Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Marine Technology

Sigmund Nilsen Myhre

Autonomous Low-Emission Kelp Farm Vessel Design

Master's thesis in Marine Technology
Supervisor: Bjørn Egil Asbjørnslett
July 2020

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M.Sc. in Marine Systems Design

Stud. techn. Sigmund Nilsen Myhre

"Autonomous, Low-Emission Kelp Farm Vessel"

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Background

An industry based on cultivation and harvesting of seaweed has gained increased interest in Norway over the last decade. It is predicted that the production could reach a level of 20 million tons by 2050. In comparison, the production level was 149 tons in 2017, while harvest was approximately 150 000 tons. This indicates that there is believed to be a strong growth in the industry, which has so far been absent. Many bottlenecks have been identified as reasons for this; from lack of proper regulations and protocols for cultivation, few commercially developed end-product applications, too high costs of cultivation and few technological solutions. Regulations are under development and the global market is expecting a large increase in demand of biofuel, food and feed for fish and other livestock, and the applications for seaweed is also expected to increase over the next coming years.

The remaining bottleneck is then the high costs related to cultivation and harvesting, which is mainly caused by the high demand of high-cost crew during deployment and harvest. To reach a production of 20 million tons annually will require new technological solutions that will either increase the efficiency of crew, reduce the required number of crew, or preferably a combination of the two.

What developments will then be required to remove the final bottleneck? Are there existing solutions that can be implemented to remove the final bottleneck? Will there be crew required for operations, or may there be solutions that can motivate the industry to operate autonomous? Should one design solution satisfy all the needs, or will there exist multiple specialized vessels for different operations?

Overall aim and focus

This Master Thesis will study the possibility of designing an autonomous vessel for seaweed farm operations. With this study, the master thesis will

- Identify system requirements for autonomous technology, strengths and weaknesses with autonomous systems, and state-of-the-art technology.
- Define requirements for deployment, harvest, storage and processing, and set cost- and time-targets for the vessel.
- Propose a vessel design for kelp farm operations, in terms of capacity and main dimensions, onboard equipment, operational profile and general arrangement.
- Identify advantages and disadvantages with the proposed design for specific operations for a kelp farm owner.
- Discuss if it is technologically and economically feasible and reasonable to design an autonomous vessel for this industry, based on the defined requirements and targets.

To answer these questions, the student will need to learn more about the seaweed industry, along with biological factors and methods and technology for cultivation. The student must also learn about autonomous vessel technology. The student should have a good understanding of the value-chain of seaweed, from seedling production to end-product.

Scope and main activities

1. Gain an understanding of the problems that are preventing seaweed cultivation to grow into a large-scale industry. This will be done by studying the value-chain of seaweed, from hatchery to end-product, understanding the biological factors that affect growth rate and growth pattern. The potential market developments will be studied, with opportunities and challenges associated to end-products.
2. Study state-of-the art technology for farm operations, including deployment, harvest, storage and pre-processing.
3. Perform a literature review to gain more insight in design methods and autonomous systems. Discuss autonomous systems in the setting of kelp farm operations, identifying what strengths and weaknesses with autonomous systems have in this setting. Study state-of-the-art autonomous technology in maritime application.
4. Define the main problems kelp farmers face today, identify the main stakeholders, needs of main stakeholders, and define a set of requirements, cost-targets and time-targets.
5. Define the main functions and a system breakdown with subsystems. Examine what solutions exist for conventional and autonomous execution and propose solution structures.
6. Analyze the solution structures to identify those that satisfies the needs of the owner and propose a solution path.
7. Design a vessel for capacity, main dimensions, operational profile, onboard equipment and general arrangement.
8. Evaluate the design based on predefined criteria from point 4.
9. Discuss the findings and conclude with the feasibility of the design, with recommendations to topics for further development.

Modus operandi

At NTNU, Professor Bjørn Egil Asbjørnslett will be the responsible advisor.

The work shall follow the guidelines given by NTNU for the M.Sc. work

Trondheim January 2020.

Bjørn Egil Asbjørnslett

Professor/Responsible Advisor

Summary

The aim of this thesis is to gain an understanding of the seaweed cultivation industry and propose a vessel design appropriate for the industry in its current state. Seaweed has been studied in biological and technical aspects. A deeper knowledge of the value-chain from hatchery to end-product gives an understanding of a vessel's role in the industry. A study of autonomous vessel technology is performed to understand system requirements, and how it can contribute in a vessel design for the industry.

The industry is in an early phase, where more experience and knowledge regarding seaweed and cultivation technology is necessary. The industry has a short season and is of a low scale. To design a vessel that will facilitate for large scale cultivation will therefore bring challenging economic targets.
A study of different operations and applied technology in the industry contributed to insights in the interactions between a kelp farm and a vessel. This identified key requirements for a vessel design for this industry. Due to high labor-costs in Norway, a feasibility study for implementing autonomous technology was performed. The technology is still immature for maritime applications. Many projects are ongoing that is likely to realize this technology over the next decades. For applications in kelp cultivation, technological developments of the operations a vessel performs is necessary to facilitate for autonomous execution. Due to the limited knowledge of cultivation, it is desirable to have crew on site during operations to increase knowledge. The potential for decreasing the operation's dependence on human interactions is large, however.

The challenges for a vessel design are to specialize to an extent that contributes to a low-cost biomass, at the same time as it has enough flexibility to adapt to a changing industry. Due to the short seasons of operation, the vessel must be multi-purpose to maintain a high utility. A high utility can also be safeguarded by following the harvest northward. Harvest is in May and June in southern Norway, but shifts to July and August in northern Norway. The main stakeholders are the kelp farm owners and fish farm owners, as this is the likely intersection for a multi-purpose vessel.

From the identified main stakeholders, a need-function-form mapping was performed in accordance with an autonomous job analysis. A solution path that aims to increase the level of autonomy is chosen. A vessel is designed to suit the chosen solution path. The payload capacity of the vessel is 33m^3, or between 9,9-28 tons. The length overall is 15m and the beam is 10m. The vessel is a zero-emission catamaran with water jet propulsion. Catamaran design is chosen for good initial stability, large deck area, and to be similar to what vessels are used by fish farmers. Water jet propulsion is suitable due to good maneuverability and no external propellers that pose a risk of entanglement with ropes. The maximum vessel draft is 1,64m.

The vessel is installed with 2000kWh in battery packages, which results in a zero-emission vessel. The required propulsion is 278kW at 9kn fully loaded, and the vessel has a minimum range of 60nm. The vessel displacement is 113tons or 110m^3. The vessel complies with all requirements of IMO MSC.267(85) in ballast condition. A harvesting speed of 8-10m/min is feasible for the vessel with the given operational profiles. The vessel is equipped with existing technology and simple procedures ensure a higher level of autonomy for the vessel than what is common in the industry.

The required freight rate of the design is 1,3NOK/kg, which is higher than the maximum set target of 1,0NOK/kg. A vessel design is therefore not sufficient to reduce the costs to a competitive level for low-cost products. The design may however be cheaper than chartering a vessel, and the currently existing solutions. A flexible vessel chartered to other industries will be required, and technological developments that improve the interactions between farm and vessel are necessary. Cost-reductions in all aspects of seaweed production is necessary to facilitate for a market based on high-volume low-cost products.

Sammendrag

Målet med masteroppgaven er å få en større innsikt i en industri basert på dyrking av tang og tare, og foreslå et fartøydesign som passer inn i denne industrien slik den er i dag. Tare har blitt studert med fokus på biologiske og teknologiske aspekter. Innsikt i verdikjeden fra kimplante-produksjon til sluttprodukt gir en forståelse for et fartøys rolle i næringen. En mulighetsstudie av autonom fartøyteknologi utføres. Dette gir forståelse for systemkrav og hvordan denne teknologien kan anvendes i taredyrking.

Industrien er i en tidlig fase hvor mer erfaring og kunnskap rundt tare og kultiveringsteknologi er nødvendig. Produksjonsnivåene er lave og industrien er basert på korte sesonger for operasjoner. Et fartøy som muliggjør storskala produksjon får da utfordrende økonomiske mål.
En studie av operasjoner og anvendt teknologi i industrien bidrar til innsikt i interaksjonene mellom et taredyrkingsanlegg og fartøy. Med dette identifiseres nøkkelkrav for et fartøydesign til denne industrien. Høye lønningsnivå i Norge motiverer implementering av autonom teknologi. Autonom teknologi er derimot umoden for anvendelse i maritime miljø. Mange prosjekter er pågående som kan muliggjøre denne teknologien over de neste tiårene. For anvendelse i tareindustri må teknologiske utviklinger skje for operasjonene som skal utføres. Ettersom at næringen er preget av få år med erfaring, er det ønskelig med mannskap tilstede under operasjoner, for å få mer kunnskap om taredyrking. Potensialet for å redusere behovet for manuelt fysisk arbeid er derimot stort.

Utfordringene ved et fartøydesign er å spesialisere det nok til at det vil bidra til et lavkost produkt samtidig som at det har stor nok fleksibilitet til å tilpasse seg en utviklende industri. Grunnet den korte sesongen må fartøyet være multifunksjonelt for å opprettholde en høy utnyttelsesgrad. Utnyttelsesgraden kan også ivaretas ved å følge høstesesongen nordover. Høsting i sør-Norge skjer i april og mai, mens den i nord-Norge skjer i juli og august. Hovedinteressentene er taredyrkere og fiskeoppdrettere, ettersom at dette er det sannsynlige skjæringspunktet for et multifunksjonelt fartøy.

Fra hovedinteressentene kartlegges behov til funksjoner og løsninger i samsvar med en autonom arbeidsanalyse. En løsningssti som sikter på å øke autonomitetsgraden til systemet blir valgt, og et fartøy blir designet for å passe denne løsningsstien.
Nyttelast-kapasiteten til fartøyet er 33m^3, eller mellom 9,9-28 tonn. Lengde over alt er 15m og bredden er 10m. Fartøyet er designet som en nullutslipps-katamaran med vannjet-propulsjon. Katamaran-utforming er valgt for egenskapene god initialstabilitet og stort arbeidsdekk. Katamaraner er ofte brukt i service til oppdrettsnæringen, som også var en motivasjon for valget. Vannjet gir god manøvrerbarhet, og fjerner faren med propeller forviklet i tau, ettersom at propellene er på innsiden av skroget. Fartøyets maksimale dypgang er 1,64m.

Fartøyet er installert med 2000kWh i batteripakker. Det resulterer i et nullutslippsfartøy. Propulsjonskraften er 278kW ved 9 knop og maks last. Fartøyet har en rekkevidde på 60 nautiske mil. Fartøyets vektdeplasement er 113 tonn, volumdeplasementet er 110m^3. Fartøyet tilfredsstiller alle stabilitetskrav fra IMO MSC.267(85) i ballast-kondisjon. En høstehastighet mellom 8-10m/min er mulig for fartøyet med gitte operasjonsprofiler. Fartøyet er utstyrt med eksisterende teknologi og enkle prosesser skal sørge for høyere grad av selvstyring for fartøyet enn hva som er vanlig i industrien.

Nødvendig fraktrate er 1,3kr/kg, som er høyere enn den satte grensen på 1,0kr/kg. Fartøydesign vil derfor ikke være nok for å redusere kostnader til et konkurransedyktig nivå for lavkost-produkter. Fartøyet er billigere enn å leie inn et skip, og kan være billigere enn de løsningene som anvendes i dag. Et fleksibelt fartøy tilgjengelig for utleie til andre industrier er nødvendig. Teknologiske utviklinger som forbedrer interaksjonene mellom anlegg og fartøy er nødvendig. Kostreduksjon i alle deler av verdikjeden for tareproduksjon er nødvendig for å muliggjøre et marked basert på stor-volum og lavkost-produkter.

Preface

This master thesis concludes my studies at the Norwegian University of Science and Technology in Marine Technology. It is based on preliminary work done in the project thesis of fall 2019. Therefore, parts of section 2, 3 and 4 is based on information from the project thesis. In section 2 most information regarding seaweed cultivation was retrieved from the project thesis, and to a larger or smaller extent re-written for this thesis. This also applies to the technology of cultivation in section 3, which has more re-work performed. The stakeholder analysis in section 4 is based on the work done in the project thesis. This was included to create a stand-alone thesis.

Writing a master thesis can be a daunting task. It has been challenging, confusing, but also interesting and enjoyable. To experience how humans around you are willing to give of their time to help you in your work is inspirational and motivational. Writing about the seaweed industry has been met with great interest and openness from many people involved in the research and commercial activity.
Thank you to Jorunn Skjermo for inviting me to the SIG Seaweed Conference 5, a truly enjoyable experience with great speakers. I would like to thank Diogo Raposo and Frank Neumann for inviting me to the office of Seaweed Energy Solutions. Thank you to Eivind Lona for giving me insights into Taredyrkingsfartøy2020, and thank you to all the rest of you whom I have talked to during this work.
A special thank you is also directed to my advisor, Bjørn Egil Asbjørnslett, for helpful advice and feedback underway.

Writing about an industry that promotes sustainability has been important for me. The ongoing climate crisis requires the attention of industry, governments and the general public. The crisis will not be solved by a single new solution, but by small and large changes in all aspects of humanity and technology. My hope is to shine light on an industry that gives a spark of hope, and to do my part to tackle this crisis.

July 7, 2020

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Nomenclature

Abbreviations

AJA Autonomous Job Analysis

AP Aft Perpendicular

AUV Autonomous Underwater Vehicle

CA Collision Avoidance

CAPEX Capital Expenditure

COG Center of Gravity

CWL Construction Waterline

DIN Dissolved Inorganic Nitrogen

DOM Dissolved Organic Matter

dwt Deadweight

FP Fore Perpendicular

GHG Greenhouse Gas

GL Growth Line

IMO International Maritime Organization

IMTA Integrated Multi-Trophic Aquaculture

LCA Life-Cycle Analysis

LCG Longitudinal Center of Gravity

Lenght WL Length on Waterline

Length BP Length Between Perpendiculars

Length OA Length Overall

LOA Level of Autonomy

LSW Light Ship Weight

MUNIN Maritime Unmanned Navigation through Intelligence in Networks

O.BL. Over Bottom Line

OPEX Operational Expenditure

PBD Point-Based Design

REMUS Remote Environmental Monitoring UnitS

RFR Required Freight Rate

ROV Remotely Operated Vehicle

RP Route Planning

SA Situation Awareness

SBD Set-Based Design

SBSD System Based Ship Design

SES Seaweed Energy Solutions

SP Solution Path

SPOKe Standardised Production of Kelp

TCG Transverse Center of Gravity

VCG Vertical Center of Gravity

VOYEX Voyage Expenditure

WHOI Woods Hole Oceanographic Institute

WW Wet Weight

Symbols

Δ Weight Displacement

η_T Total Power Efficiency

∇ Volume Displacement

ν Kinematic Viscosity

ϕ Prismatic Coefficient

ρ_{sk} Storage Density of Kelp

ρ_{sw} Density of Seawater

A_c Coefficient of Admiralty

A_D	Deck Area	P_C	Power Consumption
$A_{storage}$	Storage Area for Kelp	P_E	Towing Power
B_D	Deck Breadth	P_S	Power Storage
B_m	Beam Molded	P_T	Total Power
BM	Initial metacenter radius	PV	Present Value
C_A	Incremental Resistance Coefficient	r	Interest rate
C_b	Block Coefficient	R_N	Reynolds Number
C_F	Frictional Resistance Coefficient	R_T	Total Resistance
C_R	Residual Resistance Coefficient	S	Wetted Surface Area
C_T	Total Resistance Coefficient	T	Draft
D	Sailing Distance	t	Time Period
D_m	Depth Molded	T_c	Charging Time
dwt	Deadweight	T_m	Maneuvering Time
F_N	Froude Number	T_o	Operation Time
FV	Future Value	T_s	Sailing Time
GM	Metacentric Height	T_u	Unloading Time
I	Second Moment of Inertia	V_h	Harvest Speed
KB	Distance from keel to flotation center of hull	V_s	Sailing Speed
KG	Vertical Center of Gravity	W_E	Equipment Weight
L_D	Deck Length	W_H	Hull Weight
L_v	Payloadoad Capacity	W_k	Kelp Weight
L_{bp}	Length Between Perpendiculars	W_M	Machinery Weight
L_{oa}	Length Overall	W_{ls}	Lightship Weight
L_{wl}	Length on Waterline	$W_{M,b}$	Battery Weight in Machinery
P_B	Engine Power	y_k	Rope Yield of Kelp

1 Introduction

The world's largest aquaculture industry is the cultivation and harvesting of seaweed. The production of seaweed has grown rapidly, from 13,5 million tons in 1995, to 30 million tons in 2016 (FAO 2018). 91,3% of this production comes from China, Indonesia and the Philippines alone. The interest in seaweed cultivation has increased in European countries during the last 15 years. In Norway there has been large increase in research activity since 2008 (Skjermo et al. 2014). This research has resulted in more knowledge about seaweed in terms of nutrient contents, growth conditions, possible cultivation methods and applications.
The increase in research activity has been met by a larger activity of commercial companies. Even though the interest has been increasing, the production is still low. In 2017, the harvested biomass was approximately 150 000 tons (Fiskeridirektoratet 2019), while cultivation only produced 149 tons.

The world food production is estimated to increase by 70% within 2050, and energy consumption increase of 50% (Olafsen et al. 2012). With a limited capacity for land-based agriculture, it is expected that a large portion of the increase in food production will come from the oceans. Energy production will have to become more sustainable and renewable in the future, and the production of biofuel is thus expected to increase. This will require a large production of biomass for biofuel production.

There are many options both for food and energy production, and seaweed is one of these options. Although the production in Norway is still low, Olafsen et al. (2012) predicts that the production could reach a level of 4 and 20 million tons in 2030 and 2050, respectively. This implies that there will be a tremendous growth of the industry, if the predictions are correct. To facilitate for this growth, more knowledge has to be gained, and technological developments have to be undertaken, to increase productivity and efficiency, and reduce cost of production.

1.1 Contribution

This thesis aims to provide fundamental knowledge about the seaweed cultivation industry, and how a vessel can be designed for this industry. The thesis will study autonomous technology, and discuss it in the setting of seaweed cultivation. This will highlight the possibility of decreasing the operations dependency on human interactions.
A vessel design will be proposed based on the requirements and limitations set forth by the biology and technology of seaweed cultivation. This thesis further aims to analyze the vessel design to determine the feasibility of having a vessel solely operating in seaweed cultivation.

1.2 Outline

The thesis is structured as follows:

- Section 2 will review literature regarding seaweed biology and autonomous technology, and discuss autonomous technology in terms of seaweed cultivation.
- In section 3 the operations and technology used in seaweed cultivation will be studied. Current developments of seaweed farms and vessels are included, as well as autonomous vessel developments. The section will also study different design methodologies, to determine what methodologies are suitable for design of a seaweed farm autonomous vessel.
- Section 4 defines the problems faced in the industry, which relates to vessel operations. Key stakeholders are identified, and a need-function-form mapping is conducted along with an autonomous job analysis. A design catalogue is presented, from which many solution paths are identified. These are discussed

and analyzed at a high-level and a solution path is proposed for further development into a vessel design.

- The vessel is designed in section 5, which starts with analyzing the required payload capacity of the vessel. When the payload capacity is determined, main dimensions are established, and vessel equipment is determined. The main dimensions are compared to reference vessels, and a hull model and general arrangement follows. An evaluation of the vessel in terms of stability, resistance, harvest speed and cost is then performed.
- Section 6 discusses the vessel based on the aspects in focus in this thesis.
- Section 7 gives a conclusion to the work done in the thesis, with recommendations to further work on the topic.

2 Background for Seaweed Cultivation and Autonomous Technology

What species of seaweed exist? How do these differ in terms of nutrients, growth conditions and growth patterns? How will the growth pattern of seaweed affect the operational profile of a vessel? What end-products can seaweed be used for, and what requirements does the application of seaweed set to the quality of the biomass delivered? How does all of this relate to cultivation in Norway? These are some of the questions this section aims to answer.
A study of what market a vessel can be expected to operate in will be conducted. To discuss the potential market, it is necessary to understand the interest in seaweed cultivation, how seaweed farms may affect their local environment, and what advantages and disadvantages exist with cultivation.

This section will also study what systems are necessary for autonomous operation, and which systems become obsolete. Strengths and weaknesses with autonomy applied in seaweed cultivation will be discussed at the end of this section.

Parts of the information retrieved regarding seaweed cultivation comes from interviews conducted by the author in January and February of 2020. The questionnaire used is found in appendix A. Additional information that was not directly related to the questions in the questionnaire came from discussions during the interviews and is therefore not represented in the questionnaire. To refer to the interviews when information is retrieved from these, the reference (Myhre 2020) has been made, which only refers to the questionnaire.

2.1 Seaweed Biology

2.1.1 Species and Contents

Globally there are over 12000 species of seaweed, and in Norway there are about 475 species, where 175 are brown species, 100 are green and 200 are red species (Skjermo et al. 2014).

Red seaweeds are red in color, can grow at greater depths than green and brown species, and contains chlorophyll a and d, β-carotene and phycocyanin (Lakna 2019). Dulse (Palmaria Palmata) and Nori (Porphyra) are two red species that show a good potential for cultivation in Norway. Pictures of these can be seen in figure 1.

Figure 1: Pictures of Dulse (left)(tangandware 2014) and Nori (right)(Wikipedia 2018)

The brown seaweeds, commonly referred to as kelps, are among the largest aquatic plants and of the fastest-growing plants in the world (Skjermo 2014). These contain chlorophyll a and c, fucoxanthin, xanthophyll and β-carotene (Lakna 2019). Common species in Norway are Sugar Kelp (Saccharina Latissima), Winged Kelp (Alaria Esculenta), Oarweed (Laminaria Digitata), Tangle (Laminara Hyperborea) and the Norwegian Kelp (Ascophyllum Nodosum). Tangle and the Norwegian Kelp are the most common kelps that grow in wild kelp forests along the Norwegian coast. In figure 2, pictures of Sugar Kelp, Winged Kelp, Tangle and the Norwegian Kelp can be seen. The kelps show an especially great potential for cultivation, as these are among the world's fastest growing plants, and has a very high carbohydrate content (Skjermo et al. 2014). Sugar kelp has a carbohydrate content varying from 40-70%, mineral content between 15-45% and protein levels of 3-20%, depending on the time of year.

(a) Sugar Kelp

(b) Winged Kelp

(c) Tangle

(d) Norwegian Kelp

Figure 2: Picture of four common kelps in Norway; Sugar Kelp (a)(Gemini 2020), Winged Kelp (b)(Booher 2020), Tangle (c)(García 1988) and Norwegian Kelp (d)(vhv 2020)

Green seaweeds are green in color, can grow in freshwater as well as seawater, and contain chlorophyll a and b, and xanthophyll (Lakna 2019). One common species of green seaweed in Norway is Sea Lettuce (Ulva Lactuca), which can be seen in figure 3. The mineral content (or ash content) of Sea Lettuce is very high, up to 55% (Holdt and Kraan 2011).

Figure 3: Picture of Sea Lettuce (Proudfoot and Fretweel 2015)

2.1.2 Growth Conditions and Seasonal Variations

The major factors that affect the growth rate of seaweed is access to sunlight, nutrition levels in seawater, water temperature and plant size (Broch, M. O. Alver, et al. 2019). Water temperatures between 10-15°C are best for growth (Bolton and Lüning 1982), which means that areas from Northern Portugal to Northern Norway are suitable.

The growth-period for seaweed generally starts in February and continues until June/July, with peak growth rate in April and May (Broch and Slagstad 2012). During the winter months, November - February, seaweed show little to no growth at all, as irradiance, nutrient levels and water temperatures are low.

In the spring and summer, algal blooms lead to less nutrients in the water, which reduces the growth of seaweed. Epiphytes are organisms that grow on other plants, and these will typically cover seaweed that grows on the water surface during the summer, which leads to low, and even negative, growth (Matsson, Christie, and Fieler 2019). Seaweeds have a continuous frond loss which typically becomes severe during the summer, resulting in loss of biomass and death of plants. This forces farm owners to start harvest close to the peak growth-rate in April and May (Forbord, Skjermo, et al. 2012).

Seaweed shows large variations in nutrient levels during the year. With peak carbon-content in June and July, and a peak nitrogen-content in January (Broch and Slagstad 2012), this shows potential of year-round production of seaweed, where harvest in June and July could be for production of biofuel, whereas harvest in January could be for other applications, such as protein extraction. Sharma et al. (2018) observed significant variations as well, where deployment at 3m depth in February and harvest in June showed highest sugar content, while deployment at 8m depth and harvest in August showed highest proportion of amino acids, minerals and phenolic compounds.

The peak growth rate of seaweed will also depend on the latitude of deployment. For September deployment, the specific growth rate varied over 6 weeks from early February to end of March, and the peak absolute growth rate varied from beginning of May to beginning of July, with increasing latitude (Broch, M. O. Alver, et al. 2019). This is illustrated in figure 4. This was also studied and verified by Matsson, Christie, and Fieler (2019).

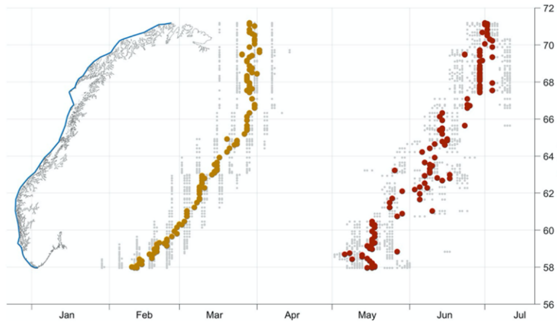

Figure 4: Peak growth rate for sugar kelp depending deployed in September as a function of latitude. The average time of the highest daily specific growth rate is indicated with yellow dots. Red dots indicate average time of daily absolute growth rate. Gray dots indicate data used to calculate average (Broch, M. O. Alver, et al. 2019).

2.1.3 The Norwegian Conditions

Norway has a large economic zone of approximately 90 000km^2 (Olafsen et al. 2012), where water temperatures typically lie between 6-10°C (HFI 2019) in the top layer. The Gulf Stream brings with its nutrients that allow seaweeds to have good growth conditions (Matdepartementet 2016). Broch, M. O. Alver, et al. (2019) modelled the cultivation potential of sugar kelp and showed yields of up to 150-200tons per hectare. The report showed that the growth potential was higher offshore than near-shore. This can be seen in figure 5.

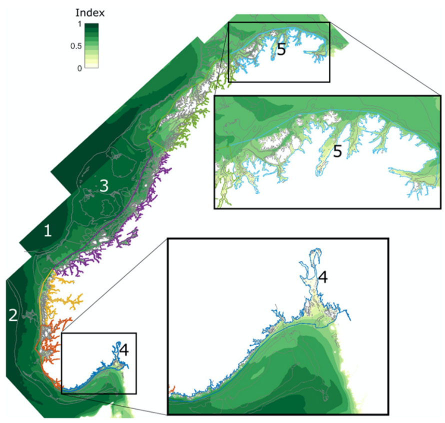

Figure 5: Spatial index for the cultivation potential of Sugar Kelp in Norway (Broch, M. O. Alver, et al. 2019). An index of 1 represents the maximum cultivation potential (up to 250 tons per hectare), and 0 the lowest (as low as 10 tons per hectare). The colors refer to different ecoregions in Norway, Skagerrak in dark blue, south North Sea in orange, north North Sea in yellow, south Norwegian Sea in purple, north Norwegian Sea in green and the Barents Sea in light blue.

The report also concluded that areas off the coast of Møre og Romsdal had better conditions, which was also studied in another report by Broch, Skjermo, and Handå (2016). For comparison, cultivation of wheat yields 3-5 tons per hectare (Skjermo 2016).From Broch, M. O. Alver, et al. (2019) it was indicated that the cultivation potential in fjords are low, likely due to low salinity and an earlier phytoplankton bloom, which results in earlier nutrient depletion in the areas. This was also shown in studies by Matsson, Christie, and Fieler (2019).

2.1.4 End-Product Applications of Seaweed

Seaweed can be utilized in many different ways, and has potential as products ranging from biofuel, food, feed and fertilizers, to cosmetics, biodegradable plastics and extracts (Skjermo et al. 2014). Different products will require different volumes and qualities of the biomass. In figure 6, some different applications of seaweed are shown within their volume-range.

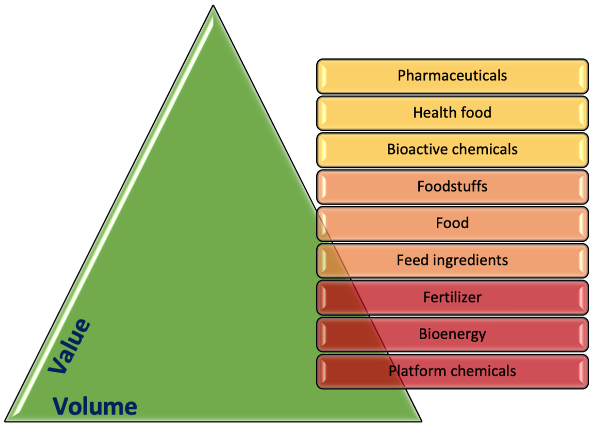

Figure 6: Representation of different applications for seaweed based on the required volume of biomass in production. Red boxes indicate high-volume market, orange boxes indicate medium-volume market, and yellow boxes indicate low-volume market. The value increases from the bottom to the top. Figure is based on Broch, Skjermo, and Handå (2016).

The application will depend on the content-level of the specific seaweed, which then is likely to affect the time of harvest.

High Volume Products
Products that require high volumes will typically be suitable for industrial applications but requires a low price.

- Alginate Production
  Tangle and the Norwegian Kelp is commonly used for production of Alginate, which is a derivative of seaweeds. Alginate has a vast area of application, and over 600 products exist (DuPont 2020). The main areas of application are in medicine, food and industrial applications. Tangle uses up to 4-5 years to grow back to a fully-grown size and is therefore not a candidate for cultivation as of 2020.
- Biofuel
  Biofuel are fuels that are produced from biomasses. Biofuels are categorized as first, second or third

generation fuels, depending on the origin of the biomass (Miljødirektoratet 2020). First generation biofuels are produced from biomasses that could be used for the production of food or feed, typically corn or wheat. Second generation biofuels are produced from waste from industry, agriculture or woods. Third generation biofuels do not require any land or fertilizer to be produced. Macroalgae is considered a source of a third-generation biofuel. In general, biomasses that have a high carbohydrate-content are good for production of biofuel. As the Sugar Kelp has among the highest carbohydrate-content of the kelp species (Holdt and Kraan 2011), and as one of the fastest growing plants on the planet, it has increased interest for applications for biofuel production.
For Sugar Kelp to become a competitive alternative, the cost-level has to be similar to that of production of other biomasses for biofuel production, or the greenhouse gas (GHG) emissions should be considerably lower over its lifecycle. Being a fast-growing plant at the lowest trophic level, it may become competitive in terms of GHG emissions. The cost of producing kelp today is however significantly higher than other biomasses, and a cost-reduction is thus necessary for kelp to become a biomass for biofuel production (Bekkevoll et al. 2019).

- Fertilizer
  The high ash-content that has been shown in kelp could potentially be used as a fertilizer (Skjermo et al. 2014), which was also discussed by Ahuja (2019), whom suggested that a mix of kelp ash and fish bone would make a complete fertilizer. This could become an attractive resource, as it could potentially reduce the negative effects of runoff from agriculture.

Medium Volume Products

- Food
  For products of food, the texture and taste are the most important factors, and quality preservation becomes more important. Sugar Kelp, Winged Kelp, Nori and Dulse are typical species used for food. Nori is commonly known as the wrap around Sushi, while Dulse is used for snacks. Sugar Kelp and Winged Kelp are typically used as spices. One problem related to seaweed as food is the relatively high iodine-content (Holdt and Kraan 2011), which can be significantly higher than the recommended daily intake (Helsedirektoratet 2018).
- Feed Resource
  Fish feed has a high protein-content, up to 30-50% (Skjermo et al. 2014). Thus, if fish feed is to be produced from seaweed, it is necessary to have species with a high protein-content. Although the carbohydrate-content is generally very high, it has been shown that some species of red and green algae have high protein-content (Holdt and Kraan 2011), up to 30-40% has been shown in Dulse and Nori. Year-round harvest could be suitable due to the seasonal variations in nutrient-content of seaweed.
  Including seaweed in the feed of animals have also shown great benefits. For dairy cows, the methane emissions were reduced by over 50% for an inclusion of 1% Asparagopsis Armata in the feed (Roque et al. 2019). Such studies have however not been conducted for the common Norwegian species.
- Biodegradable Plastics
  B'ZEOS is a company that produces plastic products from seaweed (Maurice 2019). The focus of the company is single-use products such as plastic straws, by developing zero-waste, edible, organic and sugar-free straws based on seaweed. Plastic production from seaweed can be beneficial as it is biodegradable, but as the cost of plastic production is very low, this may be a difficult market to develop.

Low Volume Products

- Health food
  Due to the high content of dietary fibers, seaweed is recognized with the popular term ”superfood”. Using seaweed as a supplement could therefore become popular, and several companies in Europe and Norway has shown interest in this (Broch, Skjermo, and Handå 2016).
- Bioactive compounds
  Seaweed contains bioactive compounds that are used in cosmetics, food supplement and in pharmaceuticals (Broch, Skjermo, and Handå 2016). These are extracted from seaweed and represents high-value products of production.

2.1.5 Genetic Aspect

In terms of genetic developments there is little to nothing to show for as of yet. At the SIG Seaweed 5 Conference it was discussed how genetic modifications or selective breeding could improve the yields of different species of kelp (Brunborg 2019). For comparison one can think of the development of corn over the last 10 000 years, as illustrated in figure 7. If a similar development through selective breeding or genetic modification can be achieved for seaweed, this can lead to significant growth, yield and content improvements.
However, it is important to keep in mind that it took 10 000 years for corn, so this is most likely not a short-term goal. It was also discussed what the potential consequences could be of deploying species with genetic modifications, as they could potentially spread to the natural kelp forests along the coastline, and in that way disrupt the natural flora. As there are no experiments on a large scale as of today, this remains an unanswered question. The Norwegian authorities have a very strict policy regarding genetically modified organisms (omsorgsdepartementet 2018), and this may prevent such developments. The yield is expected to increase over the following years, by optimization of hatchery processes, rope seeding and farm layout, but not due to selective breeding. This will include increasing the density of rope per square meter, but also the kelp density per meter rope.

Figure 7: Illustration of the development of corn over the last 10 000 years.

2.1.6 Integrated Multi-Trophic Aquaculture

As seaweed takes nutrition from its surrounding waters, there has been many discussions and research regarding seaweed grown near fish farms, in what is known as Integrated Multi-Trophic Aquaculture (IMTA). Fish farms release a large amount of dissolved inorganic nitrogen (DIN) which becomes a problem in the local ecosystem (Fossberg et al. 2018). By growing seaweed in close proximity, the seaweed may take up this DIN and thus has a bioremediation potential. This has led to a large interest from fish farmers in the development of seaweed farms in IMTA with fish farms. Larger companies in fish farming have invested in the development of seaweed cultivation, such as through the Ocean Forest project, a cooperation between Lerøy Seafood and Bellona (Seafood 2017).
Fossberg et al. (2018) studied the effects of having a kelp farm in the vicinity of a 5000 ton fish farm. It showed that a 25-hectare kelp farm could take up 1,6 of 13,5 tons of DIN from the fish farm, and that a 220-ha kelp farm would be necessary for uptake of 13,5 tons. The study showed that the kelp farm had a yield increase of 60%. Another study suggested that there is a seasonal mismatch between the uptake of DIN in kelp compared to the effluent of DIN from fish farms, resulting in a low uptake of 0.34% of the total DIN (Broch, Ellingsen, et al. 2013). Due to the later peak growth rate with increasing latitude, the effects of IMTA could potentially be better in Northern Norway.

2.1.7 Effects of Kelp Farms on Local Ecosystem

In regard to research studying the effects of large-scale farms on the ecosystem, a report was published by Hancke et al. (2018). The report discusses the positive and negative biological effects a farm can have on its local ecosystem, as well as area conflicts with other institutions.

Negative Consequences of Seaweed Cultivation

- Light-conditions
  One of the largest effects a large facility can have on the area where it is placed, is related to light-conditions below the farm. A seaweed farm will block sunlight from reaching further down in the water and may thus affect growth of other species on the seabed. The primary production of zooplankton, larvae and other organisms may thus be affected. Organisms that need sunlight to grow can grow down to 50m under the surface, so placing farms in deeper waters may be a solution.
- Nutrition Levels in Water
  Seaweed farms may affect the natural exchanging of water in an area. This can reduce the nutrition-levels in the waters, which may reduce the marine activity of a region. Seaweed will also have an uptake of nutrition's from the water, which will give a similar effect. If both effects take place, this may affect the growth of natural seaweed-forests in the area.
- Dissolved Organic Matter
  Seaweed will lose some of its biomass as dissolved organic matter (DOM), which can affect the local ecosystem around the farm. This may be through spreading of diseases and foreign species that outcompete the local species. In cases of extreme losses of organic matter, anaerobic degradation may take place, which will produce toxic sulphide gasses (Hancke et al. 2018).

Positive Effects of Seaweed Cultivation

- Nutrition Levels in Water
  As seaweed will have an uptake of nutrition's from the water, this can lead to seaweed farms acting as natural filters in its ecosystem. This can be to take up runoff from land-based agriculture, or DIN from fish farms. This would reduce the emissions in an area and lower the risk of eutrophication.

- Dissolved Organic Matter
  The DOM of seaweed farms may act as a nutritional basis for other species in the region. This can potentially lead to better conditions for marine activity.
- Uptake of CO_2
  Seaweed has a large uptake of CO_2 from waters, which may contribute in a positive way on climate. The uptake of CO_2 was estimated to be between 7-34 tons per hectare in Møre og Romsdal, depending on the location of the farm (Broch, Skjermo, and Handå 2016). CO_2 is in equilibrium between the oceans and air, and by taking out CO_2 from the sea, this will result in a larger uptake of CO_2 from the air to the sea (Hancke et al. 2018).
- Artificial Reef
  Seaweed farms may also act as artificial reefs where smaller organisms such as invertebrates can seek shelter and use the farm as feeding grounds. This could potentially lead to increased marine production in an area.

Common for all of the potential positive and negative effects of a large-scale farm, is that the effects are currently poorly documented. These effects will have to be studied more closely with the development of the industry.

2.2 Other Aspects of Kelp Cultivation

2.2.1 Life-Cycle Analysis

A life-cycle analysis (LCA) of seaweed production from hatchery to end-product showed that with the current production methods, the global warming potential (GWP) is significantly higher when producing one ton of pure protein, compared to soy bean production (Koesling 2019) (Halfdanarson et al. 2019). In the base scenario, the GWP of protein production from seaweed was 4 times higher than for soy-production. If the energy-source for drying was switched to electric energy from hydropower, the GWP potential was reduced to almost the same as for soy protein production. By harvesting the seaweed in August instead of June, the GWP potential would be further reduced, as the nitrogen-content in the seaweed increased.

2.2.2 Governmental Aspects

In 2016 the Norwegian Government released their bio economy strategy (Matdepartementet 2016). In the report, the government recognizes the potential for cultivation and harvesting of kelp, especially as a source for biofuel production, fish feed and for IMTA.
The focus of the authorities for this industry will be to develop regulations and management of areas for the industry, as well as making it easier for industry and researchers to extract biomass from natural habitats. The policymakers also wish to facilitate for IMTA.

2.2.3 Cultivation and Harvest Today

From 2015 to 2018, the production has increased from 51 tons to 178 (Fiskeridirektoratet 2019), while the sales-value increased from a total of 0,178 MNOK to 1,287 MNOK, meaning an average annual increase of approximately 50% and 90% respectively. The number of licenses for cultivation of algae has increased from 54 to 475 between 2014 and 2019, while the number of sites in 2019 was 97. Figure 8 shows the locations of the licenses registered in Fiskeridirektoratet.

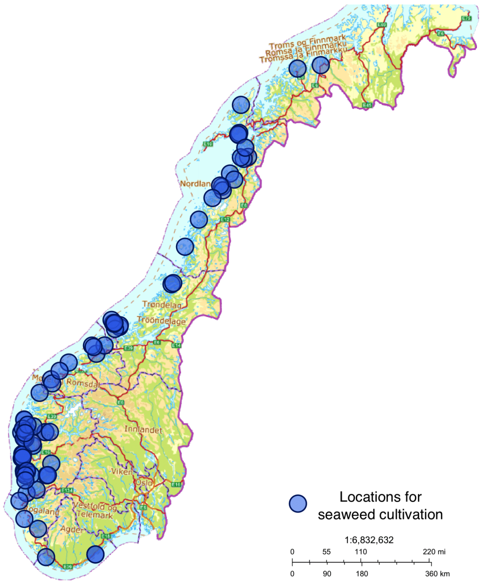

Figure 8: Blue dots indicate the location of cites where the production is macroalgae for consumption (Fiskeridirektoratet 2020).

