshoot (e.g., climate change, CO_2 emissions, land-system change) nor social challenges (e.g., life expectancy, income poverty, employment, and equality) [1]. More profound transformations are needed before 2050 to mitigate the downward trend [1]. For the production of chemicals and materials, one of the required and now generally accepted transformations is the conversion of a fossil-based, linear economy towards a bio-based, circular economy [2, 3]. To meet the increasing demand for traceable, high quality and predictable yields of biomass, seaweed aquaculture has been put forward as one of the potential solutions [4].

Since 1950, the global production of macroalgae biomass has gradually increased [5]. Production of macroalgae/seaweed has more than trebled over the past 20 years, reaching 35 M[10] tons[11] in 2019. Seaweed represents 99% hereof, leaving microalgae below 1% [6]. The production increase is driven by cultivation or aquaculture (representing 97%), as wild seaweed harvesting (representing 3%) remained stable over the years. With more than 95% most of this production is in Asia, with China accounting for 57% [5, 6].

However, the substantial growth of global algae production is not reflected by European production patterns, which have remained relatively flat [6]. In Europe algae production is still at an early development stage [7]. The European algae sector represents a marginal 0,8% of global production (~0,3 M tons) [6]. For 2019, FAO data indicate a European algae production close to 300 000 tons of which 97% from wild collection and 3% from aquaculture or cultivation [8]. The JRC algae data-catalogue [9] indicates 34 European enterprises involved in seaweed or marine macroalgae production, with Norway (12), Denmark (5) and France (4) topping the list.

As a harvesting technique manual (and mostly wild) harvesting (86%) is still the dominant technique in Europe over 14% mechanical harvesting [6]. A transition from wild harvesting to seaweed aquaculture is needed to avoid the overexploitation of wild seaweed resources [7]. In this context, offshore aquaculture has the advantage of reducing conflicts in the use of space and has a higher potential for upscaling of production [10, 7]. This cultivation method comes with multiple challenge such as forces of offshore seas, high infrastructural and logistics costs associated with offshore operations and rather low biomass yields [7, 11, 10, 12, 13, 14, 15].

Looking at application the dataset does not differentiate between algae species groups and bundles macroalgae, microalgae and spirulina. The dataset suggests direct food (33%), food

[10] Million

[11] Wet weight

supplements (14%) and animal feed application represent more than 50% of current applications (Figure 1). [7]. To expand the markets towards high-value applications such as cosmetics and pharma, a stable and reliable supply of biomass with a predictable, stable, and traceable quality, must be ensured. This involves control of the seaweed quality and conditions from harvesting until processing, as well as energy-efficient preservation to enable a year-round supply towards the processing facilities.

The Qualisea project addresses current and future supply chain challenges related to a predictable and stable biomass quality from harvesting to preservation or processing. The project aims to solve bottlenecks for further growth in European seaweed farming, and for the implementation of seaweed biomass as a raw material for food, feed, materials, and higher-value products.

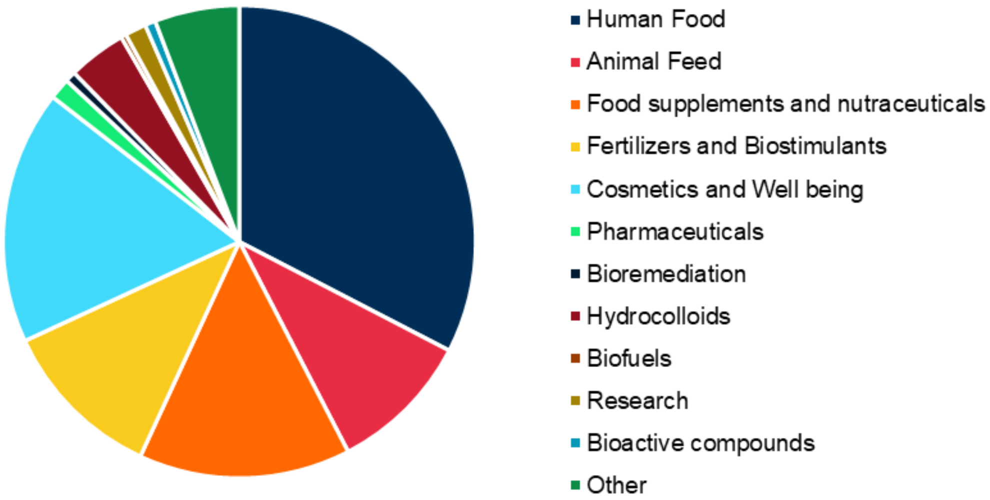

Figure 1 Biomass applications in EU [9].

1.4 Seaweed logistic challenges

The supply chain logistics involves multiple activities from harvesting to processing interconnected via transport modes. At all stages requirements related to location, cost, quality, and scheduling must be simultaneously fulfilled; creating a complex logistic challenge.

Currently, seaweed production in Europe is distributed across numerous small-scale aquaculture sites, each producing between a few tens to several hundred tonnes of fresh seaweed. The anticipated growth of the seaweed industry necessitates the development of an efficient supply chain configuration, capable of accommodating increased production volumes. This growth must also address the need for high-quality products and the demand for more efficient harvesting and transportation processes.

The seaweed supply chain encompasses several key activities, which can be broadly categorised into: (i) production and harvesting, (ii) transhipment to the shore, (iii) preservation, (iv) storage, and (v) transport to a downstream processor (DSP) (Figure 2). These activities are linked by various modes of transportation. To achieve an optimal mobilisation strategy, it is essential to simultaneously satisfy all critical conditions related to location, quantity, cost, quality, and scheduling. However, meeting these conditions concurrently presents a significant challenge. The numerous possible variations in strategy provide considerable operational flexibility but also increase the risk of suboptimal decisions, which could result in less efficient and effective supply chains.

One of the primary challenges in the seaweed supply chain is the involvement of various stakeholders, each specializing in different stages such as feedstock production, supply, collection, logistics, biomass refining, and downstream processing toward final applications. When establishing a new value chain, these activities (Figure 2) are often considered independently rather than being integrated into a cohesive system [16, 17].

Full integration is essential to assess how strategic decisions impact the economic performance and overall design of the supply chain such as the impact of;

- increased seaweed production;
- the location of seaweed aquaculture sites;
- centralised vs. decentralised preservation;
- the storage locations and capacities;
- the co-existence/co-operation with existing fishery infrastructure

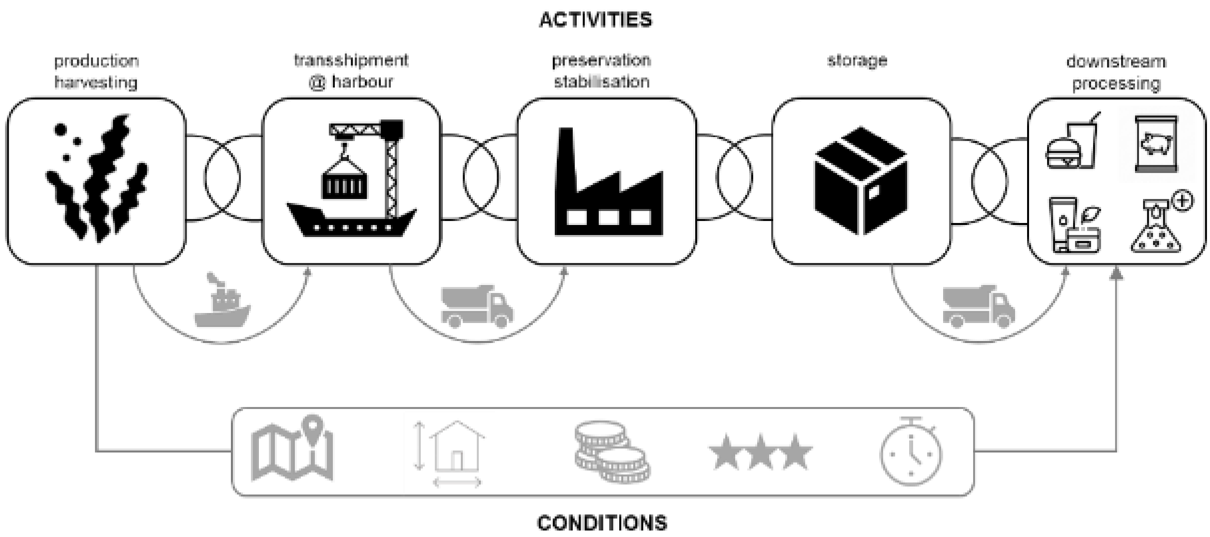

Figure 2 Main activities and conditions (location, capacity, cost, quality, planning) in the seaweed-based supply chain.

1.5 Our solution

The MooV supply chain optimization service by VITO. Our methodology involves defining supply chain needs, designing a tailored logistic model and delivering insights for scenario analysis. The model is flexible and allows evaluation of variables like production, demand, preservation activities and transport modes - ensuring relevance across different regions, seaweed types, and future industry developments.

In the Qualisea project, VITO implements its supply chain optimisation service, MooV (https://moov.vito.be/en). MooV provides data-driven support for making strategic decisions in supply chain management, such as selecting locations for new facilities or evaluating the impact of collaboration within supply chains. It is applied both in establishing new chains and in revisiting, restructuring, or integrating existing chains to enhance performance and mitigate potential disruptions. The results are presented in clear maps and graphs, making complex data easy to interpret.

The MooV service combines a custom optimisation model with the expertise of supply chain professionals. The foundation of the approach is the MooV core optimisation model, which encompasses the universal principles of supply chain optimisation. This core model is then adapted to the specific needs, characteristics, and goals of the particular supply chain under study (in this case, seaweed) referred to as the shell model.

MooV's methodology involves three key steps (Figure 3), guiding the optimisation process tailored to each unique case.

- **Define**: This step involves identifying and outlining the specific needs, characteristics, and objectives of the supply chain. It also includes gathering, processing, and analyzing essential input data required for modeling and optimisation.

- **Design**: In this phase, the shell model is developed by programming the data and information collected during the Define step. This shell model is then integrated with the MooV core optimisation model, creating a tailored Qualisea-model specific to the seaweed supply chain under study.

- **Deliver:** The final step involves applying the Qualisea model, to the specific case. This includes analyzing and interpreting the results, as well as communicating the findings and insights with the client to support decision-making.

The Qualisea model is designed TO-BE flexible and dynamic, enabling the analysis, evaluation, and direct comparison of various scenarios using the same framework. This adaptability allows for different scenarios TO-BE tested by altering key variables. For example, scenarios can be differentiated by changing:

- The available quantity or species of seaweed produced at aquaculture sites
- The location and scale of the aquaculture operations
- The methods and types of preservation activities employed
- The location and capacity of preservation facilities
- The quantity and quality specifications of seaweed products required by downstream processors
- The geographical location of demand, particularly for downstream processing
- The organisation and logistics of seaweed harvesting

The scenarios are compared with evaluate the impact of these changes on the total overall mobilisation cost within the supply chain. The flexible design of the Qualisea model allows for the adaptation of its framework, meaning that while it is in this study applied to the Norwegian case, it can be easily modified for use in other countries or regions, or for different types of seaweed in the future. This versatility ensures that the model remains relevant and applicable across various contexts and evolving industry needs.

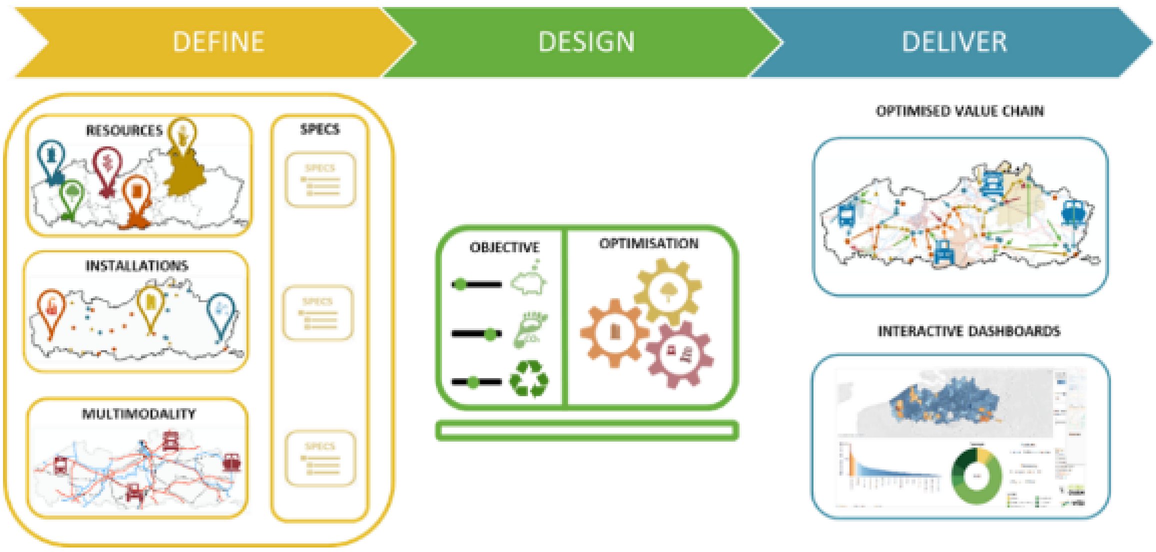

Figure 3 MooV methodology.

Figure 4 shows the plan of approach for the Qualisea project consisting of a structured, stepwise process to ensure the effective development, application, and optimisation of the seaweed supply chain model. The following key phases will guide the project:

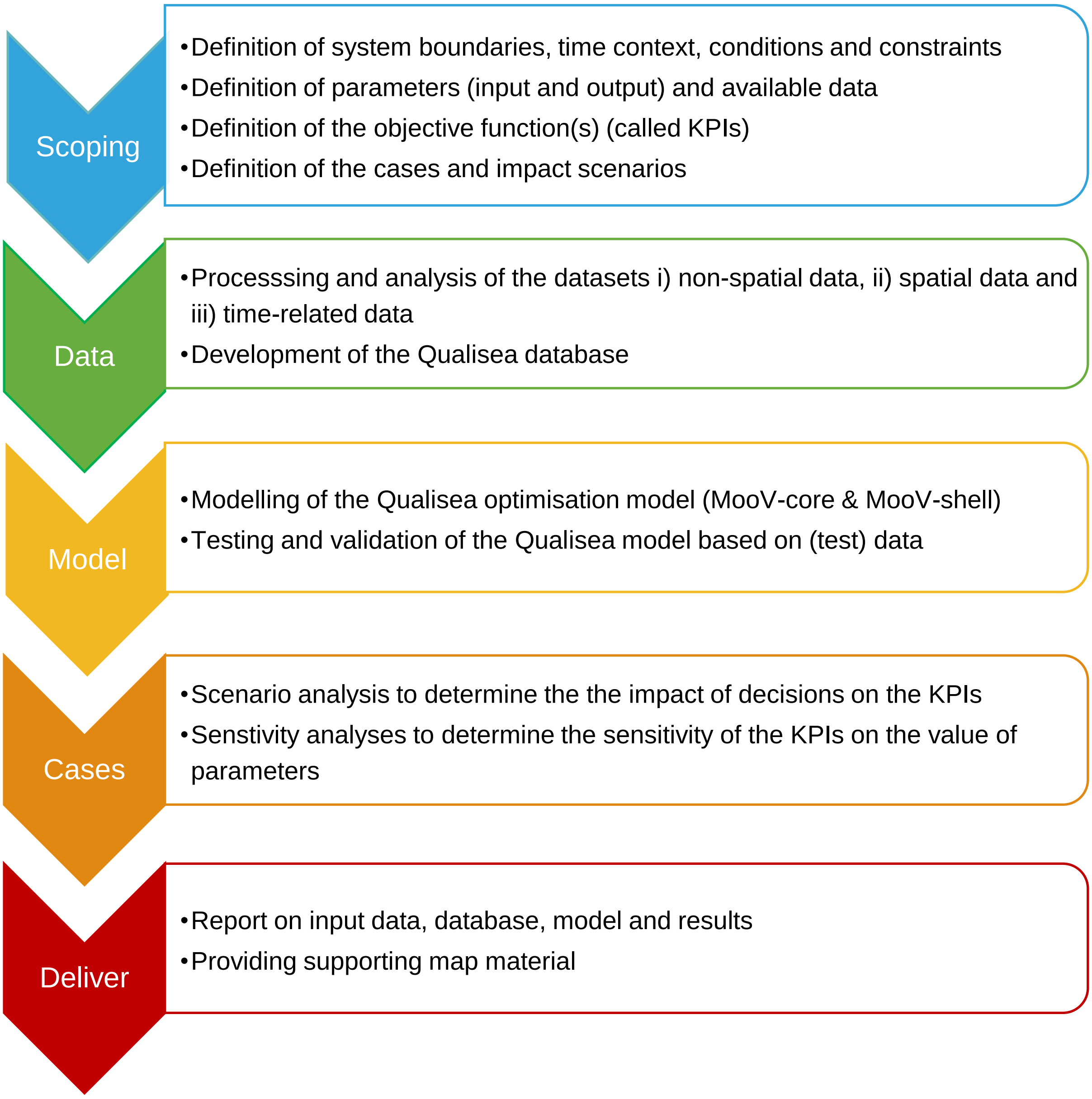

Figure 4 MooV plan of approach.

DEFINE

The logistic seaweed context

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2 DEFINE – THE SEAWEED LOGISTICS CONTEXT

This chapter defines the supply chain from the offshore aquaculture site to the onshore processor with a description of the activities, their characteristics, requirements and limitations as well as how the activities are connected to each other (cf. Figure 2).

To improve the efficiency of existing and future seaweed supply chains, MooV has developed an advanced logistics framework, referred to as the Qualisea model. The primary goal of this model is to optimise seaweed mobilisation costs while satisfying both quality standards and demand requirements from various downstream processors across different operational scenarios. The total mobilisation cost of seaweed encompasses all expenses from aquaculture production up to the delivery of the stabilised seaweed product at the downstream processor's facility.

Within Qualisea, the analysis is performed on a case study in the region of Norway focussing on the seaweed species *Alaria esculenta* and *Saccharina latissima*. In Europe, Norway is the country with the highest number of seaweed aquaculture companies [7] supported by the Norwegian strategy to develop a bioeconomy based on the production and processing of cultivated seaweeds [7, 18].

2.1 Functional requirements

2.1.1 Flexibility

The evaluation of potential mobilisation scenarios considers a wide range of factors and decision variables, including biomass availability, methods of seaweed preservation, centralised versus decentralised preservation strategies, and the required quality and quantity at the downstream processor's facility. The flexibility provided by the MooV approach is critical in defining these various scenarios and in calculating the differences in outcomes between them.

The Qualisea model is integrated with the Qualisea database, which stores case-specific and scenario-related data. This connection enables dynamic adjustments to key characteristics related to production, storage, preservation, demand, and transportation, facilitating the creation of multiple new scenarios or sensitivity analyses. Examples of adjustable characteristics within various stages of the supply chain include (as shown in Figure 2):

- Production: species, productivity, production cycle, types of intermediate products, and final products;
- Harvesting: harvesting methods, capacity, cost, harvesting cycle, and the impact on product quality;
- Preservation: preservation methods, capacity, cost, and the effect on product quality;
- Storage: storage methods, capacity, cost, and the effect on product quality;
- Downstream processing: processing methods, demand, and required product quality;
- Transport modes: transport methods, capacity, cost, and bulk density.

It is important to note that within the scope of the Qualisea project, the Qualisea model is applied to a Norwegian case study, specifically focusing on the seaweed species *Alaria esculenta* and *Saccharina latissima*. Consequently, the data and analyses presented here are tailored to this particular case. Data for other case studies may differ based on factors such as the size and number of aquaculture sites, geographic region, operational costs, and other local conditions. However, the model is designed with flexibility, ensuring that it can be equally applied to other case studies regardless of these variations.

2.1.2 Time context

The availability of seaweed biomass is closely linked to management cycles, such as harvesting seasons (see Figure 5). As a result, biomass supply is released at specific times throughout the year. Therefore, it is essential to incorporate the temporal context into the evaluation of supply chain design strategies to ensure alignment with these seasonal fluctuations in biomass availability.

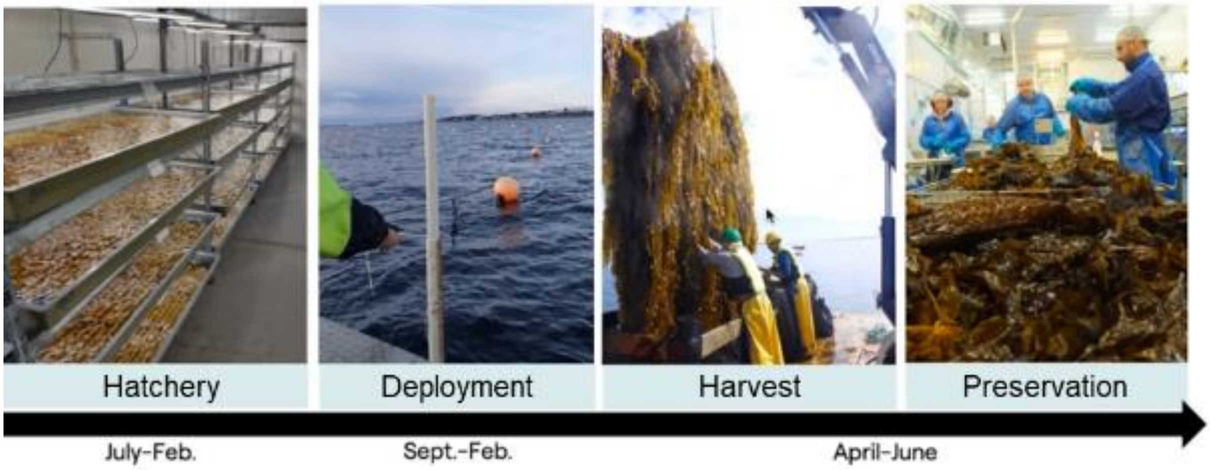

Figure 5 Time window of a harvesting season for seaweed (source: SES - Seaweed Solutions).

The time horizon represents the total duration over which the supply of seaweed feedstock is analysed and optimised (see Figure 6). In the context of the Norwegian case study, the harvest season, encompassing both harvesting and processing, occurs between April and June. Specifically, harvesting is conducted over a 30-day period from late April to early June (see Figure 5). Beyond this period, biomass quality deteriorates due to fouling, primarily by epiphytes, reducing its suitability for food and feed applications. Hatchery operations and seedling deployment at sea are excluded from this analysis. Therefore, the time horizon is defined as 30 days.

Note that this time horizon is specific to the operations outlined in this case study. The time horizon for other cases can vary, typically ranging between 10 and 40 days, depending on factors such as geographic region, scale of operations, the nature of the final products, and overall operational efficiency. To accommodate these variations, the Qualisea model is designed with the flexibility to adapt the time horizon, ensuring its applicability across different case studies and operational contexts.

The time period refers to the shortest interval within the time horizon during which decisions can be made; in this case, it is set to 1 day. This daily time frame enables precise modelling of the quantities of biomass harvested, preserved, and processed throughout a single harvesting season (i.e., the time horizon). By setting the time period to 1 day, the model can account for potential fluctuations in biomass availability and processing capacity over the course of the season.

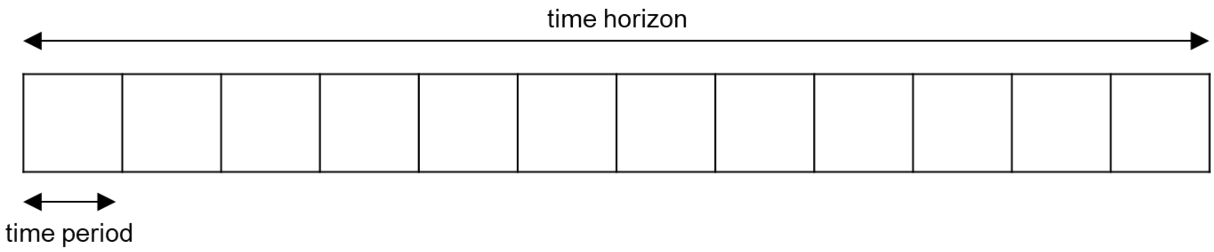

Figure 6 Visual representation of the time context.