By species, sugar kelp and winged kelp are the most common, with 92 and 82 licenses respectively. The most common products for cultivated kelp are consumption for food and as an additive or spice. As can be seen from figure 8, the distribution of cites is uneven, with a much higher density of locations in Southern Norway than in Northern Norway. The figure is however not representative for the size of production.

While cultivation of seaweed has shown significant growth over the last six years, harvesting of wild kelp populations has not increased. Harvest has been mechanized since the 1970's and has an annual harvest between 130 000 - 180 000 tons of Tangle and 13 000 - 18 000 tons of Norwegian Kelp (Fiskeridirektoratet 2015). DuPont Nutrition & Biosciences is reporting downtime on their factory due to a lack of raw material. The management for harvesting of wild kelp is strictly regulated by the Directorate of Fisheries and is not likely to see large growth in the short-term (Lona, Sunde, Berggren, et al. 2020).

The products that cultivated kelp are sold as represents a low- to medium- volume market (Skjermo et al. 2014). It is believed that in order for the industry to grow to a large-scale industry, products requiring high volumes will have to be commercialized. At the same time, such products will require a low price of biomass to ensure profitable production. The price-level is estimated to be as low as 2 NOK/kg for large-volume products (Olafsen et al. 2012).
The amount of research projects has increased significantly from 2008 (Skjermo et al. 2014). This suggests that the interest for developing the industry has increased, and improved knowledge over the last decade provides important knowledge to commercialize new products, improve hatchery technology and increase farm yields.

2.2.4 Operational Region for Cultivation and Harvest of Seaweed

With seasonal variations in the nutrient-levels in seaweed, the end-product is likely to affect the time of harvest for specific purposes. With the natural growth pattern of seaweed, the possibilities for a vessel to

operate either nation-wide or restricted to a particular region will strongly depend on the end-product and cultivation technology.
From Broch, Skjermo, and Handå (2016), deployment in September instead of February showed a potential for increasing the yield, when the harvest was in June. This indicates that deployment could be typical in September with a harvest in June. Many companies are however deploying in December or January and harvesting in April and May. As the peak growth rate and algal blooms arrive later with a higher latitude, the harvesting season will shift. The nutrient-levels of seaweed shift during season, which may lead to different harvest-patterns from farm to farm.
For biofuel, the high carbohydrate content is attractive, which typically has its peak around June and July. For fish feed, the nitrogen content is attractive, which has a higher level in August, and highest in January. For food, color, taste and texture are important factors, and these are severely reduced with biofouling during the spring and summer. Thus, harvest is typical for food applications in April and May. Year-round production was proven feasible in the Faroe Islands (Bak, Mols-Mortensen, and Gregersen 2018) but has not been successful in Norway.

The potential deployment season for seaweed could then be from September-February, while harvest could be from April-August. This indicates that a vessel has an opportunity to be active for most parts of a year, but this will require an increased product-portfolio of seaweed, and an efficient vessel that is able to follow the harvesting season northwards. Table 1 illustrates the potential season for operations for a vessel. If the industry may achieve these operational seasons, a vessel can potentially be in operation 11 of 12 months per year in the industry.

Table 1: Potential months of operations based on end-product and farm location.

Application	Food	Feed	Biofuel
Deployment	December - February	September - February	September - February
Harvest Southern Norway	April - May	May - June	May - June
Harvest Northern Norway	May - July	June - August	June - July
Optimal Harvest	May - July	January or August	June - July

With a higher cultivation potential offshore than in coastal waters, it is possible that seaweed cultivation will move offshore. The companies that are operating today and that are being established are however cultivating in sheltered waters. As showed in figure 8, the location of farms is not evenly distributed along the Norwegian coast either. The interest in cultivation is however high in all regions of the country.

2.2.5 Potential Market Developments

One important aspect of vessel design is to understand the market that it enters, as this will affect the vessel design itself, how it is utilized when it is deployed, and its eventual profitability. For the seaweed industry it is difficult to know how the market will be in 5 or 10 years. With today's situation, where there are 40 companies with permission to cultivate seaweed, where only 20 have begun to do so, and only at a pilot-farm or research-level, it is difficult to predict whether this will grow into a large-scale industry, or still remain in the low-scale as it is today.

It is likely that this development will strongly depend on what the end-product of cultivated seaweed will become. Many applications have been mentioned already, where some products will require a large volume of low-cost biomass, while others require small volumes, but will generate high values. This section will discuss the potential development of high-, medium-, or low-volume demand markets.

High Volume Demand

The world energy production is expected to increase by 50% by 2050 due to an increasing global population towards (Olafsen et al. 2012). This increase in energy production has to be met simultaneously as the production becomes renewable and more sustainable. Replacing fossil-fuels with biofuels will be part of that strategy. As different species of seaweed have high carbohydrate-contents, there is a large potential in processing into third generation biofuel. From 1 ton of Sugar Kelp, 70 liters of ethanol can be produced (Bekkevoll et al. 2019). The aviation industry consumed approximately 229 million liters of fuel in 2006 (Tajet 2006). This means that, assuming a cultivation potential of 170tons/ha, an area of approximately 238km^2 would be required to supply the aviation industry in Norway with biofuel. Seaweed would however be competing with other materials that are used for production of biofuel, such as food crops and forest waste.

Biokraft is a company that produces biofuel in Norway. The company has the largest facility for production of biofuel, located at Skogn in Trøndelag (Biokraft 2020). The facility is currently producing biofuel from fish waste but will within 2030 also include production from seaweed.

Seaweed has a potential uptake of 1500tons/km^2 CO_2 near-shore, and 3000tons/km^2 offshore (Skjermo et al. 2014) (Broch, Skjermo, and Handå 2016). Therefore, seaweed could be used as an artificial CO_2-storage, where the kelp can be cultivated, and then released to the seabed. For comparison, a cultivation area of approximately 450km^2 would neutralize emissions from aviation in Norway.

Production of Alginate has been stagnant the last years. This is mainly due to the strict management of harvest. This is therefore not expected to be an industry that will increase in scale in the coming years. Using seaweed as a fertilizer has also been discussed as an alternative (Ahuja 2019) due to its mineral contents, but further research will have to be conducted before such applications become a viable alternative.

For a high-volume demand of seaweed in the market to become a reality, it is thus expected that biofuel production would be the driving-force of such a market.

Medium Volume Demand

From Olafsen et al. (2012) it is emphasized that the world food production needs to increase by 70% by 2050. Land-based agriculture is already struggling to increase capacity due to a limited access to freshwater. Ocean-based food production only accounts for 2% of human energy consumption today and has a huge unexploited production capacity. This capacity can be exploited through increased production of seaweed as a food resource. As it doesn't require any freshwater, fertilizer or pesticides, it has an advantage as an alternative food source.
Orkla has also recognized seaweed as a product they wish to implement in their products (Brunborg 2019). If companies such as Orkla start to actively use seaweed as an ingredient in their products, this may push the seaweed industry into a much larger scale with higher volumes.

As the demand for food will increase in the future, it is expected that the demand for fish and other livestock will increase as well. It is estimated that in Norway alone, there will be a need for 4,8 million tons additional feed pellets in 2050 compared to 2010 for an increased production of fish (Olafsen et al. 2012). These pellets are mostly based on cheap soy-proteins which originates from Brazil.
The problems with these soy-proteins is related to the consequences of deforestation of the Amazon and a negative publicity due to this. Replacing these soy-proteins with a more sustainable source is of interest for fish farmers, and it is already seen that several companies have invested in the research of processing of seaweed to fish feed. Although it is expected that the largest increase in pellet production will be based on soy-protein, approximately 1,2 million tons of pellets is expected to be produced by alternative methods.

A large part of the increase in food-production towards 2050 is related to a higher standard of living in countries such as China and India, which will require a larger production of livestock. This leads to a large increase in demand for feed, which land-based agriculture will not be able to supply. Thus, a large increase in the world's food production requires a better utilization of the sea for food production. This may be a driving force for a large-scale seaweed industry, as it can be part of the solution to supply the livestock industry with feed, both land-based and ocean-based. Seaweed has also been shown to reduce the methane-emissions from cattle, which in itself could make it more attractive to implement in feed.

It was mentioned that kelp can be used as a biodegradable plastic. These products are unlikely to compete with fossil-based plastic products on price, but it is possible that the price could come below the levels of paper, which would make their products competitive. The European Union has decided to ban single-use plastics in EU by 2021 (Chatain 2019), which will create a larger interest in alternatives to fossil-based plastics.

Low Volume Demand

The low-volume products of seaweed typically require chemical treatment to extract the desired compounds. This is high-cost production that results in high-value products (Broch, Skjermo, and Handå 2016). Several companies in Europe are potential customers, and more are developing in Norway. Bio-refining of seaweed to produce both low-, medium- and high-volume products is desired by the industry to enable large-scale production. Low-volume products may play a significant role in this process, as a way to ensure profitability with low volumes.

Expected Market Demand

Applications within biofuel, food and feed show the greatest potential based on the global and national situations. If both food and feed markets increase the demand for seaweed, and biofuel production from seaweed is realized at a cost-efficient level, it is very likely that the market will increase significantly from the current level of production. For a better utilization of the whole plant, small volume products may motivate companies to more efficiently extract desired compounds from seaweed. This is however assumed to be a long-term goal for the industry.

2.2.6 Challenges

Although seaweed is expected to have a higher demand in the future, there are challenges that may prevent some developments.

- Iodine-content
  The iodine-content of kelp is relatively high compared to the recommended daily intake of iodine, which may restrict intake to 200g/week, or processing demands will be given by the Norwegian Food Safety Authority. Today kelp requires processing to reduce the iodine content before it can be sold to the market (Arlov 2019). Although there are several methods to efficiently reduce the iodine-content, this is not necessarily enough to accelerate the development of the industry for sales in food. In general, the interest for using kelp in food is low in the west, a trend that would need to be changed to allow for large growth. This may require extensive marketing of the products, or just require time for consumers to adapt. Thus, it is uncertain how this market will develop.
- Seaweed for feed production
  The protein-content of the seaweeds that are available for commercial cultivation is somewhat low, which results in a high demand for raw material for processing into pure protein. The challenge here is to reach levels of cost that are lower than those protein-sources used today, soy-based protein being the big competitor. With the current GWP of protein production from seaweed, it will not be desirable to

replace soy-based proteins either. The research on seaweed as a feed ingredient is also low, and more research on for instance the effects on animal health will be required before commercially available products may enter the market.

- Area Conflicts
  Although the Norwegian economic zone is vast, the areas are under competition from different sectors (Hancke et al. 2018). Fisheries, oil and gas, offshore wind farms, fish farms, marine traffic, nature conservation areas and a public interest in leisure areas to name a few competitors. As kelps have best growth-conditions in the top 10m of the sea, the demand for area will be high. It is estimated that an area of $1200km^2$ will be required for the production in 2050 (Olafsen et al. 2012). This may not be feasible nearshore, which may require production to move further offshore. This will require sturdier farms to be constructed, and seaworthy vessels, which is a significantly higher cost than for sheltered waters.

- IMTA
  The bioremediation potential of having kelp-facilities near salmon-farms have also been discussed. As the bioremediation potential is uncertain, it is difficult to predict this development. However, as the yield of kelps were significantly higher near a fish farm, this may lead to many IMTA projects for the benefit of seaweed farmers. As the peak growth-rate of kelp is later in the season in the North, the bioremediation potential may be substantially higher in Northern Norway than in the south. This effect was also studied by Fossberg et al. (2018). Their study concluded that the potential could be higher in Northern Norway, as biofouling of kelp did not start before August, thus the peak growth-rate of kelp and salmon was more corresponding, leading to a higher uptake of DIN in kelp from fish farms.

- Investment-will
  To develop kelp cultivation into a large-scale industry will be capital-intensive. The current situation is mostly based on research and development, and the available capital may be very restricted. Thus, development may require the interest of external individuals, groups or companies. Investing in an undeveloped industry will be a high-risk investment, and it may be difficult to receive the necessary funding.

2.3 Autonomous Vessel Technology

Over the course of history, the level of automation on vessels has increased radically. From 1850 till today, the required crew onboard has decreased from several hundred down to 16 for a large shipping vessel (Rødseth and Burmeister 2012), and today it is not unrealistic to think of unmanned vessels. Already developments have been seen within the aviation and automobile industry, but a clear breakthrough has not been made for the maritime industry. To implement such a system, it is important to understand what functions on a vessel that are performed by humans today, as these will be replaced by artificial intelligence, automated procedures, or removed completely.

2.3.1 Definition of Autonomy and Levels of Autonomy

Before studying the systems required for autonomy, it is important to understand what autonomy is. Many definitions of autonomy exist. The word itself comes from Greek and means self-governance (Dryden 2020). The definition relates to personal autonomy, but when speaking in technical terms, it refers to a systems ability to make own decisions without an operator controlling the actions (Albus et al. 1998). A system can then have different levels of autonomy (LOA) depending on how much interaction is required by an operator. Many different definitions of the LOAs also exist in literature (Marialena Vagia and Rødseth 2019)(Mallam et al. 2019)(Praetorius, Hult, and Sandberg 2020). Although the definitions are different, the main idea is similar. The lowest LOA is typically a fully manual control, whereas the highest LOA reflects a highly autonomous solution that requires no interaction from an operator (Utne 2017). Figure 9 shows an example of one definition of the different levels of autonomy, as given by Endsley (1999).

	Roles			
Level of automation	Monitoring	Generating	Selecting	Implementing
(1) Manual control (MC)	Human	Human	Human	Human
(2) Action support (AS)	Human/Computer	Human	Human	Human/Computer
(3) Batch processing (BP)	Human/Computer	Human	Human	Computer
(4) Shared control (SHC)	Human/Computer	Human/Computer	Human	Human/Computer
(5) Decision support (DS)	Human/Computer	Human/Computer	Human	Computer
(6) Blended decision making (BDM)	Human/Computer	Human/Computer	Human/Computer	Computer
(7) Rigid system (RS)	Human/Computer	Computer	Human	Computer
(8) Automated decision making (ADM)	Human/Computer	Human/Computer	Computer	Computer
(9) Supervisory control (SC)	Human/Computer	Computer	Computer	Computer
(10) Full automation (FA)	Computer	Computer	Computer	Computer

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Figure 9: Levels of Autonomy as defined by Endsley (1999).

As we can see from figure 9, the lower LOAs are based on humans participating in every role. With an increasing LOA, the computer will take over more of the roles the human has previously had, and at the highest LOA, it should not even be necessary for humans to monitor the operations.
With computers having an increasing responsibility in the roles of operation, new technology and systems have to be in place to replace the functions of the human. This will be discussed in the following.

2.3.2 Autonomous systems

When crew is removed, other systems have to be implemented to perform the necessary tasks on the vessel that were previously performed by crew. These operations include steering, outlook, maintenance, communication, and cargo handling. It is important to identify what operations an autonomous system can and will perform, and to what degree it will be done autonomously. Operations are of varying complexity, where simple operations such as voyage from start to end will allow for a high LOA, while complex operations such as rescue operations or evacuation will to a higher degree require the need for a crew to perform operations.

From the Maritime Unmanned Navigation through Intelligence in Networks (MUNIN) project it was identified some systems that would be necessary to implement for an autonomous system (Burmeister et al. 2014):

- Advanced Sensor Module
- An Autonomous Navigation System
- Autonomous Engine and Monitoring Control System
- Shore Control Center

These will be explained in more detail in the following. Figure 10 illustrates the different components.

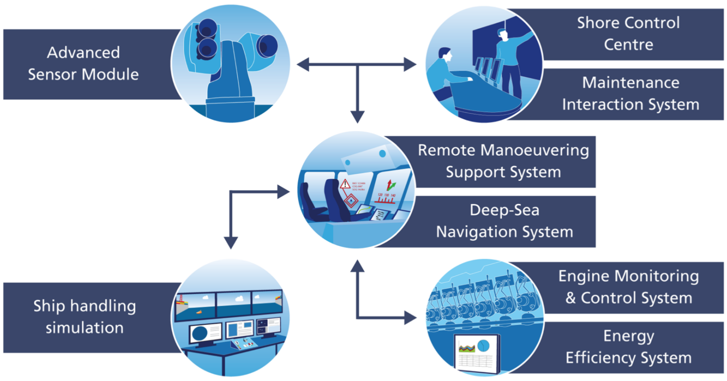


Figure 10: The components suggested for autonomous shipping in the MUNIN project (Burmeister et al. 2014).

Advanced Sensor Module
As the crew is removed from the vessel, visual and audio information is lost. This has to be retrieved in other ways that are understandable for a computer, and translatable to humans. As discussed by Jokioinen et al. (2016), many sensor types exist, from visual HD cameras, Infrared Technology and Radars, to LIDAR. Sensors are designed to optimality for their respective area of operation. Therefore, not one sensor is suitable for retrieving all necessary information at the required level of accuracy and reliability. Thus, combining several sensors to gain a complete, safe and reliable sensor module is required. This is referred to as sensor fusion. This combination will include radar technology for long- and short-range accuracy, visual HD cameras for retrieving more information and sound detection equipment. Other sources of information not internal to the ship, such as global positioning system, automatic identification system, automatic radar plotting aid and electronic chart display and information system data, may also be necessary. This will depend on the complexity of operation, and requirements from different authorities.

Autonomous Navigation System
The Autonomous Navigation System (ANS) consists of a Situation Awareness (SA) module, Collision Avoidance (CA) module, Route Planning (RP) module and a Ship State Definition (SSD) module (Jokioinen et al. 2016). An illustration of the system can be seen in figure 11.

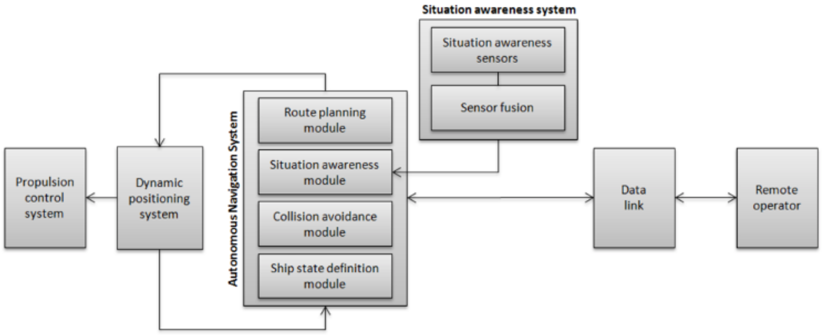


Figure 11: The Autonomous Navigation System presented by Jokioinen et al. (2016).

The SA module relies on sensors as previously discussed, and sensor fusion to deliver useful data for the module to analyze. It will detect static and dynamic obstacles, and the CA and RP modules will create a new route to avoid these obstacles. The SSD's objective is to define the state of the ship in terms of allowed operation mode for the situation and will determine whether a remote operator will have to take control, or if the vessel can do the operation itself. This system will also receive weather-data to determine a safe route based on the local weather.

Autonomous Engine and Monitoring Control System
The crew on ships performs periodic maintenance of the onboard systems, including machinery systems. When the crew is removed, this gives limitations to how much periodic maintenance can be performed during voyage, thus requiring a higher reliability of the systems onboard. This means that choosing machinery with high reliability and few mechanic components is favorable, and that redundancy may be required. It will also be beneficial to have advanced monitoring systems for predicting the state of the system, which can lead to preventive maintenance to be performed in dock to allow for continued operation of the vessel.

Shore Control Center
The number of autonomous vessels in the future is likely to be limited. This allows for establishing shore control centers where qualified operators may monitor and eventually remotely operate vessels if / when necessary (Jokioinen et al. 2016) (Burmeister et al. 2014). Such a center is believed to be a strong contribution towards autonomous vessels, as a control center can significantly increase the reliability of the system by allowing remote control of a vessel if the autonomous system should fail. A challenge posed by the remote controlling of a vessel is related to the reliability of data transferred from the vessel to the shore control center, which will depend on latency, bandwidth and the amount of data transferred. It will be important to prioritize crucial information, but it is clear that the remote-control operator will have limitations compared to an on-deck captain.

2.3.3 Autonomy in Seaweed Cultivation

- Lower Operational Costs
  The motivation for moving towards autonomous vessels is the reduction in costs due to removal of crew. In modern shipping, crew costs are as high as 45% of the operational costs (Kretschmann, Burmeister, and Jahn 2017), which signalizes that there is a great potential in cost-efficiency if crew can be efficiently reduced on board vessels.

- Higher Initial Investment
  The operations that are performed by humans will need to be replaced by computers. This includes functions such as steering, communication, lookout, various farm operations etc. This will require new technology to be developed and installed on a vessel, both for the systems required by an autonomous vessel, but also payload-related systems. Thus, although crew-related spaces will not be required, it is expected that the capital expenditure (CAPEX) of constructing the vessel will increase. It was also stated that an increase in the CAPEX investment up to 10% could be acceptable (Kretschmann, Burmeister, and Jahn 2017).

- Limited Knowledge and Experience
  For this industry, it was emphasized through interviews (Myhre 2020) that the industry is in such an early phase that having humans present at the farm is crucial to gain a deeper knowledge and understanding of how these systems work. The human intuition and creativity cannot be replaced by computers, and this is what will be required to have on site to find new solutions or methods, to detect possible problems and to solve unforeseen tasks. A fully autonomous solution may therefore not be desirable at this stage in the industry.

- High Complexity in Operations
  The operations that are performed will be different than deep-sea shipping. This is due to the coastal areas the vessel will be operating in, which have significant restrictions in navigational areas as well as the higher presence of other vessels. This will require a careful execution of the navigation, with constant object-detection and re-routing decisions to be made.
  The operations to be performed at the farm are also of high complexity, and still not fully optimized or standardized. It may be possible to implement methods to automate these procedures now, but it may be difficult to design with flexibility, in case the methods of operation change over time.

Although there are many challenges associated with autonomous operation, the potential may be high for cost reductions and increased safety of operation. Marine autonomy has mainly been focused around shipping, but lately it has gained increased interest for fish farmers, through projects such as ARTIFEX (Caharija 2016). This project aims to allow operations such as inspection, maintenance and repair to happen from shore control centers. The concept proposes a system of vessels, unmanned surface vessels, Remotely Operated Vehicles (ROV), and remote piloted aircraft systems.

A similar concept can be visualized for the seaweed industry, where the proposed vessel design is one of many vessels that may participate in operations. As these systems do not currently exist, it will require significant developments within technology, protocols and operation schedules to execute. While this may demand a high initial cost, it may be what is necessary to achieve a low-cost production that is required for a large-scale seaweed industry. If such a system is developed for fish farmers as well as seaweed farmers, it may be possible to cooperate for both industries, in terms of shore control centers, and using the same vessels for different operations. This will significantly lower the risk of investment and make it a more attractive opportunity.

2.4 Section Summary

In this section, we have gained a deeper knowledge of the biology of seaweed. There are a few species that are in focus for cultivation, namely Sugar Kelp, Winged Kelp, Dulse and Nori especially. Sea Lettuce is also a candidate for cultivation, while Tangle and the Norwegian Kelp are mainly harvested from wild populations. Seaweed is attractive for cultivation because freshwater, fertilizers and pesticides are not required. The kelps are especially interesting since they are among the fastest growing plants in the world. Simulations also indicated a high cultivation potential in Norway, due to good water temperatures, nutrient-rich waters and high irradiance during the spring and summer.
Seaweed has many possible applications, ranging from high-volume products such as biofuels and platform chemicals, to medium-volume products such as human consumption and feed for animals, to low-volume products such as pharmaceutical applications and health food. It is believed that biofuel production together with human consumption and fish feed will drive production into large-scale. This will require a low-cost and sustainable biomass, which is challenging for cultivation today.

The growth-pattern of seaweed varies throughout the year, with most of the growth happening from February till May / June. The peak-growth rate also shifted till later in the season with increasing latitude. The content-levels of different species vary, which make some species more interesting for different applications. Sugar Kelp has a high carbohydrate-content, and is a candidate for biofuel production. It has also been studied for applications in fish feed, and is a candidate there as well, although the nitrogen-content is quite low. The content-levels vary throughout the year. For Sugar Kelp, the carbohydrate-content is at its highest during the summer, while the nitrogen-content increases from June to August and is at its highest in January. This may motivate multiple-partial harvesting throughout the year.

Although the industry is still of low scale, there is significant interest from commercial companies as well as policymakers into the development of the industry. Several challenges exist, but these are expected to be solved, or not hinder development significantly.

A study into autonomous system technology was conducted. This revealed that autonomy is defined through different LOAs, where the lowest levels are manual operations, and the highest levels are without human interaction. Definitions vary from different authors, but the general concept was similar. For autonomous vessels to become a reality, onboard systems must be developed to replace the functions of humans. This includes advanced sensor modules, shore control centers, remote maneuvering, engine monitoring and control systems, and autonomous navigation systems. Such systems are expected to increase the initial investments of a vessel, and this increase should not be higher than 10%.

Autonomy in seaweed cultivation could be beneficial as an efficient way to reduce the operational costs. Due to the limited knowledge in the industry, farm owners do see the necessity of having crew on site during operations, which will make the highest LOAs undesirable. The complexity of operations at a seaweed farm would also make this challenging. But a higher LOA would reduce the amount of manual labor, which is wanted, as costs in seaweed cultivation are high.

In the next section, technology being applied in seaweed cultivation and advancements in autonomous vessels will be studied.

3 Literature Review

The previous section gave fundamental knowledge about seaweed in terms of biology, cultivation potential, end-product applications and the current scale of the industry. Marine autonomous systems were studied and gave insight into what systems are required. This section will focus on the operations and technology used in seaweed cultivation and look into advancements in autonomous vessels. The section will end by studying different design methodologies, to determine what suitable methodologies exist for application to a seaweed farm vessel.

3.1 Seaweed Cultivation Operations and Technology

The main prerequisite for technological developments is that the technology is designed on the premise of the biology of seaweed. There will be a required amount of time for hatcheries to produce seedlings. These seedlings will need a certain amount of time in water to grow to the desired size, quality and content-levels. The composition of seaweed will vary during the year, and harvest will have to take place when the composition is desirable, a process that will be difficult to control.

Technology can only improve the efficiency by a small portion, compared to the total required time for the seaweed to grow. This forces the industry to be very seasonal, with deployment typically from November-February, and harvest from April-June, with variations based on the farm location, and the end-product. In total, the required operation time of deployment and harvest will likely be less than one month per year per site for each operation. This results in demanding cost-targets for a vessel, or require flexibility to allow the vessel to be used at other farms, or other industries. To understand what is required for a good vessel design, it will be important to understand the value-chain of seaweed. This section will focus on the farm operations and applied technology in seaweed cultivation. This will help in the understanding of the interactions between a vessel, farm and seaweed.

3.1.1 Rig Installation and Farm Layouts

Seaweed cultivation will require a farm to be constructed, where seaweed can be deployed. These are artificial, man-made structures that have to be installed at a specific, desired location. These rigs may vary in size, form and layout, but in general will require the same types of material.

The typical required material consists of mooring, rig and buoys. For mooring, typically anchors or bolts are deployed at the seabed (typical depth between 20-50 meters), with 4 1.0-1.5-ton steel anchors, for rig sizes of 1ha (Bak, Mols-Mortensen, and Gregersen 2018). The rig itself can be a polysteel line, which is held in place by the mooring system. Ropes with seaweed cultures can then be attached to this fix rig and be left to allow growth of seaweed during the season. Buoys are present at the rig to make it visual to vessels on the surface, as the rig itself will be installed below the water surface. The installation is built in such a way that growth lines (GLs) may easily be replaced, while the rig itself is kept stationary. The expected lifetime of a rig is approximately 5 years (Bak, Mols-Mortensen, and Gregersen 2018).

As there is not sufficient knowledge on what the optimal layout of a farm is (Skjermo 2016), many companies have different farm layouts they are experimenting with. Seaweed Energy Solutions (SES) is a Trondheim-based company with one of the largest farms in Europe, located at Frøya (SES 2019). They patented a seaweed carrier, which is a 3D structure they believed would enable large-scale seaweed cultivation. A picture of the concept can be seen in figure 12. After testing the structure, the company concluded that it was too complicated to harvest from the structure and are now deploying GLs in a systematic horizontal layout with a large potential for automation.

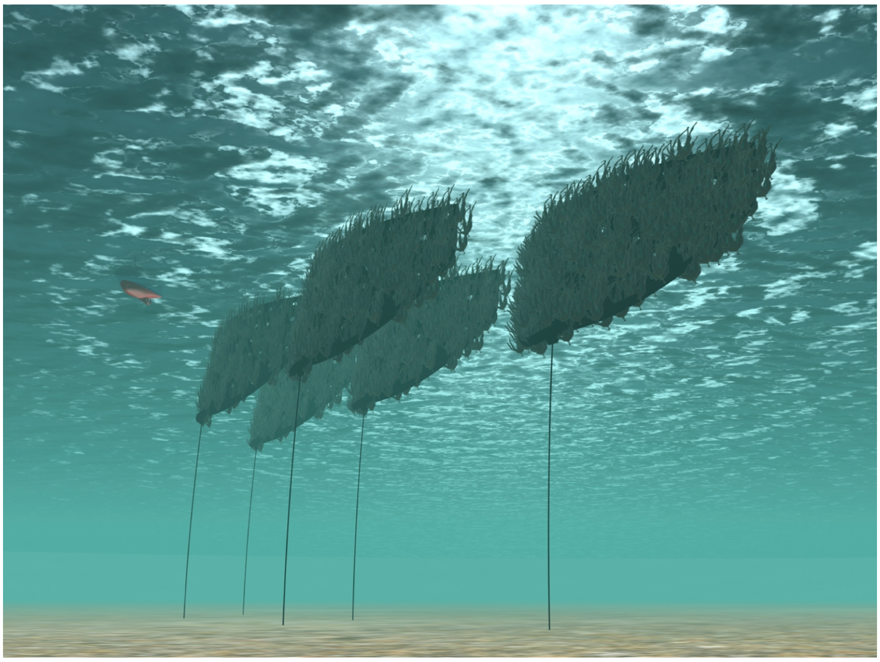


Figure 12: 3-Dimensional Farm layout concept of SES (SES 2019)

Another layout was presented by Bak, Mols-Mortensen, and Gregersen (2018), called a MACR - Macroalgal Cultivation Rig. A representation can be seen in figure 13. The advantage of their concept is that no specialized equipment is necessary for production, resulting in a low-cost farm construction.

SINTEF Ocean currently has research projects ongoing to provide more knowledge about an industry based on seaweed (SINTEF 2019). MACROSEA is a knowledge platform with 6 working packages (WP), where WP5 studied state of the art technology for seeding, deployment and harvesting of seaweed. The work included a survey that was sent out to companies in the seaweed industry, to identify what the companies were specialized for, and what development needs they saw as necessary moving onwards (M. Alver, Solvang, and Dybvik 2018). From the results of this report, a conceptual design for Standardised Production of Kelp (SPOKe) was designed (Bale 2017). A picture of the concept can be seen in figure 14.

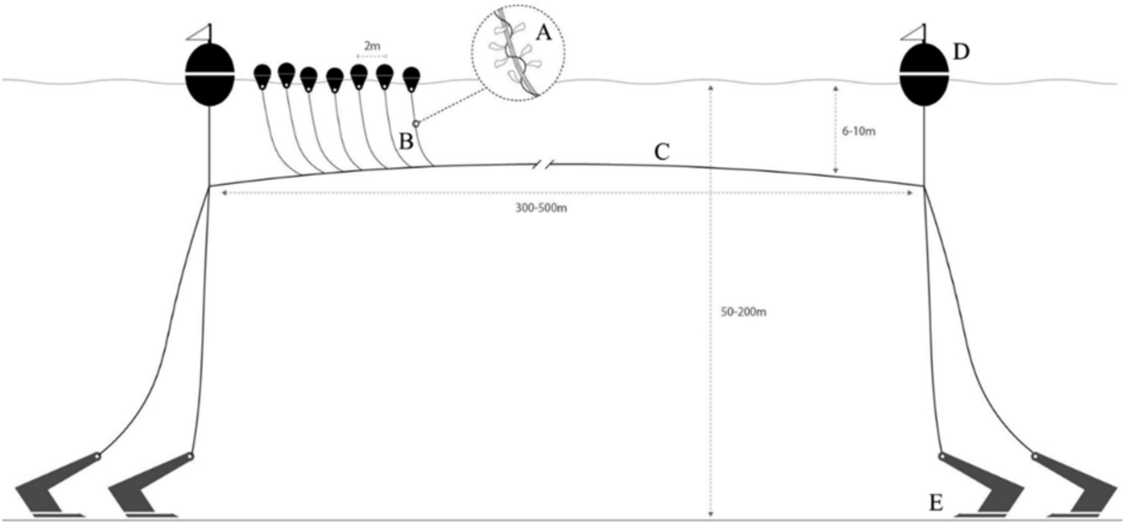


Figure 13: Macroalgal Cultivation Rig Farm layout concept of Ocean Rainforest (Bak, Mols-Mortensen, and Gregersen 2018).

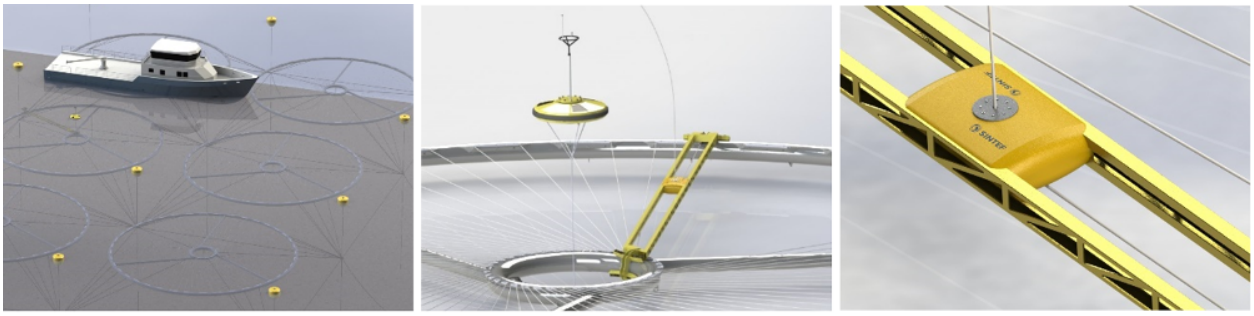


Figure 14: Standardised Production of Kelp layout by SINTEF Ocean (Bale 2017).

The SPOKe concept is inspired by the layout of fish farms and is motivated by an effort to create a standardized system with full automation and modules that are easy to use. It has a circular layout with a diameter of 25m. The layout will be able to deploy 896m of GLs over an area of 491m^2. A module is transported to the farm on a ship and is lowered down to the farm to perform the deployment or harvest. This is still in a conceptual phase that is not commercialized.

A horizontal layout concept by ProAqua AS can be seen in figure 15. The idea was that standardizing the layout could make it easy to install extra modules for upscaling of a farm.

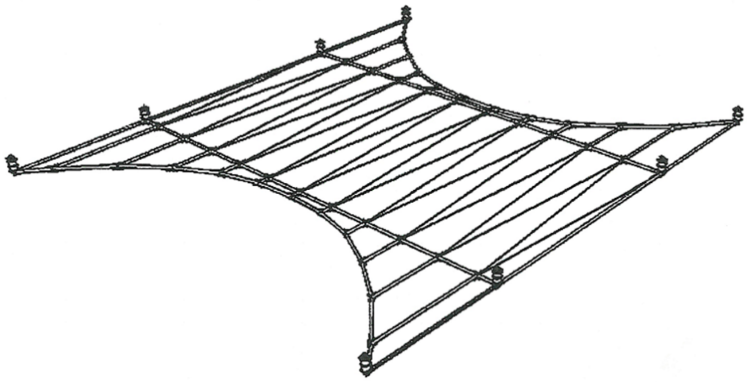


Figure 15: Modular Rig Layout of Seaweed AS (M. Alver, Solvang, and Dybvik 2018).

The concept was discarded by ProAqua as they moved on to their new concept, the ProAquaRig, which can be seen in figure 16. Here, GLs are deployed vertically, and the rig has a single point of mooring, which will allow the rig to rotate based on current directions (ProAqua 2017). This will distribute nutrition better within the rig, resulting in better yields. The rig can be elevated or lowered as one wishes, where the idea is that ready to harvest seaweed can be lowered to a depth where it will not be subject to fouling. This will create a temporary storage for seaweed, allowing for a longer harvest-window.

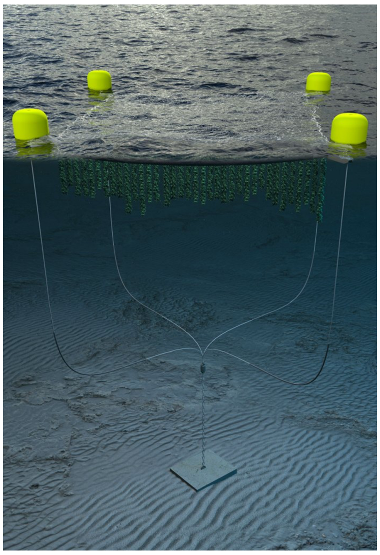


Figure 16: ProAqua Rig Farm Layout (ProAqua 2017).

There are in general few similarities between these farm layouts. Ocean Rainforest and ProAqua uses vertical lines, but in different patterns, while SPOKe and SES uses horizontal lines, in different patterns. As the industry is still in an early stage where the optimal layout is not yet determined, it will be hard to predict if any layout will become the standard or not. This may depend on the location and end-product application of the seaweed. The current trends may indicate that farm owners choose layouts that are easy to harvest from and to automate for, such as horizontal or vertical GLs in a simple layout. This may affect the potential yield, but with high costs the increased yield is not sufficiently rewarding for a more complex operation. Thus, if the methods of harvest can be significantly improved and developed for simple layouts, but also for more complex structures that may give increased yield, this may be beneficial.

3.1.2 Hatchery and Seeding Technology

The first step is the cultivation of seedlings onshore in hatcheries. Currently there are three methods of cultivating seedlings. Two of these are very similar and will be referred to as ”spraying”, while the last method will be referred to as ”direct seeding”.

Direct Seeding
Direct seeding is a method where cultures are started in the hatchery. These are cultivated in the hatchery for a period of time (experiments have been done for up to 42 days (Forbord, Steinhovden, et al. 2019)) before they are seeded on ropes using a binder on the day of deployment. The main advantages with direct seeding are higher space efficiency for cultivation, and requires less time from hatchery to deployment, as there will be no incubation time.

Spraying
This method can be done with two different stages of seedlings, meisopores or gametophytes. These cultures are cultivated in the hatchery, seeded onto 1.2mm twisted string which is then incubated in the hatchery for up to 8 weeks, yielding 5-10mm seedlings (Forbord, Steinhovden, et al. 2019). These strings are then twined around a larger carrier rope on the day of deployment.

Results from the research of Forbord, Steinhovden, et al. (2019) has currently shown greater yields for seeded string twined around carrier ropes, although some aspects will require further study before such a conclusion can be made. It was for instance discussed if a longer growth-period in sea would level out the yield-difference, or if the rope type (braided or twisted) could have an impact on the density of seedlings. It is therefore unclear which method will result in lower costs. A higher yield will increase sales revenue, but the higher space demand and incubation time for spraying will lead to higher costs than direct seeding.

The costs are still very high for seedling cultivation (Skjermo 2016), and several companies, such as Ocean Rainforest and Eukaryo, have started applying the method of direct seeding onto ropes as a way to lower costs, which was mentioned at the SIG seaweed conference (Bak 2019) (Karlsen 2019). The method of direct seeding results in the ability to have an optimum number of seedlings per length of rope, compared to spraying, which gives a high density of seedlings, and was stated to be a cost-inefficient method for seeding of GLs (Karlsen 2019).

3.1.3 Deployment

When the seedlings are delivered to the farm owner, they need to be deployed as soon as possible (within 2-3 days), as the seedlings will start to deteriorate and eventually die if they are not kept in optimum conditions. The seedlings need to be attached to a sturdy carrier rope, the GL, that has the appropriate strength and sturdiness to carry fully grown seaweed, tackle harsh weather and currents, and to be harvested from. This process is commonly referred to as ”seeding” the ropes. Typically, seedlings arrive in either of two ways as previously discussed.

Twine-seeding can be a very time-consuming process, and very costly if performed with manual labor. A ”seaweed spinner” was developed by M. O. Alver and Solvang (2018) which can do this twining mechanically. It allows the carrier rope to be entered from the top, and the end of the rope is not needed. The string is spun around, and the spinner can do this for a capacity of up to 10m/min. The machine is also very space-efficient, the size of a euro-pallet (M. Alver, Solvang, and Dybvik 2018) (Torfinn 2019). A picture of the seaweed spinner is shown in figure 17.

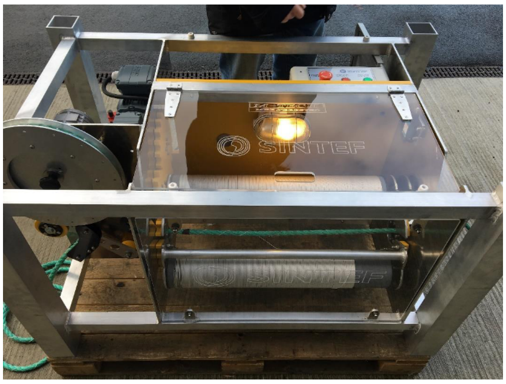


Figure 17: The seaweed spinner developed by SINTEF (M. Alver, Solvang, and Dybvik 2018).

For direct seeding, the culture is attached to the carrier rope by using a binder (Forbord, Steinhovden, et al. 2019). The company Eukaryo delivers seedlings to be applied with this method, and has developed their own machine to mechanically ”sow” seedlings onto the GL. This machine has capacity to sow 3.5-4.0km/h of rope (Karlsen 2019). In figure 18, an illustration of both the methods are shown.

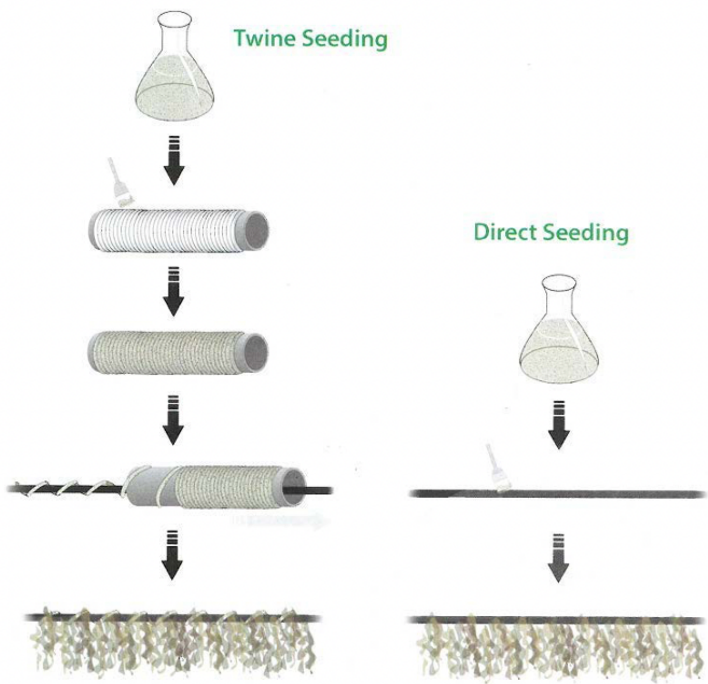


Figure 18: Illustration of the two most common seeding methods, Direct and Twine seeding (M. Alver, Solvang, and Dybvik 2018).

Due to the results from the report by Forbord, Steinhovden, et al. (2019) and from interviews with different farm owners (Myhre 2020), it is assumed that the chosen method will be twine-seeding of ropes for the first 5-year period. It is however not assumed that this will be the preferred method over the lifetime of the vessel, as further studies need to be performed to determine which method is more efficient. Direct seeding may become a preferred method due to no incubation time and to date a more efficient seeding method due to the seeding machine developed by Eukaryo. If the cultivation time in sea is increased, yields may be just as high as for twine-seeding, which will yield this a more cost-efficient method than twine-seeding. There is however no certainty in this as of yet, and it is therefore assumed that the applied method is twine-seeding.

Deployment is assumed to take place between December and January, depending on the location and preference of the farm owner. Seedling growth will be during the typical growth-season from February till May / June.

Ocean Rainforest uses direct seeding for deploying seedlings supplied by Hortimare (Bak 2019), and current numbers show that 5km of GL requires 4 people and takes approximately 5h to seed. Another 6.5 hours is required for deployment of those GLs. From interviews it was discovered that different companies preferred different methods of seeding (Myhre 2020). One company uses twine-seeding and deploys their seedlings in January over a period of 13 8-hour working days. This company also envisioned accepting biomass from different farm owners in the region, for their own processing.

For attaching the GLs to the rigs, companies use several different techniques. One company attaches the GL to the rig by twining a thin string around the rope and the rig (Myhre 2020), which they use force on a capstan to break off during harvest. Another company uses longline snap clips to attach the GLs to the farm, which they report to be a very good and simple method for handling (Myhre 2020). The ProAquaRig by ProAqua will be developed with plastic rings in which the GLs can be attached and detached from.

3.1.4 Monitoring and Inspection

Seaweed farms are typically not located in exposed waters, but inspection of the facility will still be necessary. Weather can be harsh, currents may be powerful, and ropes, seaweed, buoys or anchors may detach. Thus, inspections of the farm will be expected to take place at least every second week.

Monitoring of seaweed is also an important part of the cultivation. Harvest has a short time-window of typically 3 weeks. Initiation of harvest will however vary based on local conditions and monitoring of the farm and area becomes important. Typical measures that are taken is the water temperature, salinity and nutrient level of water. This allows companies to predict when the harvest should take place, when the biomass yield is at its highest, before biofouling occurs.

3.1.5 Harvesting methods and technology

When the seaweed has reached the preferred state in terms of content-levels, size and quality, harvest is initiated. Harvest-method varies from farm to farm, due to end-product and farm layout. The harvest usually takes place between April to June, and potentially as late as August, depending on the location. Harvesting techniques are still very labor-intensive and low-tech, and this represents a bottleneck in the industry (Bak 2019) (Chapman 2019) (M. Alver, Solvang, and Dybvik 2018). Ocean Rainforest presented a solution they are developing, which is partly mechanical, but still too inefficient for a cost-effective harvest (Bak 2019). The SPOKe concept of SINTEF Ocean has not yet had calculations to verify the harvest-rate of an automated system, but SINTEF Ocean hope it is similar to the estimated deployment time of 40 minutes for one rig.

Tango Seaweed cultivates approximately 6km of ropes at Skarveskjæret in Norway with a vertical orientation.

Harvest takes place between April and May, as fouling destroys the plants later in the season. The company has good experience with not cutting the seaweed of the ropes, but instead bringing the entire GL onto the vessel and onshore for air-drying in a hall (Chapman 2019). When the seaweed is cut of the rope, it will start to deteriorate immediately. By not cutting it off, Tango Seaweed is able to maintain the quality of the seaweed, and it makes quality inspection of individuals significantly easier, which is important when the seaweed is to be sold for food products. The major challenge with the method is that it requires a lot of space, which they do not currently have available. The method for drying takes 24 hours, which is a major bottleneck for the company.

Ocean Rainforest is cultivating between 4-5km of GLs, which are placed vertically in the sea on 10m long GLs attached to a fixed horizontal line. The company uses multiple partial harvesting, leaving approximately 15cm of the plant on the GL after harvest. In their experience, the yield increases with multiple partial harvesting, and costs are reduced by up to 75% down to 9.27€/kg (Bak 2019) (Bak, Mols-Mortensen, and Gregersen 2018).
Harvesting of 40 GLs takes approximately 3 hours with 3 people, with an average of 4 minutes per line. Yield was 500kg Wet Weight (WW) (Bak 2019). The company wishes to expand their farm, but are restricted by governments at the Faroe Island, and also see a need for automated and mechanical harvesting, to reduce costs.

In general, the harvest technology is very primitive, involving manual labor for cutting the seaweed off the GL. Some mechanization has been introduced by Ocean Rainforest, while the company Lofoten Blue Harvest has installed a rig for harvest on their vessel, which simplifies operation, but still requires manual labor to cut the seaweed off the GLs (Harvest 2020).

3.1.6 Pre-Processing

Depending on the end-product of the seaweed, some processing will have to be done. This is divided into pre-processing and final processing, in which the latter is performed at a processing facility. The pre-processing is defined as the processing which happens before the seaweed arrives at the processing facility. This may be on the vessel, or by the harbor where the seaweed is delivered.
There are many possible alternatives for pre-processing, all depending on the end-product of the seaweed. Several of these methods were discussed by Lona, Berggren, and Mo (2019a). The most relevant results will be presented here.

For human consumption, typical pre-processing involves spraying of the seaweed during harvest to remove bryozoans and vertebrates, sorting of stems, blades and fouled plants, and eventually an iodine-reduction. This reduction is necessary as the iodine-level of seaweed is high, which may be dangerous for exposed groups of people. The reduction can be done by boiling seaweed in freshwater at 32° Celsius (Stévant et al. 2017). In this thesis, it is assumed that this process is performed onshore. Different customers will either request the seaweed to be boiled before purchase, or prefer it not boiled. There are no regulations in place that sets requirements to boiling, and thus it will depend on the customer.
It has also been discussed that there is an iodine-deficiency in the general population due to a decrease in consumption of milk and other iodine-containing products, which will make it unsure whether this will be necessary or not for products in the future. Another argument that favors boiling at the processing facility is that the seaweed degrades very quickly after it has been harvested, a process that will be accelerated by boiling in freshwater. To limit this degradation of the seaweed, the boiling should take place close to the processing facility, for an optimum quality of the seaweed for the final product.

Other pre-processing may be cutting and pressing of seaweed and fermentation, which could be performed for seaweed whose end-product would be biofuel. For this application, taste, texture and color is not important.

Ensilation has been discussed as a method of conserving seaweed for longer periods of time(Lona, Berggren, and Mo 2019a), and further research into the applicability in seaweed cultivation is necessary.
The ropes that are retrieved from the farm will require cleaning if they are to be reused for the next season. The remaining seaweed has to be scraped or rinsed off the GLs, before being stored. This may be required to ensure a sustainable production.

3.1.7 Storing

Storing has been defined as its own operation, mainly due to the varying storage conditions required, depending on the end-product. Several studies have shown that the content-level, texture, taste and color of seaweed is strongly influenced by the storage conditions (Lona, Berggren, and Mo 2019a).

For seaweed used for human consumption, it is important that the high quality is preserved. The seaweed should not be stored too compact, as this will stress the plants. Thus, a density of 200-300kg/m^3 has been suggested. It is also recommended that the seaweed is covered, to protect it from freshwater (i.e. rain) and sun, as this can be considered "sudden death" (Myhre 2020) for the plants. Furthermore, it is desirable that the seaweed is kept cool during transport, as this reduces the degradation of the seaweed. Other methods of storing include storing in nets outside the vessel, or in a mix between seaweed and seawater. It is however discussed whether this will be an economically feasible method to store seaweed, as the higher complexity increases cost on an already high-cost product.

3.1.8 Transport

This is part of the final operation for seaweed, as it needs to be transported to the processing facility. In the current situation, most farm owners have their farms located near the processing facility they use, to reduce transport needs. This allows for transport-times from farm to processing to be as low as 10 minutes sailing, or in extreme cases, the complete processing is performed on the vessel, ensuring that seaweed is processed within 30 minutes of harvest (Myhre 2020). Other owners are not too concerned with the time from harvest to processing, as long as it is performed within 24 hours.
It may be reasonable to expect that a larger industry will require larger and more centralized processing facilities, which several farm owners will eventually supply to. This may increase the distance from farm to processing facility, and a vessel's range should therefore be considered during a vessel design.

3.1.9 Taredyrkingsfartøy 2020

Taredyrkingsfartøy 2020 is a project developed to find a vessel concept for the seaweed industry. The project highlights mission specifications and requirements (Bekkevoll et al. 2019), vessel design (Lona, Sunde, Berggren, et al. 2020), methods for handling and ship outfitting (Lona, Sunde, Mo, et al. 2020), storage and quality preservation (Lona, Berggren, and Mo 2019a) and finally an evaluation of a total vessel concept (Lona, Berggren, and Mo 2019b). The project proposes three vessel designs to enter the industry based on market developments. These can be seen in figure 19.

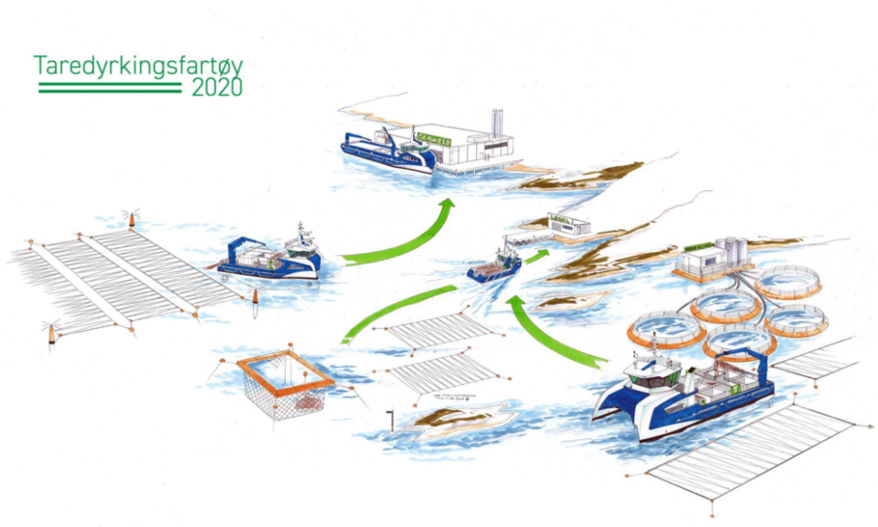


Figure 19: Illustration of the vessel concepts to enter the seaweed cultivation industry as it develops. The first vessel (bottom right) is a fish farm service catamaran that can perform operations at seaweed farms, the second vessel (middle right) is a kelp dredger that has functions for farming from seaweed farms as well, also retrieving kelp from intermediate storage solutions in sea. The third vessel (middle left) is a specialized seaweed farm vessel that can operate at farms at exposed sites, delivering seaweed to centralized locations (top middle). Cargo vessels (top middle) transport the seaweed to customers and processing facilities.

The first to enter the market is a service catamaran specialized for fish farm aquaculture, but that can operate for seaweed cultivation by installing specific modules on the vessel. The second is a kelp dredger that can also operate in seaweed cultivation, and the last design is a specialized seaweed vessel for cultivation, that will enter the market when it has grown substantially larger than it is today.

3.1.10 Harvesting Natural Kelp Forests

There are several vessels designed for harvesting of kelp from natural kelp forests. These vessels are mainly under 15m in length and use a kelp trawler to harvest the kelp. The vessels can harvest up to 300tons each day, and up to 1ton per trawl. The trawling takes from 30 seconds to 120 seconds. Assuming an average lie at approximately 90s, this suggests a 7,5h operation to reach maximum capacity. The vessels then returns to base to unload the kelp, which will be transported to the processing facility of DuPont Nutrition & BioSciences in Haugesund by other vessels, more appropriate for bulk transport. In figure 20, the trawler tool and vessel can be seen. In figure 21, a vessel used for transporting the kelp to the processing facility is shown.

Figure 20: Kelp Trawler Tool and Kelp Trawler Vessel.

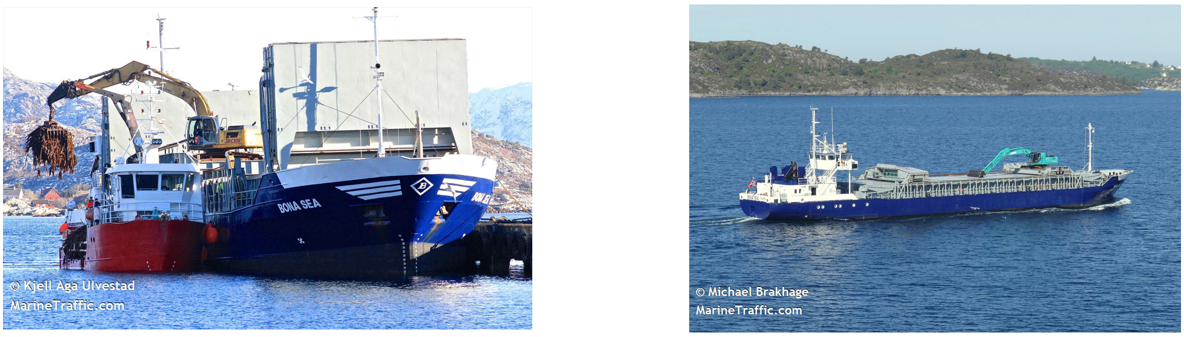


Figure 21: The vessel Bona Sea which is used for transporting harvested kelp to the processing facility in Haugesund.

Harvest from natural kelp forests show a mechanized large-scale industry, where different vessels are specialized for their specific purpose, either harvest or transport. This is similar to the expected development seen in Taredyrkingsfartøy2020.

3.2 Autonomous Vessel Developments

Although no vessels are fully autonomous today, many research projects are ongoing, and Norway is a leading country on autonomous technology for maritime applications, through companies such as Kongsberg Maritime. The company is one of the world leading companies on autonomy, already delivering Autonomous Underwater Vehicles (AUVs) for several years, and now leading the Yara Birkeland project, with several other projects ongoing.

3.2.1 MUNIN - Maritime Unmanned Navigation through Intelligence in Networks

The MUNIN project focuses on highlighting gaps between today's shipping and autonomous shipping, identifying required systems to support autonomous shipping and uses a case study with a dry bulk carrier to learn about what systems will be replaced, removed and added. Burmeister et al. (2014) believes this ship category is the most viable for autonomous shipping as the operations are not very complicated, and the cargo does not require much monitoring or treatment. The on-board systems have been designed for redundancy to increase the reliability of the design, which is crucial when there will not be crew available to do repairs when necessary. The vessel is defined to have 5 operational modes (LOA), ranging from manned operation to autonomous execution and fail-to-safe, which is engaged if systems on board or communication with shore control center fails. The vessel is planned to autonomously execute deep-sea sailing, while berthing and approach will be handled by a crew that boards the vessel close to shore.

3.2.2 Yara Birkeland

Yara Birkeland will be the world's first zero-emission autonomous container vessel developed in cooperation by Kongsberg Maritime and Yara. The vessel will replace 40 000 road journeys' (Maritime 2017) as it will sail between three ports in southern Norway. The vessel is currently being outfitted at Herøy (Teknikk 2020) and will begin operating as a manned vessel with a detachable bridge. As the technology becomes more verified, the bridge will be detached, and the vessel will move on to being remote-controlled and eventually fully autonomous by 2022. The solution relies on advanced sensor modules, automatic operations and with a pre-defined route. There will be three control centers which will handle all operational aspects of the vessel, from monitoring and control to emergency and exception handling. An illustration of the vessel can be seen in figure 22.

Figure 22: Illustration of Yara Birkeland, the zero-emission autonomous container vessel developed by Kongsberg Maritime for Yara (Maritime 2017).

3.2.3 Autonomous Technology for Ferries

Kongsberg Maritime is developing a system for automatic crossing between Horten and Moss. The system is however not completely autonomous, but will aid the onboard captain in situational awareness and decision support (Maritime 2018b). The system will automate the docking / undocking for ferries and optimize the route based on the current conditions.

3.2.4 Remote-Operated Fireboats for Ports - RALamander

Kongsberg Maritime is cooperating with Robert Allan Ltd. to develop a remote-controlled fireboat, called RALamander, for dangerous port fires (Maritime 2018a). The objective is to allow first responders to attack fires more aggressively while keeping personnel out of harm's way. The control system of the RALamander will be configurable to allow for increased level of autonomy (LOA) based on the port owners' desires. An illustration of the RALamander can be seen in figure 23. The vessel is however not fully autonomous, but will be a showcase for how complex operations can be remote controlled.

Figure 23: Illustration of the RALamander under development by Robert Allan Ltd and Kongsberg Maritime (Maritime 2018a).

3.2.5 Autoship - Horizon 2020

Autoship is a project with purpose to accelerate the transition towards autonomous ships. This project will use two demonstration cases, one for inland water ways, and one vessel, Eidsvaag Pioner, for short-sea shipping (Maritime 2020). The Eidsvaag Pioner is used for transport of feed for fish, where the operational focus ranges from transit, docking and undocking, to cargo operation and fish farm interaction.

3.2.6 AUV Technology

AUVs are not new developments relatively speaking. Kongsberg has been developing AUVs since the 1990's (Maritime 2019) and these are today commercially available. One such AUV is the Eelume, an AUV with flexible joints that greatly increases the maneuverability of the AUV compared to traditional designs (Eelume 2020). It can be equipped with different types of tools and is designed to be permanently deployed subsea.

The Woods Hole Oceanographic Institute (WHOI) is leading a research project where one of the topics is the use of the Remote Environmental Monitoring UnitS (REMUS) for monitoring health and growth of seaweed in farms, as well as the state of the farm rig and nutrient content of waters (WHOI 2017) (OSL 2020). With recent developments within object classification of macroalgae (Bewley et al. 2012), it is possible to imagine this becoming a fully autonomous solution with no requirements for a human operator. An illustration of the REMUS concept for macroalgae monitoring can be seen in figure 24.

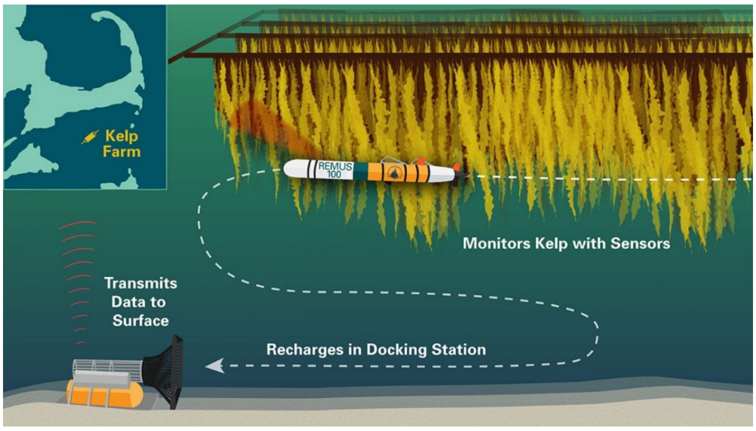


Figure 24: Illustration of REMUS monitoring a seaweed farm (OSL 2020).

3.3 Design Methods

Design is about identifying problems or needs in the world, and to find solutions that fix these problems or satisfies these needs. A problem could be that people get sick due to air pollution, or that an office building is not supplied with enough heat to keep a comfortable temperature for the staff. Problems are easily identified, because the consequences are easily observed. Needs can be both conscious and unconscious, meaning that people either are aware of the needs they have, or not. For conscious needs, the customer typically places an order for a solution to be proposed. For unconscious needs, the designer will have to persuade the customer into understanding the benefits of the design, at a higher degree than with conscious needs from the customer.

A design process should always start by identifying a problem or need that requires a solution. When this is clearly identified, it will make it far easier to understand the design space, in which all the possible and feasible solutions may lie. There are many methods to go ahead with after identifying a problem or need, ranging from point-based and set-based design, to system-based ship design. All have their strengths and weaknesses, which will be further discussed here,

3.3.1 Point-Based and Set-Based Design

Point-based Design (PBD) is commonly known as the design spiral, which is illustrated in figure 25. It was first introduced by Evans (1959) as an attempt to organize the thought-process of a complex design, such as a ship.

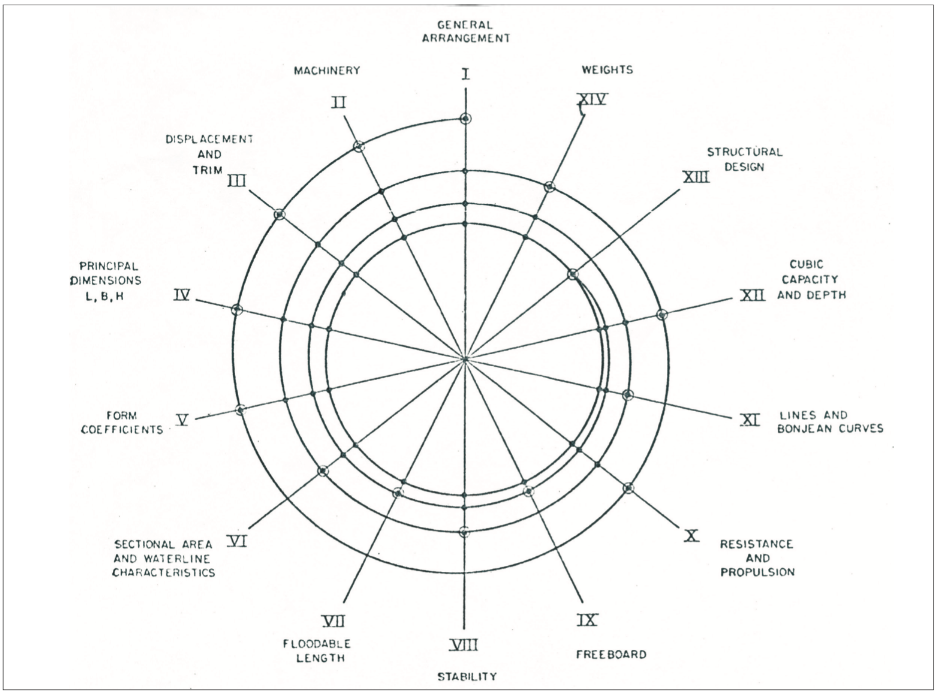


Figure 25: Design Spiral by Evans (1959).

The method assumes that the ship owner sets some requirements which limits the design space to some extent. Then, a somewhat arbitrary starting point is chosen, preferably based on previous similar designs. From the starting point, machinery is arbitrarily chosen before displacement and trim is calculated. The design spiral tries to show a "natural" process to follow for designing a ship. For each successive cycle, compromises are made, and the design space is narrowed down, ending in a final design where compromises are so small as to be assumed negligible. The spiral tries to suggest a most efficient design process.

The strength with the method is that it gives a structure to how a ship can be designed. If several similar ships exist, it will also accelerate the process, as one can use other designs with small alterations to satisfy the requirements of the current ship owner.

The method does have some weaknesses, however. One flaw of the method is that the final design will strongly depend on the starting point of the design process. At the start of a design process, the problem is often not fully understood. When the starting point is chosen, this may then have major drawbacks and be far from the optimal solution. Thus, major compromises may have to be made underway to achieve a feasible design, which will then not be an optimal solution.

The design spiral is practical to use if there is a large database of other ship designs for similar purposes. However, if the design is for a special purpose, where other similar designs do not exist, or system requirements are very different from other designs, it may be very difficult to find a good starting point. It will depend on the previous experience of the designers, which may result in choosing starting points not based on empirical data, but more "gut-feeling" decisions of the design team.

Another weakness with the method, also identified by Evans (1959), is that flaws and redundancies from the start point may be passed on in the following cycles where the design space is further narrowed down.

Another method that has been studied for use in ship-based design in the Set-Based Design (SBD) method. In a journal article by Singer, Doerry, and Buckley (2009), the advantages of SBD are discussed for application in ship-design. SBD allows engineering teams of different specializations to explore the design space, providing design alternatives to be evaluated. From the evaluation, different trade-offs between design solutions are understood, which aids to further narrow down the design space. The main idea of the method is to delay design decisions as long as reasonably possible, arguing that knowledge about a design, and requirements, are more fully understood later in the design phase. This allows decisions to be made based on more complete information, contrary to early decisions made on incomplete knowledge, which is typical for PBD methods.

This delayed decision-making also allows stakeholders to influence the design at a later stage, as the design space is not narrowed down based on a single starting-point of design. As the method promotes an understanding of the design space, it has also been shown that discovery of faults, or changes in requirements, have not resulted in major rework (Singer, Doerry, and Buckley 2009), as the team is not dependent on a single design point.

Gray, Rigterink, and McCauley (2017) performed a study between the performance of point-based and set-based design strategies for a Naval vessel. Two teams were given the task to design a vessel for the navy, with a given set of requirements and objectives. The teams were also introduced to changes in requirements and objectives underway. The results from the research showed that the SBD-team was more adaptable to changes in requirements and objectives, and the design proved to have high performance, with lower cost and higher reliability, than the design proposed by the PBD-team.

Gray, Rigterink, and McCauley (2017) believed that the process of the team was equally important as the final result, and thus also analyzed how the teams worked throughout the 14 weeks. The results showed that the SBD-team made decisions based on design-data, and not on designer preferences. It also showed that the SBD-team was able to keep the design-space open until the very end, and that changes in requirements did not cause rework for the team, but actually helped to narrow down the design space for the team, where the PBD-team had to do major rework. These differences strongly supported the author's hypothesis that Set-Based Design was a more favorable method for ship design.

3.3.2 System Based Ship Design

Levander (2006) proposed an alternative ship design method, called System Based Ship Design (SBSD). The method is based on delaying the design of the ship hull for as long as reasonably possible. The method suggests identifying system functions, and the required areas and volumes for these functions, before a hull is designed to be able to fit all these systems within. General arrangement follows the hull model, and hydrostatic as well as stability calculations are performed to verify the design. Figure 26 illustrates the design-strategy of the method.

The main advantage of the method is that system functions are clearly mapped, and if changes in system requirements are made, it will not require much re-work to find a feasible design. The method also promotes clarity, as all calculations are presented in easy-to-read spreadsheets.

A disadvantage with the method is that the design space is not explored in great detail, which means that the final design may not be a global optimum. The method also relies heavily on parameters that are typical for the given vessel type, indicating that the method relies on high experience level, or a large database of existing vessels of the same type, to find reasonable designs.

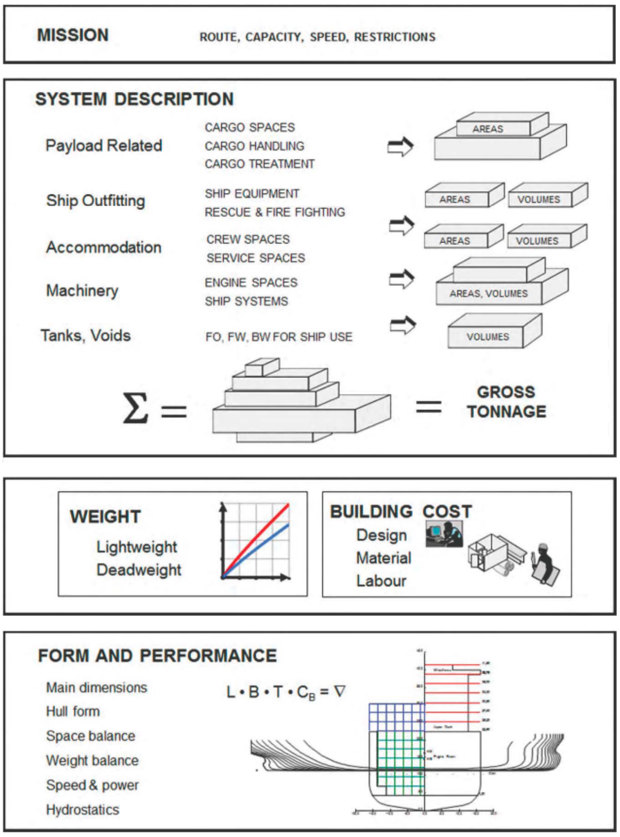


Figure 26: Illustration of the methodology of System Based Ship Design by Levander (2006).

3.3.3 Engineering Design

Engineering Design is a design method proposed by Pahl et al. (2007). It promotes a systematic way of approaching design, not limited to the designer's area of expertise. The main outline of the method is to clarify the task of the customer by identifying the needs of the customer. These needs are then translated into system functions, which are further elaborated and broken down into subfunctions, until becoming trivial tasks with clear descriptions. The designer will then find different solutions, either by finding existing solutions that can be applied to the given design problem, or by proposing new solutions to the specific subfunction. This is called the function-to-form mapping.

By finding and proposing solutions to all of the subfunctions, a design space can be drawn. By setting up the subfunctions with respective solutions in a matrix, the designer has created a "design catalogue" where the designer can mix and match solutions to respective subfunctions. From the design space or design catalogue, solution paths (SP) can be drawn, by proposing a solution to each subfunction. An example of such a process is shown in figure 27. An SP is then a set containing a solution to each subfunction, which results in a description of the system. This gives design parameters and a distinct form in the physical domain.

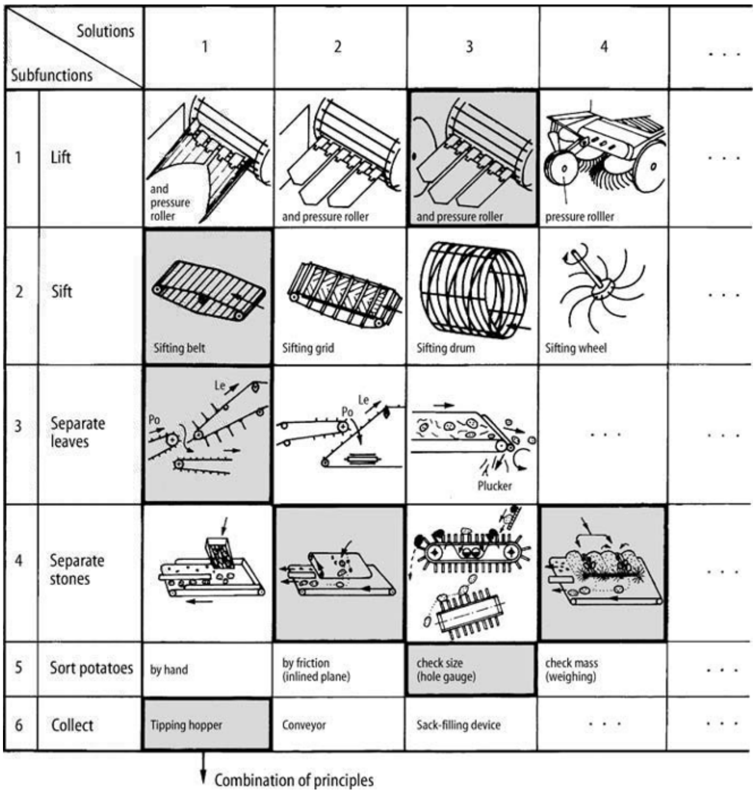


Figure 27: Example of a design catalogue for designing a potato harvesting machine (Pahl et al. 2007). The subfunctions are listed on the left side, whilst different solutions are drawn in each cell specific to the subfunctions. Boxes in grey mark a potential SP.

When a design or SP is proposed, it is evaluated to consider what the outcome or performance of the system is. The performance will typically not be completely equal to the intended system performance, and becomes an iterative process. Functions are mapped to different forms or system descriptions, which are then evaluated, showing a specific performance, which then leads to a new proposal for a design. With several iterations, the difference between the intended performance and the actual performance of the system diminishes, and a final design can be proposed. This process of needs-to-function-to-form mapping is illustrated in figure 28.

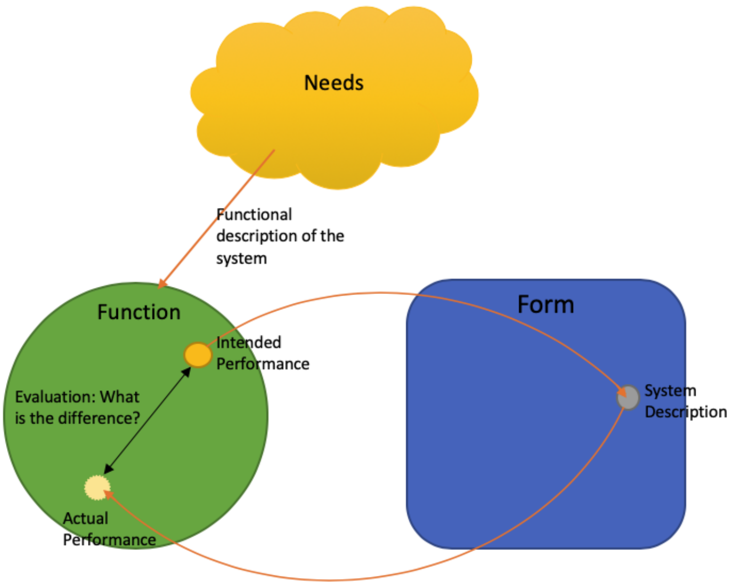


Figure 28: Illustration of the mapping between needs, function and form in the Engineering Design methodology. From the needs, a functional description of the system is made. These functions are then mapped onto the physical domain. The design is then evaluated to see if the performance is as intended. An evaluation is made on the difference, and re-iterations are made until the physical system gives the intended performance, which satisfies the needs of the customer.

The method promotes a comprehensive understanding of the underlying problem, by analyzing it in terms of customer needs, with a clear translation to system functions and trivial task subfunctions, which allows the designer to easily find new or existing solutions to solve the specific problem. This method gives a clear working structure, and it requires the designer to gain a comprehensive understanding of the underlying problem and needs. A clear mapping from needs to functions and forms becomes an iterative process, where the forms are analyzed to determine whether they have fulfilled the underlying needs or not.

As with other methods, the entire design space is not explored, which may prevent the designer from finding the global optimum solution to the problem.

3.3.4 SEATONOMY

SEATONOMY is a design methodology developed by SINTEF for autonomous systems. They define industrial autonomy as safe and efficient operation of units for direct commercial value, and thus emphasizing the importance of value creation (Grøtli, Reinen, et al. 2015). SEATONOMY defines an overall challenge with autonomous system design as creating a cost-effective trade-off for operational and design choices. This challenge is in SEATONOMY separated into three main challenges; determining the correct LOA, preparedness for all relevant critical situations, and predictable behavior within given boundaries. SEATONOMY views autonomous system design from three viewpoints, as illustrated in figure 29.

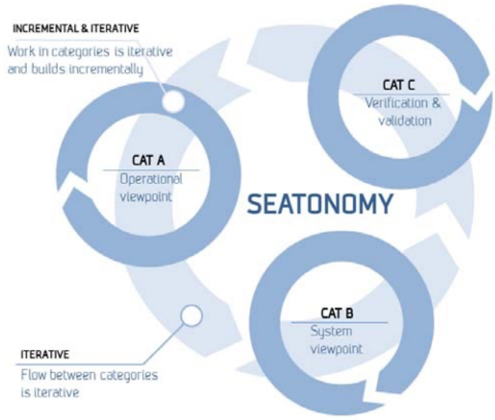


Figure 29: The three viewpoints of the SEATONOMY methodology (Grøtli, Reinen, et al. 2015).

In the operational viewpoint, the goal is to identify the needs and requirements of implementing an autonomous system. This is done in four steps. The first step is to define the operation with solutions for the operation, while the second step involves a breakdown of the operation. With the SEATONOMY methodology, it is advised to use the Autonomous Job Analysis (AJA) table in step 2 to detect operational modes, challenges and restrictions and requirements for autonomous behavior. The AJA table is focused on the breakdown of the operation, with the goal to uncover all aspects relevant for an autonomous operation. The AJA table can be seen in figure 30. The output after using the table should be a structured description and breakdown of the operation.

ID	Name	Description
1	Description of sub-goal	Give a short description of the sub-goal, focusing on the objective without too much technical detail. Achievement of the sub-goal should contribute to the achievement of a goal at a higher level, and eventually the main goal of the operation.
2	Communication	Communication flow: What key information needs to be communicated? Communication restrictions: What are the limitations?
3	Perception	Which information about the environment and the system itself must be available?
4	What are the criteria for success?	List design criteria which specify whether the sub-goal has been achieved. This can, for instance, be performance specifications related to accuracy or time.
5	What can go wrong?	Is there anything that can prevent the sub-goal from being successfully accomplished? Be specific about what characterizes abnormal behavior.
6	What is the operational safe state?	Define what state or mode should the system should go to, in order maintain the safety of the operation in the best possible way.
7	What is the human-machine interaction?	Describe the human-machine interaction. The interaction can be described in words, or with reference to some taxonomy for Levels of Autonomy, for instance as given in Table III in Appendix II .
8	Are there other premises or requirements for successful execution?	Describe other relevant premises for successful execution of the sub-goal.
9	Notes and comments	Add comments that are relevant for the sub-goal, but are not captured by the previous questions in the table.

Figure 30: Autonomous Job Analysis table of the SEATONOMY methodology with a description to what each aspect of the analysis covers and what the desired output is (Grøtli, M. Vagia, et al. 2015).

The communication aspect is focused on identifying what communication is necessary between the vessel and the operator / monitorer, and defining the restrictions in communication. Perception is the vessels ability to

gain information about its internal systems as well as its surroundings. This will be crucial information to retrieve for the system to make good decisions about its action. The aspect is focused on discovering what information will be required by the system.
Success criteria is the goal of the sub-operation. A clear definition is needed for the system to understand if it has achieved its goal or not. It is also important to identify the possible failures of the system, as this can allow the designers to plan around such events. The operational safe state is what state the vessel should enter if a failure has occurred. Lastly, the LOA for the sub-goal should be defined, and any other important aspects that were not covered already.

When the operational viewpoint has been covered, the next steps in the SEATONOMY methodology is to verify the safety and cost-effectiveness of the system, respectively.
The system viewpoint is concerned with finding a solution in terms of software and hardware to the operation as defined in viewpoint A. The steps involve defining the abilities of the operations from viewpoint A, code these accordingly, design of communication system based on the required LOA, choice of sensors and verify the safety of the system. The last viewpoint is concerned with verification and validation. This viewpoint is concerned with testing of the systems developed through viewpoint A and B, and validating these systems to the overall operation or function. This may lead to redesign and is an iterative process until the final design is verified and validated.