2.1.3 Objectives and other KPI's

The goal of the Qualisea-model is to minimise the overall mobilisation cost of seaweed from the aquaculture production up to delivery of the stabilised seaweed product at the gate of the downstream processor. In this context, the overall mobilisation cost is defined as the sum of costs of the following 6 activities (Figure 7):

The primary objective of the Qualisea model is to minimise the overall mobilisation cost of seaweed, from aquaculture production through to the delivery of the stabilised seaweed product at the downstream processor's facility. In this context, the overall mobilisation cost is defined as the sum of the costs associated with the following six key activities (see Figure 7):

1) **Cost of Seaweed Production:** This includes all expenses, both operational and capital, for seeding, hatching, deployment, growth, and crop management.
2) **Cost of Harvesting**: Comprises the rental price of the harvest vessel, including fuel and labour costs for the crew.
3) **Cost Related to the Harbour**: Covers the fixed rental fees for the use of harbours, which includes storage space for equipment and access to harbour facilities and equipment.
4) **Cost of Preservation:** Refers to the operational expenses associated with seaweed preservation and stabilisation activities.
5) **Cost of Storage**: Encompasses the operational expenses for storing preserved or stabilised seaweed.
6) **Cost of Transport**: This cost includes both transportation and transshipment expenses, as follows:
    a) **Transport between aquaculture site and harbour**: Transportation expenses for offshore transport from the aquaculture site to the harbour including offshore transshipment from the harvest vessel to another vessel for sea transport.
    b) **Transshipment at the harbour**: Unloading the vessel and the immediate loading of the truck (mainly labour costs).
    c) **Transport between harbour and preservation location**: Transportation expenses for moving the seaweed from the harbour to the preservation site including transshipment at the preservation facility (i.e., unloading the truck).

d) **Transport between preservation location and downstream processor**: Transportation expenses for moving the stabilised seaweed from the preservation site to the downstream processor including transshipment activities at both ends — loading at the preservation location and unloading at the downstream processor.

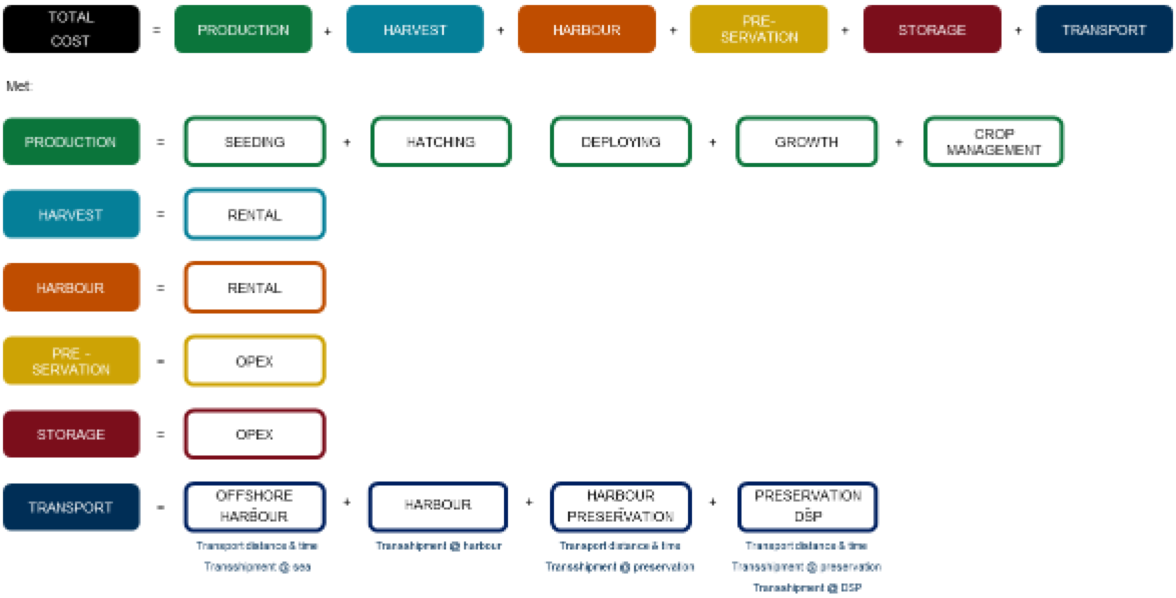

Figure 7 Objective function: Seaweed mobilisation cost.

The optimisation of the total mobilisation cost is performed considering (all cost terms):

(i) Either; the obligation to harvest and process a certain amount of seaweed (i.e. push);
(ii) Or; the obligation to meet a certain seaweed demand at the gate of the downstream processor (i.e. pull).

To analyse the impact of strategic decisions on the organisation of the supply chain, also the logistics cost is discussed separately (orange + red + dark blue cost terms). The logistics cost entails the costs related to moving the product, i.e., costs related to transport and transshipment (dark blue) as well as costs for using the harbour (orange) and for storage (red).

In addition to the overall mobilisation cost and the logistics cost (€), the total transport distance (km) and the number of vehicle movements (count) are evaluated for each scenario.

Note: an overall supply chain risk or failure cost was also discussed (e.g., 5% of the global logistics cost) but was not adopted. The risk of failure is amongst others dependant on the development stage and maturity of the supply chain, and thus is likely to change over time. The current stage as well as the trajectory (e.g., decrease) of the failure cost over time is yet unclear. Hence it was omitted from calculations, notwithstanding it being potentially important, particularly in early-stage development supply chains.

2.2 Products and activities

As illustrated in Figure 2, various activities are necessary to mobilise the seaweed. In addition to the type and source of the seaweed, several processes influence its quality and characteristics. Key factors, such as the harvest method and preservation processes, play a critical role in determining how the biomass can be stored, transported, and ultimately processed. Consequently, earlier stages in the supply chain can impose limitations on the available options for downstream processing, as certain decisions may affect the compatibility or suitability of the biomass for further steps in the production process.

Eight main activities are distinguished in the seaweed supply chain: (1) seaweed production, (2) harvest (3), transport to harbour, (4) transhipment at harbour, (5) transport to preservation, (6) preservation, (7) storage, (8) transport to downstream processing and (9) downstream processing (Figure 8).

These activities are characterised by 4 key parameters:

- **Cost**, defined in NOK/WMT (Norwegian Krone per wet metric tonne) [12];
    - Costs in the seaweed production sector are mainly referenced in WMT and are reported as such. The wet-to-dry ratio is on average a factor 10. Hence to attain dry matter tonne (DMT) a factor 0,1 (10%) is applicable;
    - Note: costs in the following sections reflect the current maturity level of seaweed production in the Norwegian case study i.e. premature stage (AS-IS scenario). For future scenarios costs, are adjusted to reflect scaling and learning curve projections (TO-BE scenarios);
- **Capacity**, defined in WMT/day;
- **Quality requirements**, such as required moisture content, particle size,etc.;
- **Mass balance**, the relationship between input and output of processes/activities is defined as a percentage (e.g. 100% product IN = 80% product OUT + 20% effluent OUT);
- **Location,** defined by coordinates.

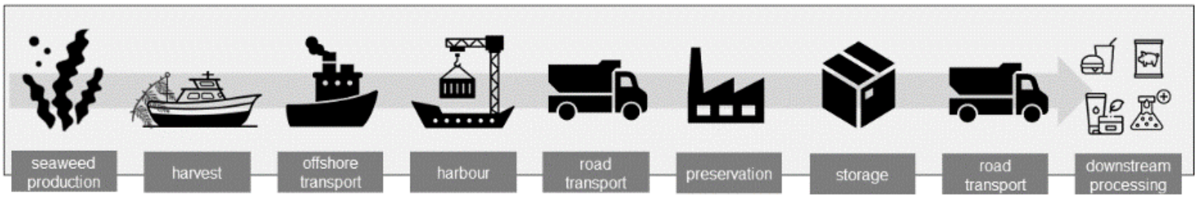

Figure 8 Process flow of the seaweed supply chain.

2.2.1 Seaweed production/cultivation

The mobilisation of seaweed starts with seaweed production or cultivation (Figure 9). Qualisea-partner Seaweed Solutions (SES) is a Norwegian seaweed company focused on cultivation, harvesting and preservation of the seaweed species *Alaria esculenta* and *Saccharina latissima* (Table 1). SES operates the value chain from spore and production of seedlings in their in-house hatchery, to deployment and harvest of fully grown seaweed at their aquaculture site in Frøya, Norway. With 65 hectare this aquaculture site is one of the largest seaweed farms in Europe. The case study for supply chain design focusses on the 2 seaweed species *Alaria esculenta* and *Saccharina latissima*, grown in South Trøndelag.

[12] The conversion from Norwegian Krone (NOK) to Euro (EUR) can be approximated by dividing the amount in NOK by 12 (rounded 11,74). [1 NOK ≈ 0,085 EUR]

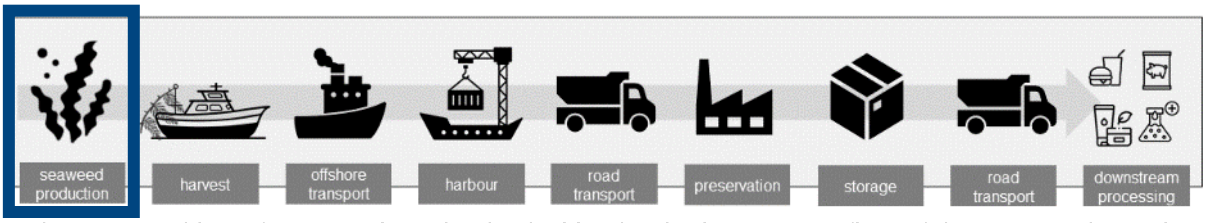

Figure 9 Position of seaweed production/cultivation in the process flow of the seaweed supply chain.

At this moment, the seaweed production cost up to the point of harvest is ca. 12.500 NOK (ca. 1.050 €) per WMT[13] and includes the seeding, hatching, deploying, growth and crop management. The current seaweed productivity is about 10 WMT/ha/y (Table 2).

However, productivity is expected to increase due to advancements in technology, improvements in cultivation techniques, and gains in efficiency, as well as the scaling up of production (refer to section 4.5). It is likely that production costs will decrease as the maturity level of the industry advances (as shown in Table 2), given that the sector is currently at an early, or infancy, stage of maturity.

To estimate the evolution of production costs, the six-tenth rule is applied as a general guideline to predict cost reductions associated with upscaling. This rule of thumb suggests that as production capacity increases, the costs do not rise linearly but rather follow a scale factor of 0,6. In other words, when production is scaled up, the cost increases by a factor less than one, resulting in cost savings as the operation grows larger. This principle helps to anticipate reductions in production costs as the industry expands and matures [19] (Figure 10). Table 2 shows the current and anticipated future (TO-BE) production and production costs with application of the six tenth rule.

Table 1 Fact sheet on selected seaweed species [20].

	Alaria esculenta	***Saccharina latissima***
English name	Winged Kelp	Sugar Kelp
Size (cultivated)	1-1.5 m	1.5 - 2 m
Europe cultivation	Along coasts with cold water and severe wave exposure, such as Norway, UK and Ireland.	Along the Atlantic coast from Portugal to Artic regions
Companies in EU [7]	16	26
Production in EU [7]	107 ton	376 ton

[13] Oral communication SES

	Alaria esculenta	*Saccharina latissima*
Applications	food (ingredient/flavour enhancer in products like soups and salads, or thickener), agriculture, horticulture; cosmetics; environmental health; industry; pharmaceutical; and biomedicine	food (ingredient/flavour enhancer in products like soups and salads, or thickener), feed (additive), cosmetics (UV protectant), drinking straw
		

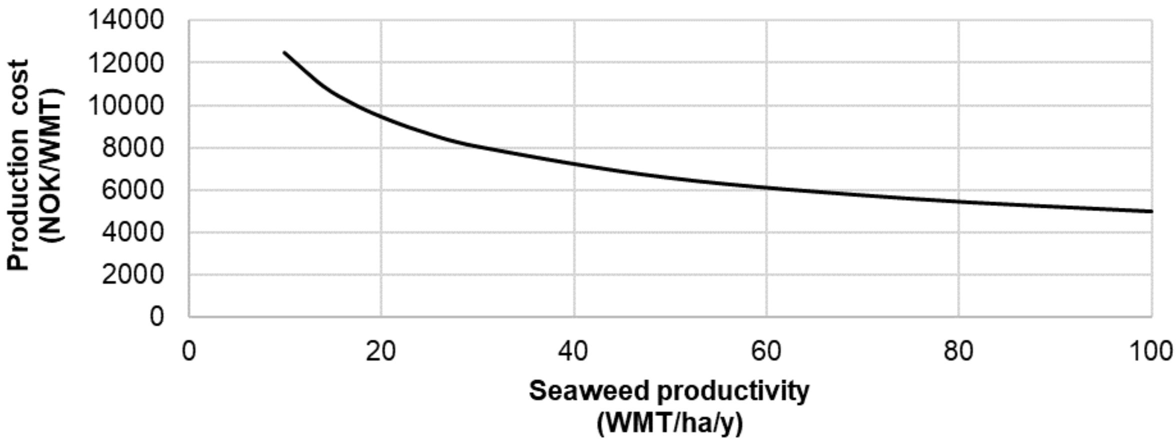

Figure 10 Relationship between seaweed productivity and production cost (NOK/WMT).

Table 2 Seaweed production – Scenario characteristics[14].

Scenario	**Production** (WMT/ha/y)	***Alaria esculenta*** *NOK/WMT*	***Saccharina latissima*** *NOK/WMT*
AS-IS	10	12 500	12 500
TO-BE 1 a	14	10 925	10 925
TO-BE 1 b	17	10 110	10 110
TO-BE base	20	9 475	9 475
TO-BE 1 d	24	8 805	8 805
TO-BE 1 e	30	8 055	8 055
TO-BE 1 f	50	6 565	6 565
TO-BE 1 g “Visionary”	75	5 585	5 585
TO-BE 1 h “Visionary”	100	4 975	4 975

[14] Refer to section 4.5

In Norway, a seaweed producer needs to obtain an aquaculture license from the Norwegian Directorate of Fisheries (NDF) ("Fiskeridirektoratet"). The first licenses for seaweed cultivation at sea in Norway have been granted in 2014. In 2019, about 834 ha was allocated to seaweed cultivation, which corresponds to a virtual production potential of approximately 8.000 WMT [7][15]. However, only 111 WMT of seaweed was produced with a total value of 5,2 million NOK (ca. 0,43 million €) [7] or ca. 39.000 NOK (ca. 3.250 €) per WMT. This volume has increased steadily towards 240 WMT in 2022 and a record-breaking 600 WMT in 2023[16]. However, production is still low and far from efficient large-scale operations as known from other sectors.

The location and size of the potential aquaculture sites in the region are essential to model the mobilisation of the seaweed throughout the supply chain. The licensed aquaculture sites authorised to grow seaweed were identified using data from the Norwegian Directorate of Fisheries (https://www.fiskeridir.no/English), resulting in 105 aquaculture sites in the area (Figure 11).

The average size of a seaweed aquaculture site in Norway is approximately 10 hectares, with individual site sizes ranging from 0,09 hectares to 40 hectares (as shown in (Figure 12). Currently, the total area designated for seaweed aquaculture in Norway spans 1 065 hectares. This provides a production potential of between 16.000 WMT per year, based on a conservative production rate of 15 WMT/ha, and 53.000 WMT per year, assuming a more progressive production rate of 50 WMT/ha. However, these potential production levels have not yet been fully realised, as only a portion of the companies with permits are actively operating, and many are still working at reduced production capacity [21].

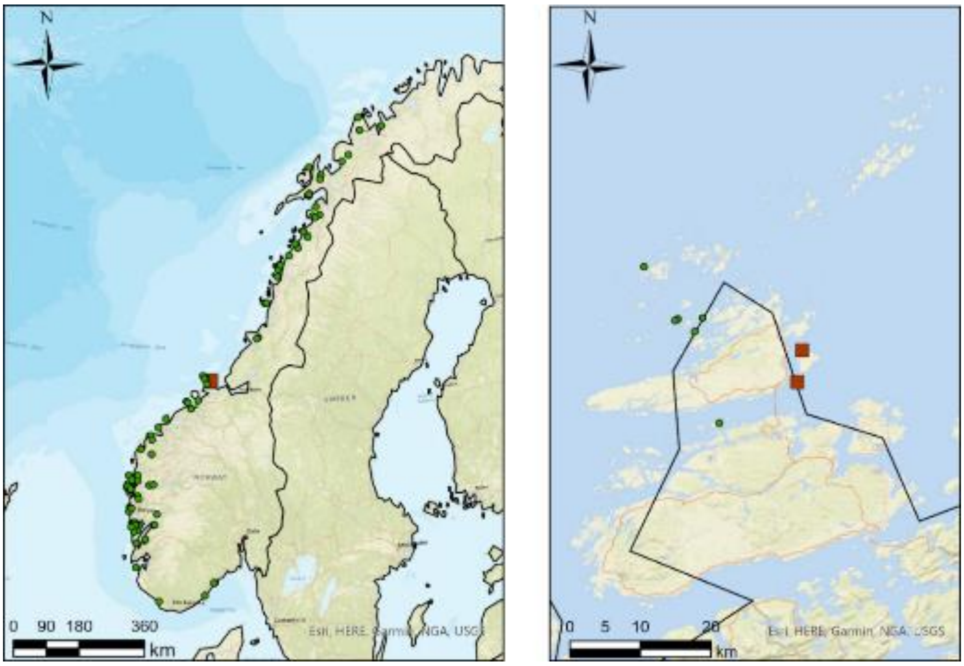

Figure 11 Location of aquaculture sites with a license to grow seaweed (NDF) with indication of the aquaculture sites of SES considered in the AS-IS scenario (red square).

[15] Corresponding with a production of ca. 10 WMT/ha.

[16] Source: Norwegian Seaweed Association

In the case study examined in the Qualisea project, the current ("AS-IS") scenario involves two seaweed cultivation sites managed by SES - Taraskjaera and Masskjaera (as shown in Figure 11). In 2021, only the Masskjaera site was actively used for seaweed cultivation, with Saccharina latissima grown on 7,2 hectares and Alaria esculenta on 11,6 hectares. The productivity for both species in 2021 was estimated at 10 WMT per hectare. This resulted in an annual yield of 72 WMT for Saccharina latissima and 116 WMT for Alaria esculenta.

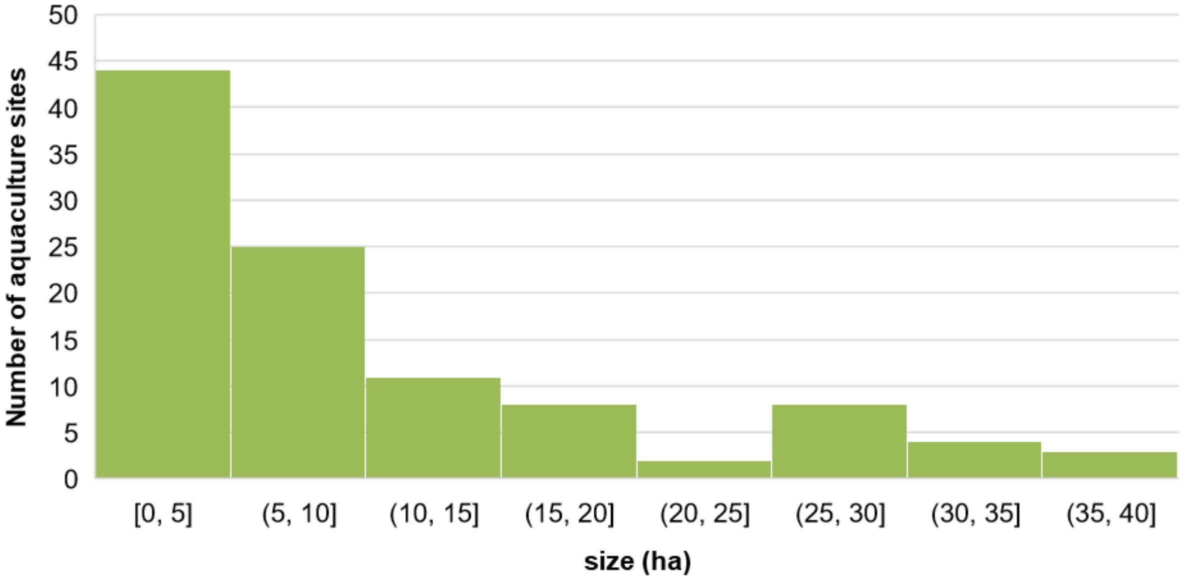

Figure 12 Size histogram of aquaculture sites with a license to grow seaweed.

For the unprocessed seaweed, delivered wet at the harbour, the selling price is ca. 23.500 NOK (ca. 1.960 €) per WMT[17]. Although a large-scale cultivation is not yet a reality, the Norwegian coast has the optimal conditions to expand further the area and location of the cultivation sites [22]. The southern region of Norway knows the highest density of aquaculture sites (Figure 13).

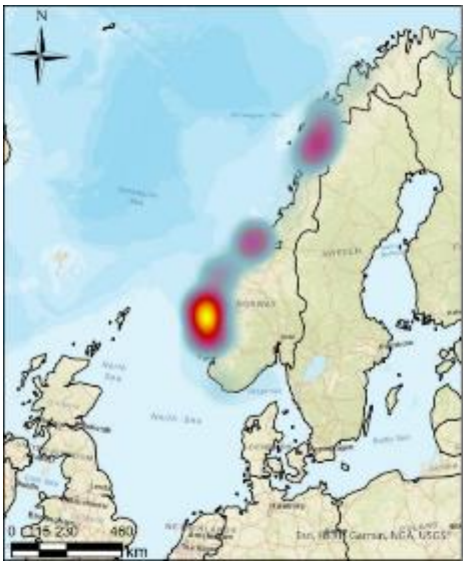

Figure 13 Seaweed production – Heatmap based area density.

[17] Oral communication SES

2.2.2 Harvest

The seaweed harvest season for *Alaria esculenta* and *Saccharina latissima* occurs from April to June. After this period, fouling (mainly by epiphytes) adversely affects the biomass quality and therefore negatively impacting the applicability especially for food and feed applications. The timing of fouling varies by location and is influenced by abiotic factors such as exposure, temperature, light, salinity, and nutrients in the sea. Generally, fouling occurs earlier at southern latitudes.

In the case study, the harvest process involves a catamaran which collects the seaweed by reeling in the ropes with seaweed. A mounted cutter trims the seaweed, which is then directly discharged into boxes filled with seawater to maintain biomass quality. The harvested seaweed is then transhipped to a barge and transported to the harbour (Figure 15).

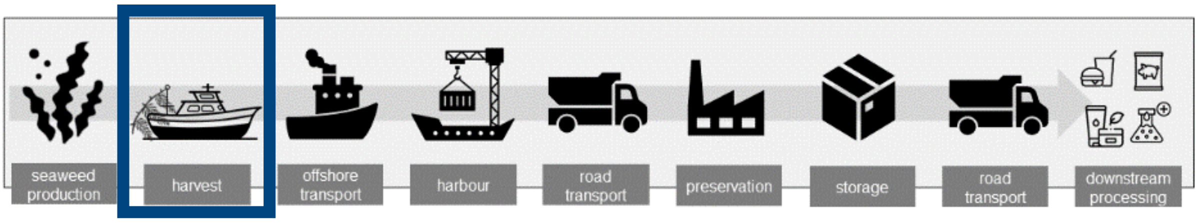

Figure 14 Position of harvest in the process flow diagram of the seaweed chain.

The catamaran holds up to 16 boxes and has a harvest rate of 4 boxes per hour. Each box contains either 0,3 WMT of *Alaria esculenta* or 0,25 WMT of *Saccharina latissima*. The catamaran's load capacity is resp. 4,8 WMT for *Alaria* or 4,0 WMT for *Saccharina* (Table 3). The total harvest cost includes a catamaran rental fee of 3.000 NOK (ca. 250 €) per hour, covering fuel cost and labour cost for the 4-person harvest crew which operates 10 hours per day.

Table 3 Harvest – Characteristics.

Harvesting type	**Seaweed species**	**Rent**	**Capacity**		
		NOK/h	n° boxes	WMT/box	WMT
Catamaran	*Alaria esculenta*	3.000	16	0,30	4,8
Catamaran	*Saccharina latissima*	3.000	16	0,25	4,0

2.2.3 Offshore transport

Once harvested, the seaweed must be transferred to shore. This process involves 2 activities: the transhipment from the catamaran to the barge and the transport from the aquaculture site to the harbour (Figure 15).