3.4 Section Summary

In this section, operations and technology in seaweed cultivation has been studied. The study showed that there are no clear methods that are preferred over others. Some companies prefer twine-seeding, where others wish for direct-seeding. Farm layouts also differ, where some concepts propose horizontally deployed GLs, in different patterns. Other companies suggest vertically deployed GLs, also with different patterns. Further research into optimal layouts needs to be conducted to determine what is a better strategy. Deployment and harvest operations are today relying on labor-intensive operations, with a low degree of mechanization. This represents a large potential for cost-reductions, by reducing the work done by crew. Farm owners are also motivated to create farm layouts that are easy to automate processes around. The short season and varying farm layouts represent a challenge in vessel design. A vessel will have a low utilization if it is only intended for seaweed farm operations, and it is difficult to find technology that is adaptable to all farm layouts.
Many methods for storage and processing may be suggested, but the knowledge around what is best for the end-product is still low. For human consumption, the quality in terms of taste, color and texture is important, and harvest will be earlier than what is desirable for other products.

The study on autonomous vessels showed that there are no large vessels that are operating fully autonomous in 2020. Yara Birkeland is likely to be a pioneer, as it is planned to be operating autonomously in 2022. Kongsberg Maritime is involved in many projects for autonomous vessels of varying complexity. The REMUS is a proposed AUV for seaweed farm monitoring, that uses existing technology in a new operation.

The design methodologies in ship design studied were point-based, set-based and system-based design. For engineering designs in general, the Engineering Design method by Pahl et al. (2007) was studied. For autonomous designs, the SEATONOMY method was studied. Set-based design seemed to be a good method to use, as it delayed design decisions for as long as reasonably possible, but the required knowledge to use the method was considered outside the scope of this thesis. System-based design is focused on voluminous designs, and was therefore determined not adequate for the current design. Point-based design explores a limited part of the design-space, but promotes a structured way to design, and is chosen as the preferred methodology. Engineering Design promotes good knowledge of the underlying problem, and is therefore chosen as a design methodology to follow as well. SEATONOMY is a method specially made for autonomous designs, and will therefore also be implemented in the design process, with a special focus on the AJA tables.

4 System Analysis

In this section a problem definition will be made based on the knowledge gained about the industry. A study of the main stakeholders will be performed, and the needs of these will be defined. A need to function and form mapping will be conducted, and an AJA determines the different sub-operations and what LOA the operations can be executed at. A study of possible SPs is conducted to determine what SP should be regarded in a vessel design.

As most licenses are given for Sugar Kelp and Winged Kelp, these are assumed to be the species in focus for cultivation in the rest of this thesis. As these seaweeds are also known as kelps, this will be the preferred word to use in the rest of the thesis.

4.1 Problem Definition

To decide what methodologies are suitable to use, it is important to define the problem at hand. With the knowledge gained from sections 2 and 3, the problem is defined.

There is a very large interest in cultivation and harvest of kelp for many different applications. Many developments have been made in terms of research and technological developments to allow the industry to grow. Even so, the industry in western countries are still of low scale. This is largely caused by the high cost of labor. Farm operations are based on manual work, and there is a desire to mechanize and automate operations to a higher degree. It is however challenging to find a good mechanized / automated solution that lowers cost. This is due to the short season of operation a vessel will have in the industry, resulting in low utility. Therefore, a design that is multi-purpose and adaptable to other industries is desirable. This may set limitations to the specialization of a vessel, and a balance must be found that will satisfy kelp farm owners, as well as potential charterers of the vessel.
A vessel should be able to perform operations in an efficient way, which will require equipment that is suitable for the different operations. Due to the limited knowledge and experience in the industry, it was observed that methods for seeding, farm layouts, storage and processing methods have large variations from farm to farm. These methods are likely to change with the development of the industry as well. It will therefore be difficult to determine the size and degree of specialization for a vessel.
The challenges are summarized:

- Increase efficiency through a specialized vessel
- Ensure flexibility for multi-purpose vessel
- Short season of operation
- Adaptable technology for a changing industry

4.2 Need-Function-Form Mapping

To develop a need-function-form mapping, it is important to know whose needs are to be mapped. This can be done through a stakeholder analysis. The needs of the key stakeholders can then be defined, and will in this thesis be exemplified through a mission description, which was used as a basis in the design process. The mission description can be seen in appendix B, and is a reflection of the current state of the industry.
To create a realistic mission description, it is important to identify the key stakeholders which will strongly influence the design requirements. Stakeholders can be individuals, groups, businesses or organizations. Stakeholders include the owner of the vessel, crew that will be working on the vessel, class society that will class the vessel, media that covers news about the investment and launch of the vessel, and any other that

may directly or indirectly benefit from the project. Different stakeholders may have conflicting interests, and it will therefore be important to classify and prioritize stakeholders. This will make decisions easier to make, as it can be compared to the priority level of stakeholders. A typical conflict of interest may be between an owner and a charterer of a vessel. The owner may want the vessel to be large and versatile for the vessel to be of interest for many different industries, while a charterer would prefer a small and specialized vessel for their specific industry.

The key stakeholder is the owner / operator of the vessel. It is here assumed that the farm owner will be the owner of the vessel. The owner will decide whether or not to invest in the proposed design, and it should therefore satisfy the needs and requirements which come from the owner. Farm owners will have specific requirements on operations based on the end-product of the kelp.

The crew are the direct users of the system, and their requirements will have a high priority in the design. There is a conflicting interest between the owner of the vessel and the crew. Crew typically will require spacious and simple to use systems, and this may be at a high cost, which will be in conflict with an owner's demand for a low-cost solution. The crew will however not have a financial leverage on the design, and satisfying needs and requirements of crew that is in conflict with the owner will require approval from the financial stakeholders.

Other farm owners may potentially charter the vessel, and will therefore be considered an important stakeholder. Different farm owners may have different layouts and methids for harvesting, processing and storage, and it may become important to take these methods into consideration during design.
Another potential charterer is fish farm owners. Chartering the vessel between different farms in aquaculture is a very likely way to ensure profitability for the vessel. Requirements from fish farm owners will then become important to take into consideration in the vessel design.

Processing facilities that accept kelp from farm owners is likely to set requirements for how the kelp is stored and treated during harvest. Currently, most farm owners are in charge of the entire process from growth to processing of kelp, and thus the processing facility is also the farm owner.
It is however more likely that larger processing facilities that accept kelp from many farms in a region will develop with a growing industry, as can be seen for kelp harvesting today. This was also mentioned in interviews as a potential development (Myhre 2020). Such facilities will require kelp to be harvested when specific content-levels are at their highest, for the processing facility to use the biomass in their production.

There is a large potential for different investors to be attracted to the industry. These range from aquaculture industry that wishes an alternative protein source for feed ingredients, the government that desire a new, sustainable industry, processing facilities for kelp that requires a low-cost biomass, or suppliers that see a large potential in increasing sales if they can accelerate development in the industry. These will all have different requirements that may be taken into consideration to increase the attractiveness of the design.

Other stakeholders include the shipyard which may give restrictions in terms of what they can construct, or the public which has a general interest in sustainable new industries. It can be the news medias that provide publicity, or it can be class societies that will set demands for safety and provide regulations for the industry.

The mission description takes the view of the key stakeholder. The aim of the mission description is to give a reflection of what kelp farm owners currently demand, and what other aspects to take into consideration. The key stakeholders are summarized:

- Kelp farm owner. This is determined to be the main stakeholder that will have the financial investment in the vessel.

- Other kelp farm owners. Few vessels suitable for kelp farming exist, and if a feasible design is provided, it may be attractive for other farm owners to charter for their own farms, if the operational window will allow for this.
- Fish farm owners. Off-season for kelp farming can be used to charter the vessel to fish farm owners. Fish farmers already have an interest in kelp farming, and a suitable design could be used for service operations within fish farm industries.
- Vessel crew. The direct users of the system, and their needs should be taken into consideration. Safety is important, and systems that are not difficult to use.

4.2.1 Needs

The owner's needs can be stated in terms of seeding, harvest, processing and storage methods. The general wish is for more efficient processes that require less personnel to perform, a so called ”no hands on rope” requirement. As the degree of mechanization in deployment and harvest is very low today, this has been identified as a main need of the farm owners. Some work has already been done, as discussed in section 3.1, but little was identified in terms of mechanization, and especially for harvest. Although this can be a very concrete need, it is important to understand the underlying reasons. Why do farm owners wish for a higher degree of mechanization in harvest?

The motivation for this is twofold. The risk of accidents and injuries may be high with crew manually handling rope on a vessel. Entanglement can potentially lead to fatal accidents. By reducing the need of hands on ropes, this risk may be significantly reduced.
The second reason is related to cost. Farm owners are motivated to reduce costs, as this will increase the available market for kelp. With high labor costs in Norway, it is not beneficial that multiple crew members are required to handle rope and kelp during operations. In general, speed at which crew can perform operations is also limited compared to mechanical solutions. By increasing the degree of mechanization, required crew and time of operation may be reduced, which again is likely to lower costs.

Kelp is also commonly marketed as a climate neutral or climate friendly product. This leads to high demands from customers in terms of the sustainability in cultivation. Some of the arguments that favors kelp as a new industry is the carbon-uptake of the plant, and no requirements in terms of freshwater or fertilizer. In the entire value-chain it is therefore important to ensure an efficient process in terms of resource usage.

Due to a short season for deployment and harvest, a vessel risks low utility if not chartered to other industries. Owners will therefore require a vessel that can be chartered off-season for kelp harvesting.

The efficiency will therefore be defined as efficiency in terms of cost, energy and time spent on operation. Cost can be measured in [NOK/kg] wet weight kelp, and efficiency in terms of energy usage can be evaluated as a life-cycle analysis of the product. The time efficiency can be measured in [m/min] harvest or deployment. It can also be determined by how many days the vessel is required to operate at a farm. The processing and storage of the kelp strongly depends on the end-product. This may change with the development of the industry, and flexibility in design will be defined as a need of the owner.

The needs of the owner can then be summarized as

- Efficient Deployment
- Efficient Harvest
- Efficient Processing and Storage
- Flexibility in Operations

4.2.2 Function Mapping

In Engineering Design by Pahl et al. (2007), a functional breakdown of a system is performed to identify design parameters, which are then analyzed in terms of the stated functions and needs. This can be done for any arbitrary system, but is best suited for component or product design. A ship is a far more complex system to design, and a system breakdown may be useful, as described by Levander (2006). In the SBSD methodology, a vessel can be defined as a system consisting of payload systems and ship systems as two separate entities. In such a definition, payload systems are defined as those systems that are needed to handle, store and treat the cargo, or payload. The payload system is the source of income for a vessel, which will have a high priority.

The ship systems are all systems necessary for the vessel to function, but that does not directly deal with the payload. This can be the hull structure, accommodation, mooring equipment, machinery etc. For a kelp harvesting vessel, the payload systems can be defined as the operations necessary to be performed at the farm, and treatment of the cargo. A third system breakdown of a vessel is related to the autonomous systems, as discussed by Fjelldal (2018). A system breakdown of the vessel is defined as shown in figure 31, which is based on the operations at a kelp farm, the SBSD methodology, and the autonomous system definition by Fjelldal (2018).

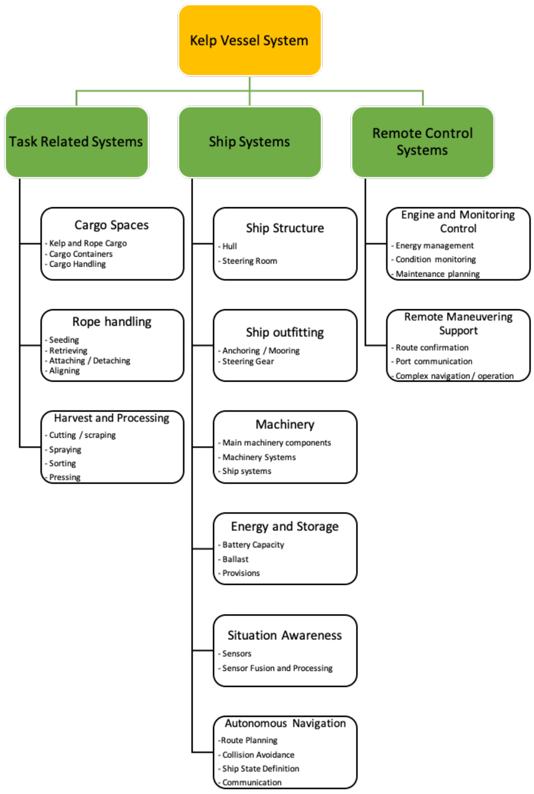


Figure 31: Systematic breakdown of a Kelp Farm Vessel System using the SBSD methodology

The subsystem "Task Related Systems" includes the technology for handling the kelp. A functional breakdown following the Engineering Design methodology is applicable for this subsystem. Two main functions were identified following this methodology:

- Seed and Deploy Growth Lines
- Harvest and Deliver Biomass in Desired State

As processing and storage onboard the vessel happens simultaneously as harvest, this was defined as delivering the biomass in the desired state to the processing facility. The functions were further divided into multiple subfunctions that together fulfill the overall function. An experience in the breakdown of main functions to subfunctions showed that it was not possible, or very difficult, to define trivial subfunctions that did not put any constraints on the design parameters. It was therefore useful to have a predefined case from which the subfunctions could be defined, where the design parameters were somewhat decided already. When the subfunctions could reasonably well describe the main function, it was possible to look into different solution forms for the different subfunctions.

These solutions were listed in a design catalogue which allows the designer to easily find SPs that define a system. The resulting design catalogue with solutions is given in table 3 and 4, while table 2 illustrates how a design catalogue is used in this thesis.

Table 2: Example of a design catalogue setup. F1-FN represent subfunctions, while A1-A5 represent different autonomy levels. Within each cell, a number of solutions exist, and are briefly described.

	A1	A2	A3	A4	A5
F1	5 Solutions	7 Solutions	...	...	X Solutions
F2	...	...			2 Solutions
F3	...		...		...
...	...	0 Solutions		...	...
FN	2 Solutions	...	...	...	Y Solutions

The design catalogue is given with subfunctions F1-FN, where N is the number of subfunctions defined, and solution sets A1-A5, which are defined as categories of solutions for different levels of mechanization, automation and autonomous design.

- **Autonomy Level A1** are the solutions that are defined as manual operations with no or a low degree of mechanization. An example is that a worker is equipped with a knife which he uses to cut the kelp from the ropes.
- **Autonomy Level A2** involves mechanized solutions that still require a human operator in order to function. An example can be a human operator controlling a crane that is used for different functions. This corresponds to what is defined as the lowest LOA of many authors.
- **Autonomy Level A3** is for solutions that are mechanized and automated. In this case, the operator may need to initiate the process, provide information to the system and oversee the operation, but is not required to do anything particular to keep the process going. The system will also provide the operator with information. An example is activating the winch to pull in ropes onto the vessel, where the operator is informed with the state of the winch (engine temperature, spare capacity, power demand). This is typical to the second lowest LOA.
- **Autonomy Level A4** is similar to A3, but the computer system with sensor information is analyzed and used to aid the operator, by suggesting actions. An instance can be to inform the operator that

containers are full and suggest to initiate covering the container, while continuing harvest over another container. The LOA will here depend on the amount of actions suggested, and if the computer narrows the set down to a few, or a single alternative.

- **Autonomy Level A5** are completely autonomous solutions, where the system itself is capable of deciding the next action and when different actions should be performed. It does not require a human operator to activate the action, or to necessarily oversee. The system will on the other hand send information to an operator to confirm that actions are being taken. An example can be an AUV that is in action to inspect the farm and growth of kelp, reporting back the condition of the rig, size of kelps and other required information. The system will do this on a scheduled basis and only report back after it has docked with the required information. This corresponds to the higher levels of LOA. The highest LOA typically also requires the system to be able to evaluate risks in its surroundings and in its current situation.

When the design catalogue is filled out with different solutions, it is possible to create SPs by choosing a solution from a cell at the desired LOA, for each subfunction. This is not only a good way to find different combinations, but is also useful to highlight what possibilities exist, and where new developments may become necessary. It is emphasized that the author is not aware of all technological solutions that exist, and the proposed solutions are only considered for the given case, meaning that other methods exist for processing, but if these were not relevant for the given case, they were not included. The design catalogue may therefore be lacking some contributions that could be useful, and it could be considered to propose a complete design catalogue that does not exclude different methods, for instance by involving companies and interested parties to suggest solutions.
The design catalogue was constructed in parallel with the AJA. The different sub-operations were defined using AJA, and by setting up different solutions in each category, it was possible to determine a desired LOA in the AJA tables.

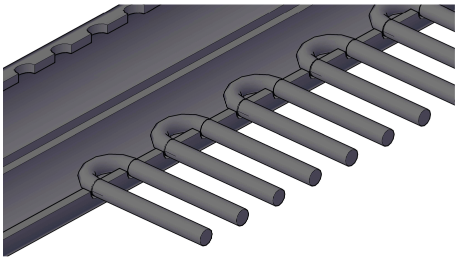
Table 3: Design Catalogue for Deployment Operation. A1-A5 are the 5 predefined levels of autonomy, F1-F5 are the respective subfunctions. Each cell containers a number of solutions that are briefly described, which should correspond to an autonomy level and a subfunction.

Subfunction		Autonomy Level				
		A1	A2	A3	A4	A5
Seed GL	F1	1) Manual Twining 2) Pre-twined at factory	1) Twine around deployed ropes	1) SINTEF Spinner		
Connect to rig	F2	1)	1) Rig for easy connection 2) With crane	1) Computer operated crane 2) rig for automatic connection 3) ROV		1) AUV
Attach GL to farm rig	F3	1) Manually	1) Knot tier such as CLAAS brothers	1) Rig design for automatic attaching 2) ROV 3) Knotless attaching		1) AUV
Deploy GL	F4	1) Crew throw ropes overboard	1) Rig layout for easy deployment	1) Rig design for automatic deployment 2) ROV		1) AUV
Disconnect from Rig	F5		1) Rig for easy disconnection 2) Release with crane	1) Computer operated crane release 2) Rig for automatic disconnection 3) ROV release		

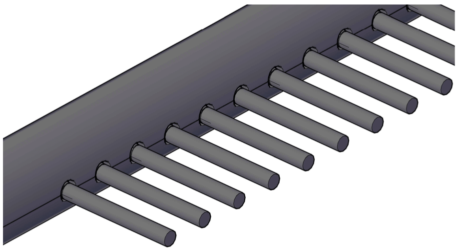
Table 4: Design Catalogue for Harvest Operation. A1-A5 are the 5 predefined levels of autonomy, F1-F7 are the respective subfunctions. Each cell containers a number of solutions that are briefly described, which should correspond to an autonomy level and a subfunction.

Subfunction		A1	A2	A3	A4	A5
Connect to rig	F1	1) Crew	1) Rig for easy connection	1) Computer operated crane 2) ROV 3) Rig for automatic connection		1) AUV
Detach GL	F2	1) Manual detaching or cutting of ropes	1) Rig for easy detaching 2) Force detaching with capstan	1) Rig for automatic detaching 2) ROV 3) Automated capstan system		1) AUV delivers rope to vessel
Retrieve GL	F3	1) Manually by crew	1) Winch controlled by crew 2) Vessel maneuvering to retrieve growth line	1) Automatic winch operation with crew aligning rope	1) Computer controlled winch, speed suggestion based on system status.	1) Winch controlled by computer, speed decided based on SA 2) Autonomous maneuvering (DP) and rope alignment system
Cut and process kelp	F4	1) Manually by crew	1) Rig for crew operations and pump control	1) Rig with automatic procedures, monitored and controlled by crew 2) ROV kelp cutting, vessel retrieves harvested kelp 3) Harvest aggregate mounted on crane	1) Rig with automatic procedures, giving suggestions to monitorer 2) AUV cuts kelp that informs vessel to retrieve full storage units	1) Rig performing actions autonomously based on SA and object classification 2) AUV cuts kelp that is pumped to vessel
Store kelp	F5		1) Leading trays and vessel storage 2) Leading trays and storage containers 3) Nets outside vessel	1) Rail system for leading trays and storage containers, monitored by operator	1) Rail system for trays over storage containers, system informs about container fill status	1) Autonomous Barge 2) Rail system for trays, system detects full storage units and fill new units
Clean and Store Ropes	F6		1) Rope scraped in ring or funnel, stored on drums	1) High-pressure spraying of ropes, winch controlled drums	1) Automatic rope handling and rope leading system detecting full drums or entangled rope	1) High pressure spraying and winch controlled drums, switched when full drums are detected
Disconnect from rig	F7	1) Manual detaching from rig	1) Rig for easy disconnection 2) Crane release controlled by operator	1) Computer operated crane release 2) Rig for automatic release 3) ROV release		

Many solutions exist for each subfunction. It is not in interest to illustrate how all of these are, but a selected few will be presented. Figure 32 shows how a knotless attaching system may function.



(a)



(b)

Figure 32: Illustration of a knotless attaching system. The tube is formed with openings where the rope goes through, as shown in (a). (b) shows the tube when it is closed, which is how it will be after deployment. The system can be rotated to allow for either horizontally or vertically deployed GLs. The illustration shows for a horizontal deployment. Concept is developed in AutoCAD.

Between each opening in the system shown in figure 32 it is possible to have clamps pressing the rope down. These clamps can then be constructed to only yield after a certain amount of pulling force is present. This will keep the ropes in place when the tube is opened, such that they will only be released when the vessel is ready for the next stretch of rope. The system corresponds to the suggested solution F3-A3-3) in table 3.

Figure 33 shows a proposal to F2-A2-1) for table 3 and F1-A2-1) for table 4. The idea is that buoys are deployed a given distance from the farm, where a vessel can enter and connect to the buoys to remain in place. At the buoys, a rope that is connected to the farm is attached. This can be retrieved by the crew and simplifies the harvest procedure. It does however not give a solution to deployment of new GLs. Combined with a knotless attaching system, this could increase the LOA of operations.

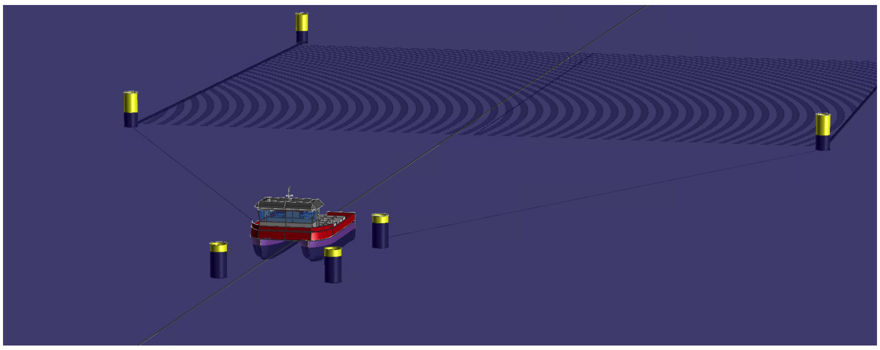


Figure 33: A connection method to the farm, where the vessel connects to buoys near the farm, and can retrieve GLs attached to these buoys. Concept developed in DELFTShip.

Figure 34 shows a proposal to F5-A3-1) or F5-A4-1) in table 4, where the idea is to use a rail system similar to what many warehouses have started to use over the last decade. The system can be attached to the frame of the vessel, for easy assembly and disassembly.

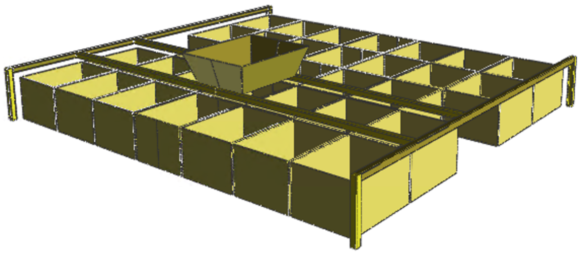


Figure 34: Rail system proposal for leading trays over storage containers. Concept developed in DELFTShip.

The concepts proposed in figures 32 and 33 will require new developments that simplifies operations at a vessel, while the concept proposed in figure 34 is based on existing solutions, and will improve the operation onboard a vessel. This is beneficial as it does not set any demand on other aspects of the production. This is however expected to be required for increasing the LOA of operations.

4.3 Autonomous Job Analysis

As the design catalogue has been constructed, a clearer picture shows the potential of increasing the LOA of a kelp harvesting vessel. By observing which categories A1-A5 the different subfunctions are missing solutions, it becomes clearer what is necessary in terms of technological development to increase the LOA. There are already several projects that have focused on the navigation and docking operations for autonomous vessels, and these operations are therefore not studied in terms of LOA in this thesis any further. The AJA tables created for the vessel were based on the main functions previously defined. This resulted in determining a desired LOA for the vessel during different tasks, which again will aid the decision towards what SPs to choose. Table 5 and 6 summarizes the finding by using the AJA tables, while the complete tables are found in appendix C and D.

Table 5: Summary of results from AJA for main function deployment. Subgoals of the operation with LOA and general notes about the goal of the sub-operation.

	1: Deployment	
Subgoal	LOA	Note:
1: Seeding	3	Risk of Entanglement
2: Connect to Rig	5	Similar to Docking
3: Attach GL	3	Few Existing Solutions
4: Deploy GL	3	Remote Controlled
5: Disconnect from Rig	5	Similar to Undocking

Table 6: Summary of results from AJA for main function harvest. Subgoals of the operation with LOA and general notes about the goal of the sub-operation.

	2: Harvest	
Subgoal	LOA	Note:
1: Connect to Rig	5	Similar to Docking
2: Detach GL	2	Few Existing Solutions
3: Retrieve GL	3-4	Goals 3-6 Simultaneously
4: Cut and Process Kelp	4	Goals 3-6 Simultaneously
5: Store Kelp	4	Goals 3-6 Simultaneously
6: Store Rope	4	Goals 3-6 Simultaneously
7: Disconnect from Rig	5	Similar to Undocking

4.4 Performance Criteria

To evaluate the vessel design of the next section, some criteria has to be set. These can be used to determine if the design may become attractive and competitive, or if other design paths should be considered.

4.4.1 Cost

The decision to invest in a product will in most cases be based on the opportunity of increased income or reduced costs, or preferably both. Thus, it is important to have a reference scenario to compare the concept solution to. In this case, as kelp cultivation is a very seasonal activity, the reference scenario is chosen to be chartering a vessel. From interviews it was learned that chartering may cost anything from 3000-6000NOK/h (Myhre 2020). By choosing a scenario where the cost is 4500NOK/h, an estimated cost scenario was made based on deployment and harvest speed, and farm sizes. The results are summarized in table 7, while calculations are given in appendix E. It is expected that for a chartered vessel, the efficiency of deployment and harvest will also increase. The cost per kg kelp is therefore expected to decrease over the next 20 years. The cost of chartering will come in addition to the cost of rig installing, maintenance, monitoring, cultivation, processing and packaging of kelp, and the total cost of kelp is not represented in this table. For a cost lower than 2NOK/kg wet weight (WW) of kelp, the vessel cost should be as low as reasonably possible. From the table, the cost is calculated to be approximately 1NOK/kg in 2036-2040. The required freight rate (RFR) is therefore set to 0,5NOK/kg, while the maximum cost should be 1NOK/kg.

Table 7: The total cost of operation and cost per mass of kelp in each period for chartering a vessel.

	2021-2025		2026-2030		2031-2035		2036-2040	
Total Cost	5,97	MNOK	17,54	MNOK	24,68	MNOK	37,82	MNOK
RFR	4,86	NOK/kg	2,34	NOK/kg	1,22	NOK/kg	0,93	NOK/kg

The table is based on an increasing harvest speed during operations, which starts at 5m/min in 2021-2025, and is assumed to end at 20m/min in 2036-2040. This will be evaluated further after the vessel design in section 5.

4.4.2 Speed

It was determined that the new solution should be more efficient than existing solutions. From conducted interviews (Myhre 2020), the harvest speed, V_h, of different companies was evaluated. These results are summarized in table 8. V_h is calculated based on an entire day of operation, and the average length of rope that was harvested during a day. This means that the actual speed during harvest is higher. The average V_h of these companies is approximately 5m/min, which will be the minimum requirement for the current design.

Table 8: The harvest speed estimations of 3 companies and the calculated average of these three. Based on information from interviews (Myhre 2020).

	Company 1	Company 2	Company 3
Harvest Speed	6 m/min	1 m/min	8 m/min
Average		5 m/min	

4.4.3 Energy and Resource Consumption

Several farm owners wish to promote their products as environmentally friendly and sustainable. Customers desire a sustainable product as well. This sets requirements on the production of kelp, and there is a general wish that the emissions in production are as low as possible. From the LCA discussed in section 2.2, it is clear that a more efficient use of energy and resources is necessary. There will not be performed an LCA in the thesis, but the vessel should be designed with a focus on low emissions.

4.4.4 Crew

No specific requirement can be given for the number of crew in operation. The main objective is that the design must ensure safe working environment for the onboard crew. The objective will be to have as few crew as reasonable, as labor costs are a major factor in the production cost. For the crew required, a ”no hands on rope” operation is preferred. This will require a high degree of mechanization and preferably automation of operations.

4.5 Solution Paths and Analysis

Tables 9, 10 and 11 show some of the possible SPs for the harvest operation, with solutions from table 4. Due to limited time, a similar analysis was not performed for deployment. It is however assumed that the general trend in each SP is also reflected in the SP for deployment. For instance, SP1 is focused on manual solutions, and it is assumed that similar choices are made for SP1 for deployment, for these to correspond.

Table 9: Solution path 1 and 2 for harvest operation. Solutions are retrieved from the design catalogue for harvest in table 4.

Solution Path 1 - Fully Manual			
F1	A1 - Crew	F5	A2 - Leading trays and storage containers
F2	A1 - Manual Detaching	F6	A2 - Rope scraped in ring or funnel
F3	A1 - Manually by crew	F7	A1 - Manual detaching from rig
F4	A1 - Manually by crew		
Solution Path 2 - Fully Autonomous			
F1	A5 - AUV	F5	A5 - Rail system for trays, detects full storage units and fill new units
F2	A5 - AUV delivers rope to vessel	F6	A5 - High pressure spraying and winch controlled drums, switched when full drums are detected
F3	A5 - Winch controlled by computer, speed decided based on SA	F7	A3 - Computer operated crane release
F4	A5 - Rig performing actions autonomously based on SA and object classification		

Table 10: Solution path 3 and 4 for harvest operation. Solutions are retrieved from the design catalogue for harvest in table 4.

Solution Path 3 - Specialized Rig			
F1	A3 - Rig for automatic connection	F5	A2 - Leading trays and storage containers
F2	A3 - Rig for automatic detaching	F6	A2 - Rope scraped in ring or funnel, stored on drums
F3	A2 - Winch controlled by crew	F7	A3 - Rig for automatic release
F4	A1 - Manually by crew		
Solution Path 4 - Specialized vessel			
F1	A3 - Computer operated crane	F5	A3 - Rail system for leading trays and storage containers, monitored by operator
F2	A3 - Automated capstan system	F6	A3 - High pressure spraying of ropes, winch-controlled drums
F3	A3 - Automatic winch operation with crew aligning rope	F7	A3 - Computer operated crane
F4	A3 - Harvest aggregate mounted on crane		

Table 11: Solution path 5 and 6 for harvest operation. Solutions are retrieved from the design catalogue for harvest in table 4.

Solution Path 5			
F1	A3 - Rig for automatic connection	F5	A3 - Rail system for leading trays and storage containers, monitored by operator
F2	A2 - Rig for easy detaching	F6	A2 - Rope scraped in ring or funnel, stored on drums
F3	A2 - Winch controlled by crew	F7	A3 - Rig for automatic release
F4	A3 - Rig with automatic procedures, monitored and controlled by crew		
Solution Path 6			
F1	A3 - Computer operated crane	F5	A2 - Leading trays and storage containers
F2	A2 - Rig for easy detaching	F6	A3 - High pressure spraying of ropes, winch-controlled drums
F3	A2 Vessel maneuvering to retrieve GL	F7	A3 - Computer operated crane
F4	A2 - Rig for crew operations and pump control		

SP1 is based on a fully manual solution. The crew is included in working tasks to a high degree, which will allow crew members to gain experience and understanding of how kelp cultivation functions. The benefit of the SP is that the crew is in full control of the operations, and have a large flexibility to adjust to different situations that may occur. It is also beneficial for crew to be at the farm and observe the interactions at the farm, as the knowledge in this industry still not high enough to allow for unmanned farm operations.
The SP does not however fulfill some of the needs that were stated by the main stakeholder. Although unmanned operations are unlikely at this point, this SP is likely to involve a large number of crew, which will result in a high cost harvest that is unlikely to have a high enough efficiency during operations compared to what good technical solutions may propose. The SP does also require crew to handle rope, and poses a high risk of operations.

SP2 is focused on a fully autonomous solution. The SP will motivate unmanned operations that may enable a vessel to operate 24/7. This will reduce the required capacity in terms of speed and size of a vessel as it can perform more trips per day than a manned vessel with a shorter operation window will allow. The cost will also be reduced when no labor costs exist. Major technological advancements have to take place before this becomes a reality, however. To develop these technologies as well as an autonomous vessel is likely to bring such high costs that a manned vessel is more likely to be cheaper.

SP3 and SP4 focuses on a highly specialized farm rig, and a highly specialized vessel, respectively. The advantage of a highly specialized farm rig is that it may enable many types of vessels to perform operations at the farm. A possible concept for this type of rig can be the SPOKe concept as in figure 14. This may become attractive as it reduces the investment cost in a vessel. It will however require a higher capital cost in the farm rig. Currently, these rigs are not expected to be durable for more than 5 years in sea. A highly specialized farm rig will increase the investment cost in the rig, and if a rig has to be replaced several times within the lifetime of a vessel, it could be beneficial to rather invest in a more specialized vessel. SP4 focuses on the specialized vessel capable of efficient operations at farm. A vessel with a high degree of specialization can be restricted in flexibility. With the short season for a vessel in kelp cultivation, this will lead to a low utility and high cost.

SP5 and SP6 are not fully manual or autonomous, and does not depend on a highly specialized vessel or rig. The main difference between the two SPs is the reliance on computer to provide information during the operations. SP5 is motivated by an operator that monitors and controls the initiation of most processes, while the system itself should be capable of detecting and helping the operator to perform operations in a safe and efficient way. SP6 aims at most of the similar solutions, but will require more control by the operator, who takes a more active role during operations.

SP5 is based on a knotless attaching system that does not currently exist, but assumes such a development to be in place, while SP6 is intended to suggest a knotting machine that can perform this operation. This may be beneficial as it reduced the reliance on farms, but knotting machines are few and complex, and typically specialized for a specific knot or rope thickness, making a development here necessary as well.

Knotless attaching systems are not necessarily too difficult to envision, and a sketch of such a system is shown in figure 32.

4.6 Section Summary

The problems relevant to vessel design were defined to highlight the areas of focus for a design. A stakeholder analysis was performed to identify what stakeholders exist and which to be prioritized. The needs of the main stakeholders were defined, and mapped to the functional domain by a system breakdown of a vessel. The payload related systems were defined, and have been subject to a functional breakdown. This was done in accordance with the AJA, which made it clear what the sub-operations were. By setting up a solution matrix based on the subfunctions and predefined LOAs, design space and opportunities were identified by suggesting solutions to each subfunction. This showed what expected LOA the vessel could achieve, and if any requirements would be set to other systems not in the current design. SPs were suggested and analyzed against each other and the stated needs and requirements. This resulted in the choice of a SP believed to be more feasible in implementation than other SPs. With the chosen SP, the next phase is determining the main design parameters for the vessel. Table 12 summarizes some findings from this section.

Table 12: Summary of the findings and conclusions of section 4.

Key Stakeholders	
Kelp Farm Owner	Other Kelp Farm Owners
Fish Farm Owners	Vessel Crew
Needs (N) and Main Functions (F)	
N: Efficient Operations	N: Flexibility
F: Seed and Deploy GLs	F: Harvest and Deliver Biomass in Desired State
Solution Path 5	
Desired LOA	3
Particulars	
Knotless attaching	Rig for automatic connection
Rail system and rig for automatic procedures	Crane for loading / unloading and connection to farm
Performance Criteria	
Harvest Speed	5m/min
Maximum RFR	1,0NOK/kg
Resource Consumption	A low-emission focus
Required Crew	As few as a safe operation requires

5 Design of A Kelp Farm Vessel

In this section, the chosen SP from section 4 will be designed onto a suitable vessel. The designed vessel will further be evaluated based on the performance criteria.

5.1 Determining Payload Capacity

To establish the main dimensions of the vessel, it is important to understand the necessary payload capacity to be handled. For a given farm, the assumed farm size and yield is given in table 13. It is further assumed that the harvest window for a kelp farm is set to 21 days. For the given farm, it is assumed that the first harvest is in May, while a second harvest can be performed in August. With a known harvest window and farm yield, it is possible to estimate a daily capacity in tons. To understand the volumetric capacity of the vessel, it is also necessary to assume the storage density of the payload, which will vary depending on the end-product and the method of storing. Bekkevoll et al. (2019) studied the attainable storage density of kelp for different treatment methods. For whole plants and cut plants, storage density at different applied pressures are given in table 14.

Table 13: Estimated farm size and yield development from 2021-2040.

	2021-2025		2026-2030		2031-2035		2036-2040	
Rope Length	49 140	m	150 000	m	270 000	m	480 000	m
May Yield	5	kg/m	7	kg/m	10	kg/m	10	kg/m
August Yield	0	kg/m	3	kg/m	5	kg/m	7	kg/m
Farm Yield May	245,7	tons	1050	tons	2700	tons	4800	tons
Farm Yield August	0	tons	450	tons	1350	tons	3360	tons

Table 14: Density of kelp for different pressures if it is stored as whole plants or cut.

	Whole Plants		Machine Cut Plants	
No pressure, 0kPa	300	kg/m^3	600	kg/m^3
Low pressure, 8kPa	500	kg/m^3	850	kg/m^3
Moderate pressure, 800kPa	1000	kg/m^3	1200	kg/m^3

For the given farm, it is assumed that for the two first periods, 2021-2025 and 2026-2030, the kelp is cultivated for application in food. From 2031, the end-product is assumed to be biofuel. This allows a change in the method of storing. It is now possible to study the varying required daily capacity for harvesting the farm within 21 days. The results are given in table 15. The vessel will be determined based on the harvest with the largest demand, which is a harvest in May.

Table 15: The required payload capacity in terms of tons and m^3 per day for a given harvest window of 21 days. The minimum storage volume is based on a maximum storage density of 1200kg/m^3, the maximum storage volume is based on a storage density of 300kg/m^3.

	2021-2025		2026-2030		2031-2035		2036-2040	
Weight	11,7	tons/day	52	tons/day	129	tons/day	229	tons/day
Minimum Volume	9,75	m^3/day	43	m^3/day	108	m^3/day	191	m^3/day
Maximum Volume	39	m^3/day	172	m^3/day	429	m^3/day	762	m^3/day

If several vessels operate within the farm, or if a vessel is capable of taking several trips per day, the dimensions of the vessel will be reduced. How many trips a vessel will be able to take per day will depend on the hours of operation per day. As the technology is not at a level where fully autonomous operation is yet possible, it is expected that the vessel will operate manned during the start. If manned operation is assumed to be within 8 or 12 hours per day, and 24-hour operation per day for fully autonomous solution, it is possible to study some combinations of fleet size, vessel size and trips per day. Table 16 shows the assumptions made to estimate the time of different operations performed during a trip, which were calculated from equations (1)-(4). Table 17 summarizes the fleet and vessel size, trips per day and required harvesting speed to complete the farm within 21 days. The harvesting speed should not exceed 2m/s, as this has been shown that at higher speeds the kelp will start to loosen from the GL, before being taken onboard the vessel (Bekkevoll et al. 2019).

Table 16: Operation time of sailing, maneuvering charging per trip for 8, 12 and 24h working days.

	Sailing Time, T_s		Maneuvering Time, T_m		Charging Time, T_c	
8 h/d	2,22	h/trip	1	h/trip	0	h/trip
12 h/d	2,22	h/trip	1	h/trip	0	h/trip
24 h/d	2,22	h/trip	1	h/trip	1	h/trip

The sailing time, T_S, is calculated as in equation (1).

$$T_s = 2 \cdot \frac{D}{V_s} = 2 \cdot \frac{10nm}{9kn} = 2,22h, \tag{1}$$

where D is the sailing distance in nautical miles, and V_s is the sailing speed of the vessel in knots. Maneuvering time, T_m, is assumed to be

$$T_m = 1h. \tag{2}$$

Unloading time is calculated as

$$T_u = V_u \cdot L_v, \tag{3}$$

where V_u is the unloading speed in s/m^3, and L_v is the payload capacity in m^3.

The harvesting time is calculated as

$$T_h = \frac{L_v \cdot \rho_{sk}}{V_h \cdot y_k \cdot 3600\frac{s}{h}}, \tag{4}$$

where ρ_{sk} is the storage density of kelp in kg/m^3, V_h is the harvest speed in m/s and y_k is the rope yield of kelp in kg/m.