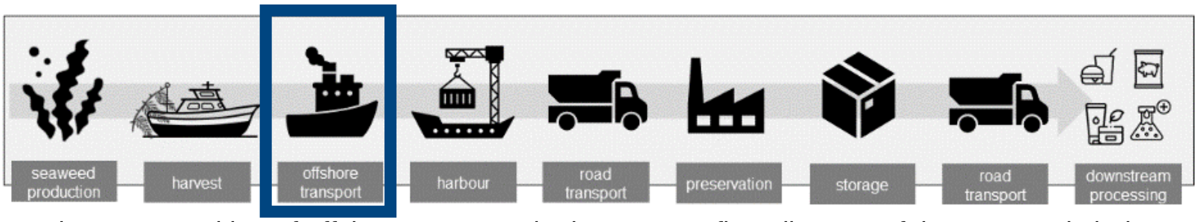

Figure 15 Position of offshore transport in the process flow diagram of the seaweed chain.

At the aquaculture site, the catamaran transfers the boxes onto a barge at a rate of 3 minutes per box. The cost for this transhipment is defined by the labour cost in combination with the barge capacity and the transfer time (Table 4). The barge crew, consisting of 2 people, operates 12 hours per day.

After transhipment from the catamaran to the barge, the barge transports the seaweed from the aquaculture site to the harbour and shuttles between both. The transport cost is defined by the distance (round-trip) TO-BE travelled (based on the fuel cost) and the travel time (based on the labour cost, assuming the barge is operated by 2 persons) (Table 4).

Table 4 Offshore transhipment and transport to the harbour - Characteristics.

Transport type	**Fuel cost** NOK/km	**Labour cost** NOK/h	**Transfer time** h/box	**Capacity** #boxes
Barge	30	500	0,05	10

For example, in the AS-IS case the cost for transport between aquaculture site and harbour (offshore – harbour in Figure 7) is calculated as follows:

- Transport cost defined by distance: a round-trip is ca. 7 km, resulting in a fuel cost of 210 NOK (ca. 17,5 €);
- Transport cost defined by travel time: the barge travels at a speed of 3 knots/h (or 5,5 km/h) leading to a trip time of ca. 1,3 h (or 75 min), resulting in a labour cost of 650 NOK (ca. 55 €);
- Transhipment cost: the boxes are transferred from the catamaran to the barge in 0,5 h (10 boxes x 3 minutes per box), resulting in 250 NOK (ca. 21 €) for transhipment.

The total cost for offshore transport in this case is 1.110 NOK (ca. 92 €).

Note: The barge cost for the AS-IS case is set to zero as the barges are completely depreciated, if not an investment cost of ca. 350.000 NOK (ca. 30.000 €) per barge should be accounted for[18].

2.2.4 Harbour

In the harbour, the boxes are transhipped at a rate of 5 WMT per hour from the barge to a truck for delivery of the boxes to the preservation location (Figure 16). This transhipment implies that no storage is foreseen at the harbour and the boxes are directly transferred from the barge to a truck ready for transport.

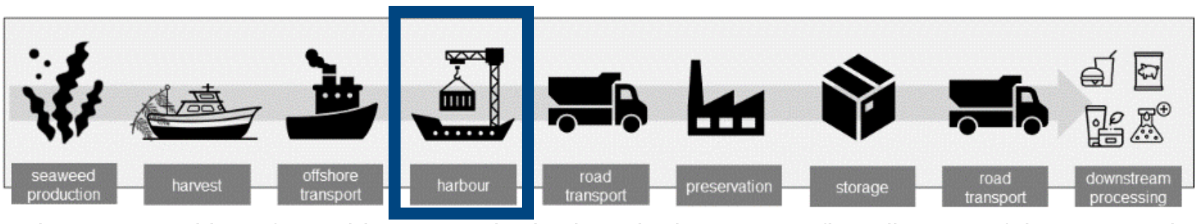

Figure 16 Position of transhipment at the harbour in the process flow diagram of the seaweed chain.

[18] Oral communication SES

The cost related to the harbour is twofold: (1) a fixed cost related to the rental of the harbour, including use of equipment and (2) the cost for transhipment determined by the throughput capacity and the labour cost, assuming a crew of 2 people (Table 5).

Table 5 Harbour - Characteristics.

Harbour type	**Harbour fee**	**Lift & handling equipment**	**Capacity**	**Labour cost**
	NOK/y	NOK/y	WMT / h	NOK / h
Dyrvik	60.000	60.000	5	500

In the case study, SES currently delivers the boxes with harvested seaweed to the harbour in Dyrvik, with a docking capacity of 3 boats (Figure 17). Dyrvik is the sole harbour utilised by SES at present.

In future (TO-BE) scenarios, additional locations are considered as potential harbours to determine the optimal sites from a list of candidate locations. These candidate locations are identified by experts from Anteo, a partner in the Qualisea project. Anteo specialises in developing decision support systems to promote sustainable growth of the Norwegian aquaculture industry. The candidate locations encompass not only existing harbours but also infrastructure from other industries where seaweed preservation might occur. Examples include silage factories, feed factories, slaughterhouses, fish reception or fish processing facilities. The selection of Anteo results in 569 candidate harbour locations.

Strategically, the region of the harbour holds greater significance than the precise location. Therefore, harbours within a 2 km vicinity of each other are clustered. This approach yields 245 candidate harbour locations from which the Qualisea model can select to configure the optimal supply chain (Figure 17).

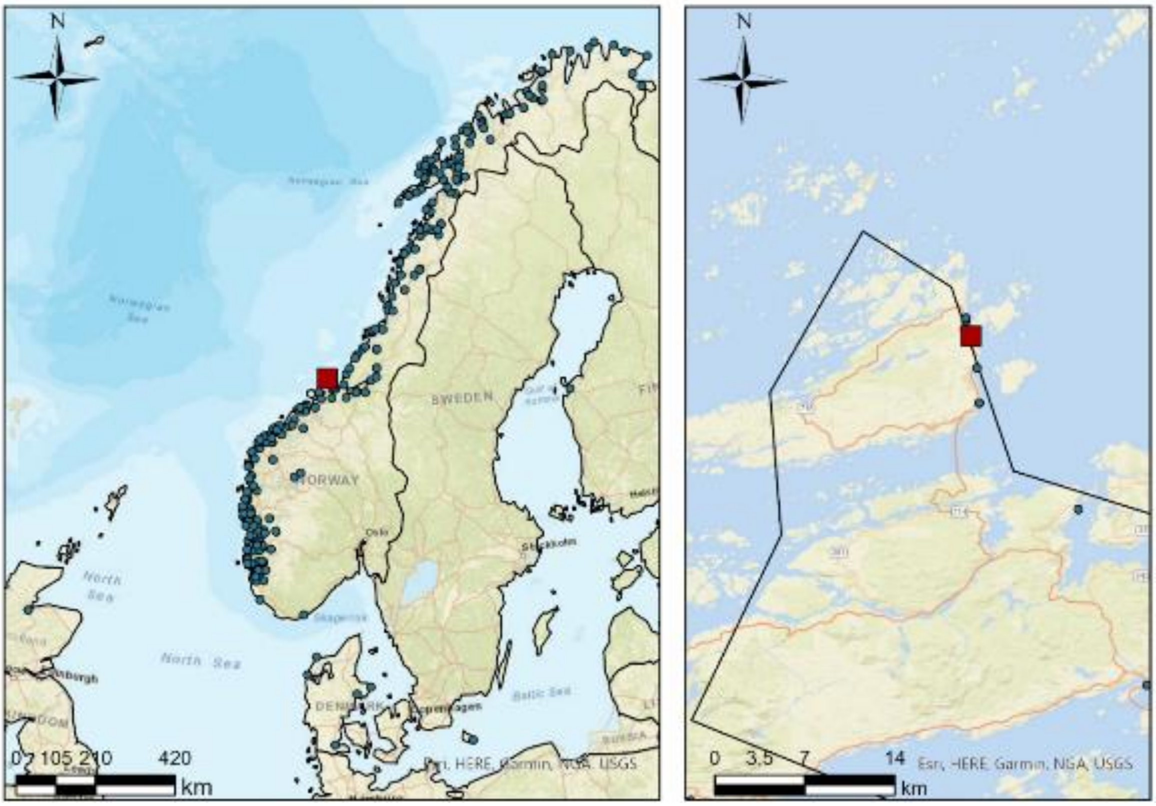

Figure 17: Harbour – Candidate harbour locations in Norway with indication of the harbour considered in the AS-IS scenario (red square).

2.2.5 Road transport to preservation

From the harbour, the boxes, filled with seaweed and fresh seawater for cooling, are transported to the preservation site (Figure 18). In the case study, road transport by truck is considered. The associated cost is defined by the transport cost based on travel distance and travel time as well as the cost for transhipment at the gate of the preservation location, i.e., unloading of the boxes (Table 6).

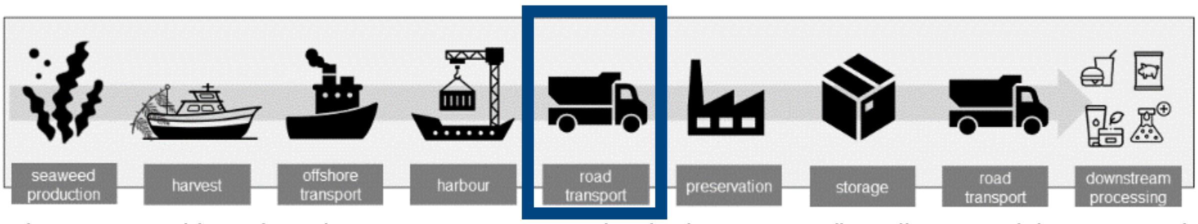

Figure 18 Position of road transport to preservation in the process flow diagram of the seaweed chain.

In the AS-IS situation, the boxes are transported by truck from the harbour of Dyrvik to the Hitramat-site in Ansnes. The travel distance covers 35 km, with an approximate driving time of 45 minutes. Transhipment costs are influenced by the required unloading time per truck and the labour expenses.

Table 6 Road transport to the preservation – Characteristics [23]

Transport type	**Fuel cost** NOK/km	**Unloading time** h	**Labour cost** NOK/h	**Capacity** #boxes	ton
40 ft truck cooled	12	0,5	430	35	10

2.2.6 Preservation

Within 48 hours after harvest, the biomass must be preserved (i.e., stabilised). From harvest to arrival at the preservation site takes approximately 3-12 hours, during which no temperature control occurs (Figure 19) and about 20% water is lost (so, 10 WMT at harvest becomes 8 WMT at the gate of the preservation site). Upon delivery at the preservation site, the seaweed is shortly (up to 15 h excl. preservation) stored in cooled conditions (4°C) while the water has been drained from the boxes.

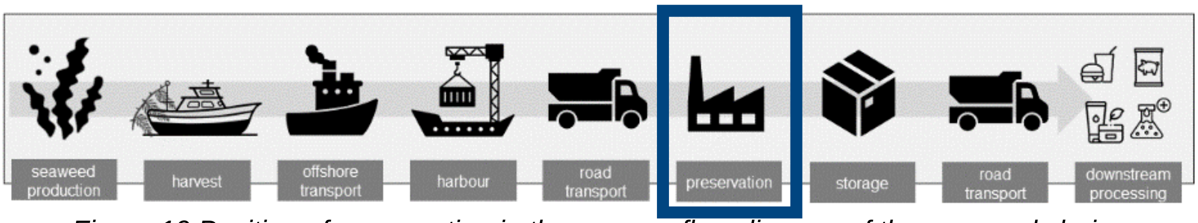

Figure 19 Position of preservation in the process flow diagram of the seaweed chain.

Within Qualisea, the consortium investigates alternative preservation methods to enable a year-round supply of high-quality biomass for down-stream processors. Different preservation options are included in the supply chain design (Table 7), each with their own characteristics and impacts on the final seaweed product.

The preservation steps are not exclusive, and several can be applied consecutively. Surface water removal and sorting always take place prior to other preservation steps. Generally, freezing is used as rapid and intermediate preservation method. Within Qualisea, fermentation and acid preservation are investigated as well as blanching which is an option for iodine reduction when targeting food applications. Drying is not included as a potential preservation option since it is expensive and requires a substantial amount of energy. In section 4.4, the impact of considering different combinations of preservation methods on the organisation of the supply chain has been investigated.

The envisioned growth of the seaweed industry will require the preservation of increased production volumes. Utilisation of existing infrastructure from other industries, like fishing and fish farming, can be a key to an upscaled and economically viable seaweed industry and is already practiced for harvest and transport vessels. The experts of Anteo selected the locations where seaweed preservation might occur, i.e., silage factories, feed factories, slaughterhouses, fish reception or fish processing facilities. Strategically, the region of preservation is more important than the precise location, the preservation sites within a 2 km vicinity of each other are clustered. This results in 92 candidate preservation locations from which the Qualisea model can select to configure the optimal supply chain (Figure 20).

Table 7 Preservation – Characteristics[19].

Preservation type	Wet weight loss %	Capacity WMT / h	OPEX* NOK / WMT
Surface water removal	30	1,00	1 000
Sort	10	1,00	4 000
Cut	0	0,70	1 100
Blanch	20	0,15	18 000
Freeze	0	1,00	2 000
Ferment	0	1,00	1 000
Acid preservation	0	2,00	750

* Note that the costs also include packaging costs and labour costs.

In the AS-IS situation, the site of Hitramat, a crab processing facility (Figure 20), is the preservation location where seaweed boxes are first unpacked and then the seaweed is rinsed and sorted. The sorted seaweed can then be further processed. Common practice leads to an active removal of remaining surface water by pressing or centrifuge, amounting to 30% of weight loss approximately (Table 7).

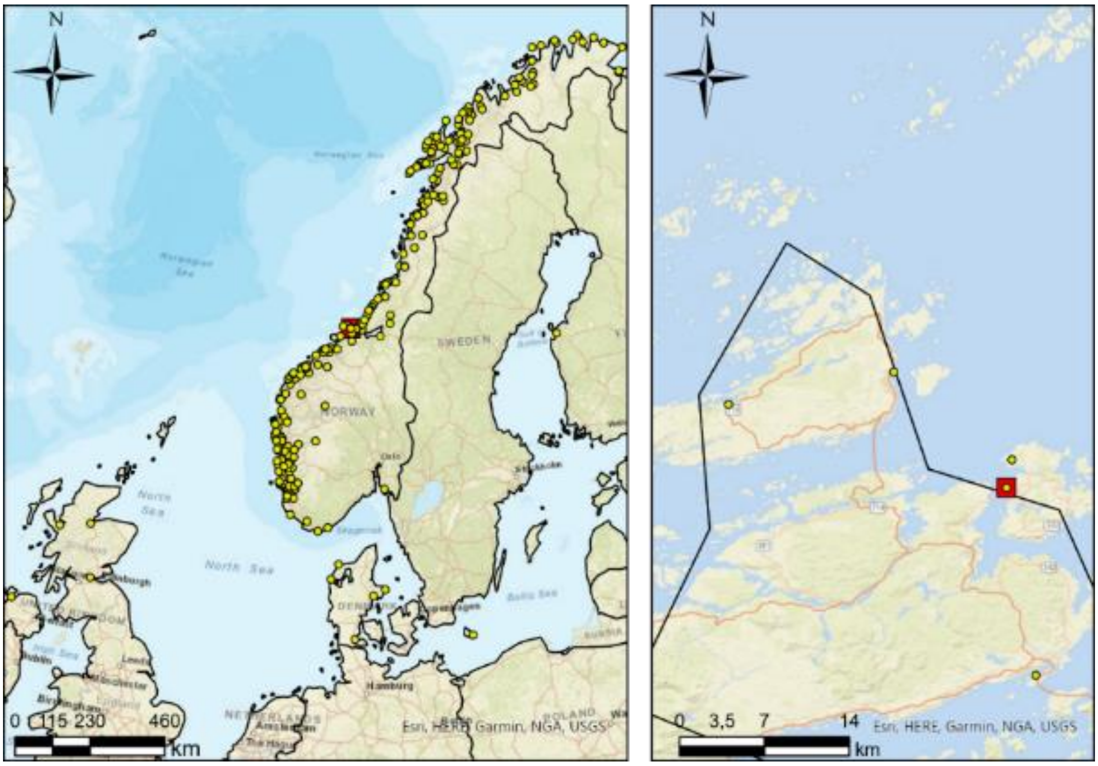

Figure 20 Preservation – Candidate preservation locations in Norway with indication of the Hitramat site considered in the AS-IS scenario (red square).

[19] The development of the seaweed supply chain is premature. The characteristics defined in the table are based on expert guesses and are subject to high uncertainty.

2.2.7 Storage

After preservation, the seaweed can be stored for a longer period (often about 6 months) to ensure year-round biomass delivery to downstream processors (Figure 21). To define the storage cost, it is assumed that long-term storage occurs at the preservation site and last 6 months. It is assumed that freezing is required, except if the seaweed is preserved by acid preservation or fermentation.

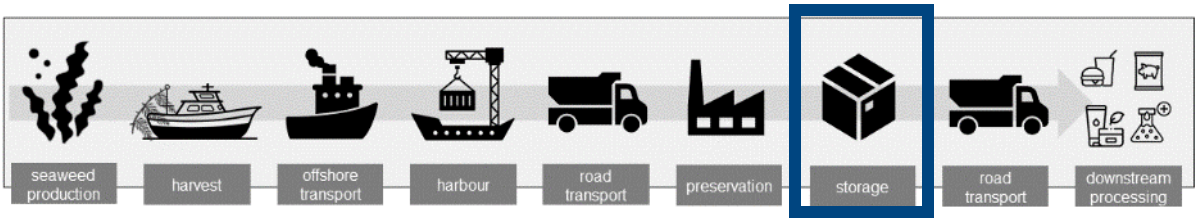

Figure 21 Position of storage in the process flow diagram of the seaweed chain.

Table 8 Storage – Characteristics.

Storage type	**OPEX** NOK/ WMT/ month[20]	**Storage capacity** WMT
Freezing	287,50	100
Ambient temperature	143,75	100

2.2.8 Road transport to downstream processor

The preserved seaweed is transported to the downstream processors by truck (Figure 22). Freezing is required, except if the seaweed has been preserved by acid preservation or fermentation.

In the current (AS-IS) situation, the cost for transport towards the downstream processor, often 10-12 h truck-drive away, is defined as a fixed cost of 30.000 NOK (ca. 2.500 €) per trip[21]. In the TO-BE scenarios, the cost for road transport to the downstream processor is defined by the transport cost based on travel distance and travel time as well as the cost for transhipment at the gate of the preservation location (i.e. loading) and the cost for transhipment at the gate of the downstream processor (unloading) (Table 9).

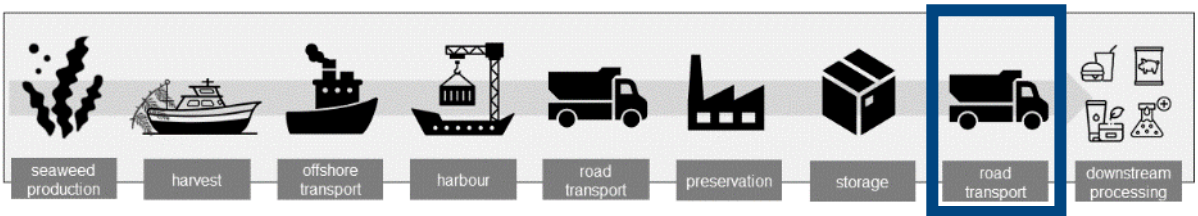

Figure 22 Position of road transport to the downstream processor in the process flow diagram of the seaweed chain.

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[20] 115 NOK (ca. 10 €) per month for a 400 kg seaweed box

[21] Equalling 35 boxes (or 10 ton) per truck

Table 9 Transport to the downstream processor – Characteristics.

Transport type	Fuel cost NOK/km	(Un)loading h	Labour cost NOK/h	Capacity #pallets	WMT
40 ft truck cooled	12	0,5	430,0	60 (2*30)	15
40 ft truck freeze	15	0,5	537,5	60 (2*30)	15

2.2.9 Downstream processing

The supply chain ends at the gate of the downstream processor (Figure 23). In Europe, the current use of cultivated brown algae as food ingredient is mainly as dried flakes or powders acting as flavour enhancer and salt substitute, ingredient in speciality products like pesto's, sea salads or as inclusion in vegan dishes (hamburgers, fish replacements etc.). To fulfil the visions about seaweed as a significant ingredient in European diets, other properties will be of importance, such as the ability of seaweed protein and polysaccharides to contribute to functional properties in the food.

On the other hand, seaweed has a long tradition for use as animal feed in the coastal regions of Northern Europe, mainly as a mineral source. Application in animal feed has been considered as a 'low-hanging fruit' in development of the market for cultivated seaweed, and several studies have been reported the recent years, mostly on ruminants, which can utilise the seaweed components to a higher degree than monogastric animals. For monogastric animals, like pigs, the emphasis has been on potential beneficial health effects [6].

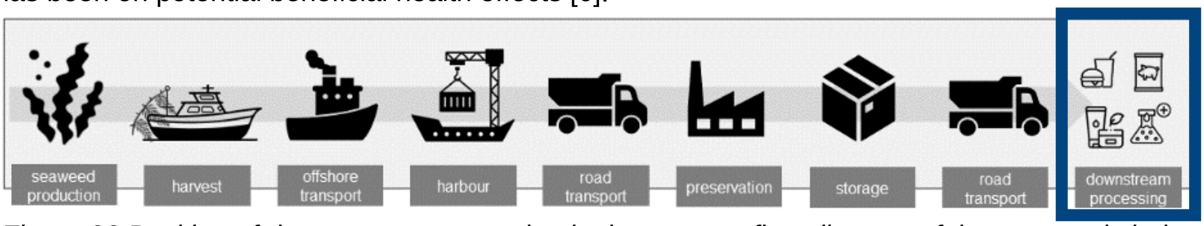

Figure 23 Position of downstream processing in the process flow diagram of the seaweed chain.

For the case study, the main large-scale end-users are assumed TO-BE feed producers. The locations and annual feed production in Europe based on:

- FEFAC, the European feed producers sector federation, publishes yearly statistics on compound feed production at country level. The most recent year available at the time of analysis is 2020 [24].
- European Pollutant Release and Transfer Register (E-PRTR), containing the location and administrative data for the largest industrial facilities in Europe. The available production facilities of feed producers have been selected by filtering on NACE code 10.91 "Manufacture of prepared feeds for farm animals". [25]
- Due to the absence of individuel production data, each feed production facility has been allocated a uniform share of its country's feed production.
- Data on Norway are delivered by Anteo.

In strategic supply chain design, the region of downstream processing is more important than the exact location, clustering of feed production facilities at the country level is applied using the H3 geospatial indexing system [26]. H3 partitions the world in uniformly sized hexagons for different spatial resolutions. The resolution determines the size (and the total number) of the hexagons, i.e., resolution 1. In addition, no production facilities in different countries are assigned to the same cluster. This results in 55 potential clusters of feed production facilities (Figure 24).

The cost related to downstream processing is not included in the calculation of the logistics cost (Figure 7) and therefore the results give an indication of the logistics costs up to the gate of the downstream processor(s).