It is worth noting that many other combinations exist that may fulfill the requirements, but the results presented in table 17 is for a selected variety with a capacity up to 12 tons. The results showed that the fleet and vessel size would increase with an increasing farm size. In volume, the given capacities are between 7,8-38,2m^3 for a storage density of 300kg/m^3. For all scenarios, V_h was within the maximum allowed. By increasing the storage density to 500kg/m^3, the maximum capacity required would become 23m^3.

Table 17: Required vessel capacity and minimum harvest speed for a chosen number of vessels and trips per day, depending on the hours of operation per day. Time periods are with corresponding farm yield as given in table 13. The harvest window is set to 21 days.

	Vessels			**Capacity**		
Hours	8 h/d	12 h/d	24 h/d	8 h/d	12 h/d	24 h/d
2021-2025	1	1	1	5,85 tons	3,90 tons	2,34 tons
2026-2030	3	2	2	8,33 tons	8,33 tons	5,00 tons
2031-2035	7	5	3	9,21 tons	8,60 tons	8,60 tons
2036-2040	10	8	5	11,45 tons	9,54 tons	9,16 tons
	Trips per Day			**Harvest Speed**		
Hours	8 h/d	12 h/d	24 h/d	8 h/d	12 h/d	24 h/d
2021-2025	2	3	5	0,61 m/s	0,35 m/s	0,27 m/s
2026-2030	2	3	5	0,77 m/s	0,77 m/s	0,54 m/s
2031-2035	2	3	5	0,79 m/s	0,57 m/s	1,09 m/s
2036-2040	2	3	5	0,60 m/s	0,70 m/s	1,30 m/s

By choosing a vessel capacity of approximately 32m^3, the vessel should have sufficient capacity, assuming that the storage density increases over the years. The working hours and storage density for the four scenarios were further assumed, as given in table 18.

Table 18: Assumed hours of operation per day and storage density of kelp for the four scenarios.

	2021-2025	2026-2030	2031-2035	2036-2040
Operations hours	8 h/d	8 h/d	12 h/d	24 h/d
Storage Density	300 kg/m^3	500 kg/m^3	600 kg/m^3	850 kg/m^3

Assuming that V_h will be approximately 2m/s, and that charging will happen simultaneously as unloading, such that only the largest of the two entities is included in the operation time, the total operation time, T_o, per trip for each scenario can be calculated as in equation (5).

$$T_o = T_s + T_m + T_h + max(T_u, T_c), \tag{5}$$

where T_c is the charging time.

Table 19 shows the minimum fleet size to complete the farm within a maximum of 21 days, when the vessel size, in m^3, and operation time is given.

Table 19: Minimum fleet size and trips per day required, when the vessel size and operation times are given.

	2021-2025	2026-2030	2031-2035	2036-2040
Vessels	1	2	3	2
Trips per day	2	2	3	5
Days to Finish	13	17	16	17

For 2021-2025, one vessel performing two trips per day reaches a capacity of 64m^3 per day, and is able to finish the farm within 13 days. For 2036-2040, the two vessels performing five trips per day finished the farm within 17 days. This indicates that the capacity chosen could be sufficient for the assumptions made.

5.2 Establishing Main Dimensions

With the volumetric capacity given, the required areas of the vessel can be estimated. Kelp should not be stored too dense, and it should not be stacked higher than 1m. Thus, containers of 1m^3 are chosen (Frøystad 2020). These are estimated to require an area of 1,77m^2 each, and the total storage area then becomes

$$A_{storage} = 1,77m^2/unit \cdot 32units \approx 57m^2. \tag{6}$$

Most of the payload related systems will be designed to be located above the containers, as this will allow the kelp to easily be led to the storage. It is not expected that payload related systems will require a lot of extra deck area. By assuming that the storage area accounts for around 65% of the required area, the main deck may be assumed to require an area of

$$A_D = L_D \cdot B_D = \frac{A_{storage}}{0,65} \approx 90m^2 = 10m \cdot 9m \tag{7}$$

where L_D is the deck length, and B_D is the deck breadth.

This should allow for sufficient area for the components, as well as areas for crew to move around. When the dimension of the main deck is established it is possible to estimate some dimensions of the vessel. If the deck-length is approximately 65% of the length of the vessel, the length overall (Length OA), L_{oa}, will be 15.38m. Due to different regulations for vessels over 15m than for those under 15m, we will set L_{oa} to 15m. Furthermore, the length between perpendiculars (Length BP) is typically set to approximately 92% of the ship length. By allowing for 0.5m on each side of the deck, the molded beam (B_m) can also be found. As the draft, T, is required to be below 2m, setting the molded depth, D_m, to 3m, the vessel should at least have a freeboard of 1m.

The lightship weight (LSW), W_{ls}, can be found as

$$W_{ls} = W_H + W_M + W_E, \tag{8}$$

where W_H is the hull weight, W_M is the machinery weight and W_E is the equipment weight.

The LSW can also be estimated based on typical LSW coefficients. For smaller cargo vessels, this coefficient is typically as given in equation (9) (Amdahl et al. 2015).

$$\frac{W_{ls}}{L_{bp}B_mD_m} = 0,18 \tag{9}$$

By using this relation, the weight displacement, Δ, can be found as

$$\Delta = dwt + W_{ls}, \tag{10}$$

where dwt is the deadweight of the vessel, which is considered anything that is not welded onto the ship. A calculation of the estimated dwt can be seen in table 20.

Table 20: Deadweight estimation for the maximum expected payload capacity.

	Units		Unit Weight		Total Weight	
Biomass	32	m^3	850	kg/m^3	27200	kg
Rope	2720	m	0,15	kg/m	408	kg
Storage Containers	32	-	100	kg	3200	kg
Rope Drums	3	-	28	kg	84	kg
Crew	3	-	150	kg	450	kg
Water	0,3	m^3	1000	kg/m^3	300	kg
Supplies	3	-	100	kg	300	kg
Lubrication	2000	kWh	0,0015	kg/kWh	3	kg
Other	1	-	555	kg	555	kg
Total					32500	kg

By finding the weight displacement, the volume displacement, ∇, can also be found, as in equation (11).

$$\nabla = \frac{\Delta}{\rho_{sw}} \tag{11}$$

where ρ_{sw} is the density of seawater in kg/m^3.

It is possible to estimate the power requirement for the vessel, based on the coefficient of admiralty, A_c, which is calculated as shown in equation (12).

$$A_c = \frac{\Delta^{\frac{2}{3}} \cdot V_s^3}{P_B}, \tag{12}$$

where P_B is the engine power.
This will however require us to estimate A_c, which can be done by studying vessels that are expected to be similar to the respective design. For this, five vessels were studied. Astrid Helene is a fully electric service catamaran for fish farms, Fosna Amon, Perlen and Engeløy are traditional fish farm service catamarans, and Taresund is a monohull kelp trawler. Vessel data and calculations are given in appendix F.

The chosen vessels are mainly catamaran hulls. Because of the short operational season for kelp farms, the vessel will be designed to be attractive for chartering to other industries as well, and especially fish farm operations. As most service vessels for fish farms are catamarans, this is the chosen hull design for the kelp farm as well. Catamaran hulls give a better initial stability, and the available deck area is typically large. This is advantageous for the kelp farm as well.

From the vessels used for comparison, a coefficient of admiralty of 45 was chosen for the current design. This allowed an estimate to be made on the power requirement of the vessel, based on equation (12).

$$P_B = \frac{(0,18ton/m^3 \cdot 13,75m \cdot 10m \cdot 3m + 32,5tons)^{\frac{2}{3}} \cdot 9^3}{45} \approx 365kW \tag{13}$$

By using energy packages delivered by Corvus Energy (Energy 2020), and by assuming an auxiliary power demand of 10%, the required installed package for a range of 100nm becomes minimum 4000kWh, which corresponds to a battery weight of 53.5 tons using the Corvus Orca. As this is approximately 72% of the assumed W_{ls}, it is concluded that the current estimates are not adequate. Installing a battery package of

2000kWh is then chosen, and will become a limiting factor for the range of the vessel. The LSW will then be calculated based on equation (8).

Smaller cargo vessels have a hull weight relation given as in equation (14) (Amdahl et al. 2015).

$$\frac{W_H}{L_{bp}B_mD_m} = 0,10 \tag{14}$$

This coefficient typically decreases with an increasing ship size. By assuming that

$$\frac{W_H}{L_{bp}B_mD_m} = 0,15, \tag{15}$$

for our vessel, the hull weight can be estimated.

The machinery system consists of the propulsion system, main engine, battery storage and other components. The chosen propulsion system is water jet propulsion, for its benefits of good maneuverability and no external propellers, which is an efficient way of eliminating the risk of rope entanglement in the propellers. Based on the expected power requirement, an engine weight was assumed, as well as other systems such as switchboard and firefighting systems. The machinery system component weights and area are summarized in table 21.

Table 21: Summary of Machinery Components with Weight and Area

	Weight		Area	
Water Jet	950	kg	1,56	m^2
Electric Motor	3400	kg	0,86	m^2
Battery Storage	25920	kg	10,24	m^2
Control and Switchboard	1000	kg	1	m^2
Fire Fighting System	1300	kg	0,5	m^2
Other Components	3030	kg	2	m^2
Total	35600	kg	16,16	m^2

The machinery system is designed for redundancy to mitigate the risk of failure. Each machinery component has two units, and to include space for crew to perform maintenance and inspections, it is assumed that the total required area is approximately $40m^2$.

The payload related systems mainly consist of kelp and rope handling equipment. This includes a rig for harvesting, winch and drums for rope handling, crane for cargo lifting and farm operation and other ship outfitting. Table 22 shows the weights of the equipment components, and the required deck area that is assumed. The crane weight was based on the PKM 18500M, which was chosen due to its range and lifting capacity (BGHYD 2020).

Table 22: Summary of estimated equipment weights and areas.

	Weight		Deck Area	
Harvest Rig	450	kg	1,5	m^2
Winch and Drums	150	kg	3	m^2
Crane and Controller	2900	kg	1,5	m^2
Pump System	200	kg	1	m^2
Bridge and Ship Outfitting	5000	kg	30	m^2
Autonomous System	300	kg	3	m^2
Total	9000	kg	40	m^2

Equipment developments are assumed to take place. This includes a seaweed rotacutter suitable for the vessel, which could be based on StormCranes (2020), or a new development all together. The harvest rig should also include a harvesting machine, which can lead the rope through and cut the kelp at a desired length from the rope. Applying pressure could be executed by using the onboard crane, or a new development that allows a tray, rotacutter and pressure-plate to be designed together.

The LSW can now be calculated as given in equation (16). As the design will be a catamaran, the hull width is assumed to be 4m.

$$W_{ls} = 0,15 tons/m^3 \cdot (13,75m \cdot 4m \cdot 3m) \cdot 2 + 35,6tons + 9tons = 94tons \tag{16}$$

This allows us to determine the weight displacement, and the following volume displacement of the vessel.

$$\Delta = W_{ls} + dwt = 94tons + 32,5tons \approx 127tons \tag{17}$$

$$\nabla = \frac{\Delta}{\rho_{sw}} = \frac{127tons}{1,025tons/m^3} \approx 124m^3 \tag{18}$$

The block coefficient, C_B, is useful for determining T, and is also very useful in resistance calculations. It describes the vessels fullness under the waterline, and is calculated as given in equation (19).

$$C_B = \frac{\nabla}{L_{bp} \cdot B_m \cdot T} \tag{19}$$

To estimate C_B, typical coefficients for different vessel categories and Froude numbers, F_N, are used. F_N is in naval architecture used to study the resistance of a vessel moving through water (Amdahl et al. 2015). It is calculated as given in equation (20). As F_N only depends on the vessel length and speed, it can be used to compare the dynamics of vessels with similar Froude numbers, even if their geometry is otherwise different.

$$F_N = \frac{V_s}{\sqrt{g \cdot L_{bp}}}, \tag{20}$$

where V_s is measured in m/s, and g is the gravitational acceleration. With the assumed vessel speed of 9kn, F_N can be determined

$$F_N = \frac{9 \cdot \frac{1852}{3600}}{\sqrt{9,81 \cdot 13,75}} \approx 0,4. \tag{21}$$

The relation between F_N and C_B can be seen in figure 35. With F_N known, the C_B is determined.

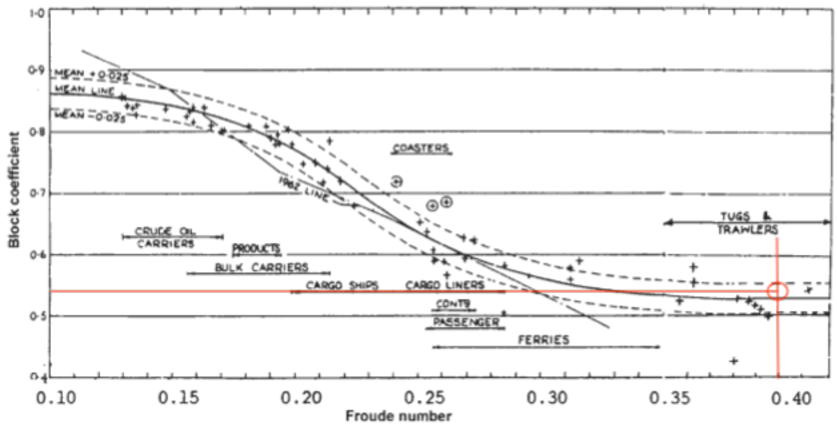


Figure 35: Relation between Froude Number and Block Coefficient for different vessel types (Watson 1998). The red ring indicates the assumed area for the current vessel design. The red support lines are used to read from the graph.

By using equation (19), T can be determined. A reiteration of the power demand is performed, and the results of the initial main dimensions, design speed and power requirements are summarized in table 23.

Table 23: Summary of Main Dimensions, Main Weights, Design Speed and Range, and Power Demand and Storage

Length OA	15	m	Lightship Weight	94	tons
Length BP	13,75	m	Deadweight	34,5	tons
Hull Beam	4	m	Weight Displacement	128,5	tons
Molded Beam	10	m	Volume Displacement	125	m^3
Depth molded	3	m	A_c	45	$m/kg^{1/3}$
Draft	2,08	m	C_B	0,55	
Design Speed	9	kn	P_T	460	kW
Range at 9 kn	40	nm	P_S	2000	kWh

To verify the result, it is possible to use typical design relations, such as dwt/∇, B_m/T and B_m/D_m relations. These relations are checked for the vessel and compared to the reference vessels. In table 24, these relations are summarized for all the vessels.

Table 24: Summary of calculated relations for the current design and reference vessels.

Vessel	Kelp Zero	Astrid Helene	Fosna Amon	Taresund	Perlen	Engeløy
dwt/∇	0,28	n/a	n/a	0,28	0,64	0,31
B_m/T	4,81	5	5	2,59	5	4
B_m/D_m	3,33	3,17	3,45	2,09	3,16	2,7

These results show that the current design does not have relations that are out of the ordinary for a vessel of its size. This is used as a verification that the dimensions are somewhat reasonable, and a hull form will thus be modelled next. Later in the design phase, comparisons should be made to verify throughout the process that the dimensions chosen are reasonable.

5.3 Hull modeling

When the main dimensions are established, the hull can be designed. A 3D model of the vessel can be seen in figure 36. Figure 37 shows the profile view of the vessel, where the aft (AP) and forward (FP) perpendiculars are marked, as well as the construction waterline (CWL) which was found after a second iteration process after the hull modelling was performed. This will be discussed later in this section. With length BP of 13,75m, assuming an equal distribution of the remaining length in the aft and bow, the AP is located at 0,625m and FP at 14,375m. The vessel was divided into 10 sections of length 1,25m between AP and FP. The hull width was set to 4.0m, and the total molded beam becomes 10m.

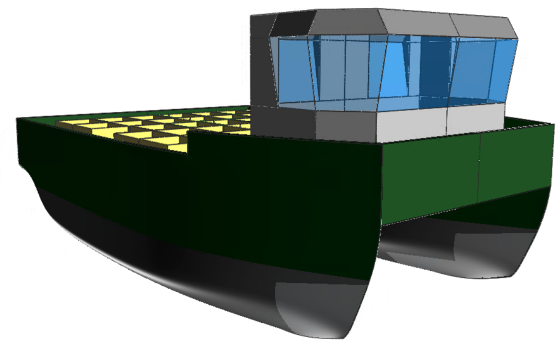


Figure 36: 3D representation of the Kelp Vessel Design from the hull model developed in DELFTShip.

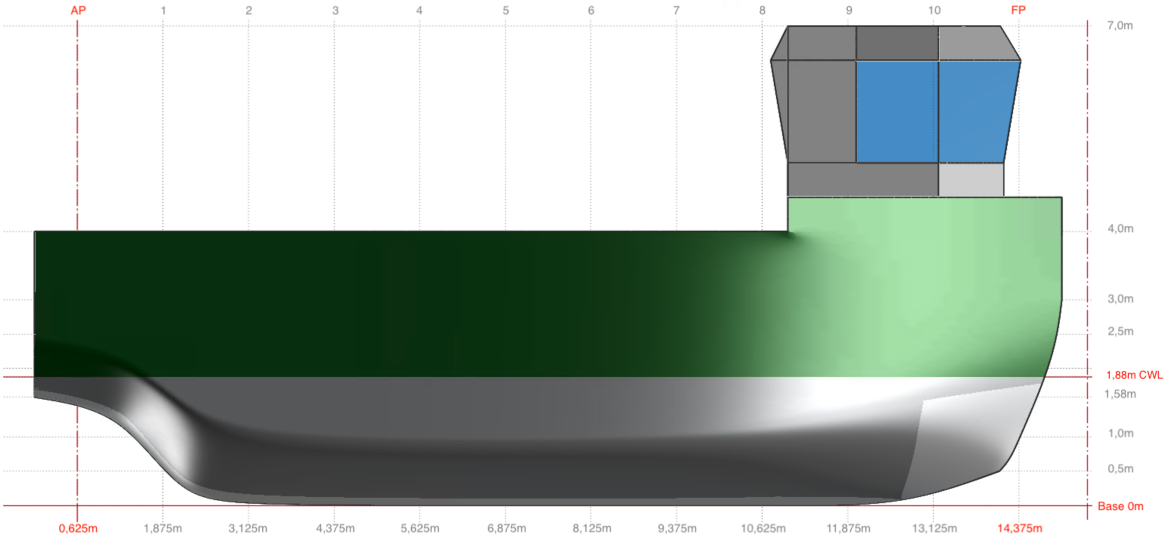


Figure 37: Profile View of the Kelp Vessel Design from the hull model developed in DELFTShip.

When the hull was modelled, the design hydrostatics could be retrieved from DELFTShip, which gives a more accurate calculation of the displaced volume and weight, and coefficients of the vessel. Assuming a shell thickness of 0,01m, and a steel weight of 7,89tons/m^3, the corresponding hull and superstructure weight could be found. The weight of the decks was calculated by retrieving the waterlines at the corresponding heights and estimating the geometric figure by rectangles and triangles. The results indicated that the hull weight was very similar to the estimate. However, the displaced volume was higher than the estimate, due to DELFTShip using the length on waterline instead (Length WL) of the length BP to calculate the displaced volume. This is more accurate, and it was therefore decided that the estimated draft based on length BP was too high. By using the length WL instead, T was estimated to 1,88m. The displaced volume calculated by DELFTShip was then very similar. A summary of these results can be seen in table 25.

Table 25: Comparison of initial calculations for displaced volume, weight, and block coefficient, to the results from DELFTShip

	Displaced Volume		Displaced Weight		Block Coefficient
Initial Calculations	125	m^3	128,5	tons	0,55
DELFTShip 2,08m Draft	152	m^3	156	tons	0,6161
DELFTShip 1,88m Draft	132	m^3	133	tons	0,5964
Initial W_H	50	tons			
W_H based on DELFTShip	52	tons			

The CWL was then set to be at 1,88m. Although the C_B is higher than anticipated, it is assumed adequate, due to a critical demand for space onboard the vessel. There has not been performed a hydrostatic analysis to determine the resistance due to the distance of each hull to each other. This should be done to determine if a hull distance of 2m between each hull is adequate. Slamming against the deck from waves between hulls will also occur, but no calculations on the impact of this has been performed, and should be studied to determine the consequences of such effects.

5.4 General Arrangement

After the hull modeling was performed in DELFTShip, these drawings were transferred to AutoCAD for general arrangement drawings. These drawings are important to verify that the dimensions of the vessel are sufficient for the required areas as previously determined, or if the vessel is potentially over dimensioned. The general arrangement should be made in accordance with stability calculations. The stability of the vessel greatly depends on the center of gravity (COG) in longitudinal (LCG), transverse (TCG) and vertical (VCG) directions, which again greatly depends on the hull shape and the placement of tanks and equipment onboard. The process of hull modeling and general arrangement may become an iterative process if it is discovered that decks are not sufficiently large enough, and this is a very time-consuming process. It is therefore important that the dimensions are determined to a somewhat high degree of accuracy before this process is executed, as one can easily become constrained to the hull model of the initial design. This can also be seen as a weakness with 3D modeling the design, as it often restricts the creativity going forward.

Figure 38 shows the profile-view of the vessel with general arrangement. For the complete set of general arrangement drawings, the reader is referred to appendix G.

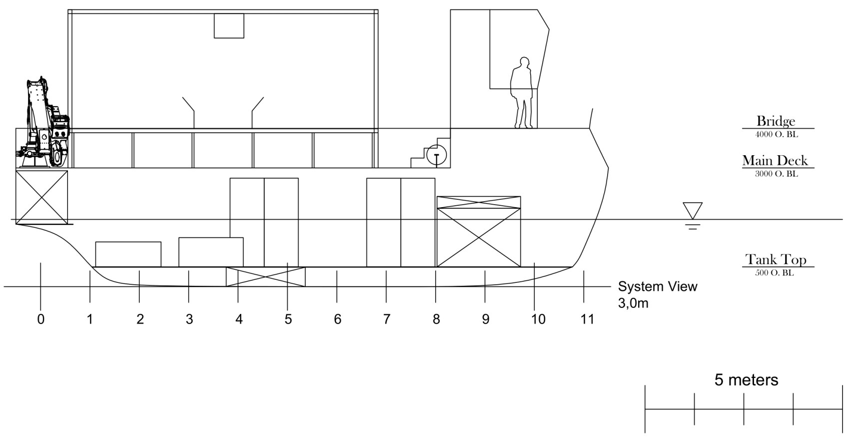


Figure 38: The profile view of the designed vessel with general arrangement, retrieved from AutoCAD.

The vessel consists of three decks as shown in figure 38, the machinery deck located on the tank top, the main deck and the bridge deck. Ballast tanks are placed in the aft and bow of the vessel, and one on the starboard side under the machinery deck. Other tanks such as for fresh water and wastewater are located on top of the ballast water tanks in the bow. The payload related systems are placed on the main deck, while most ship systems are located on the machinery deck and the bridge deck. Arrangement was made in accordance with COG calculations to ensure low trim, but ballast tanks were concluded necessary. The general arrangement drawings were made with the maximum load condition in mind.

5.5 Vessel Performance

With a design proposal given, it is possible to evaluate the performance of the vessel in the given scenarios. With the expected development of the market, the vessel will be evaluated for each 5-year period between 2021-2040.

5.5.1 Early Intact Stability

The Center of Gravity of a vessel is important to find, as it is a parameter that is often used to predict the initial stability of a vessel. It is usually found after a vessel is launched, but there are methods to predict it before a vessel is constructed. The calculations have been performed when the hull was modelled, given assumptions about the general arrangement, and was checked after the general arrangement was decided as well. A typical measure is to calculate the initial metacentric height (GM), which should be positive for good initial stability. GM is calculated as given in equation (22), where KB is the distance from keel to the flotation center of the hull, BM is the initial metacenter radius, and KG is the vertical center of gravity.

$$GM = KB + BM - KG \tag{22}$$

KB and KG are known entities for a vessel, while BM must be calculated based on the CWL. KB can be estimated based on the shape of the hull under CWL. For a square shape, KB will be $\frac{1}{2} \cdot T$, while for an upside-down triangle, KB is $\frac{2}{3} \cdot T$. For the hull model, the shape was determined to be

$$KB \approx \frac{\frac{1}{2} \cdot T + \frac{2}{3} \cdot T}{2}. \tag{23}$$

BM can be found as

$$BM = \frac{I}{\nabla}, \tag{24}$$

where I is the second moment of inertia.

By retrieving the waterline for the CWL, BM can be calculated. Figure 39 shows the predicted areas of the waterline. With two different geometric forms, the second moment of inertia was calculated for one hull with parallel axis theorem applicable for the scenario. The results for BM, KB, KG and GM are given in table 26. For the calculation of KG, see appendix H.

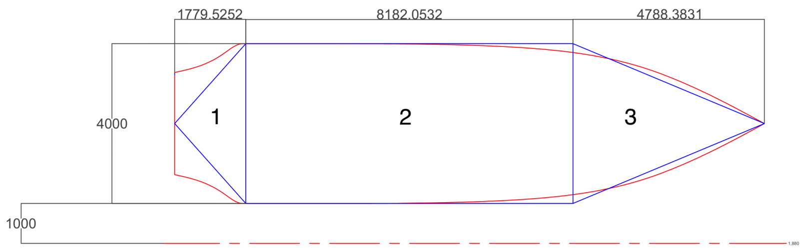


Figure 39: The waterline at CWL 1.88m is given in red, blue lines indicate the approximated geometric forms which are numerated 1-3, and black text shows the dimensions in millimeters. The red dashed line is the centerline of the vessel.

Table 26: Transverse Initial Stability Calculations at T equal to 1,88m.

Center of Buoyancy (KB)	Metacentric Radius (BM)	Center of Gravity (KG)	Metacentric Height (GM)
1,1 m	6,6 m	2,3 m	5,4 m

As the metacentric height is calculated to be well over zero, we can conclude that the initial stability of the vessel is sufficient. This was also verified through DELFTShip stability calculations with the chosen stability criteria IMO MSC.267(85) - Minimum design criteria applicable to all ships. When the loading conditions were determined, it was discovered that the draft of the vessel was not as high as 1,88m, but lower in all loading conditions. A re-evaluation was not made after this was discovered. The fully loaded maximum draft was determined to be 1,64m from the stability calculations. The reports from the stability calcuations for each relevant loading condition can be seen in appendix I.

5.5.2 Ship Resistance and Required Power

A popular method of predicting the required machinery power on a vessel is the Guldhammer Harvalds method. The method is applicable for vessels with a slenderness number between 4 and 8. The slenderness number is calculated as in equation (25).

$$\frac{L_{wl}}{\nabla^{\frac{1}{3}}} \tag{25}$$

The current design has a slenderness number of 3,0, which is too low to be precisely applicable for the method. It was however decided to check against the Guldhammer Harvalds method, and performing an analysis with the Holtrop method for ship resistance, to compare the two results. Estimated using Guldhammer Harvalds method gives a required power of maximum 255kW for unloaded condition, and 272kW in loaded condition in 2036-2040. The diagrams were for higher slenderness numbers, and an estimation on the increase in resistance due to a lower slenderness was made. Calculation of the resistance and power requirement using Guldhammer Harvalds method can be seen in appendix J. Note that the calculations were performed with an assumed draft of 1,88m with the design hydrostatics resulting from this draft. The numbers there are therefore somewhat higher than with the fully loaded draft of 1,64m. The results presented here are for T equal to 1,64m.

Another method for ship resistance estimation is Holtrop and Mennen's method (Roh and Lee 2018). This is a statistical method based on regression analysis of considerable resistance data for different vessels. This method is also more suitable for larger vessels, but is more flexible than Guldhammer Harvald's method. It requires a larger amount of input parameters, which makes it less attractive in an early design phase. The method was used in this thesis to extract the estimated ship resistance. These calculations were not made by the author himself, and the results should thus only be used as a reference.

The results from using Holtrop and Mennen's method showed that for a design speed of 9kn, the total ship resistance was 13,47kN. This resulted in a power demand from the engine of approximately 300kW fully loaded. The results from both methods are summarized in table 27 and 28.

Table 27: Summary of ship resistance, R_T, towing power, P_E, and engine power, P_B, calculated using Guldhammer Harvald's method, Holtrop Mennen's method and the average of the two methods. The results are for the vessel in fully loaded condition.

	Design Speed		Ship Resistance		Towing Power		Engine Power	
Guldhammer Harvald's method	9	kn	10,7	kN	109	kW	272	kW
Holtrop and Mennen's method	9	kn	11,1	kN	113	kW	283	kW
Average Resistance and Power	9	kn	10,9	kN	111	kW	278	kW

Table 28: Summary of ship resistance, towing power and engine power calculated using Guldhammer Harvald's method, Holtrop Mennen's method and the average of the two methods. The results are for the vessel in empty condition with ballast.

	Design Speed		Ship Resistance		Towing Power		Engine Power	
Guldhammer Harvald's method	9	kn	10,0	kN	102	kW	255	kW
Holtrop and Mennen's method	9	kn	9,8	kN	100	kW	250	kW
Average Resistance and Power	9	kn	9,9	kN	101	kW	253	kW

As the results from both methods were somewhat similar, the average result of the two methods are used. Compared to the reference vessels, the results are somewhat dissimilar. A reiteration with a more appropriate resistance estimate should therefore be conducted.

5.5.3 Operational Profile

The operational profile can be evaluated based on the given capacities, farm sizes and vessel power consumption, P_C. Until now, the charging time has been assumed for different operations. When the required power is known, it is possible to calculate the remaining power onboard during the daily operation. This will allow us to determine how many trips the vessel can take before a recharge is necessary.

The charging time of the batteries are given by their C-rate, which is a measure of how long it takes to charge or discharge a battery. The chosen batteries have a C-rate of 3C, which means that charging one battery is given as

$$T_c = \frac{1}{3}h = 20 minutes. \tag{26}$$

This corresponds to a charging rate of 375kW. By assuming that the battery packages in both hulls can be charged independently of each other, the charge-rate becomes 750kW. Table 29 summarizes the calculated and assumed power requirements during each operation.

Table 29: The calculated power requirements for the different operations.

Sailing Unloaded	253	kW
Harvest and Maneuver	75	kW
Sailing Loaded	278	kW
Maneuver to Dock	83	kW
Unloading and Charging	-750	kW

Figure 40 shows the operational profile for the 2021-2025 scenario for harvesting, where the power consumption for different operations are given as color-coded bars, while the energy storage onboard is given with the black line, with values on the secondary axis. The operational profile for 2036-2040 is shown in figure 41.

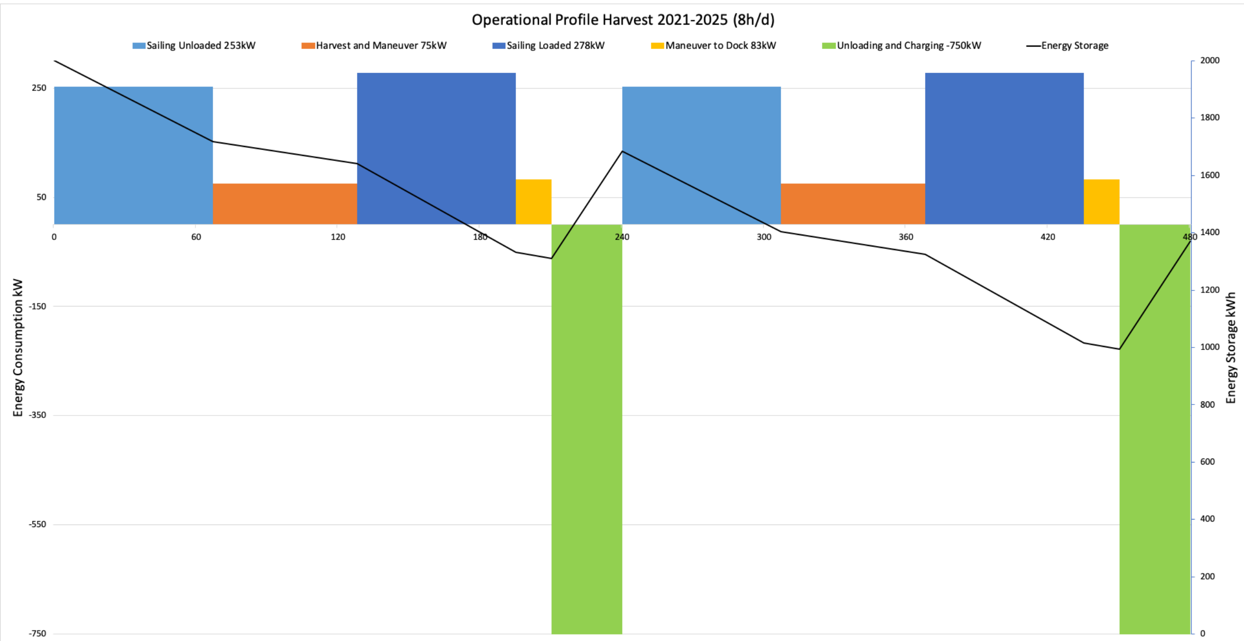


Figure 40: Operational Profile for the vessel in 2021-2025. Energy consumption for different operations are color-coded as given on top, with values given on the primary vertical axis on the left-hand side. Energy storage onboard is given with the black line, with reference values given on the secondary vertical axis on the right-hand side. The horizontal axis shows minutes after initiation at 08:00.

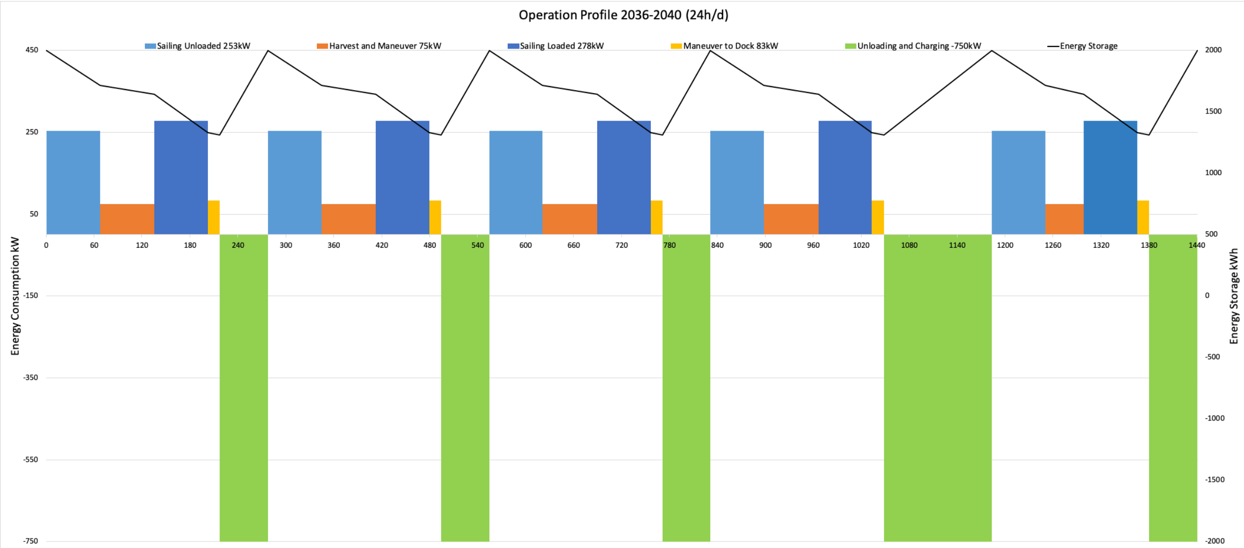


Figure 41: Operational Profile for the vessel in 2036-2040. Energy consumption for different operations are color-coded as given on top, with values given on the primary vertical axis on the left-hand side. Energy storage onboard is given with the black line, with reference values given on the secondary vertical axis on the right-hand side. The horizontal axis shows minutes after initiation at 00:00.

The operational profile for 2036-2040 given in figure 41 shows that the vessel would not need a full hour of charge after each trip. The energy storage is 1310kWh after one trip and reaches full capacity after one hour of charging. The vessel could however initiate the next trip with less than full energy storage, and this could potentially allow the vessel one more harvest each day, increasing its capacity further. This has however not been evaluated in this thesis. All the operational profiles for 2021-2040 are given in appendix K.

When the times of operation were calculated, it was detected that the vessel uses less than eight hours for two trips. This was adjusted by using the rest of the time for charging, which allows a charge of 30 minutes between the two trips. This was beneficial as it will charge 375kWh in 30 minutes, and it also allows a break for the crew at the middle of the day during the charging of the vessel. At the end of the day the vessel will charge until it is fully charged. The work schedule is shown in figure 42. All work schedules for 2021-2040 are given in appendix L.

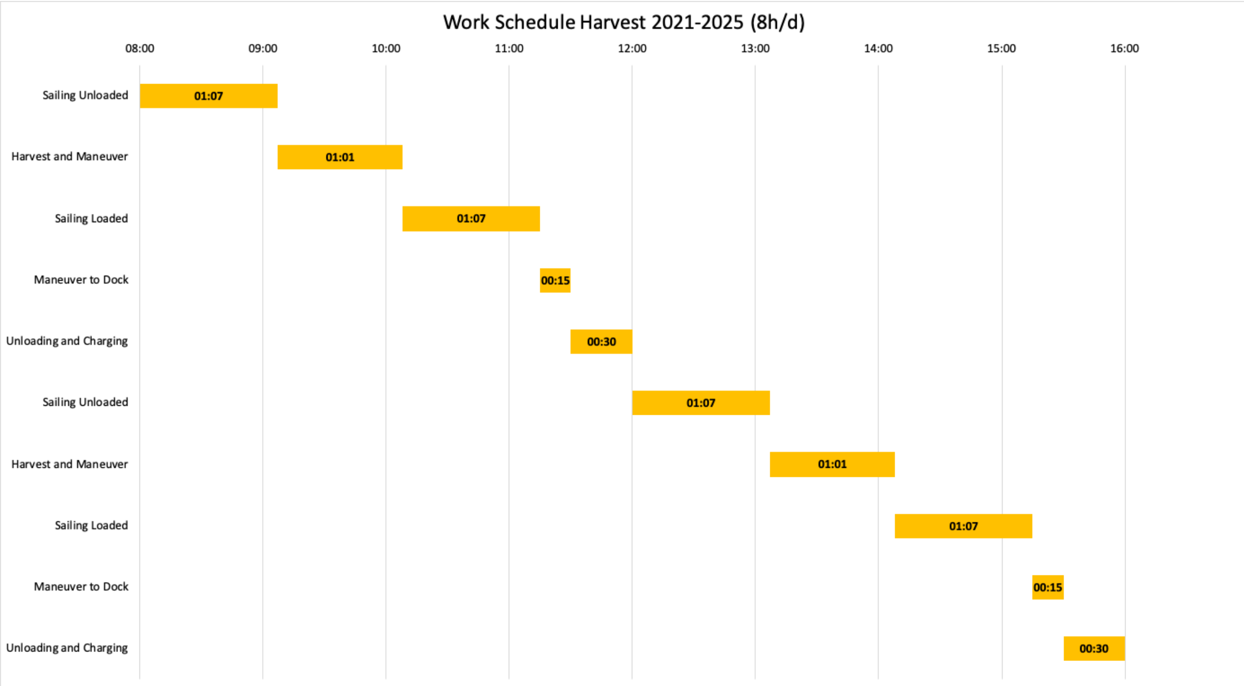


Figure 42: The work-schedule for an 8h/d working day. The day starts at 08:00 and ends at 16:00. The times in the bars show how long the different operations take. The operations are specified on the left-hand side of the figure. The time of day is shown in the top of the plot.

5.5.4 Harvest Speed

V_h is calculated by finding the length of rope a vessel will harvest from each day, and dividing it by the length of operation per day for each vessel. It is calculated as shown in equation (27). The results can be seen in table 30

$$V_h = \frac{W_k}{y_k \cdot T_o}, \tag{27}$$

where W_k is the kelp weight harvested each day, in kg.

Table 30: The calculated harvest speed for each time-period, compared to the set minimum requirement.

	2021-2025	2026-2030	2031-2035	2036-2040
Harvest Speed	8 m/min	9 m/min	8 m/min	10 m/min
Target	5 m/min	5 m/min	5 m/min	5 m/min

5.5.5 Economic Perspective

For any design, the cost is very important to calculate, as it is often a determining parameter for an investor. Typically, costs are divided into three main categories, CAPEX, operational expenditure (OPEX), and voyage expenditure (VOYEX). CAPEX is the cost of the physical objects of a project, which in this case is the building cost and maintenance of the vessel. The OPEX are the costs related to keeping the system in operation. This includes labor costs, power costs and other resources necessary during operation. VOYEX are the costs related to the current voyage. These costs include canal fees, towage, berth, port charges and so on.

The building costs include the steel costs, machinery costs, auxiliary machinery cost, equipment costs and the autonomous system costs. These costs will also include earnings for the wharf, financial costs of the project, engineering and administrative costs. The building costs are summarized in table 31, where the autonomous system is assumed to increase the total cost of the vessel by 10%. The calculations can be seen in appendix M, where the unit costs are based on Amdahl et al. (2015), and the autonomous build cost was based on Kretschmann, Burmeister, and Jahn (2017).

Table 31: Summary of the building cost elements for the vessel.

Cost element			Cost element		
Steel	1,8	MNOK	Administrative	1,0	MNOK
Main Machinery	2,0	MNOK	Engineering	1,0	MNOK
Auxiliary Machinery	1,0	MNOK	Financial	0,5	MNOK
Crew Equipment	1,5	MNOK	Wharf	0,5	MNOK
Other Ship Equipment	1,0	MNOK			
Autonomous System	0,7	MNOK			
Total Vessel Cost	8,0	MNOK	Total Build Cost	11,0	MNOK

The operating cost will depend on how many hours of operation are required. The power usage is calculated based on the determined days required to finish operation and the predicted power requirement. Table 32 summarizes the annual power usage for one vessel.

Table 32: Annual power consumption of deployment and harvest for the four time periods.

Operation	20215-2025		2026-2039		2031-2035		2036-2040	
Power Consumption Deployment	9478	kWh	13158	kWh	14746	kWh	16294	kWh
Power Consumption Harvest	23877	kWh	36627	kWh	44050	kWh	55657	kWh
Total Annual Power Consumption	33355	kWh	49785	kWh	58796	kWh	71951	kWh
Average Annual Power Consumption	53472	kWh						

The annual power consumption in table 32 is given for the period the vessel operates. On average, the vessel is in operation 25 out of 365 days for kelp farm operations, given the assumptions in this section. If P_C is scaled to assume a year-round operation, the annual power consumption becomes

$$P_C = 53472kWh \cdot \frac{365}{25} = 780691kWh \approx 0,8GWh \tag{28}$$

The OPEX for one year can then be calculated. This is summarized in table 33. The average operation and maintenance cost is based on 15 years of manned operation, and 5 years of unmanned operation.

Table 33: The total operation cost for the vessel for the period the vessel operates in deployment and harvest.

Cost Element	Unit Cost		Quantity		Cost	
Power Consumption	1	NOK/kWh	0,8	GWh	0,8	MNOK
Average Operation and Maintenance	9,0	% CAPEX	11	MNOK	1,0	MNOK
Operation Initiation	0,5	MNOK	1	-	0,5	MNOK
Total Annual Operation Cost					2,3	MNOK

The operational expenditure are costs that are ongoing, and will be so during the lifetime of the vessel. It is therefore useful to find the present value, PV, of the operational expenditure to make some estimates on the life-cycle cost of the vessel. As we know the future value, FV, for each year, PV can be calculated as

$$PV = FV \cdot \frac{(1+r)^t - 1}{r \cdot (1+r)^t}, \tag{29}$$

where r is the interest rate as a decimal, and t is the time period in years.

With $FV = 2,3MNOK$ and assuming r of 10%, the PV of the operational expenditure becomes

$$PV_{OPEX} = 2,3MNOK \cdot \frac{(1+0,1)^{20} - 1}{0,1 \cdot (1+0,1)^{20}} \approx 20MNOK. \tag{30}$$

The life-cycle cost of the vessel can then be summarized, and compared to the amount of harvested kelp. This will give us a RFR for kelp, which is an important parameter to measure.

Table 34: Summary of major cost components, handled payload during lifetime, and RFR.

CAPEX	11	MNOK
OPEX	20	MNOK
Total Vessel Cost	31	MNOK
Number of Vessels Required	3	-
Total Fleet Cost	93	MNOK
Total Kelp Harvest May	43978500	kg
Total Kelp Harvest August	25800000	kg
RFR May Harvest	2,1	NOK/kg
RFR August Harvest	3,6	NOK/kg
RFR Total Harvest	1,3	NOK/kg

As we can see from table 34, the required freight rate is 1,3-3,6NOK/kg for this vessel. With a target cost of 0,5NOK/kg, this is a strong indication that it will be difficult to invest in a vessel that will solely be operating in the kelp industry. The vessel will require a higher utility to reduce the costs in the industry.

5.6 Section Summary

This section has been focused on designing a vessel for operations in kelp cultivation. The section started by determining a payload capacity of 32m^3, and from that determining the required deck area and vessel dimensions. The capacity was determined based on the assumptions regarding market development and

storage density. From the main dimensions, a battery capacity was determined, which gave a limited range, compared to the desired range of the vessel. The design parameters were then compared to reference vessels to determine if the current design seemed reasonable, before a hull model was developed in DELFTShip. This hull model was used to give more precise estimates on the most important dimensions of the vessel, namely volume and weight displacement, draft, C_B, stability and loading conditions.
The line-drawings of the vessel was then transferred to AutoCAD where general arrangement drawings were made. The COG of the vessel was calculated, which resulted in the implementation of ballast tanks that would reduce vessel trim. The section ended with evaluation of the design in terms of stability, vessel resistance and power consumption, vessel cost and harvest speed.

Table 35: Outline specification for the vessel, based on results from this section. Gross Tonnage (GT) and Gross Volume is based on results from DELFTShip.

Mission Description					
Operation Area	Norwegian Coastline, Møre og Romsdal				
Description	Kelp Farm Operations Vessel				
Target Market	Kelp Cultivation				
Main Characteristics					
Hull Type	Catamaran Hull		Gross Volume	347	m^3
Length OA	15,0	m	Gross Tonnage	87	GT
Length BP	13,75	m	Lightweight	77	tons
Hull Beam	4,0	m	Deadweight	36	tons
Molded Beam	10,0	m	Displacement	113	tons
Max Draft	1,64	m	dwt/displacement	0,32	
Depth to Main Deck	3,0	m	Range	60	nm
Machinery and Rough Power Demand					
Machinery Type	Battery Powered Electric Motors with Water Jet Propulsion				
Propulsion Power	300	kW	Main Machinery	2x250	kW
Power Storage	2000	kWh	Auxiliary Power	75	kW
Tanks and Capacities					
Water Ballast	25	m^3	Kelp Storage	33	m^3
Fresh Water	0,4	m^3	Wastewater	0,4	m^3
Vessel Cost					
CAPEX	11	MNOK	OPEX	20	MNOK
Total Cost	31	MNOk	RFR	1,3	NOK/kg (WW)
Vessel Performance					
Harvest Speed	8-10	m/min	Crew	2-3	
Emissions	Electric Vessel		LOA	3	

6 Discussion

This section will discuss some aspects of the work that has been done in this master thesis.

The design methodologies presented in this thesis all rely on experience and parameters from similar ship designs, to a varying extent. Set-based design would not necessarily require this, but it was beyond the scope of this thesis to design a vessel with this methodology.
Engineering design was used to analyze the payload-related systems onboard the vessel. The author experienced limitations with the method for a complex system such as a ship design, but for focus on the payload-related systems, it was a good method to apply. This was possible to do by defining the vessel as three subsystems, which was a strategy adopted from the SBSD methodology.
SEATONOMY was a useful tool for discussing the LOAs of the operations, especially through the AJA. By creating a design catalogue, it became clear what LOAs would be realistic to achieve for the vessel. SEATONOMY and AJA especially is created for use of a design team. This made it challenging to perform alone, as it potentially has limited the creativity and discussion around different scenarios.

The suggested vessel design resulted in a minimum cost of 1,3NOK/kg. The target cost of the vessel was 0,5NOK/kg, and a maximum of 1NOK/kg. This was chosen because other costs, such as rig, rope, seedlings and processing are not included in the vessel cost. Based on a price of biomass of 2NOK/kg, the results indicate that a vessel must be multi-purpose and chartered to other industries off-season, to reduce the cost of production.
The vessel design is based on development of a larger industry than what is currently existing. This assumption is made due to the large interest around kelp, with its possible applications, and development trends in Norway and globally. The uncertainty around the development of the market will make a specialized vessel unattractive at this stage. The RFR for the vessel will be higher if the harvested biomass is lower than assumed.

For chartering a vessel, the RFR ranged from 0,93-4,86NOK/kg. Vessel chartering assumed an increase in harvest speed from 5-20m/min. If this is not possible with one vessel, the cost of chartering would be higher in all scenarios. This suggests that a vessel design may be attractive, if the option is chartering.
This thesis has focused on the cost of the design, and has not taken into consideration the actual sales prices of kelp. This is likely to be significantly higher than the cost-target at 2NOK/kg for production.

The onboard technologies for the vessel are not complex or new. Simple operations are assumed to be adequate for increasing the efficiency of harvest. Some developments are assumed for the onboard technology. Seaweed rotacutters already exist, but a development for a rotacutter appropriate for movement on rails is assumed tp take place. Methods to apply pressure to the kelp in containers must also be developed.
Developments are assumed to improve the interactions between the farm and the vessel, and that a dedicated harvesting machine is developed to allow for precise cutting. Designing a vessel based on external developments will increase the risk, but a good dialogue between the farm owner and vessel designer could ensure these developments take place.

The vessel is designed as an electric catamaran with water jet propulsion. Electric vessels reduce the emissions around kelp cultivation operations, but also reduces the range of the vessel. If the vessel is to operate along the coastline at many different kelp-farms, this is limiting for the design. With the industry in its current state, this should however not be problematic.
The vessel was designed as a catamaran due to multihull characteristics of good initial stability and large available deck area. Through the design process, this was verified. Catamarans are also typically used in fish farm service operations. Designing the vessel as this may increase its attractiveness in chartering to other industries, which is required to reduce the costs. A study on fish farm service catamaran operations and requirements have not been conducted in this thesis, however. Catamaran-design limits the vessels

opportunity of having large spaces available for storage of kelp. This can be problematic if production is of a large scale. Due to the low scale production in the industry today, it was determined more suitable to design a vessel that could be attractive for fish farmers as well.
Effects of resistance on multihulls have not been considered, and should be calculated for the design. Water jet propulsion was chosen as it does not have any external propellers. Several farm owners reported problems with vessels with a draft over 2m, as it resulted in rope entanglement in the propeller. Water jet propulsion is an efficient way to remove the external propeller. This propulsion system is however more appropriate at higher speeds, and power addition due to lower speeds with water jet propulsion should be included.

The general arrangement drawings showed that the vessel is area critical. A reevaluation of the required areas should be performed to determine if a larger vessel is required for the onboard equipment.

Resistance calculations are based on Guldhammer Harvald's method and Holtrop Mennen's method. The methods showed similar results for the ship resistance. The results are uncertain, as both methods are typically applicable for vessels larger than the current design. The effects of a multihull-vessel on ship resistance was not evaluated. A more thorough calculation of ship resistance should therefore be conducted. Early intact stability calculations for the vessel shows that the vessel has good stability. The vessel had acceptable levels for all stability criteria in IMO MSC.267(85) - Minimum design criteria applicable to all ships. These criteria are however for vessels above 24m in length, and it is not known to the author what criteria are applicable to vessels shorter than 24m. A verification on the criteria for smaller vessels should therefore be conducted.

To implement autonomous technology in the industry, major technological developments have to be made within the farm and farm layout, deployment technology and methods, harvesting and processing of kelp. It is unlikely that a vessel that is designed to be manned for 15 years and unmanned for 5 years is desirable. Owners may either wish the vessel to be manned for the entire period, or only for a very short period, until unmanned operation is proven feasible and can be implemented. It is however attractive to reduce the role of crew in operations, which should be done through higher LOAs than what the industry is currently at. This will however require developments not only on the vessel, but also at the farm, to improve the interactions between the farm and the vessel.

Other developments that may increase or reduce the complexity of a vessel has not been considered. A vessel could be required to perform complex operations, such as deployment, harvesting and onboard processing. But farm developments may enable the farm to perform deployment and harvest, requiring a vessel to only provide input and transport harvested kelp out of the farm. This may potentially reduce the requirements of a vessel to the functionality of a barge. These developments are however uncertain, and further studies should be conducted.
The discussion is summarized:

- Higher RFR than target, lower RFR than vessel chartering.
- Mostly existing technology to be installed on the vessel.
- Requires developments that enable a better interaction between farm and vessel
- Low draft and no external propellers enables high flexibility in farm operations.
- Zero emission technology increases product sustainability, but reduces vessel range.
- High potential for increasing vessel operations LOA, low potential for highest LOA.
- Uncertain system requirements due to unknown technological developments at farms and for processing.

7 Conclusion and Further Work

This section concludes the master thesis and suggests further work on the subject.

7.1 Conclusion

This thesis has studied aspects of seaweed cultivation, including biology and technology. Combined with a technology study for autonomous vessels, this led to a vessel design with the aim of increasing a kelp farm vessels LOA. This was done by combining PBD with Engineering Design and the SEATONOMY methodology. Combining these methodologies was useful for designing a vessel for a new industry, where the aim was to increase the LOA of operations. PBD gave a structured and organized approach to vessel design. Engineering Design identified the most relevant stakeholders and their needs. Combined with SEATONOMY, the main operations were discussed and reflected around in terms of autonomous execution. By creating a design catalogue, many different SPs were identified and discussed, and the attainable LOA of the vessel determined. The combination of these methodologies resulted in a vessel design focused around the operations to be performed.

The proposed design is an electric-powered catamaran vessel with water jet propulsion. The vessel promotes sustainable operations and eliminates the risk of rope entanglement by having internal propellers in the water jets. The catamaran design enables the vessel to have good initial stability, a large work deck, and a similar design to fish farm service vessels. The onboard equipment is intended for modular design, to allow for replacement of equipment based on the operations and technological developments in the seaweed cultivation industry.
Resistance calculations show a required power of 278kW during sailing which gives the vessel a range of approximately 60nm at 9kn, with 2000kWh installed power. The vessel complies with all stability criteria in ballast condition for IMO MSC.267(85).

The vessel meets the requirements set for a minimum harvesting speed of 5m/min and has a low complexity that should allow crew to perform safe operations. Developments of the market, farm technology and processing methods are assumed. The assumptions will increase the utility of the vessel, and improve the interactions between the farm and a vessel. This was determined to be required to increase the LOA of the vessel operations. There is a large potential in increasing the LOA from today's operations, but full autonomous operation is neither possible nor desired at this stage in the industry.

The RFR of the design is 1,3NOK/kg (WW), while the maximum required was set to 1NOK/kg (WW). This verifies that a vessel that is not chartered to other industries will not contribute to lower costs down to a competitive level for large-volume products. The RFR of the design is however lower than chartering a vessel, and may become attractive if the price of biomass is higher than 2NOK/kg, which was the assumed price in this thesis.
The vessel is designed to be similar to fish farm service catamarans, to enable chartering to this industry. A study of the requirements for operations a fish farm service catamaran performs was not conducted.
The utility of the vessel can be significantly increased with cultivation developments that enable a longer period for deployment and harvest, based on the location and end-product. If the vessel has sufficient range and efficiency, it can follow these seasons along the coastline.

A vessel design that increases the LOA of kelp harvesting is likely to reduce the overall cost of operation. If the vessel is chartered off-season, the cost can be significantly reduced. Developments within all aspects of kelp cultivation is required to reduce costs to a level that enable large-scale production for low-cost products. A special focus should be directed towards the interactions between farm and vessel.

7.2 Further Work

This section suggests further work on the topic.

- A study of fish farm service operations should be conducted. The study should determine what operations are performed, and what requirements this sets to a vessel. This should be compared to the current vessel design to determine the feasibility of chartering the vessel to such industry.
- Technological developments for onboard equipment is likely to be required to increase the LOA and efficiency of operations. Such developments are also required for farms and methods of deployment, harvest, storage and processing. A special focus on the interactions between a farm and vessel should be prioritized.
- The main dimensions should be reevaluated based on the general arrangement.
- Resistance estimation methods applicable to the ship type should be applied to determine the power requirement of the vessel to a higher degree of certainty.
- The vessel was not evaluated based on a deployment operation. This evaluation should be performed to determine if the vessel is applicable to several kelp farm operations, or if it is more suitable only for harvest.

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Appendix

A Questionnaire Used During Interviews

Spørreskjema

Spørsmål	Ja	Nei	Detaljer	Merknader
Om anlegg for dyrking av tare				
Lokasjon til anlegg				
Størrelse på anleggene – Anlegg 1				
Størrelse på anleggene – Anlegg 2				
Størrelse på anleggene – Anlegg 3				
Utforming av anleggene				
- Sirkulære				
- Firkantede				
- Annen utforming				
Skal det dyrkes på tau?				
Skal det dyrkes på nett?				
Skal det dyrkes med andre dyrkingsmetoder?				
Hvilke arter dyrker dere?				
Dyrkingslinene skal stå vertikalt				
Dyrkingslinene skal stå horisontalt				
Hvor tett skal dyrkingslinene stå?				
Hvilke dybde skal dyrkingslinene stå?				
Hvor mange km tau skal settes ut?				
Hva forventes av dyrkingsresultat?				
- Hvor mange tonn pr. anlegg?				
- Hvor mange kg/m tau?				
- Hvor mange kg/m^3?				
Værforhold på lokasjon til anlegg				
- Signifikant bølgehøyde				
- Strømningsforhold				
- Vindhastighet				
- Temperatur				
- Lysforhold				
Om høsting av tare og utsett av kimplanter				
Hvilke sesong forventer dere at høsting skal skje i?				
Skal det høste fra samme kimplanter flere ganger (flere delhøstinger)?				
eller ønskes det å bytte kimplanter hver sesong?				
Når vil utsett av nye kimplanter finne sted?				
Er det et ønske om maksimalt tidsvindu fra høsting til levering på prosesseringsanlegg?				
Eier dere egne skip til utsett og høsting?				
Hvis ja: - Hva brukes de til utenom sesong? - Hvilke dimensjoner har skipet? (Lengde, bredde, dybde og dypgang) Hvis nei:				

- Hvorfor ikke? - Leier dere inn skip, og er det ønskelig å fortsette slik?				
Produkt og kvalitetskrav				
Hvilke produkter ønsker dere å selge?				
Hvilke deler av planten brukes til fremstilling av sluttprodukt?				
Setter sluttproduktet krav til kvalitet på levert tare?				
Påvirker sluttproduktet håndteringen av tare under høsting (skånsom høsting, eventuelt ikke så nøye..)?				
Hvilke metode for mellomlagring bruker dere før taren leveres på prosesseringsanlegg?				
- Våt lagring (i sjøvann)				
- Luftlagret (bulk)				
- Kjølelagring (fryses)				
- Utenfor skipet?				
Om prosesseringsanlegg				
Lokasjon på anlegg for prosessering?				
Kapasitet på prosesseringsanlegg?				
Helårs drift eller sesongbasert?				

B Mission Description Created for Vessel Design

The objective is to design a system that can efficiently seed and deploy growth lines and harvest kelp. The kelp should be processed and stored according to the requirements set by the intended end-product of the kelp and transported to shore for further transport to processing facility.

Mission

- Seed and deploy growth lines horizontally in farm
- Harvest mature kelp from growth lines
- Process and store kelp according to current quality-demands set by the end-product.
- Monitor and Inspect farm
- Transport kelp from farm to processing facility

Area

The area of operation is at the farm which is located near Frøya in Trøndelag at a sheltered location. The distance from harbor to farm is 10nm. Other kelp farm owners are located in the vicinity, and it is desirable that the vessel can participate in operations at other farms within 100nm.

Season

Operations are highly seasonal. Deployment will be conducted in December or January, and deployment of delivered seedlings must be carried out within 72 hours. It is desirable that the total deliveries of seedlings are kept to a minimum.
Harvest will take place in May for food-applications and must be completed within 3 weeks after initiation. A second harvest is planned in the future for other applications and is planned to take place in August.

Operations

- Deployment:
  - The seeding method applied is twine-seeding
  - Growth lines shall be deployed at square-shaped farm in horizontal direction at 2m depth.
- Harvest:
  - Kelp should be cut 15cm under the stem
  - Kelp must be sprayed clear of vertebrates and bryozoans
  - Kelp should be stored in protection against sunlight and freshwater, and should be stored cool.
  - Kelp should be stored as whole blades, at a maximum density of 300kg/m^3
  - Ropes must be scraped clear of remaining kelp and brought to shore

Special Considerations

- Safe operation, "no hands on rope" is preferred.
  - High degree of mechanization and automation is desirable
  - Low complexity is important
- Lower cost, higher speed and larger capacity than existing solutions
  - Cheaper than chartering a vessel
  - Cost-target: <2kr/kg (wet weight)

- Low energy demand
- Possibility to charter vessel to other farms with different requirements

Classification
Regulations for Vessels under 24m.

Registry
Norway

Applicable Regulations
- Legislation of Norwegian Maritime Authority

C Autonomous Job Analysis Tables for Deployment

Deployment of Growth Lines (1/5)

ID	Question	Answer
1	Description of sub-goal	Twine seed string around carrier rope
	Communication	Vessel must receive relevant information about the length and size of the ropes to be twined. Low latency and high bandwidth connection to shore control center for remote-monitoring of the operation.
	Perception	Internal sensor system must be active to ensure correct execution of the operation.
	Success Criteria	String should be twined successfully and at a correct density around the carrier rope. The growth line must be stored adequately after twining.
	What can go wrong?	String or carrier rope can be wrongly feeded into spinning machine. String is not adequately twined around carrier rope. Ropes can get entangled. Ropes are not adequately stored after twining. Communication link to shore control center is lost.
	What is the operational safe-state?	Terminate twining process and crane return to resting-position.
	Level of Autonomy	Automatic execution of process with operator actively monitoring the operation.
	Other premises / requirements	
	Notes / comments	

Deployment of Growth Lines (2/5)

ID	Question	Answer
2	Description of sub-goal	Approach and connect to farm rig
	Communication	Rig layout and connection method must be communicated to the vessel.
	Perception	Situational awareness system must be active to identify the farm, connection area and other objectives.
	Success Criteria	Farm is correctly identified and vessel is safely connected to the farm.
	What can go wrong?	Farm is not identified or identified too late. Connection is not made.
	What is the operational safe-state?	Maintain position in pre-designated safe-zone
	Level of Autonomy	Autonomous execution with operator monitoring the situation
	Other premises / requirements	
	Notes / comments	

Deployment of Growth Lines (3/5)

ID	Question	Answer
3	Description of sub-goal	Attach growth line to farm
	Communication	Correct attaching method must be communicated to the vessel.
	Perception	
	Success Criteria	Growth line is safely attached to the rig.
	What can go wrong?	Growth line is not attached to the rig. Growth line becomes entangled.
	What is the operational safe-state?	Remain in position
	Level of Autonomy	Remote controlled
	Other premises / requirements	
	Notes / comments	

Deployment of Growth Lines (4/5)

ID	Question	Answer
4	Description of sub-goal	Deploy growth lines
	Communication	Farm layout and size, length of growth lines to be deployed.
	Perception	Orientation of the farm and vessel. Verify correct deployment of growth lines
	Success Criteria	Growth lines are deployed in correct pattern and density.
	What can go wrong?	Growth lines become entangled. Growth lines are not in pattern.
	What is the operational safe-state?	Remain in position, stop all movements of rope.
	Level of Autonomy	Remote controlled
	Other premises / requirements	
	Notes / comments	

Deployment of Growth Lines (5/5)

ID	Question	Answer
5	Description of sub-goal	Disconnect from farm
	Communication	Disconnection method must be communicated
	Perception	Farm layout and vessel orientation. Disconnection method must be observed.
	Success Criteria	Vessel is safely disconnected and removed from farm
	What can go wrong?	Vessel is not disconnected, vessel collides with farm
	What is the operational safe-state?	Stop disconnection, operator intervenes
	Level of Autonomy	Controlled by operator
	Other premises / requirements	
	Notes / comments	

D Autonomous Job Analysis Tables for Harvest

Harvest Kelp (1/7)

ID	Question	Answer
1	Description of sub-goal	Approach and connect to farm rig
	Communication	Rig layout and connection method must be communicated to the vessel.
	Perception	Situational awareness system must be active to identify the farm, connection area and other objectives in the area. The system must recognize the orientation of the vessel to correctly enter the connection
	Success Criteria	Farm is correctly identified and vessel is safely connected to the farm. Vessel does not block for other marine traffic.
	What can go wrong?	Farm is not identified or identified too late. Connection is not made. Communication is lost, or false information about the farm is communicated
	What is the operational safe-state?	Maintain position in pre-designated safe-zone
	Level of Autonomy	Autonomous execution with operator monitoring the situation
	Other premises / requirements	
	Notes / comments	

Harvest Kelp (2/7)

ID	Question	Answer
2	Description of sub-goal	Detach growth line from farm and attach to vessel
	Communication	Correct detaching method must be communicated to the vessel. Correct attachment on vessel must be communicated
	Perception	System must identify area for detaching growth line, and area to attach growth line
	Success Criteria	Growth line is detached from rig and attached to vessel
	What can go wrong?	Growth line is entangled. Growth line is not detached from the rig, growth line is not attached to vessel
	What is the operational safe-state?	Maintain position, stop all movements attaching / detaching operations
	Level of Autonomy	Mechanic execution controlled by operator
	Other premises / requirements	
	Notes / comments	

Harvest Kelp (3/7)

ID	Question	Answer
3	Description of sub-goal	Retrieve growth line
	Communication	Information about currents and wind-directions must be provided. Farm layout and harvest-direction must be communicated to align ropes and vessel. Length and size of ropes must be communicated.
	Perception	System must identify weather conditions and vessel movements and orientation. Growth line must be correctly detected, and ensured not entangled and clear path for retrieval.
	Success Criteria	Vessel aligns for harvesting correctly. Rope is safely pulled onboard and stored after harvest.
	What can go wrong?	Vessel does not align with growth lines. Growth lines are entangled. Vessel performs operation in unstable conditions. Kelp is scraped off before it enters the vessel.
	What is the operational safe-state?	Maintain position, stop all movements of rope.
	Level of Autonomy	Automatic execution controlled by operator
	Other premises / requirements	
	Notes / comments	

Harvest Kelp (4/7)

ID	Question	Answer
4	Description of sub-goal	Process and Cut Kelp
	Communication	Restrictions must be communicated: Harvest method, time available for harvest, processing method, maximum harvest speed, species for harvest, last reported size and density
	Perception	Rope length, kelp size, density and health.
	Success Criteria	All kelp is processed according to requirements, and is correctly harvested with correct method.
	What can go wrong?	Equipment failure preventing correct processing, or kelp is not cut or cut incorrectly
	What is the operational safe-state?	Stop movement of ropes and equipment, keep position
	Level of Autonomy	Automatic process controlled and monitored by operator. System provides information such as speed, size and density of kelp, and energy monitoring
	Other premises / requirements	
	Notes / comments	Different restrictions may change over time, or for different farm owners

Harvest Kelp (5/7)

ID	Question	Answer
5	Description of sub-goal	Store Kelp
	Communication	Storage method, density and quality must be communicated. Amount to be stored must be communicated,
	Perception	Identify full containers, container placement, harvest area
	Success Criteria	Kelp is lead to storage and stored correctly
	What can go wrong?	Kelp falls outside containers. Kelp is stored with too low or high density. Containers are overfull. Full containers are not identified. Kelp gets stuck.
	What is the operational safe-state?	Stop harvest and maintain position
	Level of Autonomy	Automatic execution monitored by operator. Operator is informed about full containers and which are currently being filled.
	Other premises / requirements	
	Notes / comments	

Harvest Kelp (6/7)

ID	Question	Answer
6	Description of sub-goal	Clean and Store Ropes
	Communication	Storage method for ropes must be communicated, and demand for cleaning of ropes.
	Perception	Status of storage method (i.e. Capacity of drum), rope length and condition
	Success Criteria	Rope is cleaned and stored correctly
	What can go wrong?	Rope is not cleaned, rope is entangled, rope breaks, rope is not stored correctly, full storage is not identified
	What is the operational safe-state?	Stop all rope movements
	Level of Autonomy	Automatic execution monitored by operator. Operator is informed about rope-cleaning and status of storage
	Other premises / requirements	
	Notes / comments	

Harvest Kelp (7/7)

ID	Question	Answer
7	Description of sub-goal	Disconnect from farm
	Communication	Disconncetion method must be communicated
	Perception	Farm layout and vessel orientation. Disconnection method must be observed.
	Success Criteria	Vessel is safely disconnected and removed from farm
	What can go wrong?	Vessel is not disconnected, vessel collides with farm
	What is the operational safe-state?	Stop disconnection, operator intervenes
	Level of Autonomy	Controlled by operator
	Other premises / requirements	
	Notes / comments	

E Cost of Vessel Chartering

The calculations for estimating the cost of chartering a vessel over the period 2021-2040.

	2021-2025		2026-2030		2031-2035		2036-2040	
Deployed Rope	49140	m	150000	m	270000	m	480000	m
Yield 1st Harvest	5	kg/m	7	kg/m	10	kg/m	10	kg/m
Yield 2nd Harvest	0	kg/m	3	kg/m	5	kg/m	7	kg/m
Deployment Speed	9	m/min	14	m/min	17	m/min	20	m/min
Harvest Speed	5	m/min	10	m/min	15	m/min	20	m/min
Hours of Deployment	91	h	178,57	h	264,71	h	400	h
Hours of Harvest	163,8	h	500,00	h	600,00	h	800,00	h
Period	5	y	5	y	5	y	5	y
Charter Price	4500	kr/h	4968,11	kr/h	5485,47	kr/h	6056,41	kr/h
Annual Inflation	1,02		1,02		1,02		1,02	
Average Charter Price	4683,64	kr/h	5171,11	kr/h	5709,33	kr/h	6303,56	kr/h
Cost of Deployment	0,43	MNOK	0,92	MNOK	1,51	MNOK	2,52	MNOK
Cost of Harvest	0,77	MNOK	2,59	MNOK	3,43	MNOK	5,04	MNOK
Total Cost of Period	5,97	MNOK	17,54	MNOK	24,68	MNOK	37,82	MNOK
Cost per WW Kelp	4,86	kr/kg	2,34	kr/kg	1,22	kr/kg	0,93	kr/kg

F Vessel Comparison

List of data from vessels used for comparison, and calculated relations relevant for comparison and assumptions regarding own design. The first set of rows are input data, where cells listed with a [1)], [2)], [3)], [4)] or [5)] are calculated based on the assumptions given in the end of the table. The second set of rows are the calculated relations.

	Astrid Helene		Fosna Amon		Taresund		Perlen		Engeløy	
dwt	29,37[1)]	tons	58,4[1)]	tons	129,89[2)]	tons	300	tons	256	tons
Length OA	13,97	m	14,98	m	17,17	m	18	m	25,44	m
Length BP	12,71[3)]	m	14,6	m	15,5	m	16,38[3)]	m	23,15[3)]	m
Breadth Moulded	7,6	m	10	m	8,9	m	12	m	12	m
Depth Moulded	2,4	m	2,9	m	4,25	m	3,8	m	4,45	m
Draft	1,52[4)]	m	2,0	m	3,43	m	2,4	m	3,0	m
Break Horsepower	286,86[5)]	hp	1000	hp	1000	hp	1000	hp	1729,22[5)]	hp
Break Kilowatt	214,00	kW	746[5)]	kW	746	kW	746[5)]	kW	1290	kW
Design Speed	8	kn	11	kn	7,8	kn	8,6	kn	8,7	kn
B_m/D_m	3,17		3,45		2,09		3,16		2,70	
B_m/T	5,00		5,00		2,59		5,00		4,00	
$L_{oa} \cdot B_m \cdot D_m$	254,81	m^3	434,42	m^3	649,46	m^3	820,8	m^3	1356,97	m^3
$W_{ls}/(L_{oa} \cdot B_m \cdot D_m)$	0,18		0,18		0,18		0,18		0,18	
W_{ls}	45,87	tons	78,2	tons	116,9	tons	147,74	tons	244,25	tons
Displaced Volume	146,86	m^3	292,00	m^3	473,17	m^3	471,74	m^3	833,41	m^3
Displaced Weight	75,24	tons	136,60	tons	246,79	tons	447,74	tons	500,25	tons
Block Coefficient	0,50		0,46		0,51		0,93		0,59	
Coefficient of Admiralty	42,64		47,32		25,03		49,9		32,17	
dwt / ∇	0,2		0,2		0,27451		0,64		0,31	

Assumptions:

[1)] dwt / ∇ = 0,2

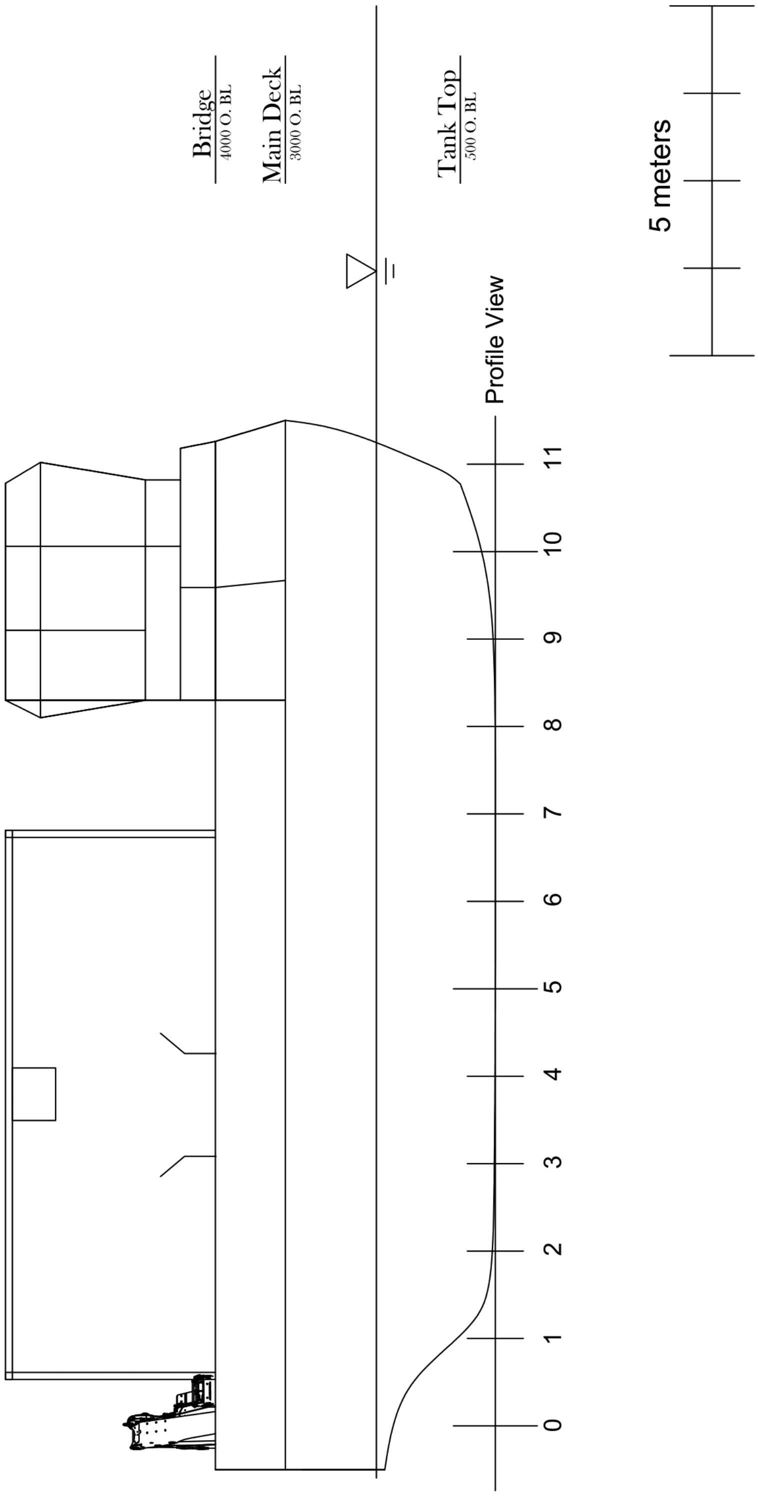
[2)] $237m^3 \cdot 500kg/m^3$

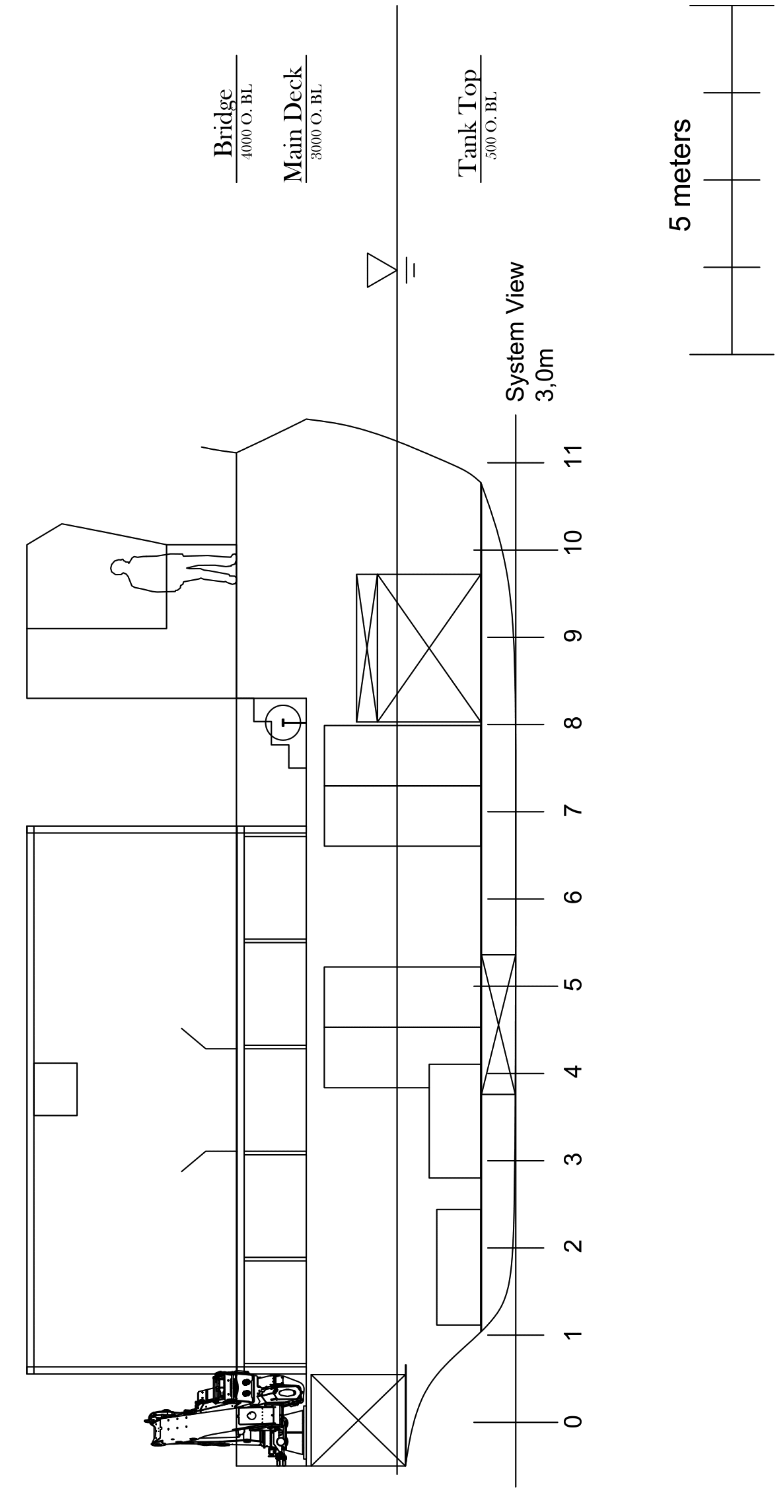
[3)] $L_{bp} = 0,91 \cdot L_{oa}$

[4)] $B_m/T = 5$

[5)] $1hp = 0,746kW$

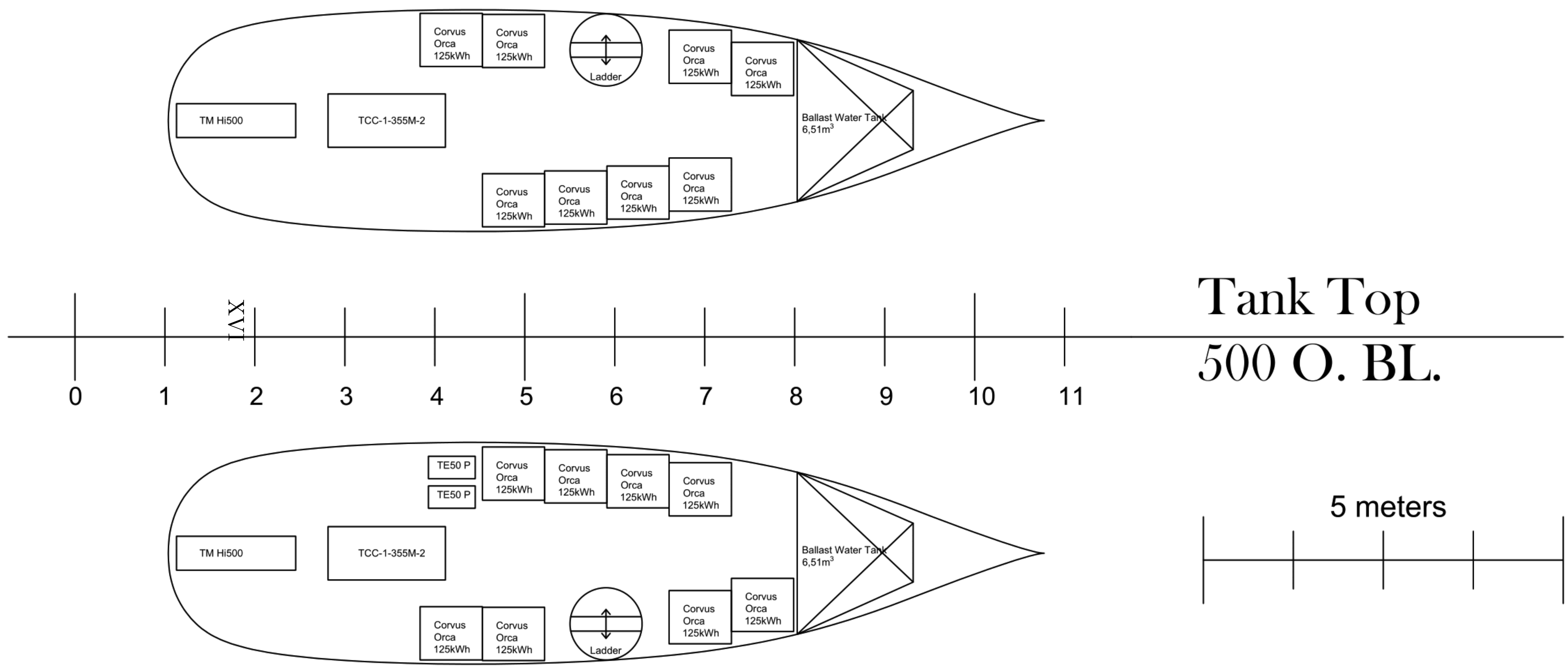
G General Arrangement Drawings



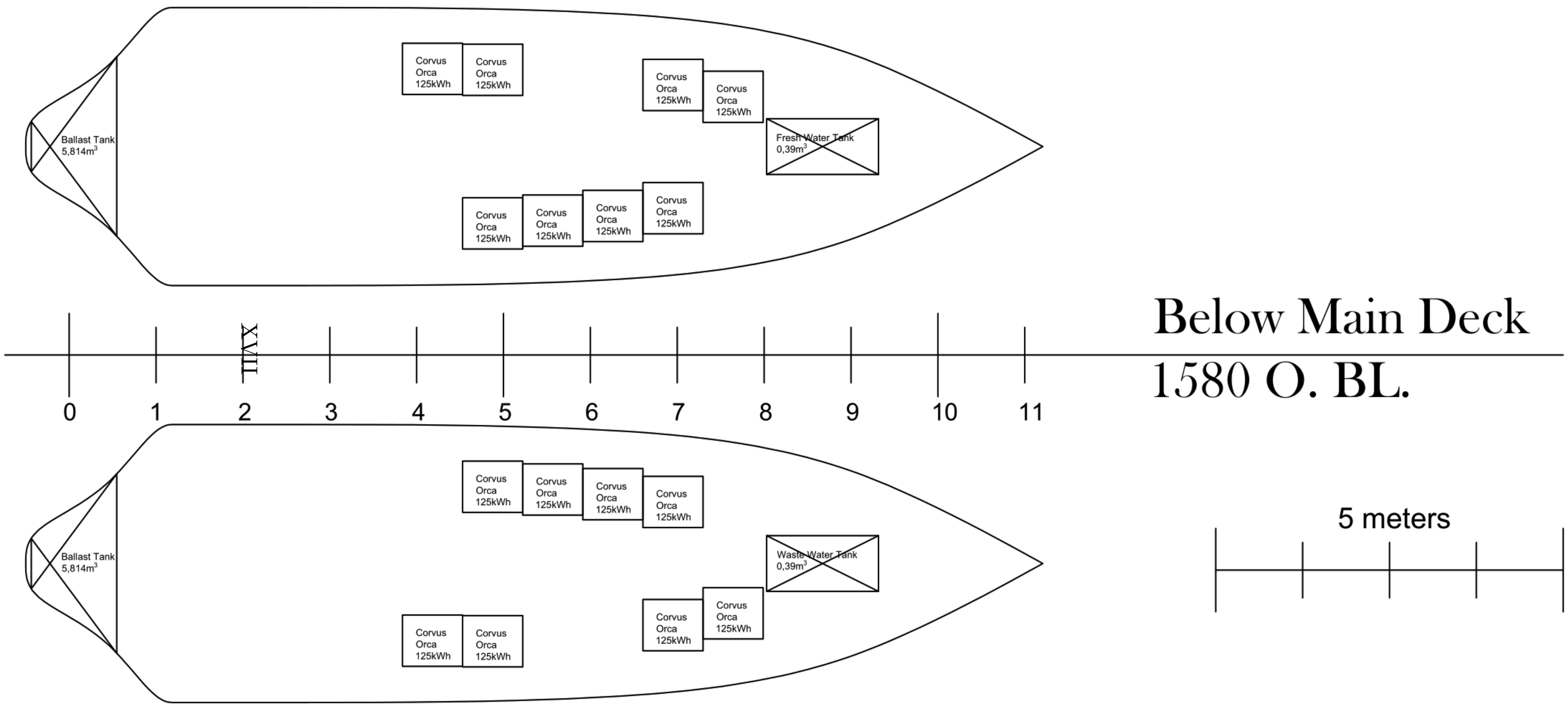


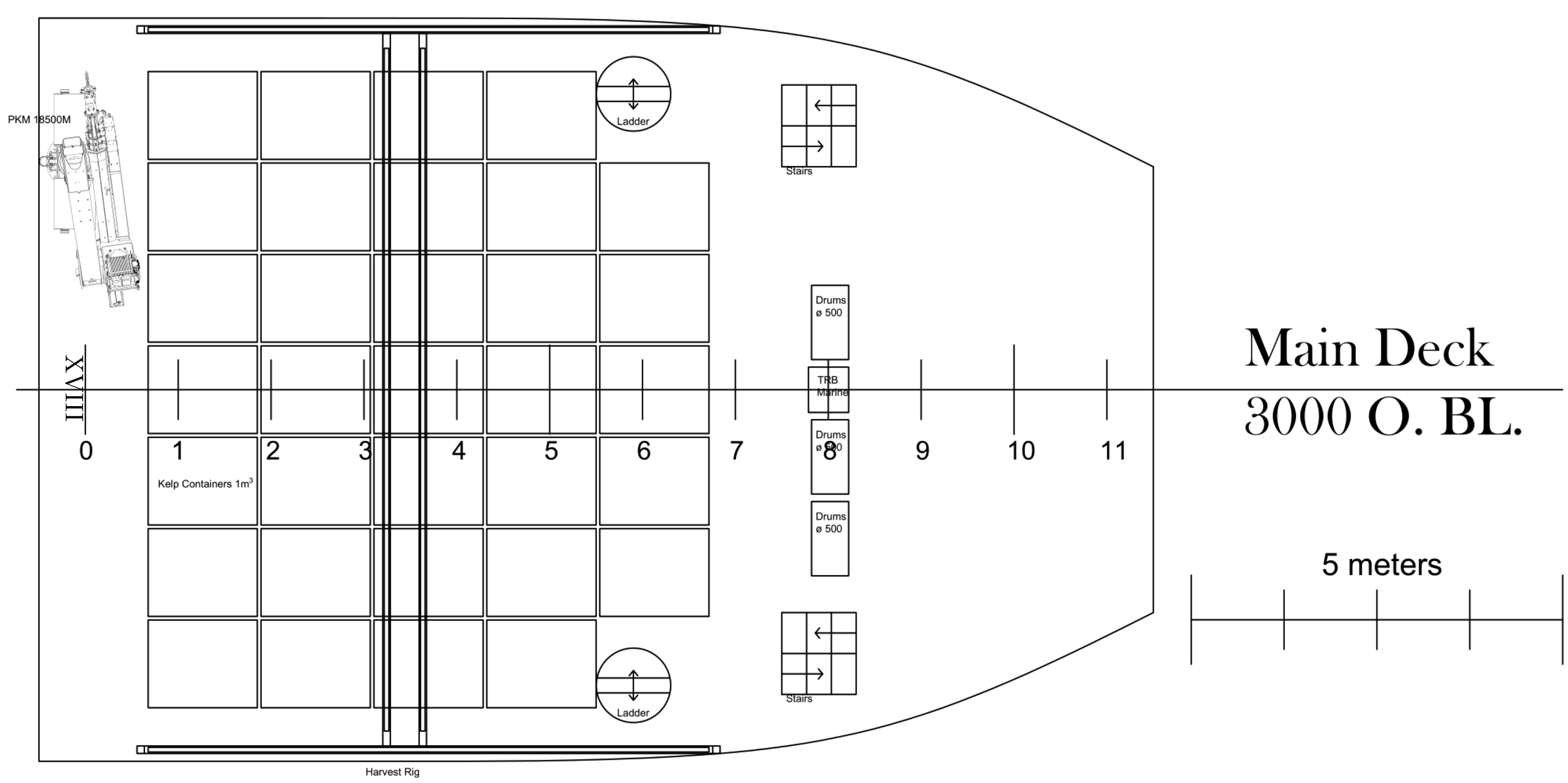
Bridge
4000 O. BL
Main Deck
3000 O. BL
Tank Top
500 O. BL
5 meters
System View
3,0m
0
1
2
3
4
5
6
7
8
9
10
11

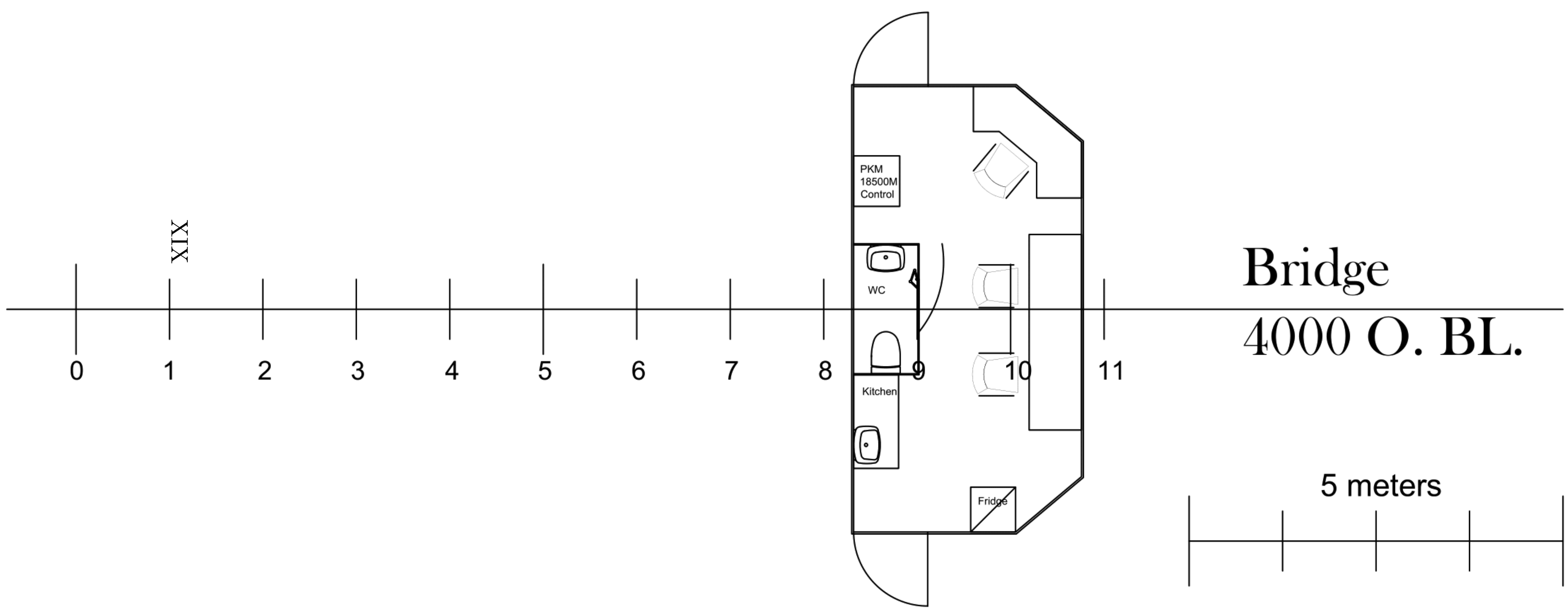
Tank Top
500 O. BL.



Below Main Deck
1580 O. BL.




Main Deck
3000 O. BL.
5 meters
PKM 18500M
XVIII
0
1
2
3
4
5
6
7
8
9
10
11
Kelp Containers 1m³
Ladder
Ladder
Stairs
Stairs
Drums
ø 500
TRB
Marine
Drums
ø 500
Drums
ø 500
Harvest Rig


Bridge
4000 O. BL.
XIX
0
1
2
3
4
5
6
7
8
9
10
11
PKM
18500M
Control
WC
Kitchen
Fridge
5 meters

H Calculation of Center of Gravity of Vessel

The calculations for COG in longitudinal, vertical and transverse directions, both unloaded during harvest, and fully loaded for a storage density of 850kg/m^3.

	Loaded	Unloaded			
Component	Weight [kg]		LCG [m]	TCG [m]	VCG [m]
Crane	2070	2070	0,13	2,56	3,81
Crane Control	250	250	10,70	1,38	4,69
Winch	80	80	10,01	0	3,17
Pumps	200	200	6,10	-2,02	0,63
Water Jets	1192	952	2,24	0	0,82
Electric Motors	3400	3400	4,33	0	0,87
Battery Pack	25920	25920	7,39	0	1,62
Hull	40000	40000	6,35	0	1,95
Bridge	4200	4200	11,67	0	5,96
Harvest Rig	500	450	4,62	0	5
Kelp Containers	31350	3300	4,53	0	3,45
Rope Drums	516	84	10,03	-0,67	3,25
Crew & Provisions	500	300	11,92	0	3,5
Fresh Water	200	0	11,09	-3	2,3
Waste Water	200	0	11,09	3	2,3
Ballast Tank Aft	11500	0	0,20	0	2,25
Ballast Tank Bow	13000	0	14,19	0	1,25
Ballast Tank SB	2000	0	6,00	-3,0	0,26

	Loaded [kg]	Unloaded [kg]	Loaded [$kg \cdot m$]			Unloaded [$kg \cdot m$]		
	Weight		LCG	TCG	VCG	LCG	TCG	VCG
Total Contribution	137878	73206	884741	11044	320677	486901	5303	158294
Center of Gravity [m]			6,42	0,08	2,33	6,65	0,07	2,16

I Loading Conditions

The loading condition reports from DELFTShip will follow in this section. The page-numbering with the following stability documents will not follow the same page-numbering as the rest of the appendix. The rest of this page is intentionally left blank.

Empty Sailing Harvest 2021-2040

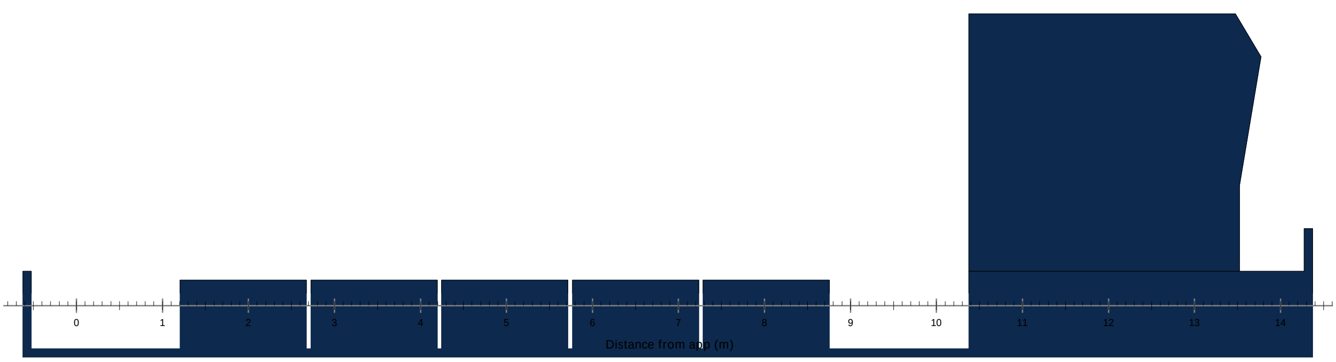
Kelp Zero

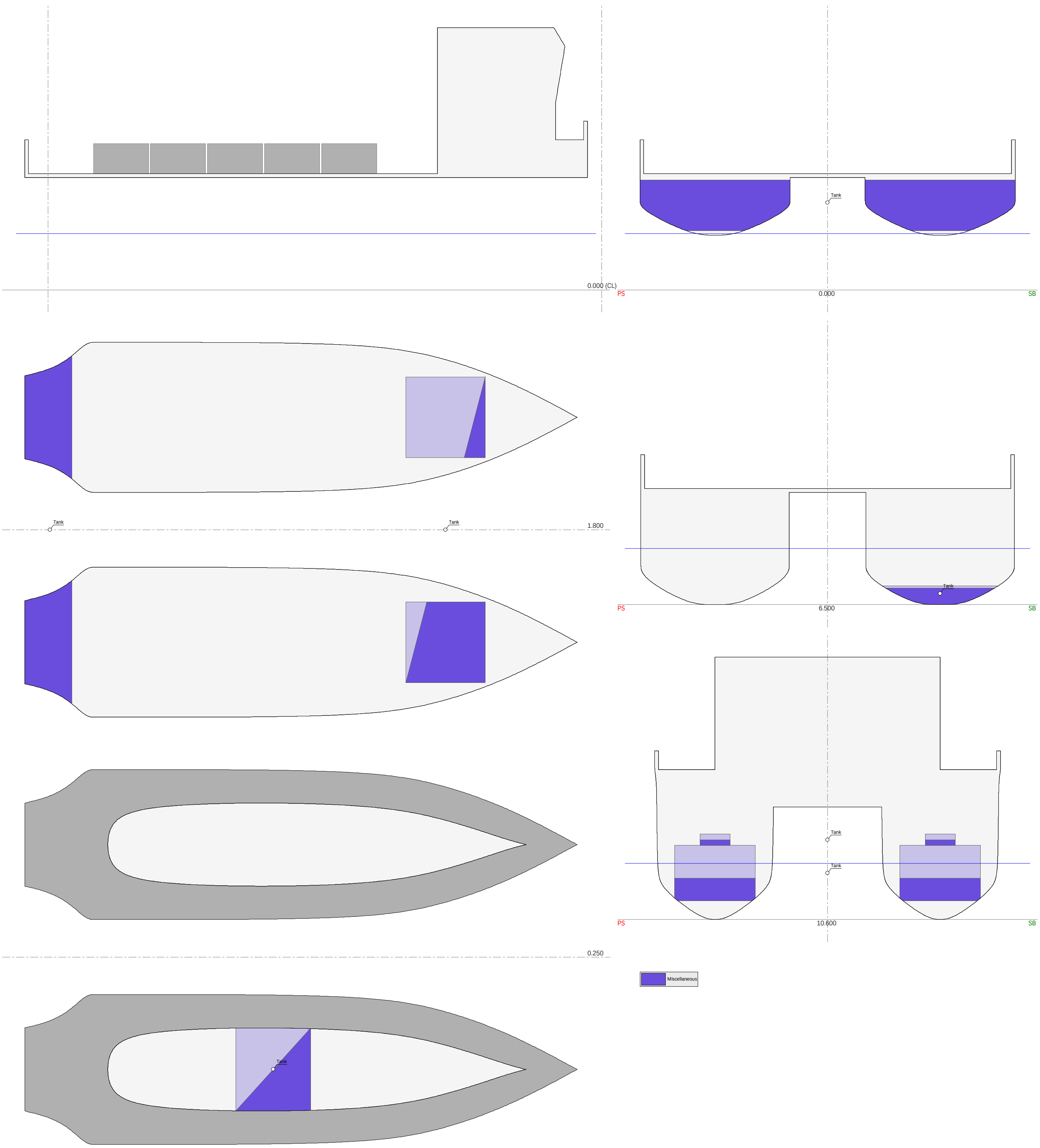
Designer		Sigmund Nilsen Myhre	
Created by			
Comment			
Filename		LeakPointFix.fbm	
Design length	14.750 (m)	Midship location	7.375 (m)
Length over all	15.000 (m)	Relative water density	1.0250
Design beam	8.000 (m)	Mean shell thickness	0.0100 (m)
Maximum beam	10.000 (m)	Appendage coefficient	1.0000
Design draft	1.665 (m)		

Calculation settings

Center of gravity of tanks containing liquids	:	Actual COG

Silhouette 2





Hydrostatic particulars

List	0.0 (SB) (Degr.)	GG'	1.101 (m)
Draft aft pp	1.505 (m)	VCG'	3.309 (m)
Mean moulded draft	1.503 (m)	Max VCG'	2.346 (m)

Hydrostatic particulars

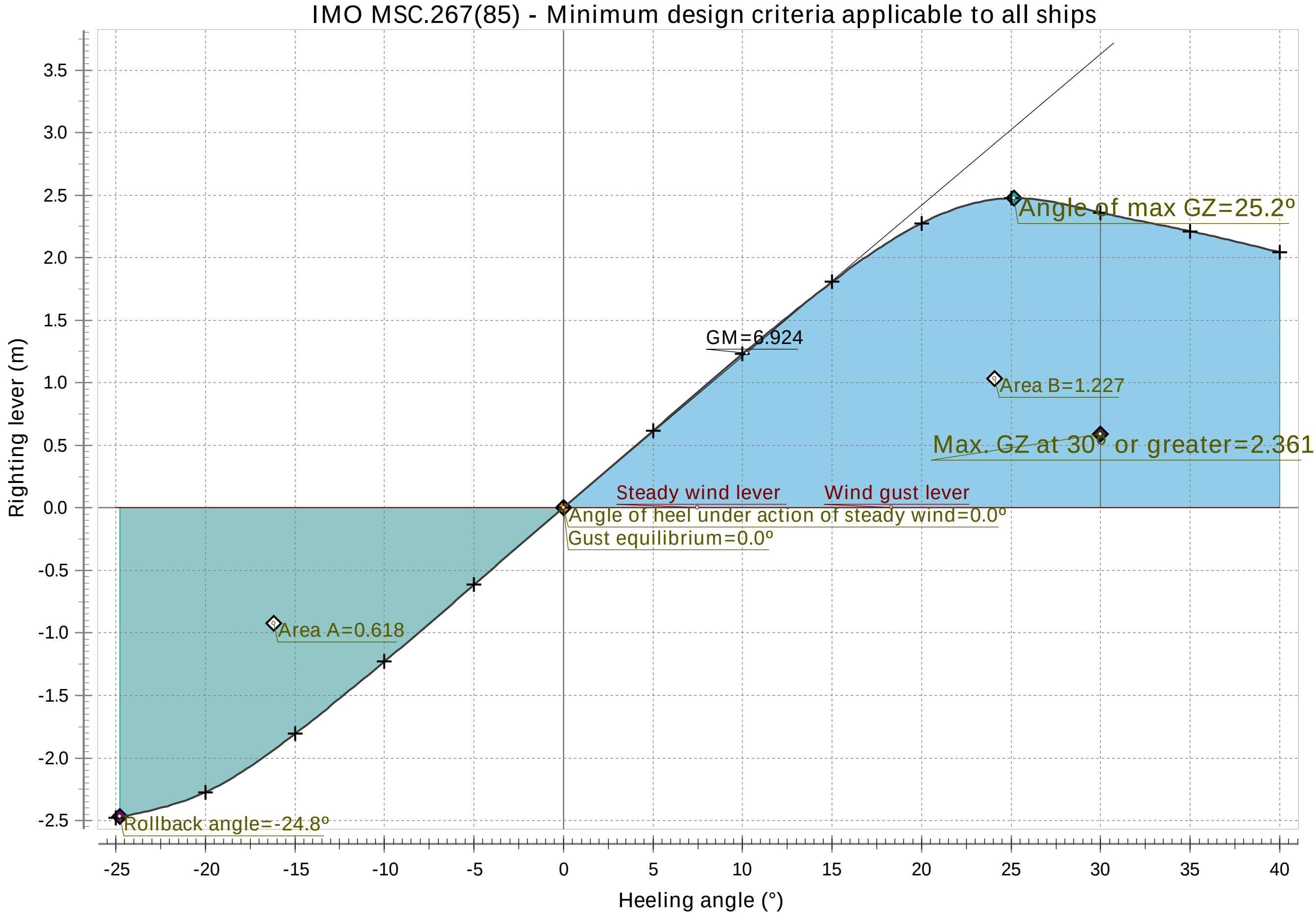
Draft forward pp	1.501 (m)	GM solid	8.025 (m)
Trim	-0.004 (m)	G'M liquid	6.924 (m)
KM	10.233 (m)	Immersion rate	0.922 (t/cm)
VCG	2.208 (m)	MCT	0.656 (t*m/cm)

Description	Density (t/m³)	Fill%	Weight (tonnes)	LCG (m)	TCG (m)	VCG (m)	FSM (t*m)
Miscellaneous							
Tank	1.0000	40.0	5.205	10.563	0.000 (CL)	0.808	83.647
Tank	1.0000	100.0	11.628	0.019	0.000 (CL)	2.323	0.000
Tank	1.0000	83.6	1.729	5.999	-3.000 (SB)	0.261	4.016
Tank	1.0000	50.0	0.379	10.841	0.000 (CL)	2.055	22.855
Rig			0.450	4.615	0.000 (CL)	5.000	0.000
Containers			3.300	4.527	0.000 (CL)	3.445	0.000
Drums			0.084	10.025	-0.668 (SB)	3.250	0.000
Crew & Provisions			0.500	11.924	0.000 (CL)	3.500	0.000
Totals for Miscellaneous			23.275	4.017	-0.225 (SB)	2.066	110.518
Lightship			77.142	7.192	0.068 (PS)	2.251	
Deadweight			23.275	4.017	-0.225 (SB)	2.066	110.518
Displacement			100.417	6.456	0.000 (CL)	2.208	110.518

Righting levers

Heeling angle	Draft	Trim	Displacement	KN sin(ø)	VCG sin(ø)	GG' sin(ø)	TCG cos(ø)	GZ	Area
(Degr.)	(m)	(m)	(tonnes)	(m)	(m)	(m)	(m)	(m)	(mrad)
0.0º (CL)	1.503	-0.004	100.417	0.000	0.000	0.000	0.000	0.000	0.000
5.0º (PS)	1.499	0.052	100.417	0.895	0.192	0.086	0.000	0.616	0.027
10.0º (PS)	1.482	0.182	100.417	1.769	0.383	0.155	0.000	1.230	0.107
15.0º (PS)	1.438	0.355	100.417	2.551	0.572	0.173	0.000	1.807	0.240
20.0º (PS)	1.353	0.564	100.417	3.201	0.755	0.171	0.000	2.274	0.420
25.0º (PS)	1.201	0.885	100.417	3.577	0.933	0.168	0.000	2.476	0.630
30.0º (PS)	0.904	1.001	100.417	3.628	1.104	0.163	0.000	2.361	0.842
35.0º (PS)	0.570	1.065	100.417	3.635	1.267	0.156	0.000	2.212	1.041
40.0º (PS)	0.204	1.112	100.417	3.611	1.419	0.149	0.000	2.043	1.227

Stability curve
IMO MSC.267(85) - Minimum design criteria applicable to all ships



Evaluation of criteria

IMO MSC.267(85) - Minimum design criteria applicable to all ships

International Code on Intact Stability (2008), Part A, §2.2 - §2.3

Description	Attained value	Criterion	Required value	Complies
Area 0º - 30º	0.8420 (mrad)	>=	0.0550 (mrad)	YES
Area 0º - 40º	1.2273 (mrad)	>=	0.0900 (mrad)	YES
Area 30º - 40º	0.3853 (mrad)	>=	0.0300 (mrad)	YES
Max. GZ at 30º or greater	2.361 (m)	>=	0.200 (m)	YES
Lower angle	30.0 (Degr.)			
Upper angle	90.0 (Degr.)			
Angle of max GZ	25.2 (Degr.)	>=	25.0 (Degr.)	YES
Initial metacentric height	6.924 (m)	>=	0.150 (m)	YES
Severe wind and rolling criterion (weather criterion)				YES
Wind silhouette:	Silhouette 2			
Wind pressure	51.4 (kg/m^2)			
Wind area	21.47 (m^2)			
Steady wind lever	0.000 (m)			
Deck immersion angle	34.52 (Degr.)			
Wind gust lever	0.000 (m)			
Ratio of areaA/areaB	0.504	<=	1.000	YES
Maximum allowed static heeling angle	0.0 (Degr.)	<=	16.0 (Degr.)	YES
Max allowed ratio static angle/deck immersion angle	0.000	<=	0.800	YES

The condition complies with the stability criteria

Full Harvest 2021-2025

Kelp Zero

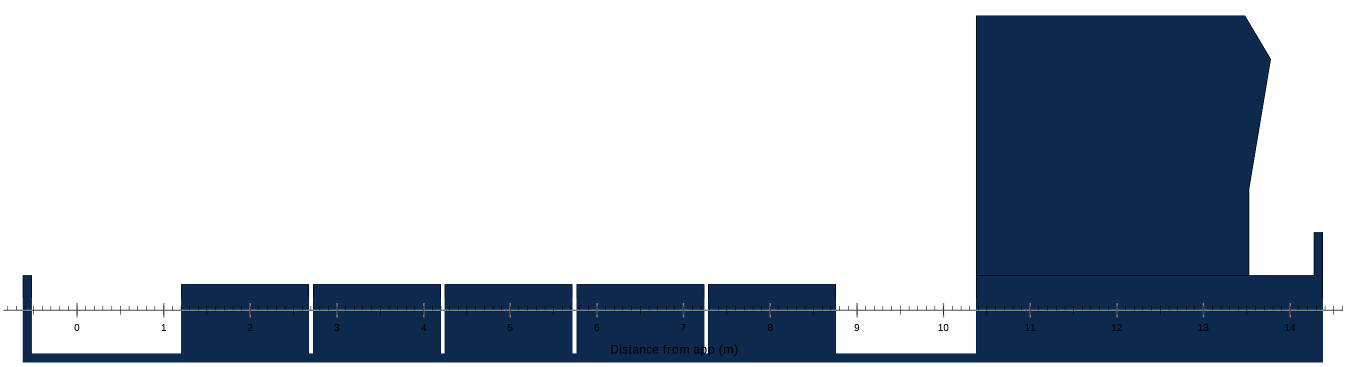
Designer	Sigmund Nilsen Myhre		
Created by			
Comment			
Filename	VesselDesign.fbm		

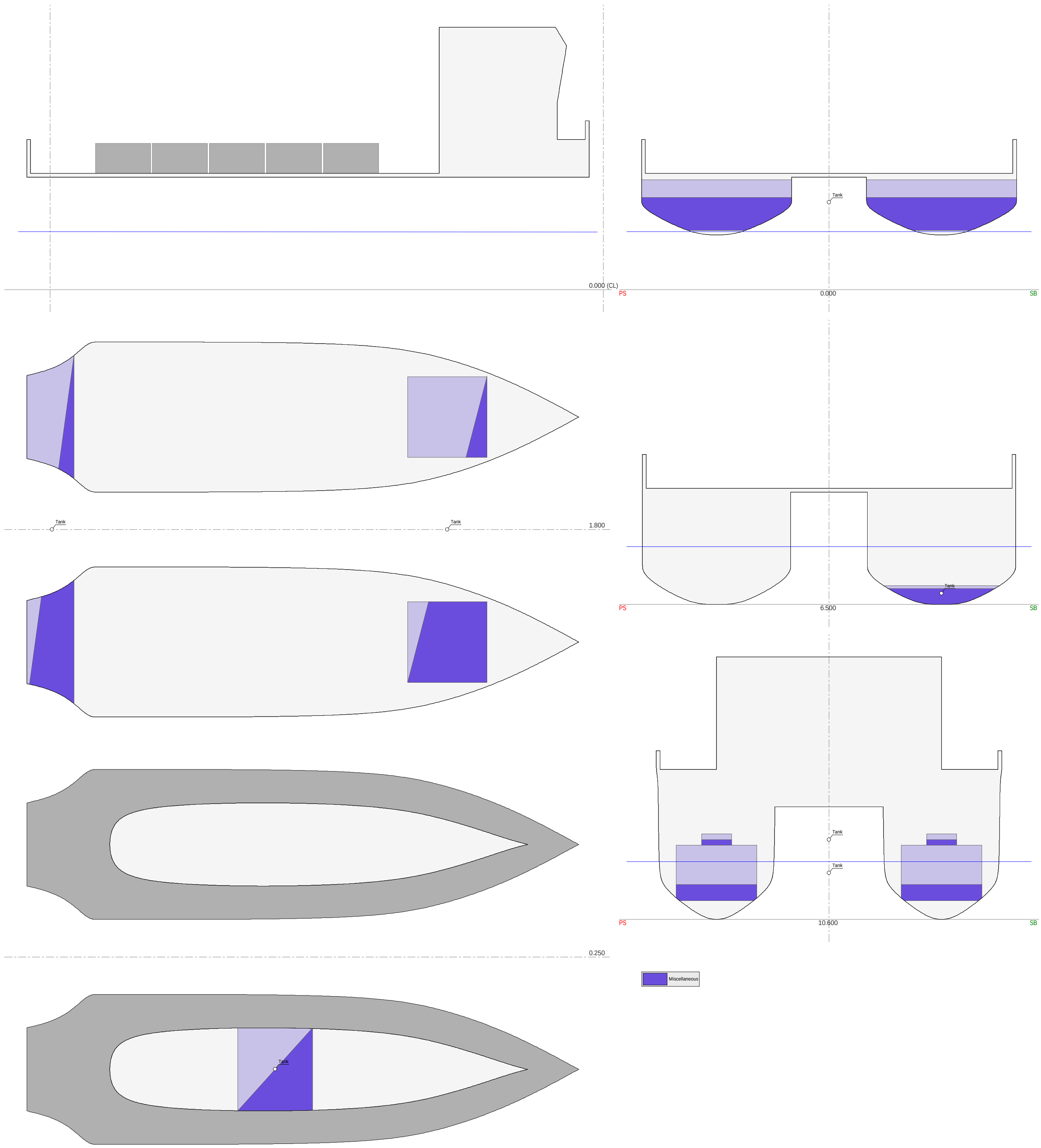
Design length	14.750 (m)	Midship location	7.375 (m)
Length over all	15.000 (m)	Relative water density	1.0250
Design beam	8.000 (m)	Mean shell thickness	0.0100 (m)
Maximum beam	10.000 (m)	Appendage coefficient	1.0000
Design draft	1.880 (m)		

Calculation settings

Center of gravity of tanks containing liquids	:	Actual COG

Silhouette 2





0.000 (CL)
PS
0.000
SB
Tank
Tank
Tank
1.800
PS
6.500
SB
Tank
Tank
PS
10.600
SB
0.250
Tank
Miscellaneous

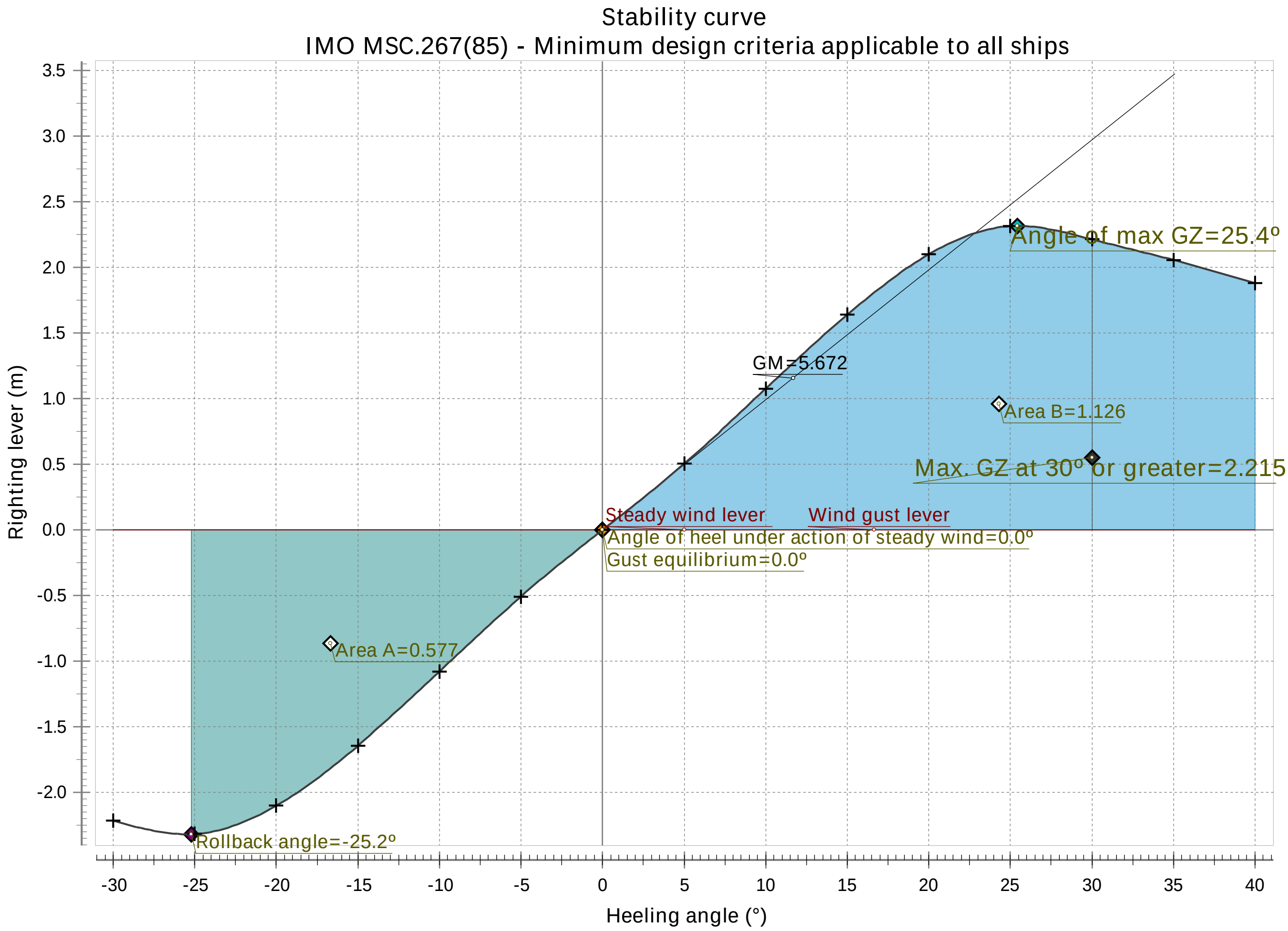
Hydrostatic particulars

List	0.0 (PS) (Degr.)	GG'	2.042 (m)
Draft aft pp	1.542 (m)	VCG'	4.363 (m)
Mean moulded draft	1.540 (m)	Max VCG'	2.715 (m)
Draft forward pp	1.539 (m)	GM solid	7.714 (m)
Trim	-0.004 (m)	G'M liquid	5.672 (m)
KM	10.035 (m)	Immersion rate	0.932 (t/cm)
VCG	2.322 (m)	MCT	0.671 (t*m/cm)

Description	Density (t/m3)	Fill%	Weight (tonnes)	LCG (m)	TCG (m)	VCG (m)	FSM (t*m)
Miscellaneous							
Tank	1.0000	28.0	3.644	10.552	0.000 (CL)	0.719	83.317
Tank	1.0000	60.0	6.977	0.028	0.000 (CL)	2.076	102.073
Tank	1.0000	80.0	1.654	5.999	-3.000 (SB)	0.253	3.838
Tank	1.0000	50.0	0.379	10.841	0.000 (CL)	2.055	22.855
Rig			0.500	4.615	0.000 (CL)	5.000	0.000
Full Containers			13.200	4.257	0.000 (CL)	3.445	0.000
Full Drums			0.381	10.025	-0.668 (SB)	3.250	0.000
Crew & Provisions			0.000	12.000	0.000 (CL)	4.200	0.000
Totals for Miscellaneous			26.735	4.301	-0.195 (SB)	2.525	212.083
Lightship			77.142	7.192	0.068 (PS)	2.251	
Deadweight			26.735	4.301	-0.195 (SB)	2.525	212.083
Displacement			103.877	6.448	0.000 (PS)	2.322	212.083