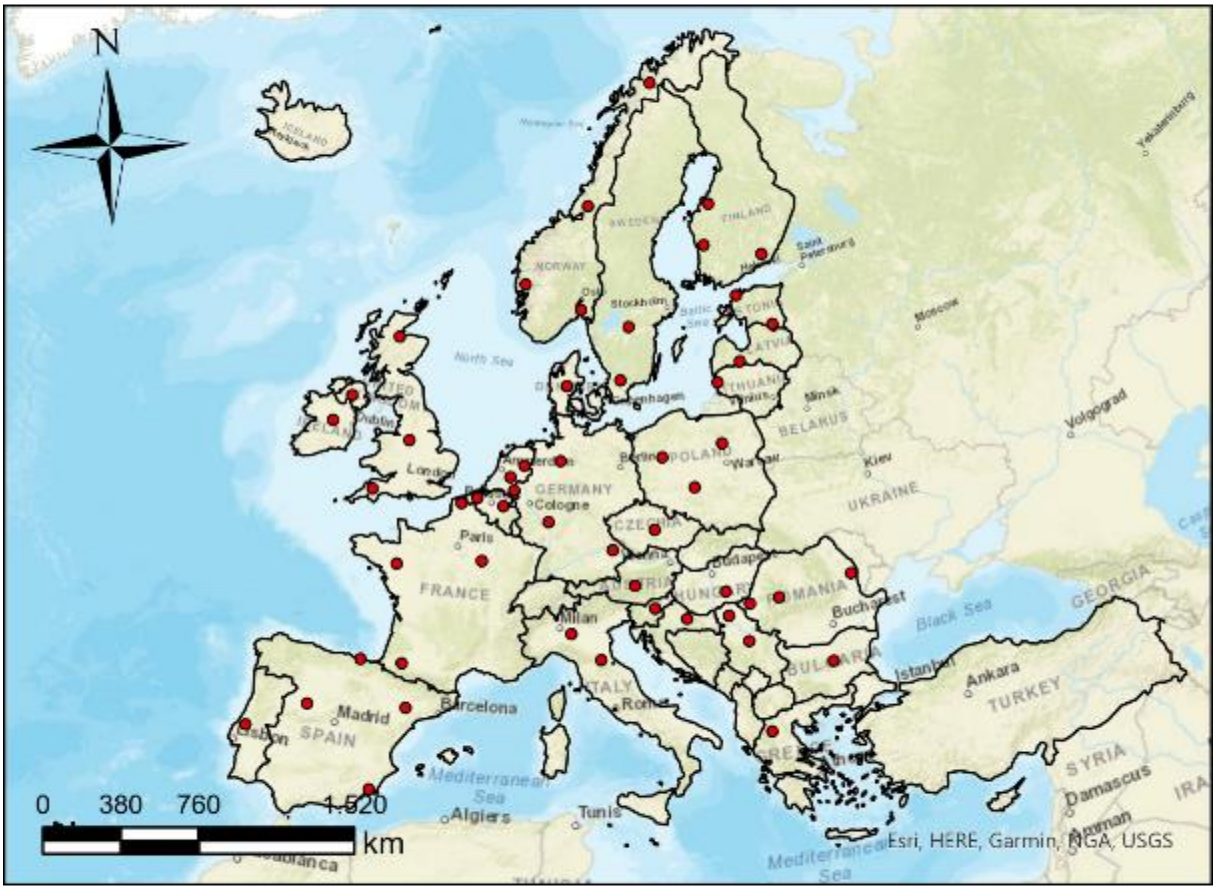

Figure 24 Downstream processing – Candidate clusters for downstream processing in Europe.

2.3 Network flow diagram

The entire process from feedstock production to downstream processing does not necessarily have to happen in one place (Figure 25). After a growth period of 8 months (September – April) the seaweed is harvested in the aquaculture site from April to June. Barges transport the harvested seaweed in boxes to the harbour where the boxes are directly transhipped to a truck and transported to the preservation site. After preservation and packaging (and storage), the seaweed is transported to the downstream processors by truck.

The network flow diagram is the basis for the development of the Qualisea MooV-model and has the ambition to include all potential flows between activities (and locations) in the seaweed chain.

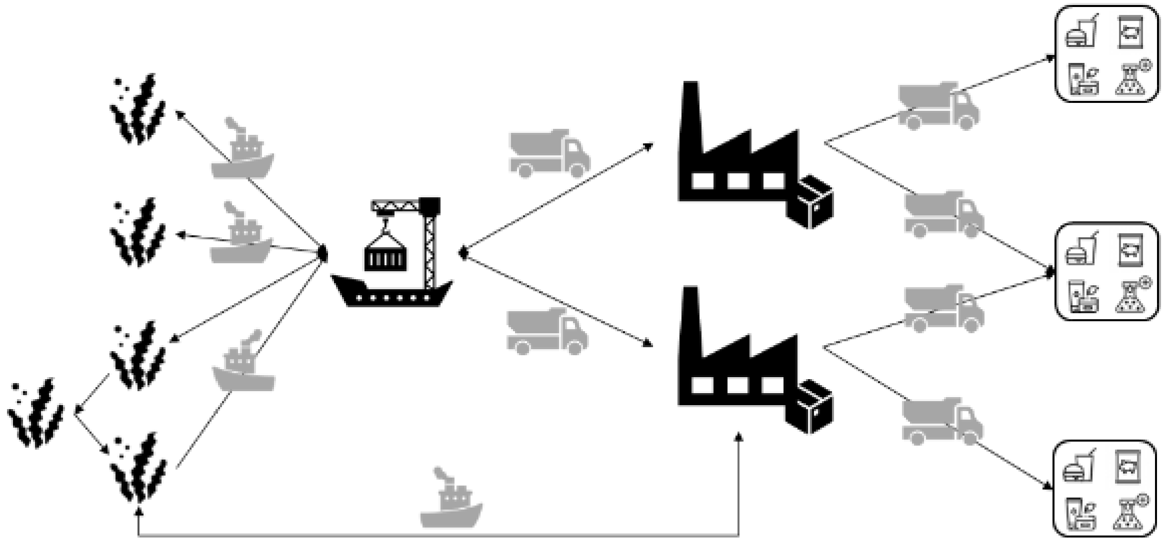

Figure 25 Network flow diagram as a generic representation of the seaweed supply chain.

DESIGN

The logistic seaweed model

vito MOOV

3 DESIGN – THE SEAWEED LOGISTICS MODEL

The MooV model, developed by VITO, is a proprietary supply chain optimization tool that forms the foundation of the seaweed logistics model. Designed to assess key decision parameters such as cost and performance, it equally also allows to evaluate circularity and sustainability aspects.

By integrating seaweed-specific characteristics (see Chapter 2), the MooV model is customized into the purpose-built seaweed logistic model – the Qualisea model. This flexible framework allows seamless modifications in characteristics, enabling consistent and reliable analysis across diverse logistics scenarios. The results highlight the impact of different configurations on the key decision parameters.

To analyse the impact of different configurations in the future seaweed supply chain design on the performance of the chain and the overall mobilisation cost of the seaweed, the MooV core model is used (section 3.1). The MooV core model is specifically developed to address complex supply chain challenges, aiming to assess the effects of decisions, and changing circumstances on the overall supply chain performance. The MooV-core model incorporates the fundamental supply chain logics that characterise any supply chain.

Around the core model, a shell is modelled that captures the specific characteristics of the Qualisea case. The advantage of this approach lies in its adaptability: specific elements can be added, changed, or removed without altering the core model. Consequently, this approach allows to carry out different scenario analyses with the same model, ensuring comparability between scenarios.

From a technical point of view, the MooV platform has a modular structure and combines a knowledge base (Python and ArcGIS Pro), a database (PostgreSQL/PostGIS) and an inference engine with the MooV model (MILP with Python script, solved with Gurobi 11).

3.1 MooV core

The MooV core integrates i) a transhipment problem and ii) a capacitated facility location-allocation problem, iii) where product characteristics can change during an activity. This implies that the model calculates the logistics of (changing) products through a network of supply chains, considering the capacities and location of the activities in that network.

The degrees of freedom within the network are often limited. Within the MooV core, 3 groups of constraints capture the universal supply chain logic:

- Physical and regulatory restrictions on the combinations between products and activities on the one hand and between activities themselves on the other; as well as the permitted activities at production locations, storage locations and conversion locations;
- Restrictions that enforce a balanced mass balance in the product flows to and from activities/locations, taking into account the available (multimodal) transport network;

- Restrictions that ensure that demand must be met; for example, to a certain end product (i.e. primary product from the conversion process) or by-product (i.e. secondary product from the conversion process).

3.2 Qualisea – shell

For Qualisea, the specifics defined in chapter 2 are transcripted into the shell of the MooV model. Such specifics include amongst others:

- The definition of the objective function;
- The addition of parameters related to describe the specifics and constraints of the seaweed supply chain;
- The impact on the quantity of output products in function of feedstock input, as well as preservation technology.

3.2.1 Objective function

The objective function combines mathematical equations dictating that the overall mobilisation cost must be minimised while meeting a set of constraints and relationships between the decision variables. Each combination of decision variables is a potential solution. However, only the combinations that meet the constraints are feasible.

The primary objective of the Qualisea MooV model is to minimise the overall mobilisation cost from the aquaculture site over preservation and storage up to the gate of the downstream processor(s) while fulfilling a specific demand (i.e., capacity of seaweed at the gate of the downstream processor) (Figure 7). The general objective function (section 2.1.3) is defined by:

$$min \quad COST_{tot} = COST_{production} + COST_{harvest} + COST_{harbour} + COST_{preservation} + COST_{storage} + COST_{transport} \quad \textit{Equation 1}$$

The production cost ($COST_{production}$) depends on the quantity of seaweed of type *f* produced in aquaculture site *i* in time period *t* ($production_{it}^{f}$) and the production cost depending on seaweed type *f* ($COST_{production}^{f}$).

$$COST_{production} = \sum_{ift} production_{it}^{f} * COST_{production}^{f} \quad \textit{Equation 2}$$

The harvesting cost ($COST_{harvest}$) depends on the number of harvesting vessels of type *h* required to harvest at aquaculture site *i* in time period *t* (Y_{it}^{h}) and the rental price of these vehicles ($COST_{rent}^{h}$).

$$COST_{harvest} = \sum_{iht} Y_{it}^{h} * COST_{rent}^{h} \quad \textit{Equation 3}$$

The cost for the harbour ($COST_{harbour}$) is defined by the number of days in the harvesting season (*T*), the daily rental price of the harbour at location *j* of type *s* ($COST_{rent\ j}^{s}$) if that harbour is used ($OPEN_{j}^{s}$).

$$COST_{harbour} = \sum_{js} T * \ COST_{rent\ j}^{s} * OPEN_{j}^{s} \quad \textit{Equation 4}$$

The cost for preserving the seaweed to ensure long-term storage ($COST_{preservation}$) depends on the quantity of seaweed of type *f* treated by preservation type *p* (X_{jt}^{fsp}) and the cost for the applied preservation method *p* ($COST_{preservation}^{p}$).

$$COST_{preservation} = \sum_{fjspt} X_{jt}^{fsp} * COST_{preservation}^{p}$$ *Equation 5*

After preservation the seaweed can be stored for a longer time. The cost related to storage ($COST_{\text{storage}}$) is defined by the quantity of seaweed stored ($\sum_{jst} inv_{jt}^{fs}$) and the storage cost per ton in that storage site *j* of type *s* ($COST_{j}^{s}$). An average storage period of 6 months is assumed.

$$COST_{storage} = \sum_{jst} inv_{jt}^{fs} * COST_{j}^{s}$$ *Equation 6*

The transport cost ($COST_{transport}$) is defined by:

- the **cost for offshore transport** defined by the number of vessel movements between aquaculture sites (*i*) and harbours (*j*) (Y_{ijt}^{zs}), the round-trip travel distance ($dist_{ij}^{z}$), fuel cost ($COST_{fuel}^{z}$), round-trip travel time ($time_{ij}^{z}$) and labour cost ($COST_{labour}^{z}$),
- the **cost for offshore transhipment** is specified by the number of vessel movements between aquaculture sites (*i*) and harbours (*j*) (Y_{ijt}^{zs}), the handling time for transhipment ($handling^{z}$) and the labour cost ($COST_{labour}^{z}$),
- the **cost for transhipment at the harbour** is based on the quantity of seaweed delivered to the harbour at location *j* ($\sum_{i}^{fz} X_{ijt}^{fzs}$), the transfer capacity at the harbour (capacity_{j}^{s}) and the labour cost of the crew ($crew * COST_{labour}^{z}$),
- the **cost for onshore transport between harbour and preservation location** is specified by the number of vehicle movements between harbours (*j*) and preservation locations (*l*) (Y_{jl}^{suzt}), round-trip travel distance ($dist_{jl}^{z}$), fuel cost ($COST_{fuel}^{z}$), round-trip travel time ($time_{jl}^{z}$) and labour cost ($COST_{labour}^{z}$),
- the **cost for transhipment at the gate of the preservation location** is specified by the number of vessel movements between harbours (*j*) to preservation locations (*l*) (Y_{jl}^{suzt}), the handling time for transhipment ($handling^{z}$) and the labour cost ($COST_{labour}^{z}$),
- the **cost for onshore transport between preservation location and downstream processor** is specified by the number of vehicle movements between preservation locations and downstream processors ($\text{Y}_{\text{jk}}^{\text{sczt}}$), travel distance ($dist_{jk}^{z}$), fuel cost ($COST_{fuel}^{z}$), travel time ($time_{jk}^{z}$) and labour cost ($COST_{labour}^{z}$),
- the **cost for transhipment at the preservation location (loading) and the transhipment at the gate of the downtream processing (unloading)** is specified by the number of vessel movements between preservation locations (j) and downstream processing locations k (Y_{jk}^{sczt}), the handling time for transhipment ($loading^{z}$ and $unloading^{z}$) and the labour cost ($COST_{labour}^{z}$).

$$COST_{transport} =$$

$$\sum_{ijszt}\left[2 * \ Y_{ijt}^{zs} * \left(dist_{ij}^{z} * COST_{fuel}^{z} + time_{ij}^{z} * COST_{labour}^{z}\right)\right] +$$

$$\sum_{ijszt}(Y_{ijt}^{zs} * handling^{z} \ * COST_{labour}^{z}) +$$

$$\sum_{jst} crew(\frac{\sum_{i}^{fz} X_{ijt}^{fzs}}{capacity_{j}^{s}} * COST_{labour}^{z}) +$$

$$\sum_{jlsuzt}\left[2 * Y_{jl}^{suzt} * (dist_{jl}^{z} * COST_{fuel}^{z} + time_{jl}^{z} * COST_{labour}^{z})\right] +$$

$$\sum_{jlsuzt}\left[Y_{jl}^{suzt} * handling^{z} \ * COST_{labour}^{z}\right] +$$

$$\sum_{jksczt}\left[Y_{jk}^{sczt} * (dist_{jk}^{z} * COST_{fuel}^{z} + time_{jk}^{z} * COST_{labour}^{z})\right] +$$

$$\sum_{jksczt}\left[Y_{jk}^{sczt} * loading^{z} \ * COST_{labour}^{z}\right] + \left[Y_{jk}^{sczt} * unloading^{z} \ * COST_{labour}^{z}\right]$$ *Equation 7*

Additionally, the total transport distance and the number of transport movements (#) needed to mobilise the feedstock from the aquaculture sites to the downstream processors are calculated.

In future research, also environmental (e.g., emissions) or social (e.g., jobs) objectives can be minimised or maximised, as well as a weighted combination of multiple objectives.

3.2.2 Constraints

The constraints reflect the limitations and conditions under which the seaweed supply chain operates. These constraints are sourced from expert knowledge of the Qualisea partners. The most important constraints are listed below.

- Physical constraints (e.g. capacity, feedstock quality or origin) imposing limitations on the allowable combinations between feedstock and activities, between activities mutually, and on the allowed activities at the harvest locations, storage locations and end-processing locations.
- Product conversion constraints, defining the conversion of a product into another (intermediate or final) product due to an activity (e.g. preservation).
- Network flow constraints define the allowed mass (and volume) flows between i) aquaculture site and harbour, ii) harbour and preservation site, and iii) preservation site and downstream processing site. TO-BE able to address different offshore transport strategies (section 4.7), allowed mass flows between aquaculture sites mutually are also defined (Figure 25).
- Seaweed availability: At the start of the harvesting season, each aquaculture site has an initial stock of harvestable seaweed (if used). A constraint is added to update the available stock of harvestable seaweed in each period t depending on the quantity that has been harvested in the previous period (t-1).
- Harvesting operation: Loading the boxed harvested seaweed from the catamaran onto a barge is modelled as a separate step in the supply chain (i.e. Y_{ijt}^{zs}). This loading step is modelled as a transhipment location which implies that boxes cannot be stored between time

periods (i.e. no inventory) and the quantity of incoming seaweed is constrained by the catmaran and barge capacity.

- Time limitation: It is assumed that all seaweed must be stabilised within 40 days from the start of the harvest season. Incoming boxed seaweed is unpacked, sorted and rinsed before any other processing activities. Seaweed at any processing stage can be stored in freezers at the preservation site. Furthermore, it is defined that the biomass must be preserverd within 48 hours after harvest.

DELIVER

The logistic seaweed results

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4 DELIVER – THE SEAWEED LOGISTICS RESULTS

The analysis begins with the AS-IS scenario, reflecting Norway's 2021 seaweed supply chain, currently in its early development stage.

Future TO-BE scenarios explore the impact of varying demand, productivity, preservation methods (freezing, acid preservation, fermentation, blanching), and offshore transport strategies.

Key performance indicators (KPIs) include mobilisation cost, logistics cost, mileage, and the number of harvesting vessels required. The scenarios assess the effects of scaling production, enhancing technology, and optimizing transport methods. Results are compared with a base scenario to evaluate the impact of strategic decisions on supply chain efficiency.

4.1 Overview

The MooV analysis starts with the definition of the AS-IS scenario which reflects the current situation of the case study in the region of Norway focussing on the seaweed species *Alaria esculenta* and *Saccharina latissima* grown by SES in the year 2021. At this moment, their seaweed supply chain is in a premature stage of development.

If the maturity level increases, it is assumed that the production capacity doubles to 20 WMT per ha and the six-tenths factor is applied to estimate the production cost (Table 2). TO-BE able to define the impact of different decisions on the overall mobilisation cost as well as the configuration of the value chain, 1 scenario has been chosen as the base scenario (section 4.3), which is the starting point and reference for each scenario group. The TO-BE scenarios investigate potential future scenarios for seaweed cultivation in Norway by varying 4 different dimensions:

1. **Demand**: the estimated demand at the gate(s) of the downstream processor for processed/stabilised seaweed (varying from 3 000 ton over 10 000 ton to 30 000 ton).
2. **Productivity**: the seaweed yield per hectare will increase due to technological improvements, efficiency improvements and upscaling of production. This scenario studies the impact when the productivity is 14 WMT/ha, 17 WMT/ha, 20 WMT/ha, 24 WMT/ha, 30 WMT/ha and 50 WMT/ha. Two visionary scenarios are added considering a productivity of 75 WMT/ha and 100 WMT/ha.
3. **Preservation method**: the preservation method to use to preserve or stabilise the fresh seaweed for longer periods to widen its applicable use cases (e.g., for mixing in animal feed). Four preservation methods are compared: 1) freezing, 2) acid preservation, 3) fermentation and 4) freezing and blanching.

4. **Offshore transport strategy:** 2 offshore strategies are compared, 1) a small barge transports the seaweed from the aquaculture site to the harbour and shuttles between both or 2) a large barge passes by several aquaculture sites (i.e. pickup round).

To analyse and define the impact of different strategic decisions and parameters, the results are described in comparison with the base scenario considering the following KPIs (section 2.1.3):

- **Mobilisation cost:** expresses the overall mobilisation cost of seaweed from the aquaculture production up to delivery of the stabilised seaweed product at the gate of the downstream processor (Figure 7). The cost is expressed in NOK per ton output.
- **Logistics cost:** expresses the total logistics cost including costs for transport and transshipment as well as costs related to using the harbour and storage. The logistics cost is expressed in NOK per ton output.
- **Mileage:** expresses the total travel distance to deliver the stabilised seaweed at the gate of the downstream processor. The mileage is expressed in km / ton output and km per trip.
- **Number of vessels/vehicles:** expresses the total number of vessels (barge and catamaran) and vehicles (trucks) needed to deliver the stabilised seaweed at the gate of the downstream processor. The number of vehicles are expressed in number of trips / ton output.

4.2 Norwegian case-study (AS-IS)

Currently, seaweed is grown by SES at the aquaculture site of Masskjaera (Figure 26). In 2021, 72 WMT of *Saccharina latissima* and 116 WMT of *Alaria esculenta* is produced on this site. The seaweed is harvested between April and June and delivered by barge to the harbour of Dyrvik. From the harbour of Dyrvik the boxes with fresh seaweed are transported to Hitramat TO-BE unboxed and frozen. From the Hitramat site, the frozen seaweed is delivered to different processing facilities. Since the destination is not known, a fixed fee of NOK 30.000 per trip (ca. 2.500 €) is assumed.

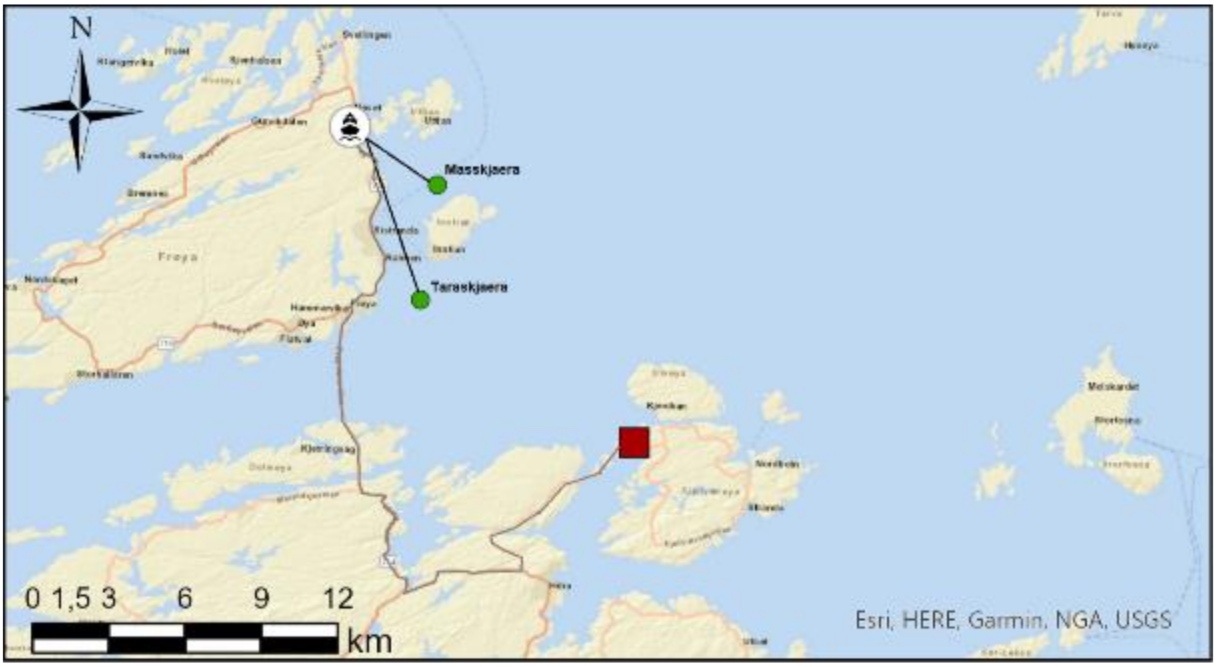


Figure 26 AS-IS - The supply chain configuration with indication of the aquaculture sites, the Dyrvik harbour and the Hitramat preservation site.

For this AS-IS situation, the overall mobilisation cost of the seaweed amounts to ca. 42.000 NOK per WMT frozen seaweed (ca. 3.500 €). Production/cultivation accounts for 19.800 NOK (ca.3.500 €) or 47% of this cost. Production/cultivation includes the seeding/hatching, deploying, growth and crop management (Figure 27). Secondly, preservation (unboxing and freezing) represents 8.152 NOK (ca. 680 €) or 19%.

In the current (AS-IS) situation, all activities are conducted on a small scale. Offshore transport (barge) only requires 9 km per ton output while onshore transport towards the Hitramat site accounts for 13 km per ton output (Figure 28). Due to the small scale of the operations, the costs related to logistics (i.e., costs related to transport and transshipment, costs for using the harbour and for storage) contributes for 20 % to the overall mobilisation cost. Onshore transport towards downstream processor adds up to 8 % of the overall mobilisation cost. However, this result assumes that the downstream processor is about 10-12 h truck-drive away considering a fixed cost of NOK 30.000 (ca. 2.500 €) per trip, equalling 35 boxes per truck.

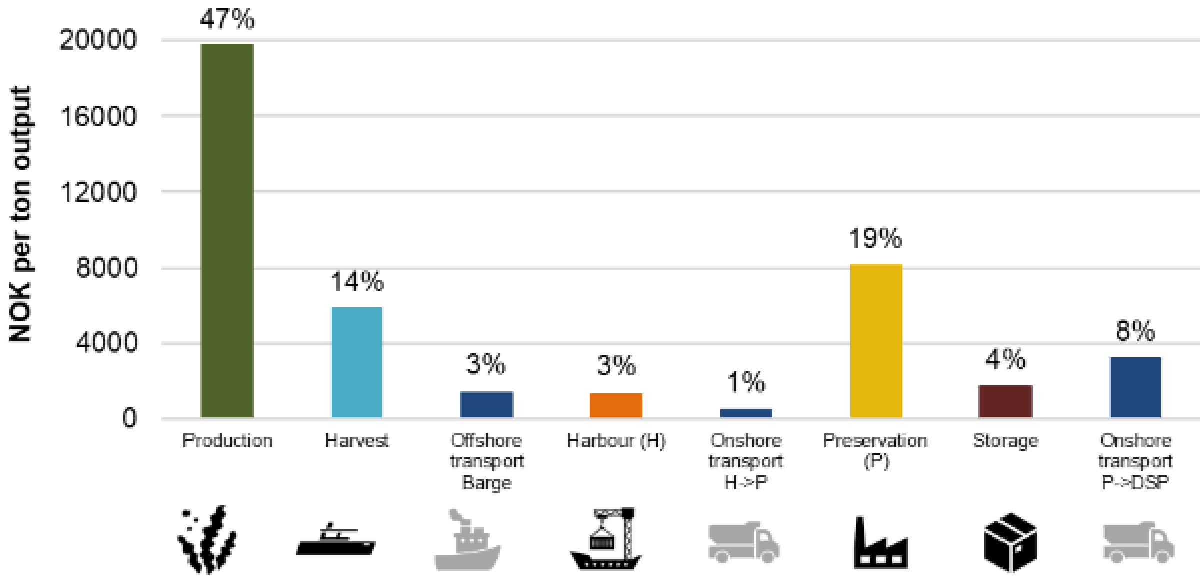


Figure 27 AS-IS – Overall mobilisation cost in NOK per ton output and indication of the share of each activity in the overall mobilisation cost (%)[22].

[22] Grey icons reference cost directly linked to transport (barge/truck).

Currently, 1 catamaran is hired for harvesting for 23 days (Figure 28 - right). During these days, 1 barge performs on average 3 trips a day to transport the boxes from the aquaculture site to the harbour in Dyrvik and 1 truck per day drives between Dyrvik and the Hitramat site (Figure 28 - right).

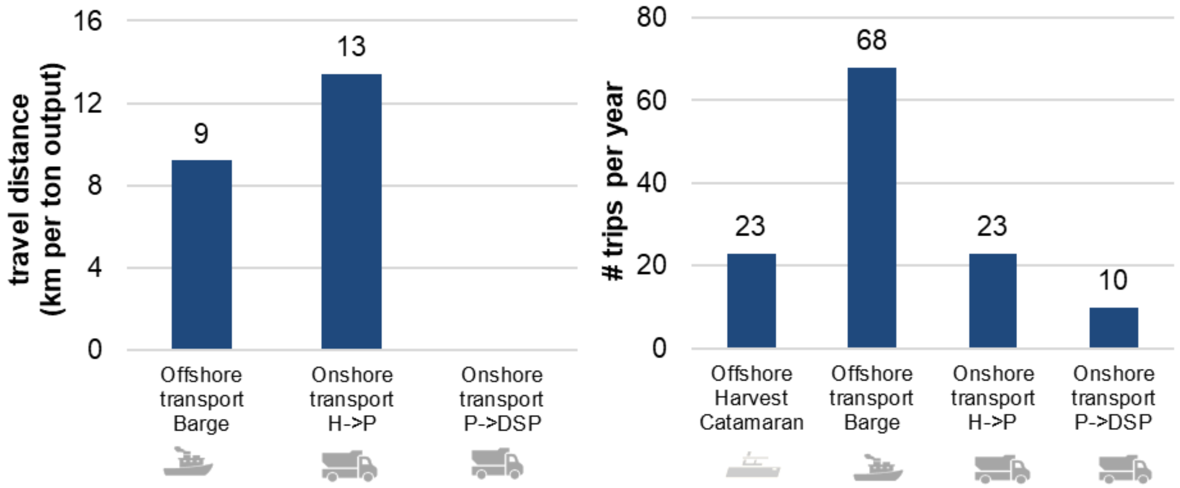


Figure 28 AS-IS – Travel distance in km per ton output (left) and number of trips per year (right).

The logistics costs contribute for 20 % to the overall mobilisation cost (Figure 27) and entail the costs related to transport and transshipment, costs for using the harbour and for storage. When focussing on the logistics costs only, 37 % of the logistics cost is related to offshore activities of which 13 % relates to offshore transport (from aquaculture site to harbour), 7% relates to transshipment activities (from catamaran to barge and from barge to harbour) and 16% relates to the rental or usage of the harbour and the equipment (Figure 29). In comparison with road transport, in which transshipment only accounts for 1 to 8 % of the logistics cost, transshipment related to offshore transport is high (44 %). This is due to the number of people needed as well as the time needed for transshipment in the harbour (i.e., capacity).

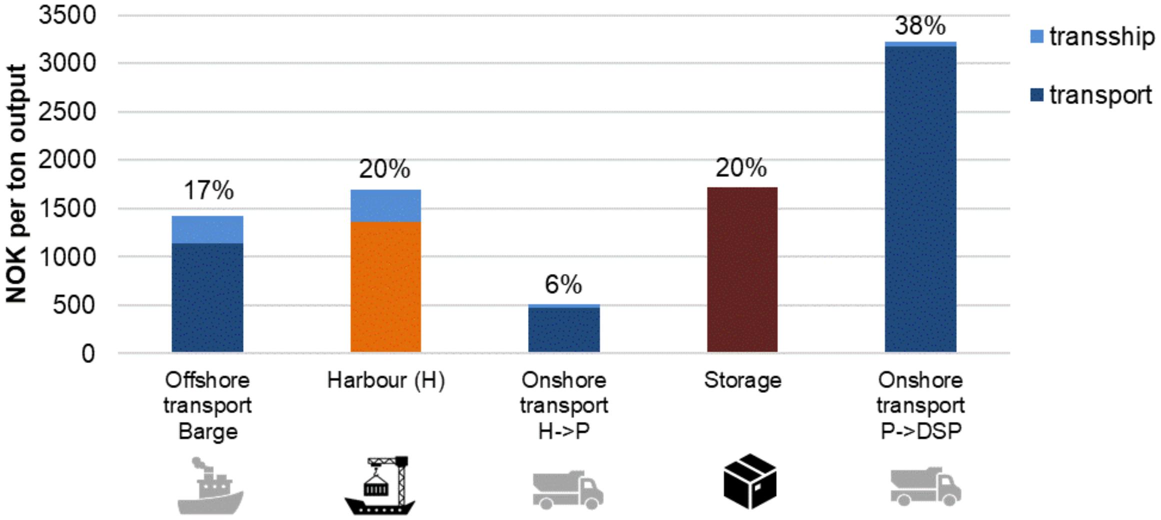
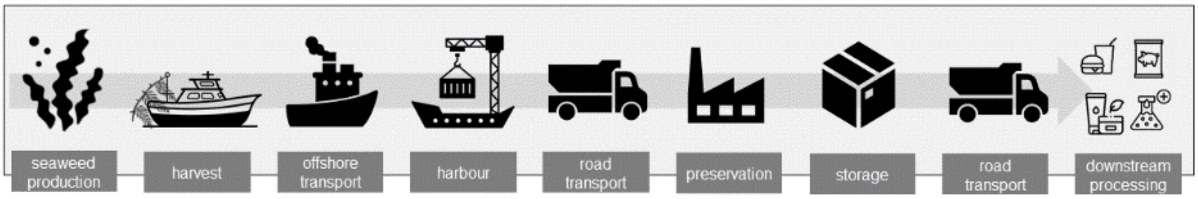


Figure 29 AS-IS – Logistics cost in NOK per ton output and indication of the share of each activity in the overall logistics cost (%).

4.3 Baseline scenario (TO-BE)

To define the impact of different parameters or decisions on the overall mobilisation cost as well as on the configuration of the supply chain, a prospected baseline scenario is defined, which is the starting point and reference for impact-comparison with other future scenarios (see sections 4.4-4.7).

The baseline scenario (Figure 30) assumes that the maturity level of seaweed production increases reaching a capacity of 20 WMT per ha, requiring a production cost of 8.250 NOK (ca. 690 €) per WMT. Seaweed production can occur at any of the 105 aquaculture sites defined in section 2.2.1 (Figure 11). A catamaran is used for harvesting (Table 3) while a barge (Table 4) transports the boxes with seaweed to one of the harbours shown in Figure 17. At the harbour, transshipment occurs from the barge to a truck which delivers the boxes with seaweed (Table 6) to one of the preservation facilities (Figure 20), where the seaweed is unboxed, sorted and frozen (Table 7). Capacity restrictions are maintained as defined in the AS-IS situation. The base scenario considers a total demand of 5.000 ton frozen seaweed to be delivered at minimum 10 potential downstream processing locations with each a maximum demand of 300 ton frozen seaweed (Figure 24).



20 WMT per ha		back and forth			freeze			5 000 ton

Figure 30 TO-BE baseline scenario – Overview of main parameters.

To deliver 5.000 ton frozen seaweed to the downstream processors, 7.937 WMT is harvested at 38 aquaculture sites. In addition, the supply chain consists of 26 harbours, 25 preservation sites and 17 downstream processors (Figure 31). The selection of the aquaculture sites is determined by the location of the harbours and preservation locations as well as the area of the sites to meet the required 7.937 WMT of fresh seaweed as efficient as possible considering availability and capacity of catamarans and barges.

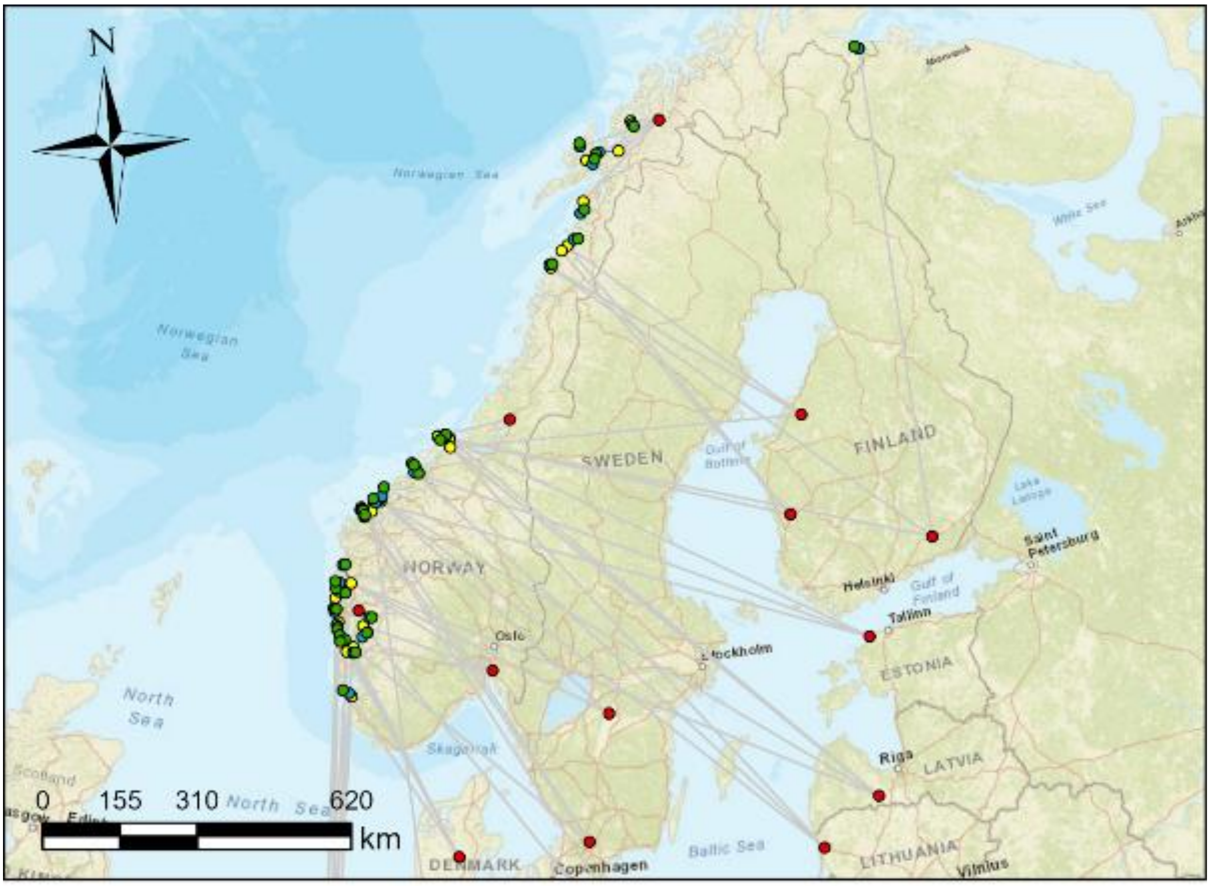


Figure 31 TO-BE baseline scenario – The optimal supply chain with indication of the selected aquaculture sites (green), harbours (blue), preservation sites (yellow), and downstream processing sites (red).

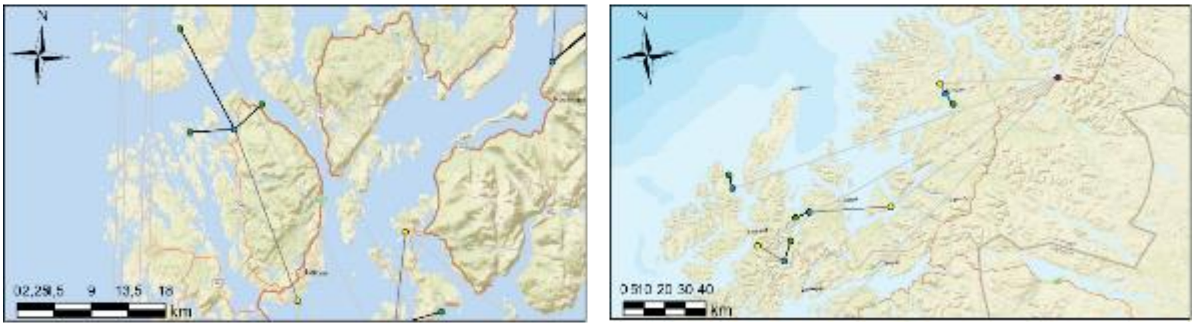


Figure 32 TO-BE baseline scenario – Close-up of the optimal supply chain in 2 regions with indication of the selected aquaculture sites (green), harbours (blue), preservation sites (yellow), and downstream processing sites (red).

Based on the assumptions, described in section 2.2, the overall mobilisation cost in the TO-BE scenario is 38.991 NOK (ca. 3.250 €) per WMT frozen seaweed. 15.205 NOK (ca. 1.267 €) 39% of this relates to the seaweed production including the seeding/hatching, deploying, growth and crop management (Figure 33). Secondly, preservation (unboxing and freezing) represents 8.254 NOK (ca. 680 €) per WMT or 21%

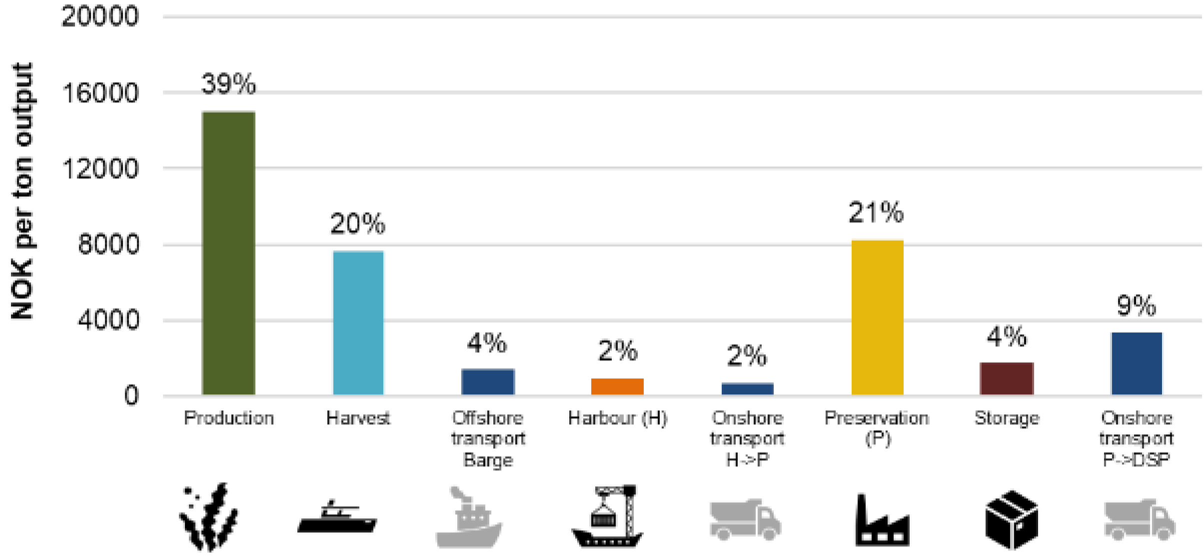


Figure 33 TO-BE baseline scenario – Overall mobilisation cost in NOK per ton output and indication of the share of each activity in the overall mobilisation cost (%).

The logistics costs account for 21% (ca. 680 €) of the overall mobilisation cost (Figure 33). In the overall logistics costs, 29% is related to offshore activities, with 13% relating to offshore transport (from aquaculture site to harbour), 8% relating to transshipment activities (from catamaran to barge and from barge to harbour) and 8% relates to the rental or usage of the harbour and the equipment (Figure 34). In comparison with road transport, in which transshipment only accounts for 1% to 9% of the logistics cost, transshipment related to offshore transport is high (37%) (Figure 34).

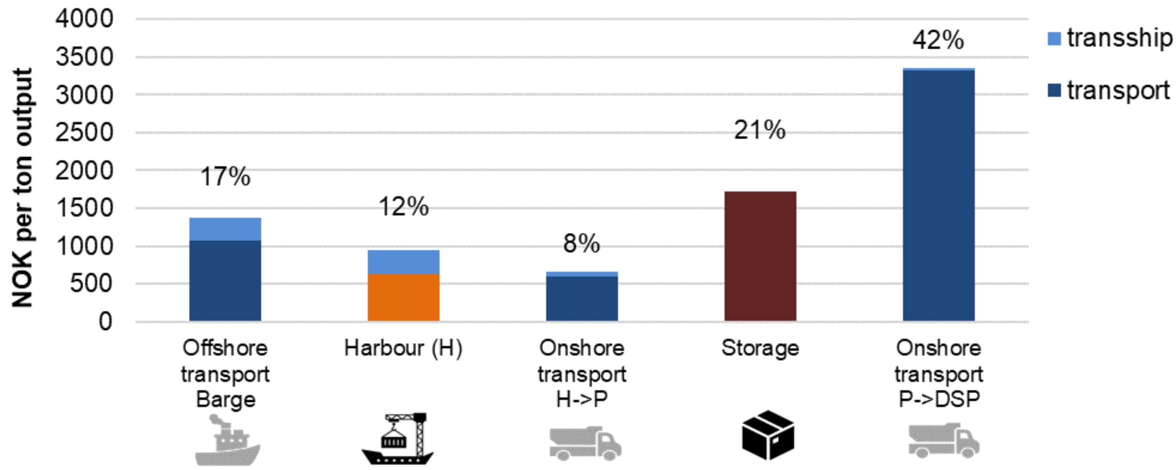


Figure 34 TO-BE baseline scenario – Logistics cost in NOK per ton output and indication of the share of each activity in the overall mobilisation cost (%).

The aquaculture sites closest to a harbour have been selected, resulting in an average offshore (roundtrip) travel distance of 9 km per ton output (Figure 35 A). Per round trip, a barge travels on average 14,7 km (Figure 35 C) which is small in comparison with the average minimum travel distance between aquaculture site and harbour, i.e., 37,6 km per round trip.

The onshore transport cost towards the preservation sites contributes only 9% to the overall logistics cost. The travel distance has been reduced as much as possible by selecting harbours and preservation sites in the vicinity of each other, considering the location of aquaculture sites and downstream processing sites. Per round-trip, the truck drives on average 60 km (Figure 35 C).

The onshore transport cost towards the downstream processors contributes most (36%) to the logistics cost (Figure 34). The travel distance per trip accounts on average 955 km per trip covering a region concentrating on the Scandinavian and Baltic countries (Figure 31).

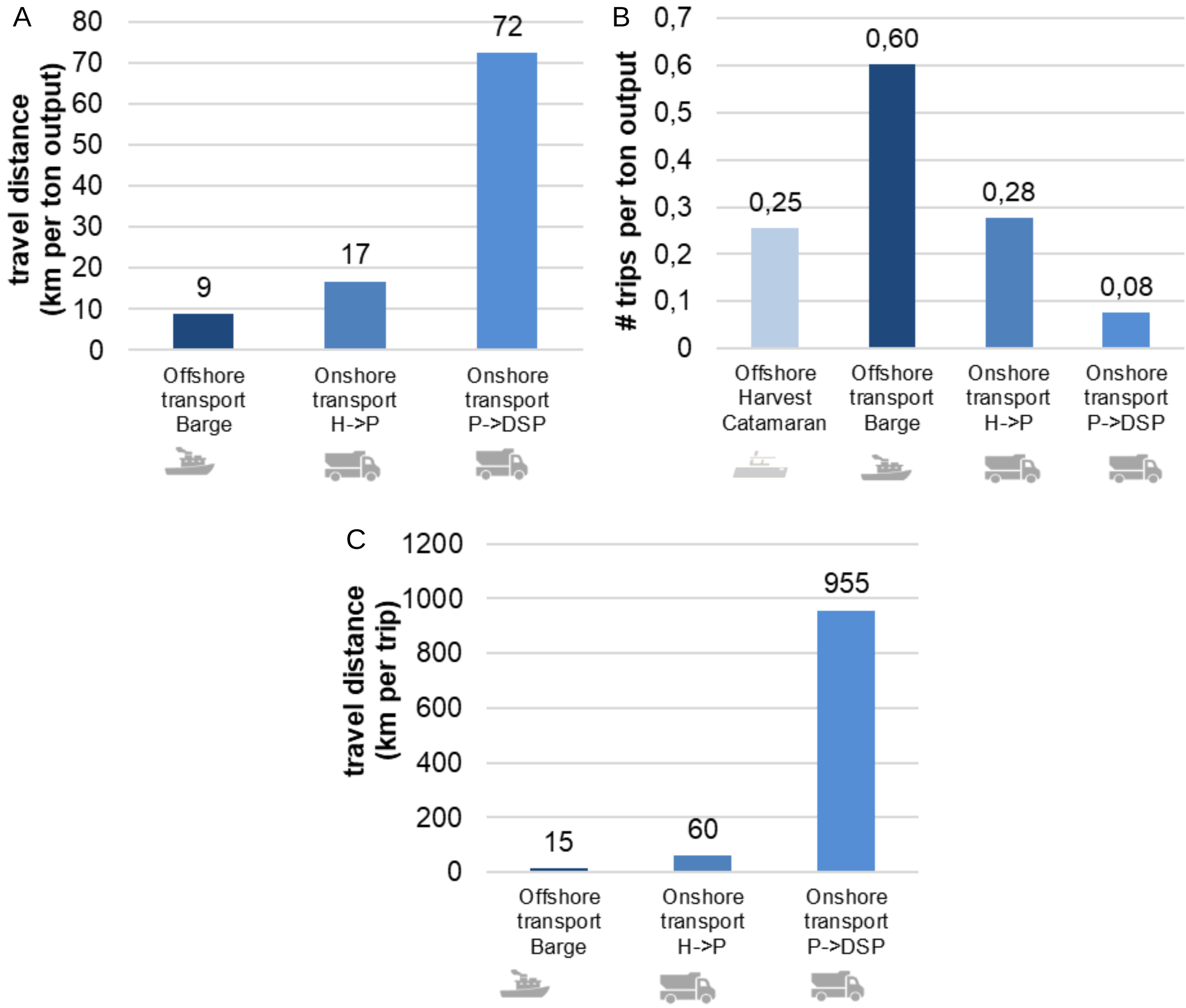


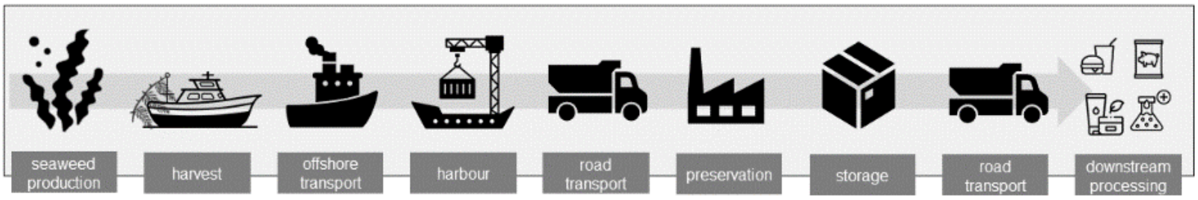
Figure 35 TO-BE baseline scenario – Travel distance in km per ton output (A), number of trips per ton output (B) and travel distance in km per trip (C).

Based on Figure 35 B, the average load factor of the different transport types can be defined:

- *Offshore transport by barge*: 0,6 trips per ton output corresponds to 8,8 boxes per trip. Considering a barge capacity of 10 boxes, this results in a load factor of 88%.
- *Onshore transport between harbour and preservation location by truck*: 0,28 trips per ton output corresponds to 19 boxes per trip. Considering a truck capacity of 30 boxes, this results in a load factor of 63%. Due to the time constraint that the biomass must be preserverd within 48 hours after harvest, a truck drives between the harbour and the preservation location each day of the harvesting season.
- *Onshore transport between preservation location and downstream processor by truck*: 0,08 trips per ton output corresponds to 12,5 ton output per trip. Considering a truck capacity of 15 ton, this results in a load factor of 83%.

4.4 Impact of demand (TO-BE)

This scenario group addresses the expectation that the demand for (frozen) seaweed will grow overtime. Four demand scenarios are compared while the other parameters of the baseline scenario are maintained (Figure 36): 3.000 ton frozen seaweed per year – 5.000 ton frozen seaweed per year (baseline scenario) – 10.000 ton frozen seaweed per year – 30.000 ton frozen seaweed per year.



20 WMT per ha		back and forth				freeze			**3 000 ton – 30 000 ton**

Figure 36 Impact of demand – Overview of main parameters TO-BE adapted.

Two adaptations to the scenario description are needed:

- Considering the assumed 105 potential aquaculture sites meeting a productivity of 20 WMT per ha, it is not feasible to deliver the total demand of 30 000 ton frozen seaweed. The total area currently available for seaweed aquaculture in Norway is 1 065 ha, creating a production potential between 21.300 WMT per year or about 13.300 ton frozen seaweed (assuming a productivity of 20 WMT per ha). Therefore, the final demand scenario has been set to a demand of 13.300 ton frozen seaweed.
- The scenarios in which a demand of 10.000 and 13.300 ton frozen seaweed is requested results in an infeasible solution due to limited capacity at harbours and/or preservation locations. For these scenarios, the maximum capacity of harbours and

preservation locations is multiplied by 5 (to 1.000 boxes per day). Figure 39 gives an indication of the required capacity of these harbours.

To deliver the rising demand of frozen seaweed from 3.000 ton to 13.300 ton, the number of required aquaculture sites rises from 19 (or 269 ha) to 98 (or 1 055 ha) (Figure 37 A), or from 18% of the potential aquaculture sites to 96% of the potential aquaculture sites.

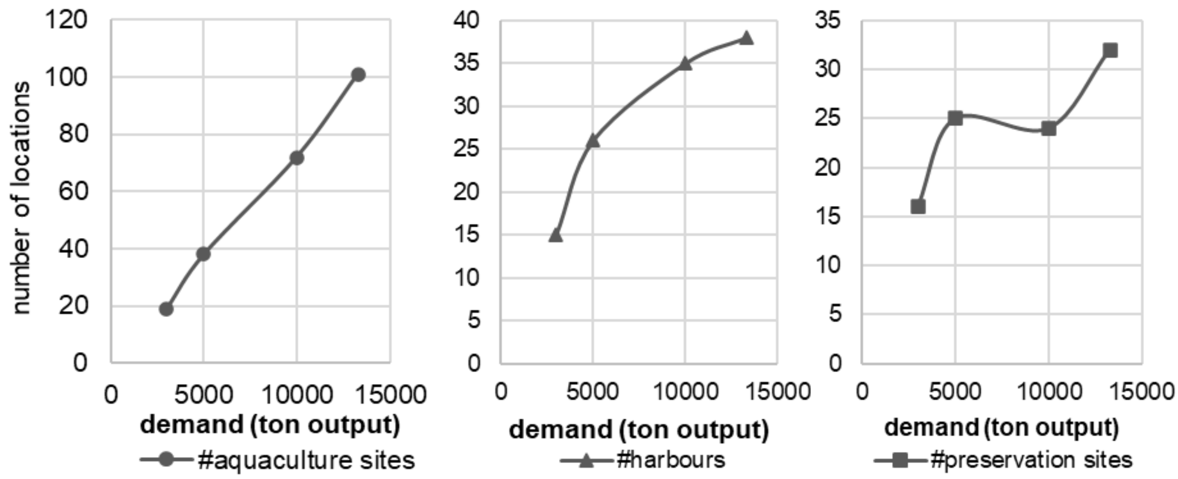


Figure 37 Impact of demand on the number of selected aquaculture sites (A), harbours (B) and preservation sites (C).

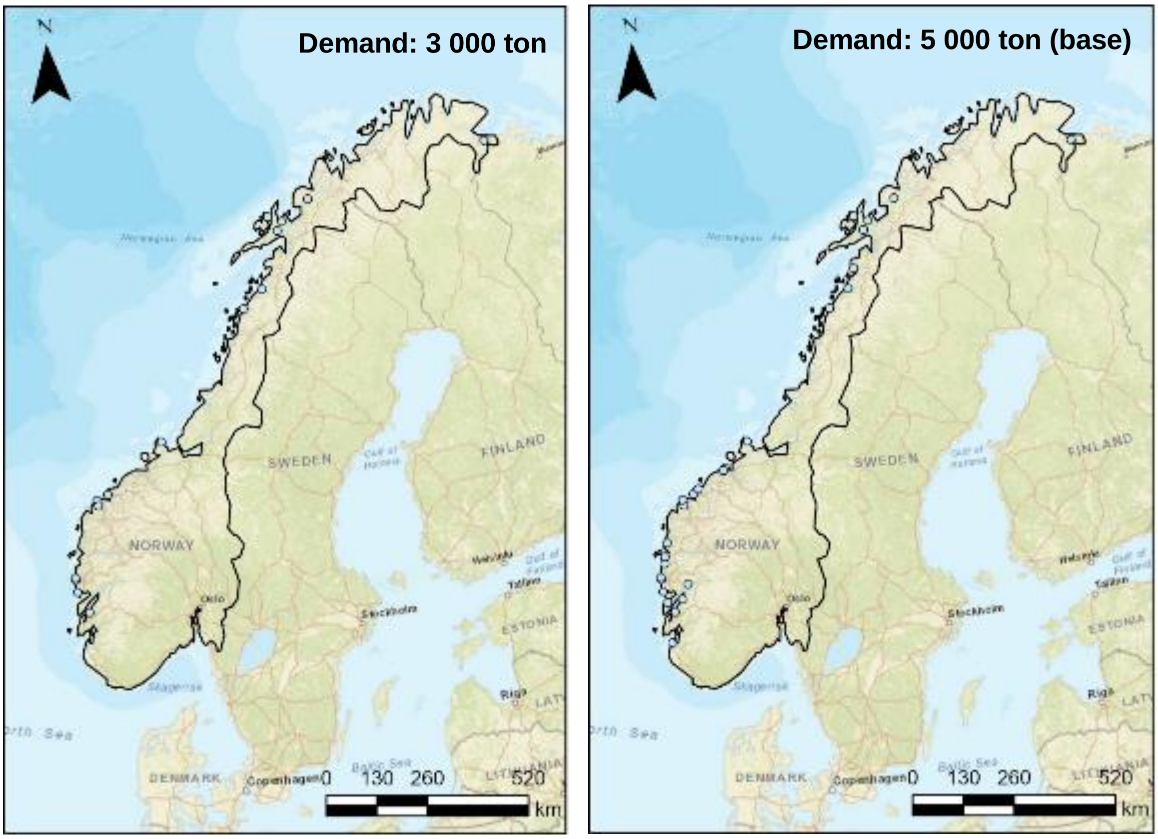
While increasing the demand, the selected aquaculture sites from the lower demand scenarios are retained (Figure 38). This implies that the aquaculture site network is gradually extended. Hence, the aquaculture sites, selected in 3.000 ton scenario (Figure 38 - orange), are the most optimal aquaculture sites in the region considering the assumed seaweed production, and location of potential harbours, preservation locations and downstream processors.

	3.000	5.000	10.000	13.300
	0	0	0	0
	x	x	x	x
	0	x	x	x
	0	0	x	x
	0	0	0	x

Figure 38 Impact of demand on the location of the selected aquaculture sites.

To accommodate the rising demand for frozen seaweed from 3.000 ton to 5.000 ton, the number of required harbours increases from 15 to 26 (Figure 37 B). When the demand stands at 3.000 ton frozen seaweed, most harbours deliver between 60 to 75 boxes per day, with an average of 80 boxes. However, with a demand of 5.000 ton frozen seaweed, the number of boxes drops averaging at 36 boxes per day. Notably, most harbours are aligned with 1 preservation site, maintaining a 1-on-1 relationship in most cases (Figure 37 C).

For demands of 10.000 and 13.300 tons of frozen seaweed, the current capacity of the harbours and the preservation sites faces constraints, rendering an infeasible solution. Therefore, the capacity is upgraded to a maximum of 1.000 boxes per day. The analysis indicates that meeting a demand of 10.000 tons necessitates 35 harbours (Figure 37 B), with most accepting between 320 to 335 boxes per day (averaging at 296 boxes) (Figure 39). Meanwhile, fulfilling a demand of 13.300 ton frozen seaweed requires 38 harbours (Figure 37 B) with daily deliveries ranging from 303 to 336 boxes (on average 394 boxes per day), reaching a maximum of 600 boxes per day in 1 harbour (Figure 39). Increasing the capacity of preservation sites leads to a reduction in the number of selected preservation locations compared with harbours (illustrated in Figure 38 C). This suggests that preservation sites also function as centralisation hubs, effectively minimising transportation towards downstream processors.



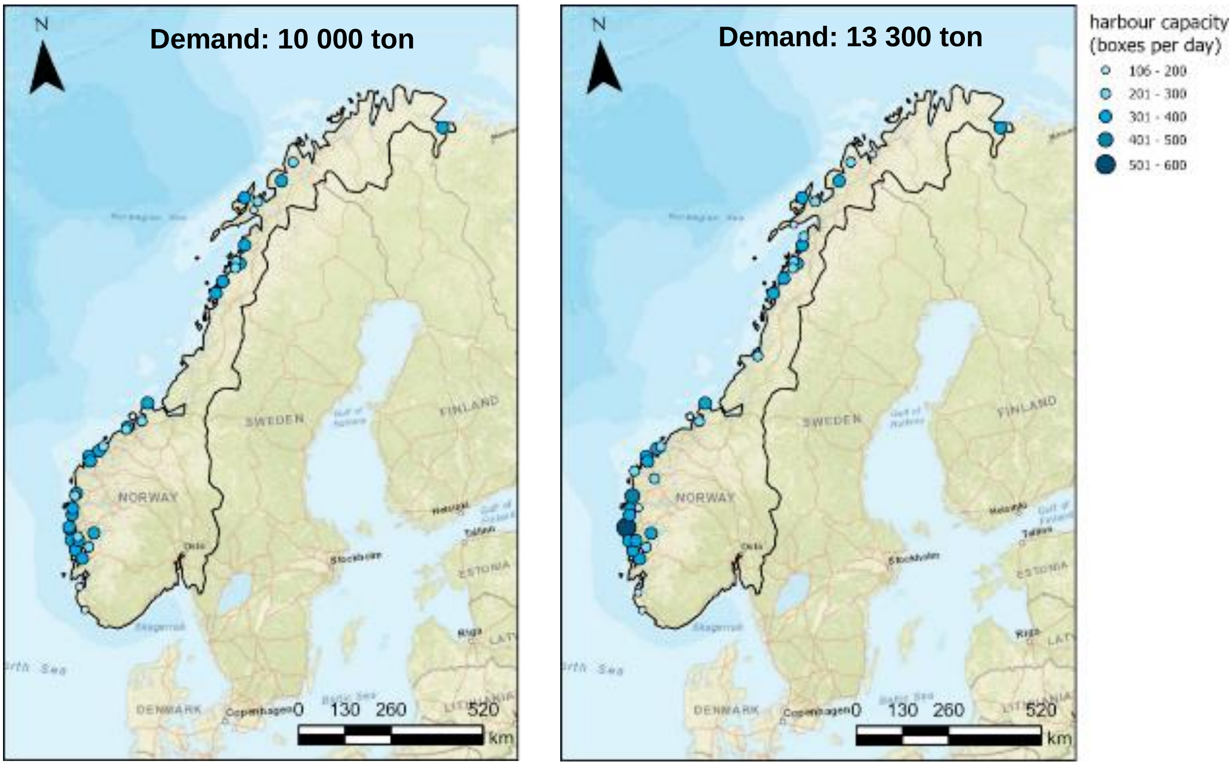


Figure 39 Impact of demand on the location and capacity of the selected harbours.

When the demand for frozen seaweed rises to 10.000 and 13.300 tons, the overall mobilisation cost remains consistent compared with the baseline scenario (Figure 40). Across all scenarios, 39% of the cost pertains to the seaweed production encompassing the seeding/hatching, deploying, growth and crop management, while 21% of the total mobilisation cost is attributed to preservation (Figure 40). The mobilisation cost primarily encompasses operational expenditure (OPEX) and factors like travel distance and time, without considering the impact of capacity adaptations on capital expenditure (CAPEX), hence explaining minor changes relative to the baseline scenario.

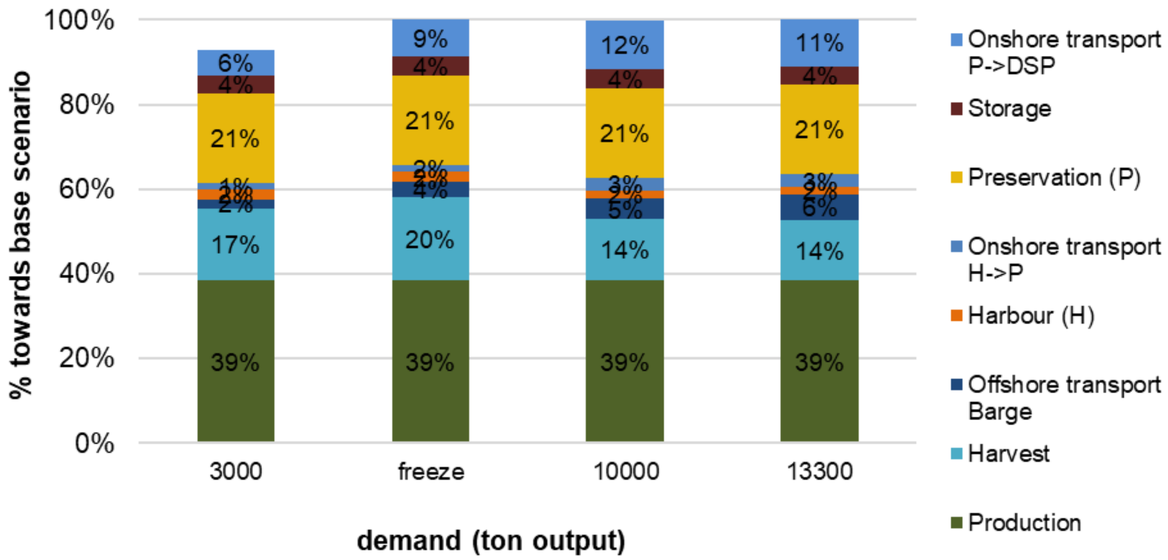


Figure 40 Impact of demand – overall mobilisation cost compared with the baseline scenario (demand = 5.000 ton output) and indication of the share of each activity in the overall mobilisation cost (%).

In the low demand scenario of 3.000 ton of frozen seaweed, the overall mobilisation cost decreases by 7%. Since the share of cost for seaweed production and preservation remain the same, the drop can be attributed to a drop in harvesting – offshore cost as well as a drop in costs related to transport towards downstream processing. Both point to the impact of a local network in which aquaculture sites are closely located to harbours and downstream processors are located more closely to the preprocessors (Figure 42).

In the baseline scenario, the logistics costs constitute 21% of the overall mobilisation cost (Figure 40). Focusing solely on logistics costs, demand significantly impacts expenses, reducing the cost by 22% when demand drops to 3.000 ton of frozen seaweed and increasing by 29% when demand rises to 10.000 ton of frozen seaweed (Figure 41*)*. The primary contributor to this variance is offshore transport by barge, which triples between 3.000 ton to 13.300 ton. Additionally, onshore transport costs double when demand rises to 13.300 ton of frozen seaweed.

In the baseline scenario, 17% of the overall logistics costs are attributed to offshore transport by barge (*Figure* 41). This cost can decrease to 13% with lower demand, where aquaculture sites closest to harbour are prioritised, resulting in a 42% reduction in the average offshore (roundtrip) travel distance (to 4,7 km per ton output) (Figure 42). In this case, a barge travels on average 8,6 km per trip which is a reduction by 42% in comparison with the baseline scenario.

With increased demand to 10.000 ton, offshore transport costs increase by 35%. The need for more aquaculture sites extends the offshore travel distance by 71%, to 25 km per trip (Figure 43). If nearly all aquaculture sites are utilised (to meet the 13.300 ton demand), the travel distances increase to 33 km per trip (a multiplication factor of 2,3). Moreover, the absolute cost of using the harbours triples when doubling the demand from 5.000 ton to 10.000 ton, yet the relative cost per ton decreases by 22%, suggesting more efficient harbour utilisation.

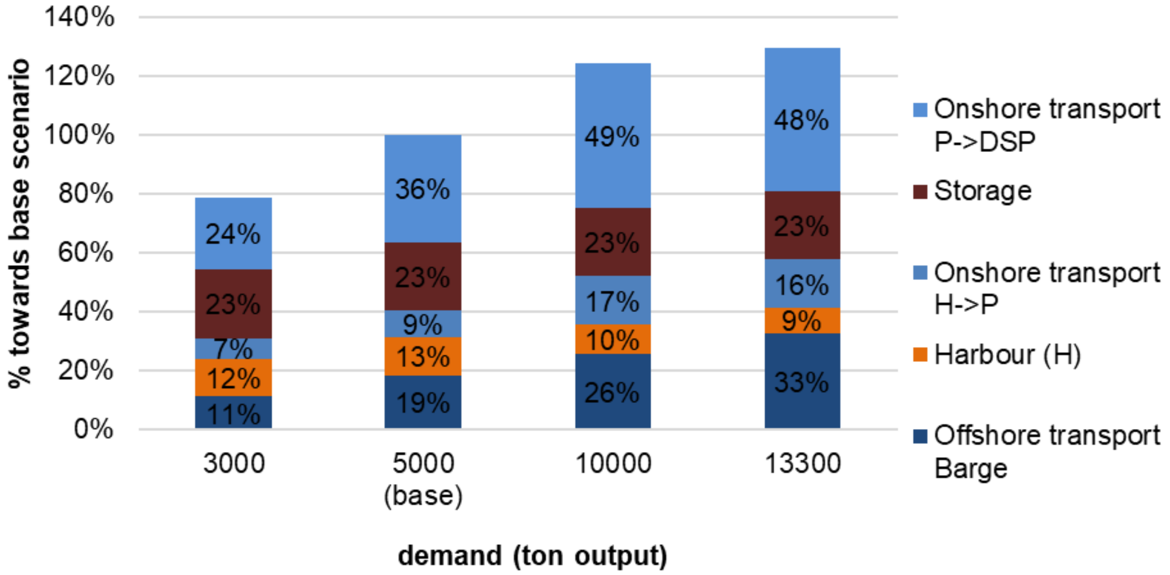


Figure 41 Impact of demand on the logistics cost compared with the baseline scenario (demand = 5.000 ton output) and indication of the share of each activity in the overall mobilisation cost (%).

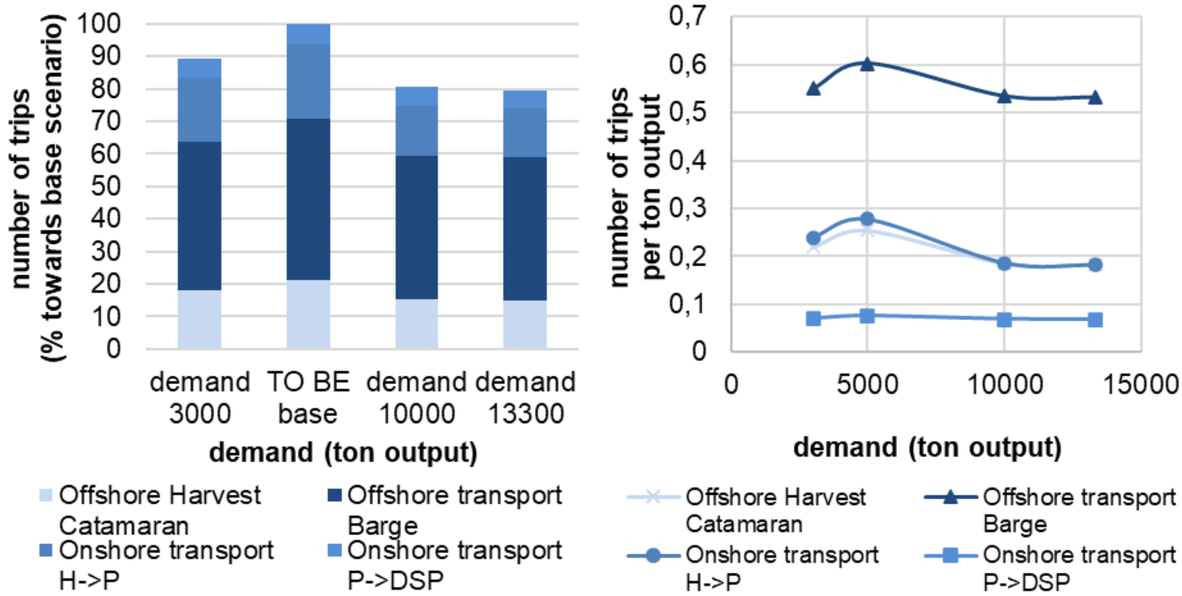


Figure 42 Impact of demand – Travel distance compared with the base scenario (5.000 ton per year) (left) and number of trips per ton output (right).

Furthermore, onshore transport costs towards the downstream processors increase by approximately 32% compared with the baseline scenario, as more processed seaweed needs transportation to downstream processors, located at a larger distance from Norway (Figure 43 C). Travel distances per trip extend from ca 900 km per trip to 1.400 km per trip by expanding the network to Austria, Belgium and even Italy. Conversely, reducing demand to 3.000 ton frozen seaweed decreases onshore transport costs to downstream processors is reduced by 33%, limiting the demand network to Norway, Finland, Sweden, and Denmark. Here, the travel distance is reduced to 713 km per trip (Figure 43).

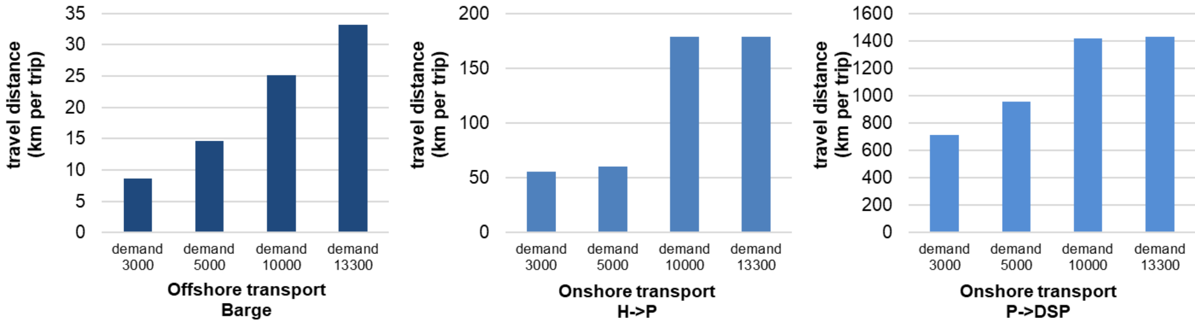


Figure 43 Impact of demand on the travel distance per trip during offshore transport (A), onshore transport between harbour and preservation location (B) and onshore transport between preservation location and downstream processor (C).

Figure 44 summarises the travel distance for the demand-scenarios per ton of frozen seaweed delivered to the downstream processors. For the 13.300 ton scenario the offshore transport doubles (+100%) while the onshore transport increases with +44%.

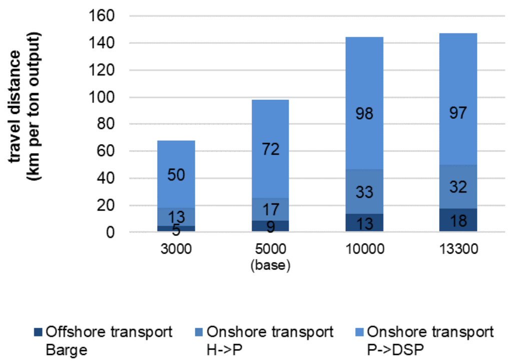


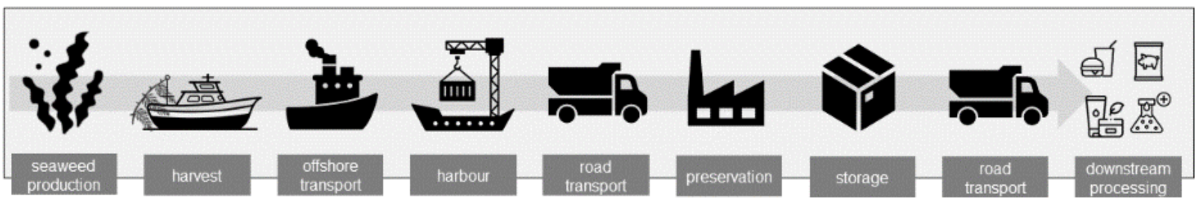
Figure 44: TO-BE impact of demand – Travel distance in km per ton output

Based on Figure 42 B, the average load factor of the different transport types can be defined:

- *Offshore transport by barge*: In the baseline scenario, 0,6 trips per ton output corresponds to a load factor of 88%. In the other scenarios, the number of trips is reduced to 0,53 trips per ton output, resulting in a load factor of 100%.
- *Onshore transport between harbour and* preservation location *by truck*: In the baseline scenario, 0,28 trips per ton output corresponds to a load factor of 63%. If more seaweed is harvested the throughput at the harbour corresponds more the capacity of the truck and the load factor increases to 98% (or 0,18 trips per ton output).
- *Onshore transport between* preservation location *and downstream processor by truck*: 0,08 trips per ton output corresponds to 12,5 ton output per trip. Considering a truck capacity of 15 ton, this results in a load factor of 83%. This load factor is constant.

4.5 Impact of productivity (TO-BE)

This scenario investigates the impact of a prospected increase in seaweed productivity (WMT/ha) over time due to technological improvements, efficiency improvements and upscaling of production. The seaweed production increases gradually from 14 WMT per ha to 100 WMT per ha, while retaining the other parameters in the baseline scenario.



14 - 100 WMT per ha		back and forth			freeze			5 000 ton

Figure 45 Impact of productivity – Overview of adapted parameters

Improving productivity has a direct impact on the efficiency of the seaweed supply chain, notably reducing the number of required aquaculture sites to deliver 7.937 WMT of fresh seaweed (Figure 46 A). Analysis reveals a substantial decline in selected aquaculture sites, particularly evident when productivity increases from 14 WMT per ha to 30 WMT per ha, resulting in a 54% reduction from 54 sites to 25 sites. Interestingly, beyond 50 WMT per hectare, the decrease in selected aquaculture sites drops with 35%. This non-linear relationship underscores the dynamics among aquaculture sites, harbours, preservation locations and downstream processors in the supply chain. The selection process prioritises larger sites situated in proximity to essential nodes, such as harbours and preservation sites, optimizing transportation distances. Since no CAPEX costs for preservation are included, the most optimally located preservation site is selected in relation to the location of the downstream processor. Therefore, the travel distance for onshore transport between processor and downstream processor is constant (Figure 47 C).

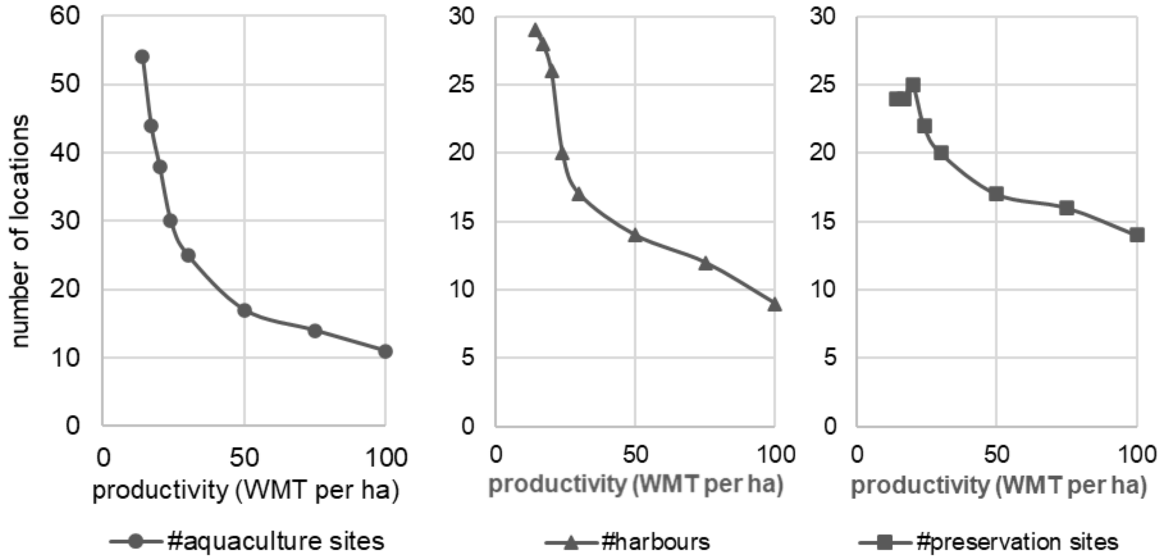


Figure 46 Impact of productivity on the number of selected aquaculture sites (A), harbours (B) and preservation locations (C).

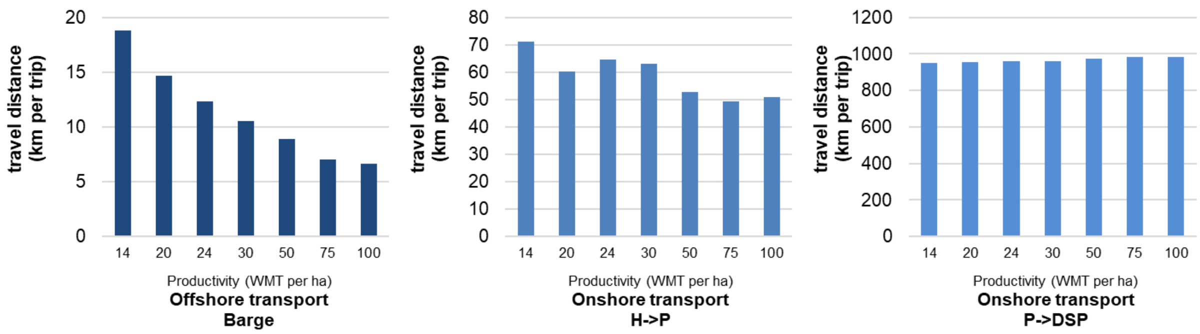


Figure 47 Impact of productivity on the average travel distance per trip for offshore transport (A), onshore transport between harbour and preservation location (B) and onshore transport between preservation location and downstream processor (C).

The overall mobilisation cost experiences a significant decrease with escalating productivity, lowering from the baseline 38.991 NOK (ca. 3.250 €) per WMT to 2.600 € per WMT in cases achieving a visionary 100 WMT per hectare output (Figure 10). A fivefold increase in productivity compared with the baseline scenario results in a notable 26% reduction in overall mobilisation costs. The bulk of these savings stem from the changed cost for seaweed production due to efficiency and technology increase in seeding/hatching, deploying, growth and crop management which changes according to the 6/10th rule (Figure 48). Despite these improvements, the seaweed production costs still account for 44% to 20 % of the overall mobilisation cost. Additionally, preservation expenses, encompassing unboxing and freezing, contribute significantly, accounting for 21% of the overall mobilisation cost or 8.254 NOK (ca. 690 €) per WMT of frozen seaweed.

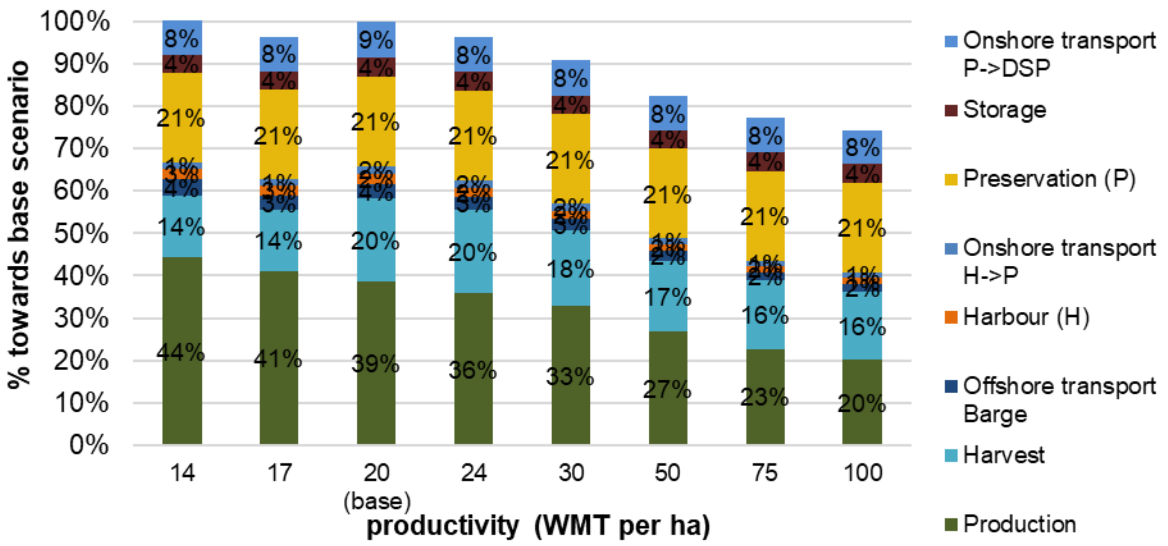


Figure 48 Impact of productivity on the overall mobilisation cost compared with the baseline scenario (20 WMT per ha) and indication of the share of each activity in the overall mobilisation cost (%).

The costs for harvesting are highest in the baseline scenario (contribution of 20%), primarily due to the lower efficiency factor of the catamaran, which stands at 56%. This discrepancy indicates that the harvested quantity does not align with the catamaran's capacity, emphasizing site selection based on location rather than efficiency. In alternative scenarios, harvesting costs decrease thanks to improved catamaran efficiency, reaching 94% for 14-17 WMT per hectare and 82% for 100 WMT per hectare.

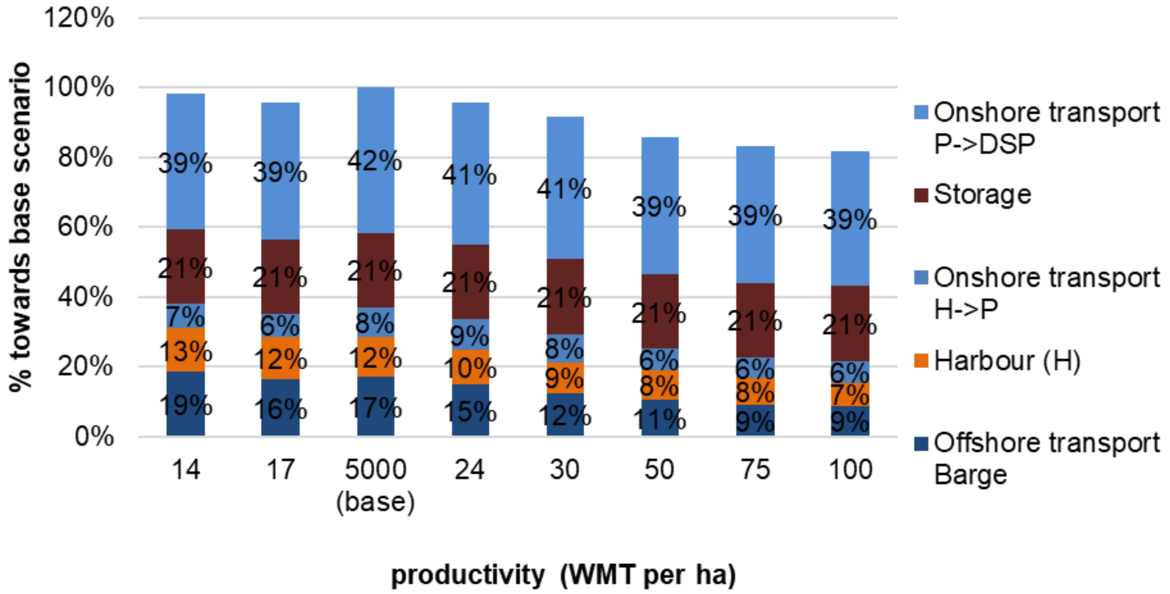


Figure 49 Impact of productivity – Share of logistics cost in total mobilisation cost (%) and indication of the share of each activity in the overall mobilisation cost (%).

Despite consistent shares of logistics costs ranging from 17% to 20% compared with the baseline scenario (Figure 48), overall logistics costs decrease by approximately 8% with a productivity increase to 30 WMT per hectare and by 18% with a rise to 100 WMT per hectare. This reduction primarily stems from decreased costs for offshore activities. Specifically, costs per barge for offshore transport decrease due to reduced travel distance per trip (Figure 47) and per ton output

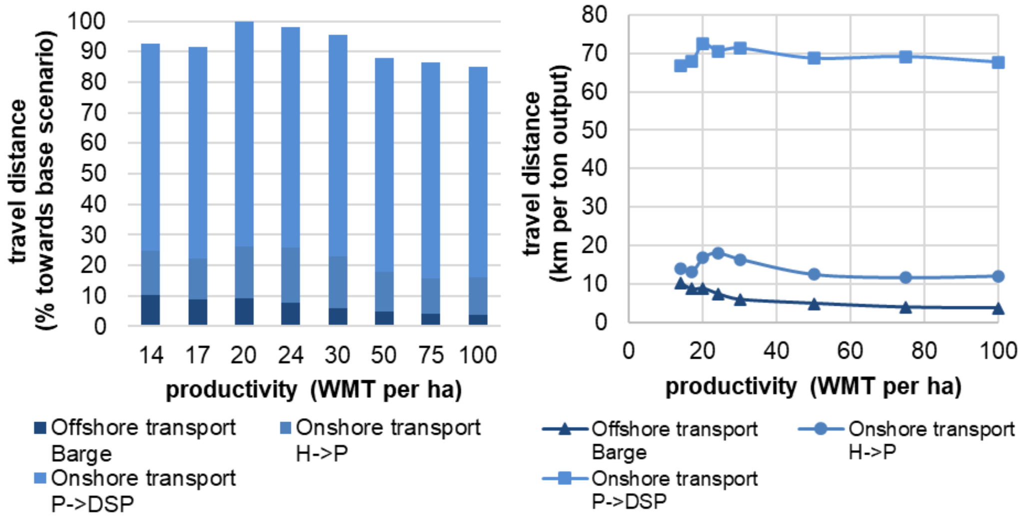
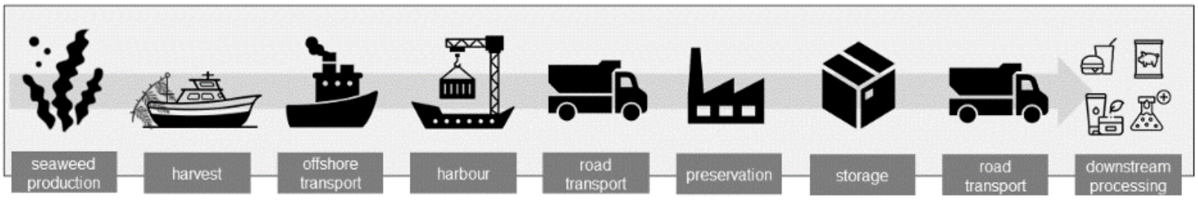


Figure 50 Impact of productivity on the travel distance compared with the baseline scenario (A) and on the travel distance per ton output (B).

(Figure 50), coupled with increased barge load factors, escalating from 88% in the baseline scenario to 98% in low productivity scenarios and 95% in high productivity scenarios). Furthermore, costs for harbour activities diminish from 13% to 7% owing to fewer harbours, resulting in reduced rental expenses.

4.6 Impact of preservation method (TO-BE)

The core focus of the Qualisea project revolves around exploring enhanced preservation methods to achieve superior stabilisation and conservation of seaweed. This scenario delves into the repercussions of various preservation techniques on both the overall mobilisation cost and the structure of the supply chain. Four preservation methods are evaluated: freezing (baseline scenario), acid preservation, blanching and fermentation, each offering unique advantages and considerations (Figure 51). The (combination of) preservation methods accounted for are listed in Table 10.



20 WMT per ha		back and forth			**Freeze Acid Blanch Ferment**			5 000 ton

Figure 51 Impact of preservation method – Overview of adapted parameters.

Table 10 Impact of preservation method – Combinations of preservation.

	Baseline scenario Freeze	**TO-BE Blanch+Freeze**	**TO-BE Ferment**	**TO-BE Acid pres.**
Surface water removal	X	X	X	X
Sort	X	X	X	X
Cut (a)	(X)	(X)	(X)[23]	(X)
Blanch (b)		X	(X)[24]	
Freeze	X	X		
Fermentation			X	
Acid preservation				X[25]
Drying (c)				

[23] Cutting the seaweed when fermenting might result in an easier mixing of the fermenting inoculum with the seaweed.

[24] In the future blanching might become a relevant option in combination with fermentation. For now fermentation still needs justification as a valid conservation/preservation method.

[25] No differentiation between lactic or citric acid preservation is made as alike costs are expected.

a) Cutting would result in reduced cost for packaging and transport due to higher density (more ton/m³). Whether the seaweed is cut or not depends on the client's request.

a) Blanching is an option for iodine reduction/removal[26] from seaweed when targeting food applications. Qualisea cultivation partners argue that with present stat of the art blanching is not a short-term option for scale up.

b) Drying is not withheld for now. However, fermentation prior to drying could be a future option. The fermentation would allow to extent the seaweed shelf-life before drying, hence buffering the needed drying capacity at the moment of harvest.

Compared with the base scenario, the overall mobilisation cost is reduced with respectively 8% and 7% in case of acid preservation and fermentation. However, in the case involving freezing and blanching, the mobilisation cost increases by 84%. This substantial increase is attributed to heightened preservation expenses, which escalate almost fivefold due to the addition of blanching (from 21% to 91%), a process associated with high energy costs. Moreover, seaweed production costs rise by 23% in blanching scenarios, necessitating the mobilisation of 25% more fresh seaweed (9.920 WMT of fresh seaweed compared with 7.937 WMT of fresh seaweed).

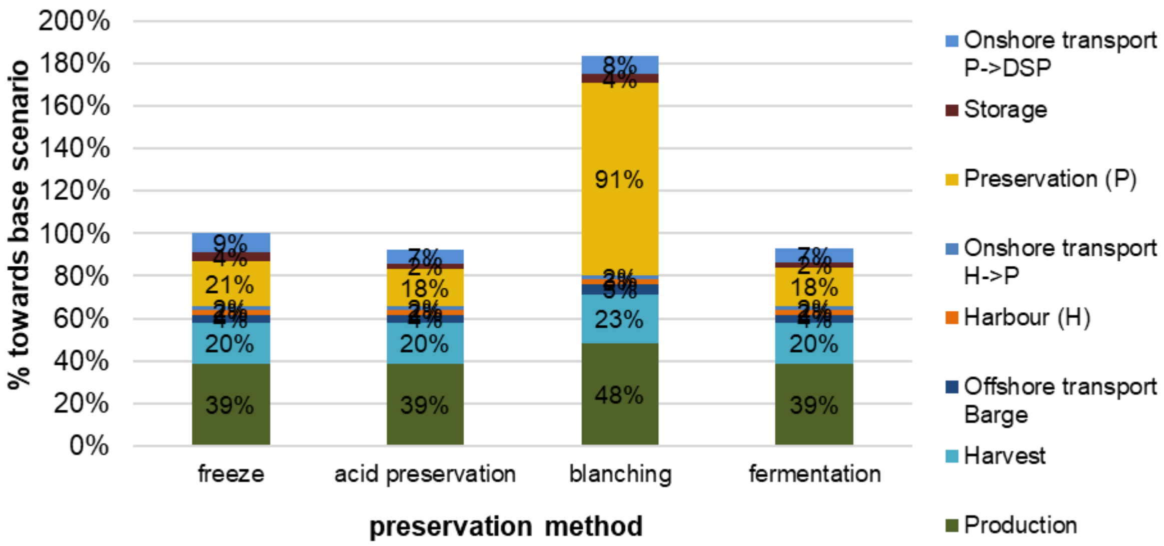


Figure 52 Impact of preservation method on the overall mobilisation cost in % towards the baseline scenario and indication of the share of each activity in the overall mobilisation cost (%).

Analysis further reveals that scenarios employing acid preservation and fermentation exhibit similar supply chain configurations compared with freezing. However, logistics costs are reduced by 20% due to the possibility to store and transport the processed seaweed at room temperature (Figure 53). Conversely, blanching scenarios require a 7% increase in logistics costs, primarily driven by

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[26] Iodine: potentially dangerous for human consumption in case of thyroid deficiencies, which is why strict regulations on recommended daily intake exist (geographically different) – blanching is necessary in many food applications as it reduces the iodine content substantially. For feed, the iodine issue has not been identified as a limiting factor to date.

the need to mobilise 25% more fresh seaweed (Figure 53). The main difference in logistics cost is defined for offshore transport for which an increase of 32% is defined (Figure 53). This uptick in fresh seaweed demand necessitates the utilisation of additional aquaculture sites (50 vs. 38), consequently extending offshore travel distances by 16% to 17 km per trip.

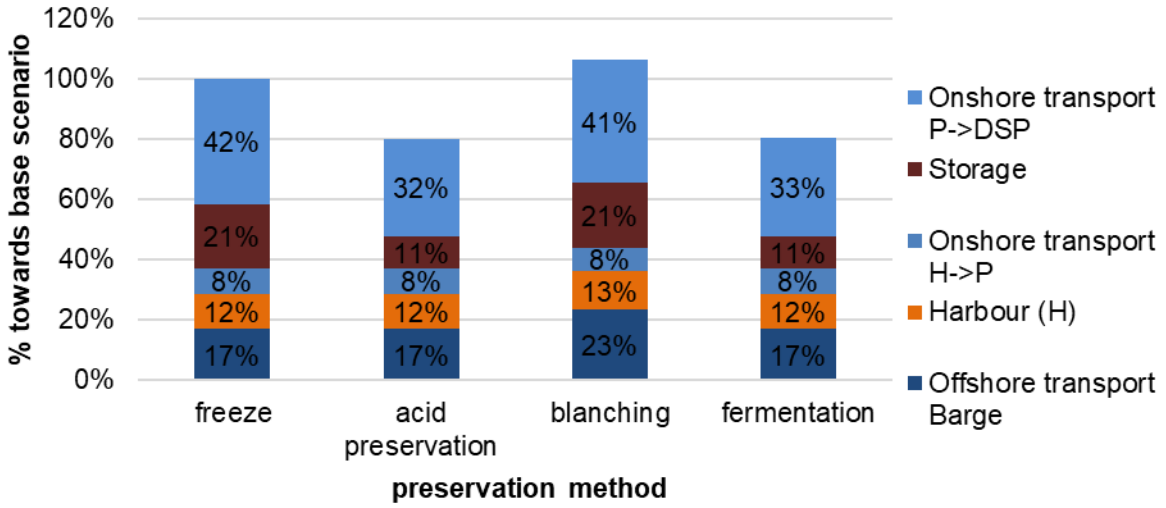


Figure 53 Impact of preservation method – Logistics cost in NOK per ton output and indication of the share of each activity in the overall mobilisation cost (%).

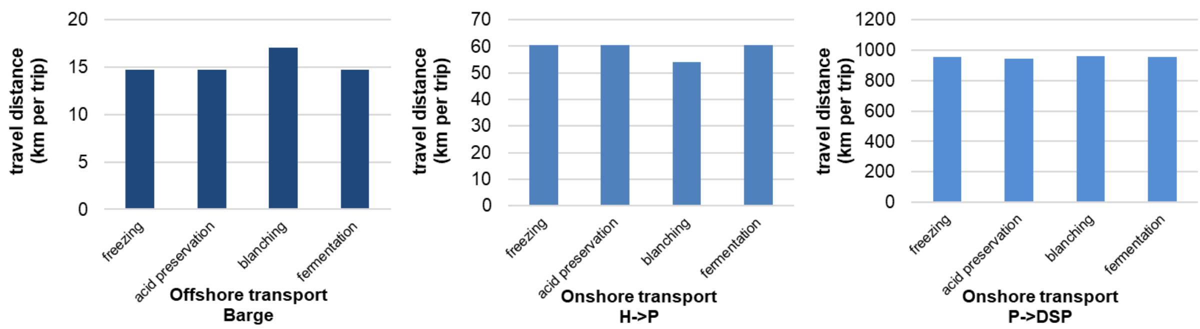


Figure 54 Impact of preservation method – Travel distance per ton output and number of trips compared with the baseline scenario.

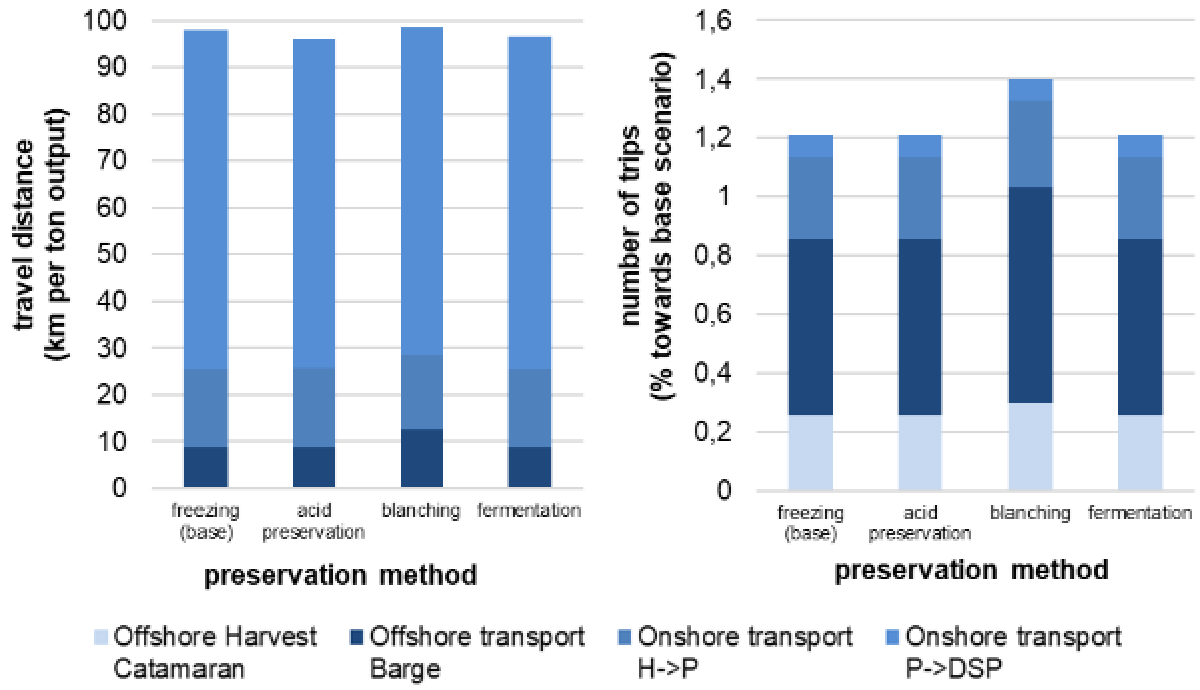
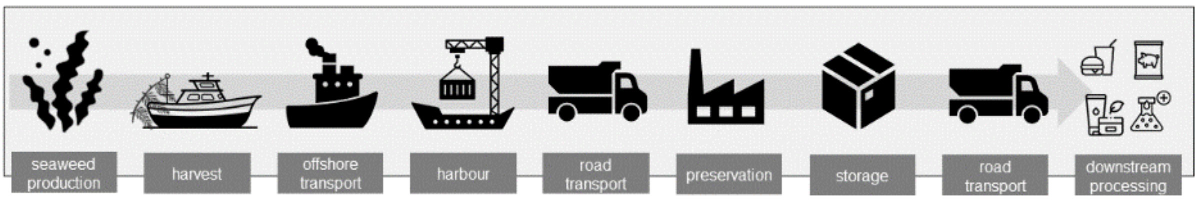


Figure 55 Impact of preservation method – Travel distance per ton output and number of trips compared with the baseline scenario.

4.7 Impact of offshore transport strategy (TO-BE)

This scenario investigates the impact of 2 offshore transport strategies on the configuration of the supply chain (Figure 56). On the one hand, the baseline scenario considers a small barge with a capacity of 10 boxes which transport the seaweed from the aquaculture site to the harbour and shuttles between both sites. On the other hand, a large barge passes by several aquaculture sites (i.e., pickup round).



20 WMT per ha		**pick-up round**			freeze			5 000 ton

Figure 56 Impact of offshore transport strategy – Overview of adapted parameters

To apply the same model utilised in the previous scenario analyses, a multi variate density-based clustering has been performed to identify clusters of aquaculture sites situated within 15 km of each other, with a minimum of 4 sites per cluster. This yields 8 clusters with a harvestable potential ranging from 572 WMT per year to 2.733 WMT per year (Table 11). These clusters are dispersed along the Norwegian coastline, with a notable concentration observed in the South Trøndelag region (*Figure* 57).

Table 11 Impact offshore transport strategy – Characteristics of the clusters

	Cluster colour	Number of aquaculture sites	Total area (ha)	Harvestable potential (WMT)	Minimal route distance (km)
1	Orange	4	31	622	101
2	Ferrari red	7	74	1474	110
3	Lime green	8	61	1224	123
4	Yellow	5	29	572	43
5	Aquamarine	7	137	2733	79
6	Forest green	7	47	929	154
7	Navy blue	4	54	1070	21
8	Maroon red	5	29	585	68

In addition, the limitation on the capacity of the harbours and preservation locations is relaxed, implying that both harbours and preservation locations now have unlimited capacity. The costs associated with harbour usage remain unchanged and are unaffected by the harbour capacity variations.

Since the capacity of the barge is unknown, a sensitivity analysis has been conducted by adjusting the barge size, ranging between 10 boxes (the same as the baseline scenario) and 100 boxes.

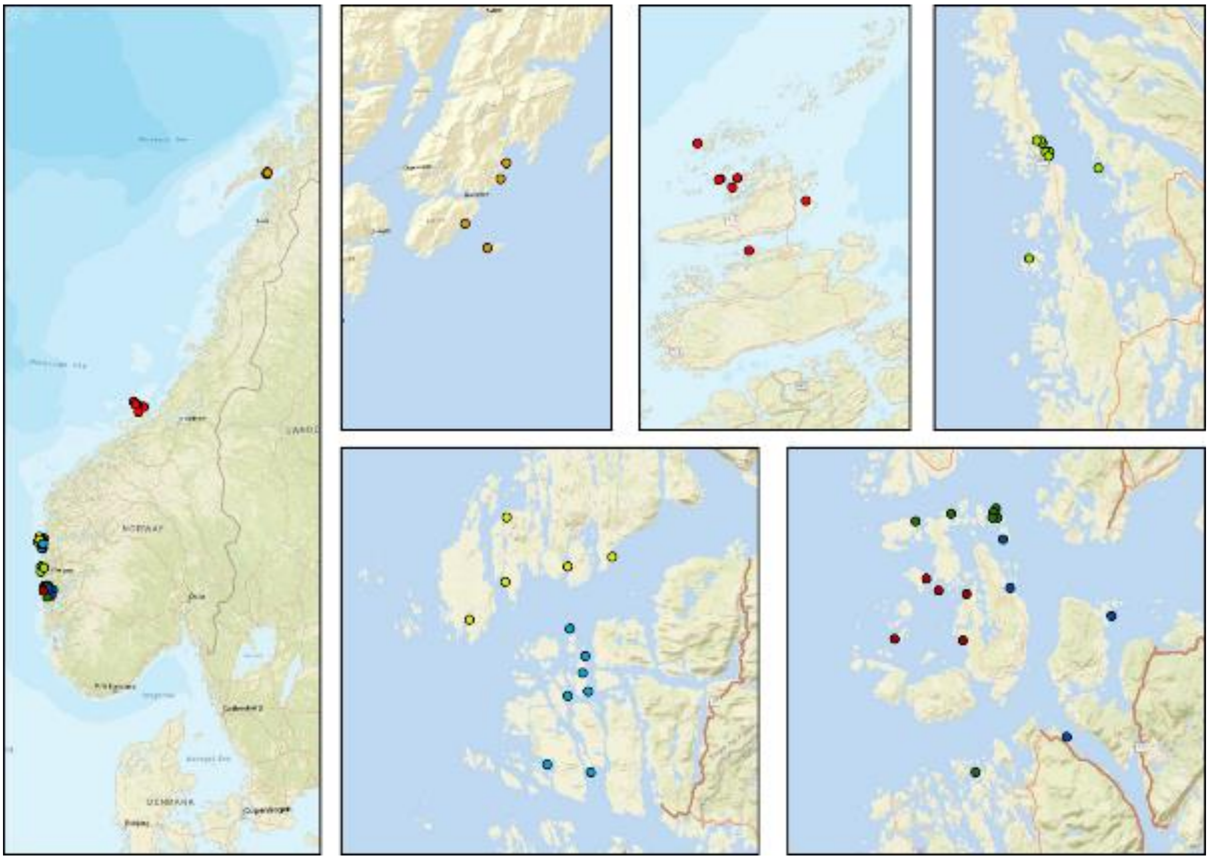


Figure 57 Impact offshore transport strategy – Clusters.

Compared with the baseline scenario, implementing the pickup tour strategy leads to a reduction in the overall mobilisation cost, particularly when the barge has sufficient capacity (Figure 58). With a barge capacity of 25 boxes or more, the overall mobilisation cost decreases by 4%, to a decrease of 10% if a barge capacity of 100 boxes is considered. This cost variance is primarily influenced by changes in harvesting expenses and offshore transport costs via barge.

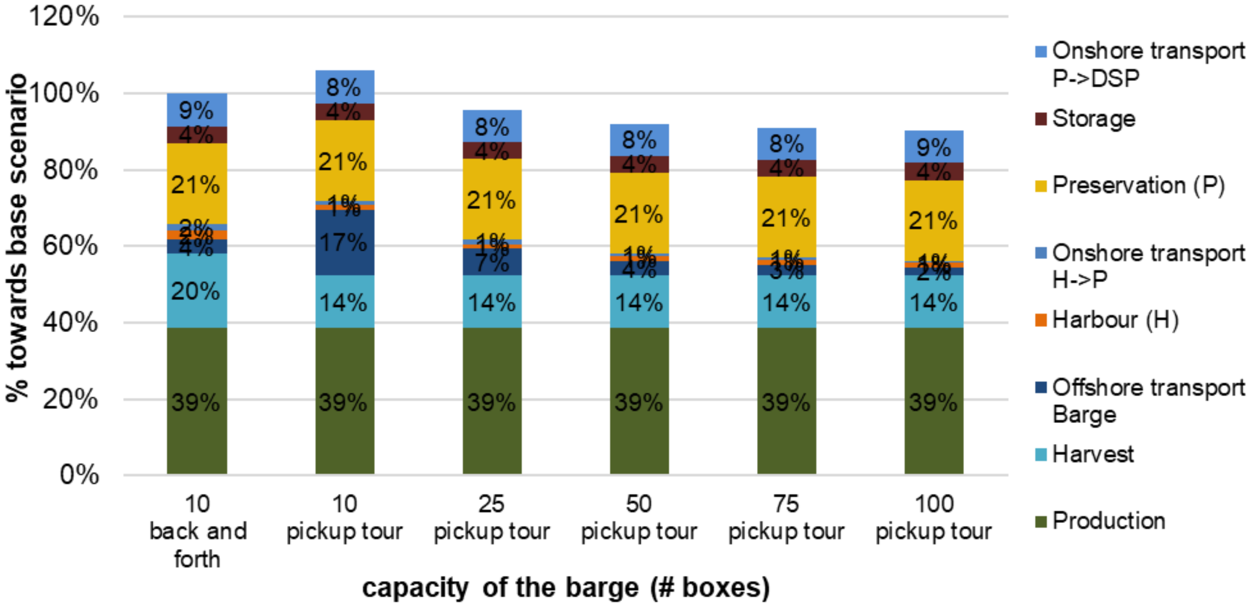


Figure 58 Impact offshore transport strategy on the overall mobilisation cost and indication of the share of each activity in the overall mobilisation cost (%).

Introducing the pickup tour strategy significantly lowers harvesting costs, dropping from 7.638 NOK (ca. 636 €) to 5.400 NOK (ca. € 450) per WMT. This efficiency improvement is attributed to a more optimal utilisation of the catamaran, with its capacity usage increasing from 61% to 97%. Aligning the capacities of the barge and catamaran contributes to this cost reduction.

However, if the same barge capacity is used as in the baseline scenario (i.e., capacity of 10 boxes), the mobilisation cost increases by 6%, primarily due to a substantial rise in offshore transport costs (Figure 58). This increase results from the assumption that the barge must complete the full pickup round during each departure from the harbour, even when maximum capacity is met along the route. Consequently, the travel distance per ton output rises to 41 km, nearly five times higher than the baseline scenario (Figure 59 B) and an offshore transport cost which is almost 5 times higher (Figure 59 A).

For barge capacities of 25 boxes or higher, the overall mobilisation cost is lower than the baseline scenario, primarily driven by reduced harvesting costs (Figure 58). However, with a 25-box capacity, offshore transport costs remain relatively high, nearly double those of the baseline scenario, with an average travel distance of 17 km per ton output.

Based on the equation in Figure 59 B, it has been calculated that a barge capacity of 53 boxes results in similar offshore transport costs and travel distance per ton output as the baseline scenario, where the barge shuttles between aquaculture sites and the harbour.

Increasing barge capacity to 75 boxes and 100 boxes enables further reductions in offshore transport costs by 5% and 8% respectively (Figure 59 A) leading to a travel distance of 6,5 km per ton output and 5,1 km per ton output respectively (Figure 59 B).

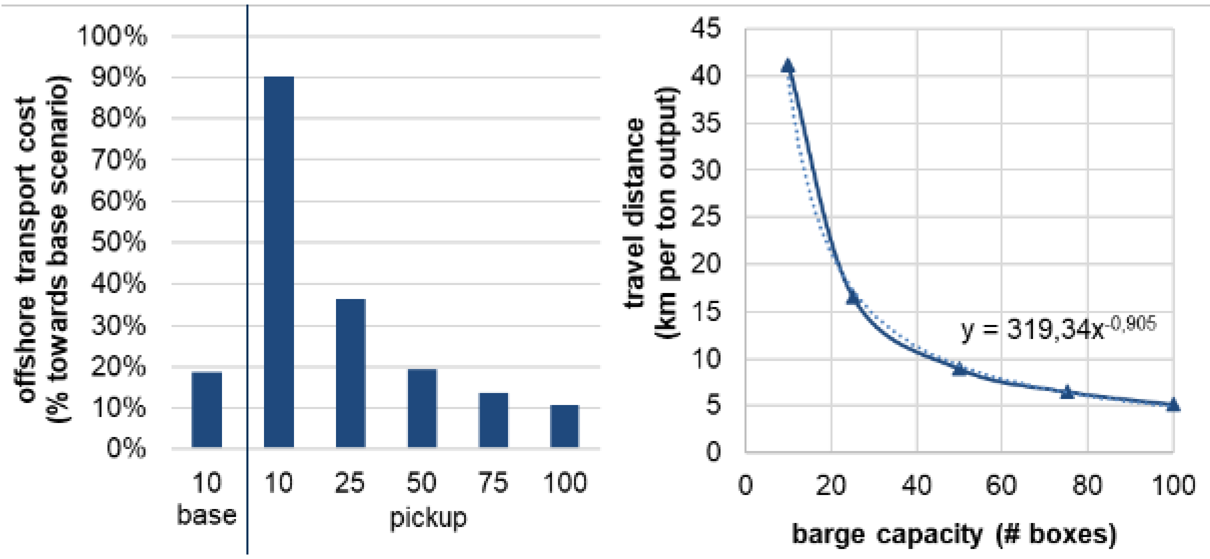


Figure 59 Impact offshore transport strategy on the share of offshore transport in the logistics cost compared with the baseline scenario (A) and the impact on the travel distance in function of the size of the barge (defined in number of boxes) (B).

CONCLUSIONS

NEXT STEPS

5 CONCLUSIONS AND NEXT STEPS

Qualisea aims to tackle supply chain challenges in European seaweed farming by ensuring predictable and stable biomass quality from harvesting to processing, optimizing production and transportation processes, and involving stakeholders across the supply chain. The project seeks to facilitate the expansion of the seaweed industry by identifying bottlenecks for growth and the implementation of seaweed biomass in various applications such as food, feed, materials, cosmetics, and pharmaceuticals.

The MooV approach, applied within Qualisea, analyses different configurations in the future seaweed supply chain design to understand their impact on overall performance and mobilisation costs. The Qualisea model, built on the MooV-core, addresses complex supply chain challenges, and assesses the effects of decisions and changing circumstances. Within Qualisea, the MooV analysis is conducted on a case study in Norway, specifically targeting the seaweed species *Alaria esculenta* and *Saccharina latissima*.

5.1 Seaweed logistics conclusions

The analysis of various scenarios reveals critical insights into the seaweed supply chain dynamics and cost implications. The baseline scenario serves as a benchmark for evaluating the impact of various parameters on the mobilisation cost, travel distance and supply chain configuration. With a focus on achieving efficiency, the baseline scenario outlines the operations from seaweed production to downstream processing. Despite the complexity of the supply chain, the analysis reveals key cost components, with seaweed production/cultivation and preservation constituting significant portions, respectively ±40% and ±20% of the overall mobilisation cost. Also, logistics costs play a pivotal role (±20% of the overall mobilisation cost) of which ±30 % is related to offshore activities. Strategic decisions, such as site selection and transport capacity optimisation, are instrumental in minimising costs and maximizing efficiency. Cost savings can be achieved by including proximity-based site selection and load factor optimisation.

Impact of demand

As demand rises, so do the challenges in terms of capacity constraints at harbours and preservation sites, necessitating adjustments in infrastructure and logistics. Despite the increase in demand, the overall mobilisation cost (per ton output) remains relatively stable, showcasing the adaptability of the supply chain to meet growing needs efficiently. Seaweed production and preservation consistently account for a significant portion of costs, highlighting the need for improvements in these research areas. Moreover, logistics costs become notably more significant with increasing demand (from 16% to 21%). The primary contributor this shift is offshore transport via barge.

The analysis of changing demand for frozen seaweed underscores the complex interplay between production, preservation, demand, and logistics. The findings emphasise the need for adaptive strategies to balance cost-effectiveness with meeting increasing demands, ensuring the sustainability and viability of the frozen seaweed supply chain in the face of evolving market dynamics.

Impact of seaweed production/cultivation

The exploration of increasing seaweed productivity from 14 to 100 WMT per hectare underscores the potential for significant cost savings through technological advancements, efficiency improvements and upscaling of production. Higher productivity leads to a streamlined supply chain, with fewer aquaculture sites required to meet demand targets. This reduction in required aquaculture sites translates into lower overall mobilisation costs, demonstrating the importance of technological innovation in driving efficiency gains. Overall, this scenario underscores the imperative of continuous innovation and adaptation to ensure the resilience and sustainability of the seaweed supply chain in a dynamic landscape.

Impact of preservation methods

The evaluation of preservation methods sheds light on the trade-offs between cost and effectiveness. This scenario evaluates the impact of four preservation methods (freezing, acid preservation, blanching, and fermentation) on overall mobilisation costs and supply chain configuration. While certain methods may offer superior preservation qualities, they often come with higher associated costs. Understanding these trade-offs is essential for decision-making, ensuring that the chosen preservation method aligns with both quality objectives and cost considerations.

Acid preservation and fermentation stand out as cost-effective alternatives, reducing overall mobilisation costs by ±10% compared with freezing. These methods offer potential logistical benefits for preserved seaweed since freezing conditions are no longer required, making them attractive options for cost-conscious supply chain strategies. Alternatively, the combination of freezing and blanching increases the overall costs by 84%. This surge is primarily attributed to the fivefold increase in preservation expenses, soaring from 21% to 91% due to the addition of blanching, accompanied by heightened seaweed production costs since blanching necessitates the mobilisation of 25% more fresh seaweed. These findings underscore the intricate balance between preservation efficacy, production costs, and logistics optimisation in shaping a resilient and efficient seaweed supply chain.

Impact of offshore transport strategy

The comparison between the baseline scenario and the pickup tour strategy implementation underscores the pivotal role of optimizing transport logistics in aquaculture operations. Using larger barges that navigate through multiple aquaculture sites has displayed promising potential for reducing costs, especially when accompanied by sufficient capacity. This efficiency enhancement primarily stems from the improved utilisation of transport vessels, resulting in decreased harvesting expenses and overall mobilisation costs. However, it's clear that the success of these strategies depends heavily on barge capacity, with larger capacities yielding more favourable cost outcomes. These findings highlight the importance of aligning vessel capacities with operational requirements to maximise efficiency and minimise expenses in offshore transport logistics within the aquaculture industry. The effectiveness of these strategies is contingent upon factors such as vessel capacity and route optimisation.

5.2 General conclusions

The comprehensive analysis of various scenarios provides valuable insights for optimizing the seaweed supply chain, balancing cost considerations with efficiency and quality objectives. By understanding the implications of different parameters and decisions, stakeholders can make informed choices to enhance the efficiency and competitiveness of the supply chain in a dynamic market environment. This underscores the strategic interplay between site selection and transportation logistics, emphasizing proximity to key nodes for optimal efficiency. Despite the complexity of the supply chain, the analysis reveals key cost components, with seaweed production and preservation constituting significant portions. As the seaweed industry scales up, the significance and intricacy of logistics also escalate. Notably, offshore transport costs become more pivotal, emphasizing the importance of factors such as transshipment efficiency, barge capacity, and optimizing pickup rounds.

5.3 Next steps

The seaweed supply chain is currently in its early stages of development, necessitating several assumptions to project scaling and learning curve scenarios for the future. As the seaweed industry matures in Norway, the data within the Qualisea database can be readily adjusted to reassess scenarios and explore their effects on mobilisation costs and supply chain structures. Moreover, the flexible design of the Qualisea model, currently utilised in the Norwegian setting, offers the potential for future application in other countries, regions, or various types of seaweed.

The next research steps include:

1. Investigating geographical disparities, particularly between northern and southern Norway, to comprehend their influence on seaweed supply chain dynamics.
2. Integrating CAPEX considerations to analyze the implications of various infrastructure setups, such as large versus small harbours and diverse storage capacities as well as the optimisation of the number of harbours and preservation locations in combination with the capacity.
3. Enhancing the existing model to accommodate pickup rounds alongside back-and-forth backup arrangements, aiming to minimise clustering and optimise transportation logistics.
4. Exploring the feasibility of pickup rounds to enhance efficiency, considering factors like optimal routes, scheduling, and quantity-based pickup strategies. In addition to the scenario examining offshore transport via a pickup round, future projections could explore the use of so-called "factory ships." While the current analysis investigates a barge with a capacity of 100 boxes, increasing the barge's loading capacity is subject to constraints not only related to the maximum structural loading limits of the barge but also to operational factors. Specifically, during the pickup route, there is significant waiting time for harvesting and loading at sea. If the barge's capacity is increased excessively, the seaweed harvested at the beginning of the pickup route may deteriorate by the time the barge reaches the harbor. An alternative approach involves the potential deployment of larger "factory ships," analogous to well boats used in the salmon industry. These ships would enable immediate preservation of the seaweed upon onboarding, effectively addressing quality degradation. This immediate processing capability would extend the permissible residence time of seaweed on the ship, allowing for larger harvest volumes to be collected during a single pickup round without compromising the quality of the product

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