Righting levers

Heeling angle	Draft	Trim	Displacement	KN sin(ø)	VCG sin(ø)	GG' sin(ø)	TCG cos(ø)	GZ	Area
(Degr.)	(m)	(m)	(tonnes)	(m)	(m)	(m)	(m)	(m)	(mrad)
0.0º (CL)	1.540	-0.004	103.877	0.000	0.000	0.000	0.000	0.000	0.000
5.0º (PS)	1.536	0.055	103.876	0.875	0.202	0.167	0.000	0.506	0.022
10.0º (PS)	1.521	0.186	103.877	1.733	0.403	0.253	0.000	1.076	0.090
15.0º (PS)	1.480	0.359	103.876	2.505	0.601	0.263	0.000	1.642	0.209
20.0º (PS)	1.400	0.569	103.877	3.154	0.794	0.262	0.000	2.099	0.374
25.0º (PS)	1.269	0.902	103.876	3.553	0.981	0.258	0.000	2.314	0.569
30.0º (PS)	0.993	1.050	103.877	3.628	1.161	0.252	0.000	2.215	0.768
35.0º (PS)	0.665	1.101	103.877	3.633	1.332	0.244	0.000	2.057	0.954
40.0º (PS)	0.306	1.125	103.877	3.607	1.492	0.234	0.000	1.881	1.126



Evaluation of criteria

IMO MSC.267(85) - Minimum design criteria applicable to all ships

International Code on Intact Stability (2008), Part A, §2.2- §2.3

Description	Attained value	Criterion	Required value	Complies
Area 0º - 30º	0.7677 (mrad)	>=	0.0550 (mrad)	YES
Area 0º - 40º	1.1260 (mrad)	>=	0.0900 (mrad)	YES
Area 30º - 40º	0.3583 (mrad)	>=	0.0300 (mrad)	YES
Max. GZ at 30º or greater	2.215 (m)	>=	0.200 (m)	YES
Lower angle	30.0 (Degr.)			
Upper angle	90.0 (Degr.)			
Angle of max GZ	25.4 (Degr.)	>=	25.0 (Degr.)	YES
Initial metacentric height	5.672 (m)	>=	0.150 (m)	YES
Severe wind and rolling criterion (weather criterion)				YES
Wind silhouette:	Silhouette 2			
Wind pressure	51.4 (kg/m^2)			
Wind area	21.47 (m^2)			
Steady wind lever	0.000 (m)			
Deck immersion angle	32.52 (Degr.)			
Wind gust lever	0.000 (m)			
Ratio of areaA/areaB	0.513	<=	1.000	YES
Maximum allowed static heeling angle	0.0 (Degr.)	<=	16.0 (Degr.)	YES
Max allowed ratio static angle/deck immersion angle	0.000	<=	0.800	YES

The condition complies with the stability criteria

Full Harvest 2026-2030

Kelp Zero

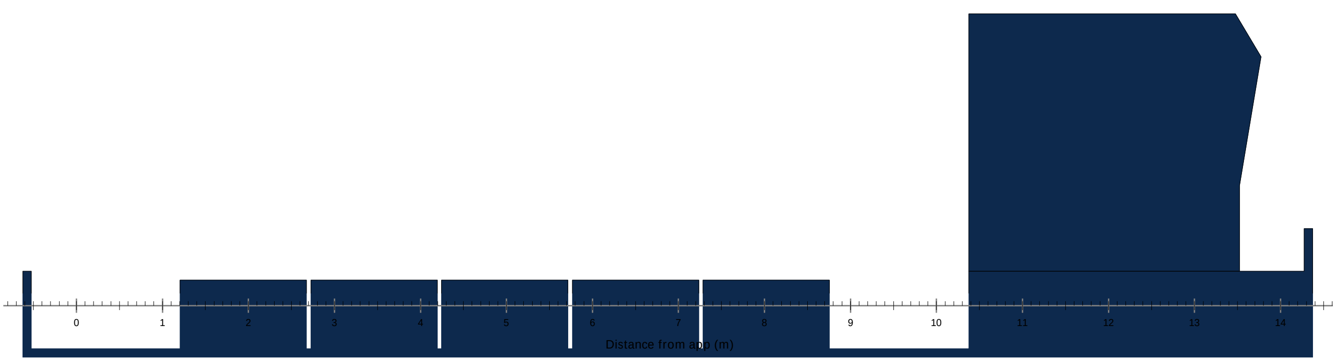
Designer	Sigmund Nilsen Myhre
Created by	
Comment	
Filename	LeakPointFix.fbm

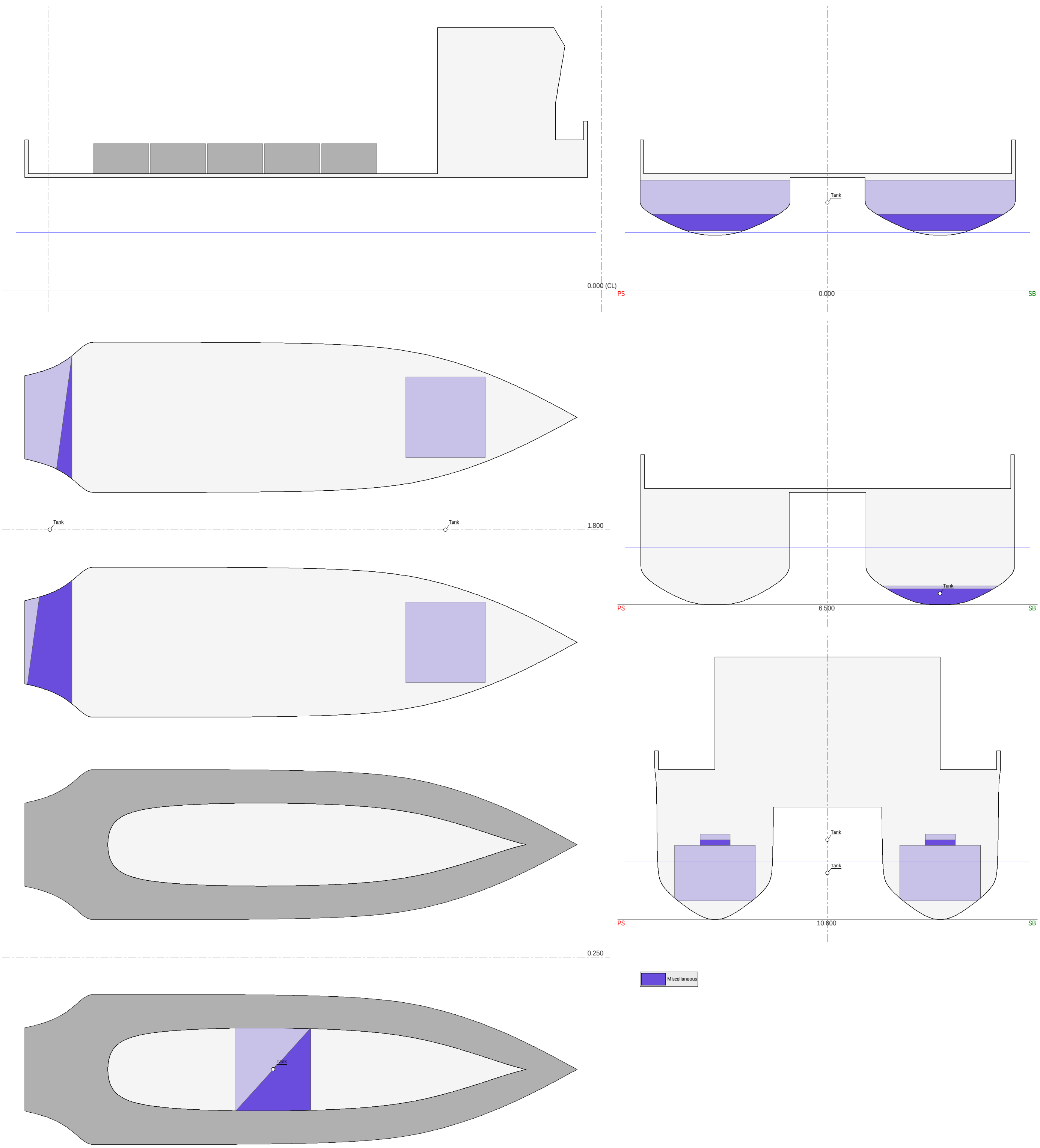
Design length	14.750 (m)	Midship location	7.375 (m)
Length over all	15.000 (m)	Relative water density	1.0250
Design beam	8.000 (m)	Mean shell thickness	0.0100 (m)
Maximum beam	10.000 (m)	Appendage coefficient	1.0000
Design draft	1.665 (m)		

Calculation settings

Center of gravity of tanks containing liquids	:	Actual COG

Silhouette 2





Hydrostatic particulars

List	0.0 (SB) (Degr.)	GG'	1.075 (m)
Draft aft pp	1.533 (m)	VCG'	3.538 (m)
Mean moulded draft	1.533 (m)	Max VCG'	2.657 (m)

Hydrostatic particulars

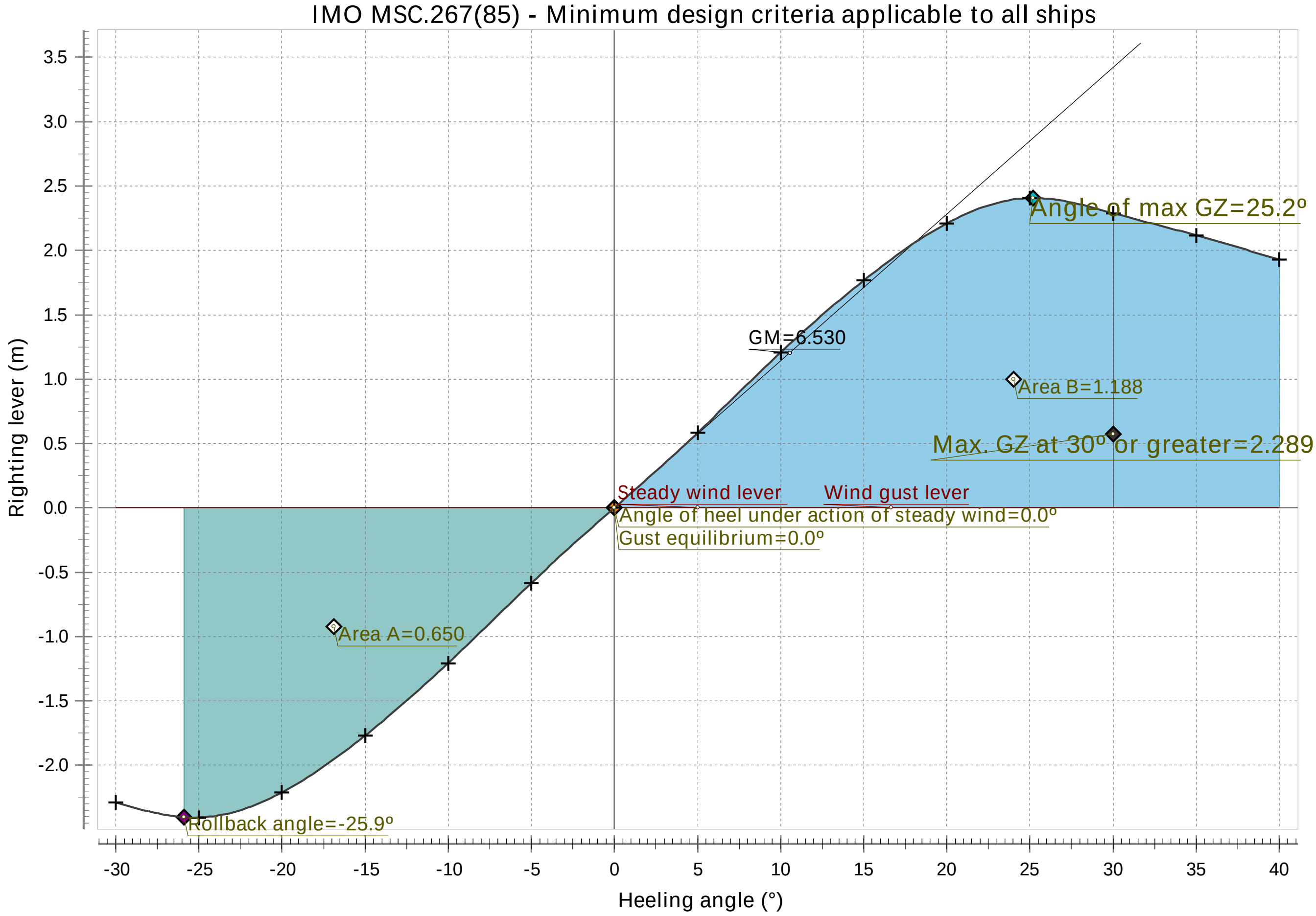
Draft forward pp	1.533 (m)	GM solid	7.605 (m)
Trim	0.000 (m)	G'M liquid	6.530 (m)
KM	10.068 (m)	Immersion rate	0.930 (t/cm)
VCG	2.463 (m)	MCT	0.655 (t*m/cm)

Description	Density (t/m3)	Fill%	Weight (tonnes)	LCG (m)	TCG (m)	VCG (m)	FSM (t*m)
Miscellaneous							
Tank	1.0000	0.0	0.000	10.578	0.000 (CL)	1.248	0.000
Tank	1.0000	24.0	2.791	0.049	0.000 (CL)	1.824	84.241
Tank	1.0000	80.0	1.654	5.999	-3.000 (SB)	0.253	3.838
Tank	1.0000	50.0	0.379	10.841	0.000 (CL)	2.055	22.855
Rig			0.500	4.615	0.000 (CL)	5.000	0.000
Full Containers			19.800	4.257	0.000 (CL)	3.445	0.000
Full Drums			0.438	10.025	-0.668 (SB)	3.250	0.000
Crew & Provisions			0.500	12.000	0.000 (CL)	4.200	0.000
Totals for Miscellaneous			26.062	4.265	-0.202 (SB)	3.090	110.935
Lightship			77.142	7.192	0.068 (PS)	2.251	
Deadweight			26.062	4.265	-0.202 (SB)	3.090	110.935
Displacement			103.204	6.453	0.000 (SB)	2.463	110.935

Righting levers

Heeling angle	Draft	Trim	Displacement	KN sin(ø)	VCG sin(ø)	GG' sin(ø)	TCG cos(ø)	GZ	Area
(Degr.)	(m)	(m)	(tonnes)	(m)	(m)	(m)	(m)	(m)	(mrad)
0.0º (CL)	1.533	0.000	103.204	0.000	0.000	0.000	0.000	0.000	0.000
5.0º (PS)	1.529	0.060	103.203	0.879	0.215	0.080	0.000	0.584	0.025
10.0º (PS)	1.514	0.193	103.204	1.739	0.428	0.105	0.000	1.207	0.103
15.0º (PS)	1.473	0.370	103.203	2.513	0.637	0.108	0.000	1.768	0.234
20.0º (PS)	1.393	0.587	103.204	3.162	0.842	0.110	0.000	2.210	0.409
25.0º (PS)	1.258	0.933	103.204	3.556	1.041	0.109	0.000	2.406	0.612
30.0º (PS)	0.980	1.087	103.204	3.628	1.231	0.107	0.000	2.289	0.819
35.0º (PS)	0.651	1.150	103.204	3.634	1.413	0.104	0.000	2.118	1.011
40.0º (PS)	0.290	1.185	103.204	3.609	1.583	0.099	0.000	1.927	1.188

Stability curve
IMO MSC.267(85) - Minimum design criteria applicable to all ships



Evaluation of criteria

IMO MSC.267(85) - Minimum design criteria applicable to all ships

International Code on Intact Stability (2008), Part A, §2.2 - §2.3

Description	Attained value	Criterion	Required value	Complies
Area 0º - 30º	0.8186 (mrad)	>=	0.0550 (mrad)	YES
Area 0º - 40º	1.1876 (mrad)	>=	0.0900 (mrad)	YES
Area 30º - 40º	0.3689 (mrad)	>=	0.0300 (mrad)	YES
Max. GZ at 30º or greater	2.289 (m)	>=	0.200 (m)	YES
Lower angle	30.0 (Degr.)			
Upper angle	90.0 (Degr.)			
Angle of max GZ	25.2 (Degr.)	>=	25.0 (Degr.)	YES
Initial metacentric height	6.530 (m)	>=	0.150 (m)	YES
Severe wind and rolling criterion (weather criterion)				YES
Wind silhouette:	Silhouette 2			
Wind pressure	51.4 (kg/m^2)			
Wind area	21.47 (m^2)			
Steady wind lever	0.000 (m)			
Deck immersion angle	32.62 (Degr.)			
Wind gust lever	0.000 (m)			
Ratio of areaA/areaB	0.547	<=	1.000	YES
Maximum allowed static heeling angle	0.0 (Degr.)	<=	16.0 (Degr.)	YES
Max allowed ratio static angle/deck immersion angle	0.000	<=	0.800	YES

The condition complies with the stability criteria

Full Harvest 2031-2035

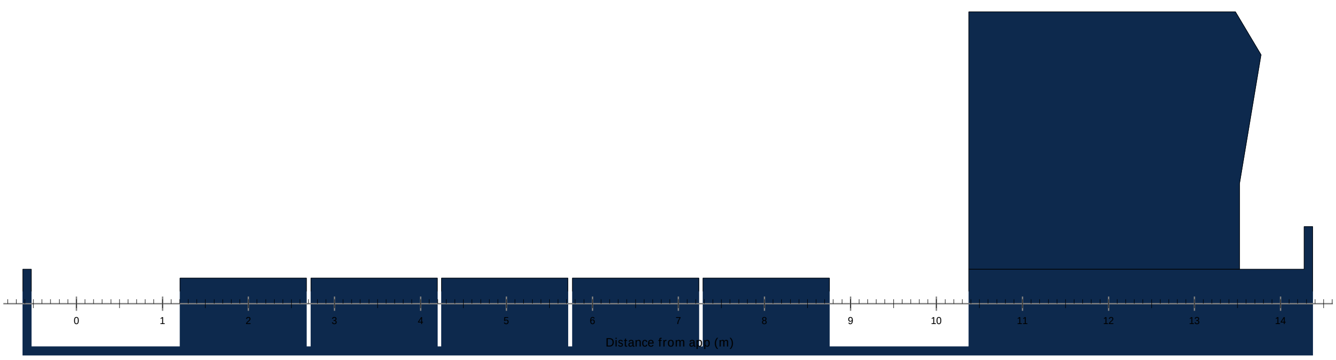
Kelp Zero

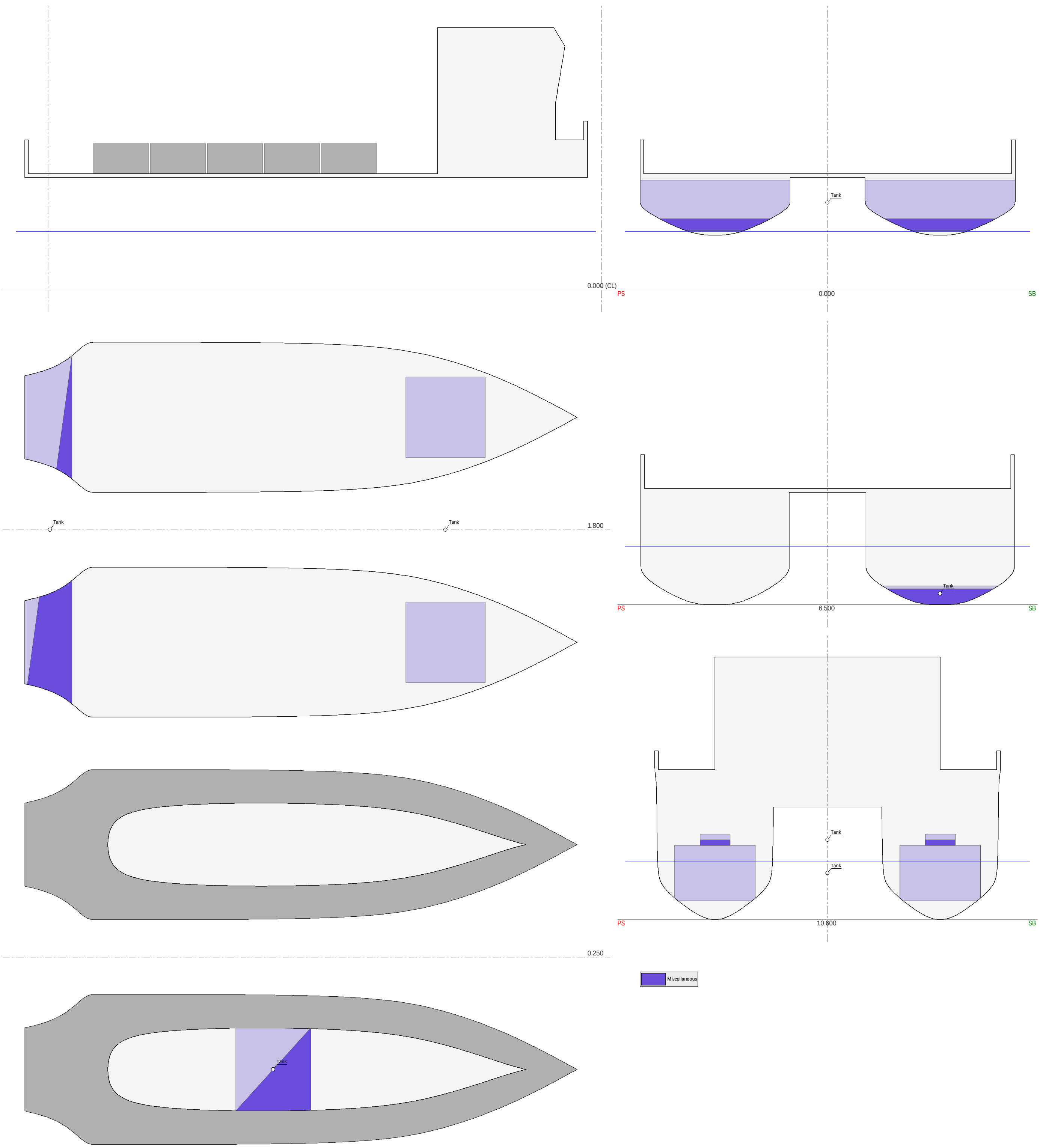
Designer		Sigmund Nilsen Myhre	
Created by			
Comment			
Filename		LeakPointFix.fbm	
Design length	14.750 (m)	Midship location	7.375 (m)
Length over all	15.000 (m)	Relative water density	1.0250
Design beam	8.000 (m)	Mean shell thickness	0.0100 (m)
Maximum beam	10.000 (m)	Appendage coefficient	1.0000
Design draft	1.665 (m)		

Calculation settings

Center of gravity of tanks containing liquids	:	Actual COG

Silhouette 2





Hydrostatic particulars

List	0.0 (SB) (Degr.)	GG'	0.943 (m)
Draft aft pp	1.560 (m)	VCG'	3.442 (m)
Mean moulded draft	1.560 (m)	Max VCG'	2.919 (m)

Hydrostatic particulars

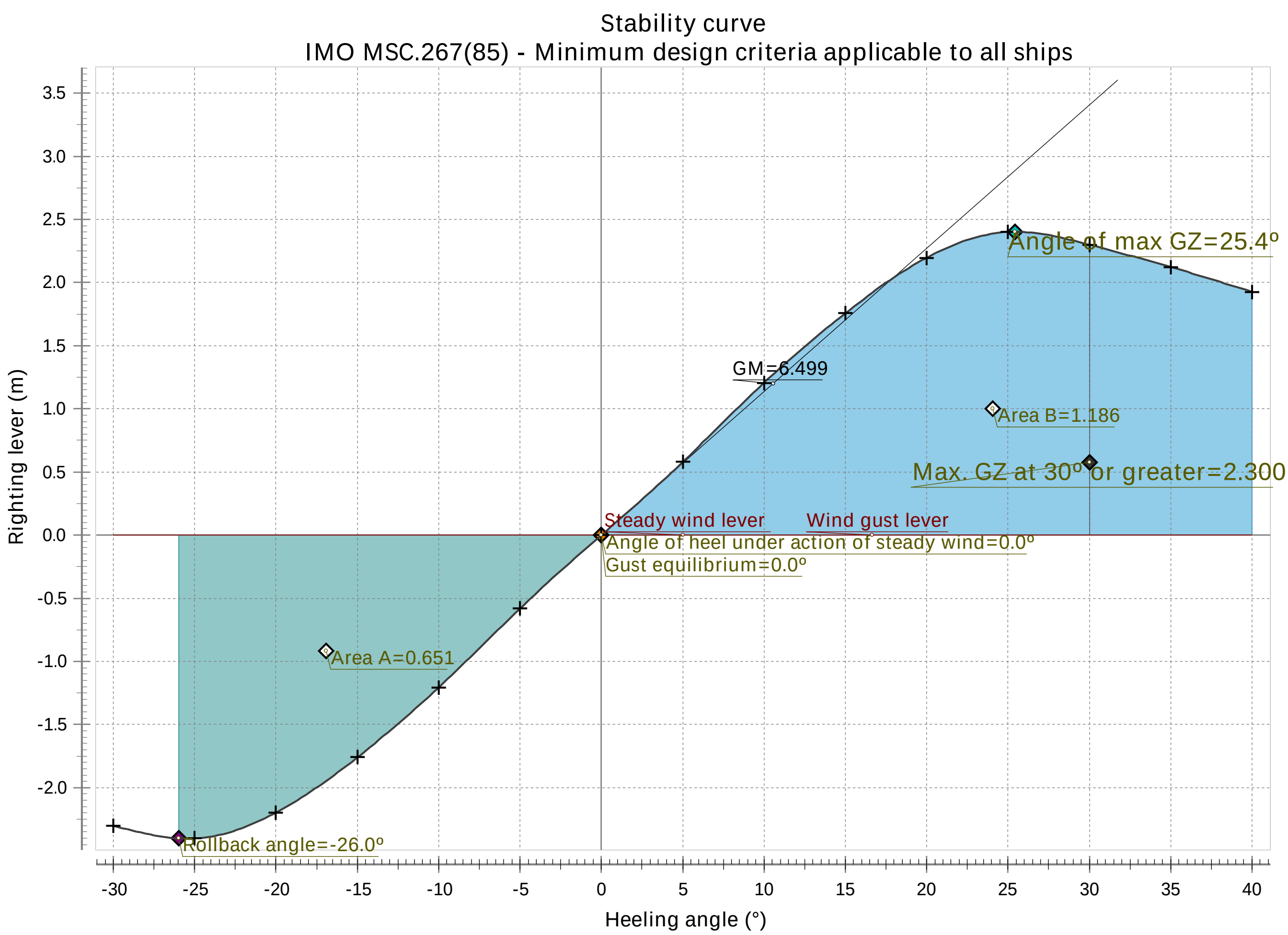
Draft forward pp	1.560 (m)	GM solid	7.442 (m)
Trim	-0.001 (m)	G'M liquid	6.499 (m)
KM	9.941 (m)	Immersion rate	0.938 (t/cm)
VCG	2.499 (m)	MCT	0.671 (t*m/cm)

Description	Density (t/m³)	Fill%	Weight (tonnes)	LCG (m)	TCG (m)	VCG (m)	FSM (t*m)
Miscellaneous							
Tank	1.0000	0.0	0.000	10.578	0.000 (CL)	1.248	0.000
Tank	1.0000	16.0	1.861	0.057	0.000 (CL)	1.756	72.936
Tank	1.0000	80.0	1.654	5.999	-3.000 (SB)	0.253	3.838
Tank	1.0000	50.0	0.379	10.841	0.000 (CL)	2.055	22.855
Rig			0.500	4.615	0.000 (CL)	5.000	0.000
Full Containers			23.100	4.257	0.000 (CL)	3.445	0.000
Full Drums			0.537	10.025	-0.668 (SB)	3.250	0.000
Crew & Provisions			0.500	12.000	0.000 (CL)	4.200	0.000
Totals for Miscellaneous			28.530	4.422	-0.187 (SB)	3.168	99.630

Lightship	77.142	7.192	0.068 (PS)	2.251	
Deadweight	28.530	4.422	-0.187 (SB)	3.168	99.630
Displacement	105.672	6.444	-0.001 (SB)	2.499	99.630

Righting levers

Heeling angle	Draft	Trim	Displacement	KN sin(ø)	VCG sin(ø)	GG' sin(ø)	TCG cos(ø)	GZ	Area
(Degr.)	(m)	(m)	(tonnes)	(m)	(m)	(m)	(m)	(m)	(mrad)
0.0º (CL)	1.560	-0.001	105.672	0.000	0.000	0.000	0.001	-0.001	0.000
-5.0º (SB)	1.556	0.057	105.672	0.866	0.218	0.068	0.001	0.579	0.025
-10.0º (SB)	1.541	0.190	105.672	1.715	0.434	0.074	0.001	1.206	0.103
-15.0º (SB)	1.502	0.367	105.672	2.482	0.647	0.077	0.001	1.758	0.233
-20.0º (SB)	1.426	0.585	105.672	3.129	0.855	0.078	0.001	2.196	0.407
-25.0º (SB)	1.304	0.931	105.672	3.536	1.056	0.078	0.001	2.401	0.609
-30.0º (SB)	1.045	1.118	105.673	3.628	1.249	0.078	0.001	2.300	0.816
-35.0º (SB)	0.720	1.167	105.673	3.632	1.433	0.076	0.001	2.123	1.009
-40.0º (SB)	0.365	1.189	105.672	3.605	1.606	0.072	0.001	1.926	1.186



Evaluation of criteria

IMO MSC.267(85) - Minimum design criteria applicable to all ships

International Code on Intact Stability (2008), Part A, §2.2 - §2.3

Description	Attained value	Criterion	Required value	Complies
Area 0º - 30º	0.8160 (mrad)	>=	0.0550 (mrad)	YES
Area 0º - 40º	1.1858 (mrad)	>=	0.0900 (mrad)	YES
Area 30º - 40º	0.3699 (mrad)	>=	0.0300 (mrad)	YES
Max. GZ at 30º or greater	2.300 (m)	>=	0.200 (m)	YES
Lower angle	30.0 (Degr.)			
Upper angle	90.0 (Degr.)			
Angle of max GZ	25.4 (Degr.)	>=	25.0 (Degr.)	YES
Initial metacentric height	6.499 (m)	>=	0.150 (m)	YES
Severe wind and rolling criterion (weather criterion)				YES
Wind silhouette:	Silhouette 2			
Wind pressure	51.4 (kg/m^2)			
Wind area	21.47 (m^2)			
Steady wind lever	0.000 (m)			
Deck immersion angle	31.19 (Degr.)			
Wind gust lever	0.000 (m)			
Ratio of areaA/areaB	0.549	<=	1.000	YES
Maximum allowed static heeling angle	0.0 (Degr.)	<=	16.0 (Degr.)	YES
Max allowed ratio static angle/deck immersion angle	0.000	<=	0.800	YES

The condition complies with the stability criteria

Full Harvest 2036-2040

Kelp Zero

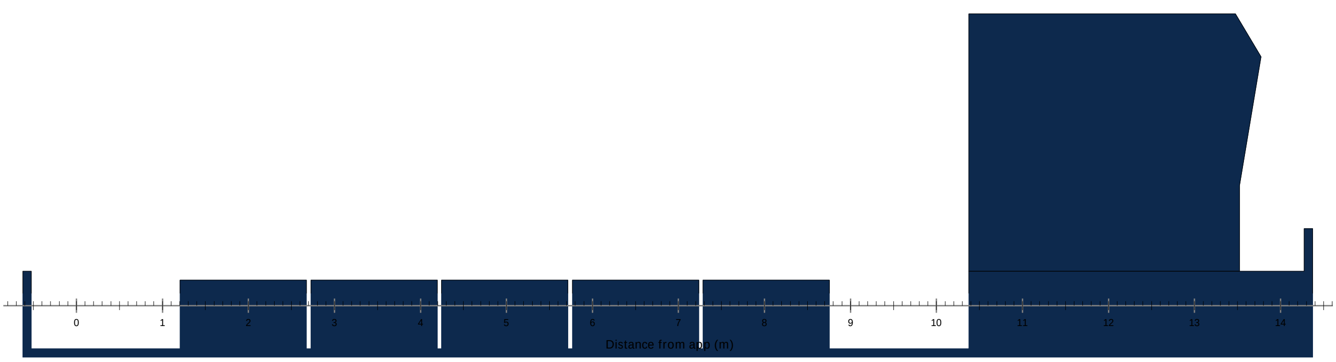
Designer	Sigmund Nilsen Myhre
Created by	
Comment	
Filename	LeakPointFix.fbm

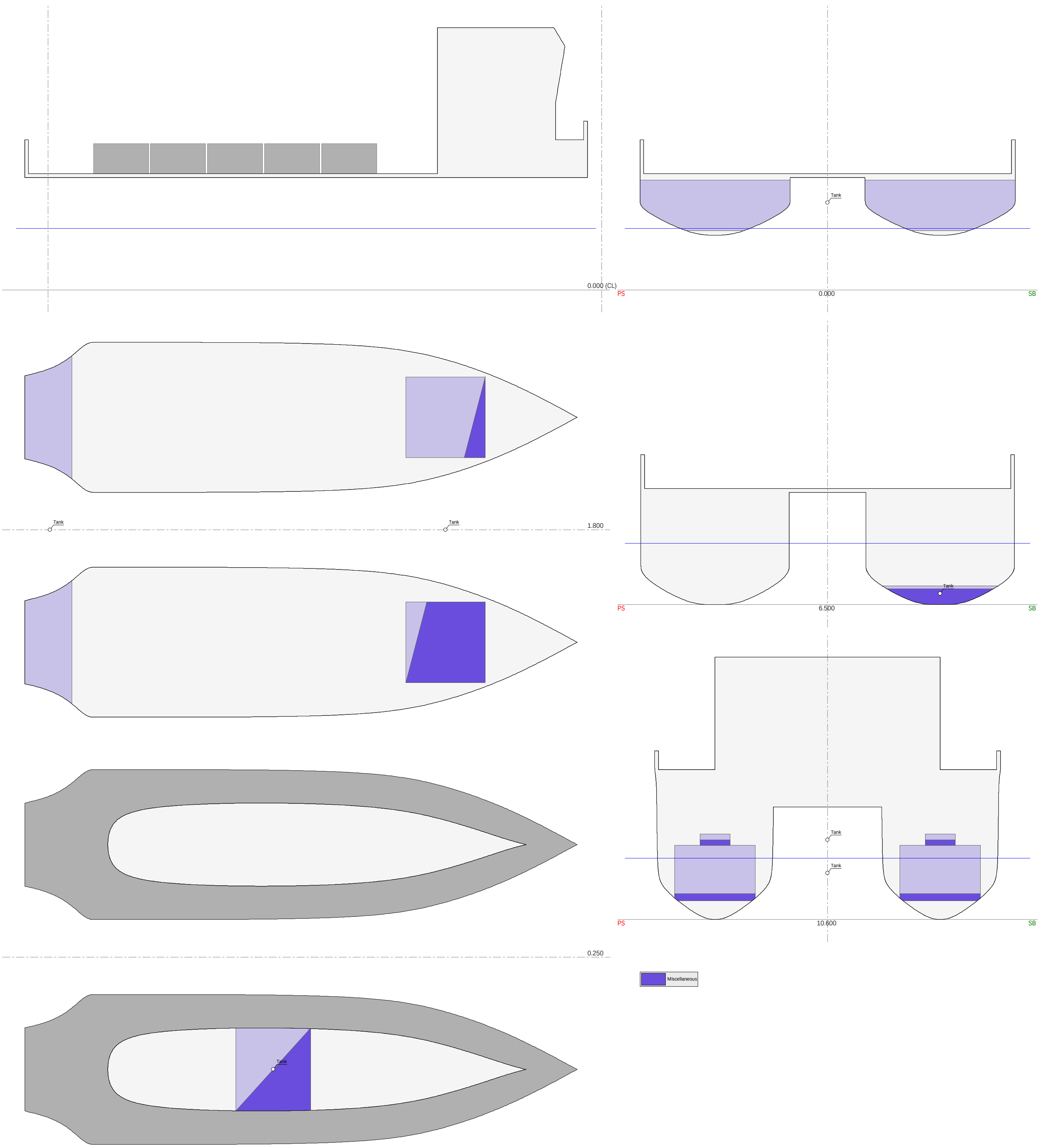
Design length	14.750 (m)	Midship location	7.375 (m)
Length over all	15.000 (m)	Relative water density	1.0250
Design beam	8.000 (m)	Mean shell thickness	0.0100 (m)
Maximum beam	10.000 (m)	Appendage coefficient	1.0000
Design draft	1.665 (m)		

Calculation settings

Center of gravity of tanks containing liquids	:	Actual COG

Silhouette 2





Hydrostatic particulars

List	0.0 (SB) (Degr.)	GG'	0.943 (m)
Draft aft pp	1.638 (m)	VCG'	3.488 (m)
Mean moulded draft	1.638 (m)	Max VCG'	3.720 (m)

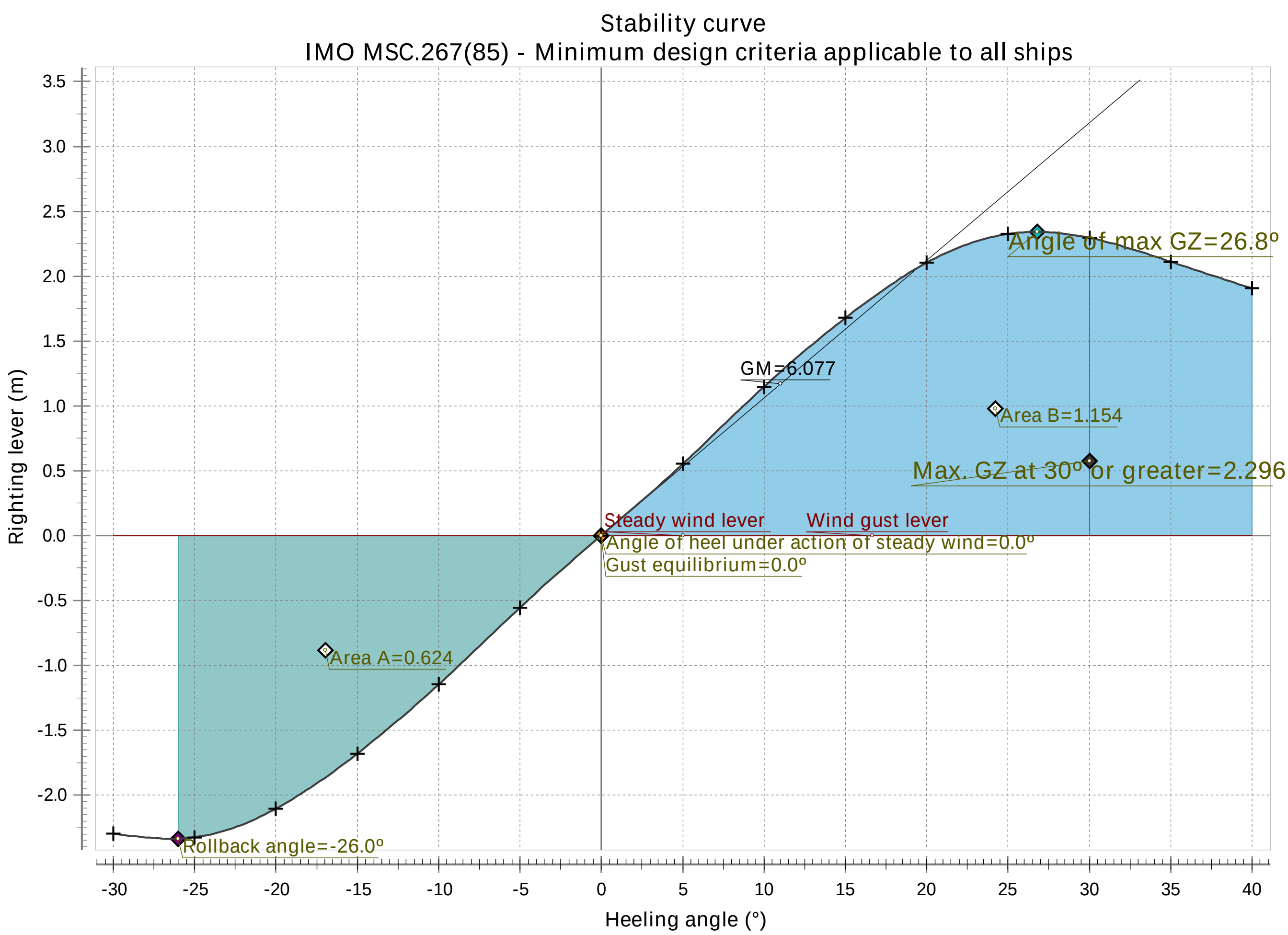
Hydrostatic particulars

Draft forward pp	1.638 (m)	GM solid	7.020 (m)
Trim	0.000 (m)	G'M liquid	6.077 (m)
KM	9.565 (m)	Immersion rate	0.957 (t/cm)
VCG	2.545 (m)	MCT	0.713 (t*m/cm)

Description	Density (t/m³)	Fill%	Weight (tonnes)	LCG (m)	TCG (m)	VCG (m)	FSM (t*m)
Miscellaneous							
Tank	1.0000	12.0	1.562	10.526	0.000 (CL)	0.597	79.913
Tank	1.0000	0.0	0.000	0.019	0.000 (CL)	2.323	0.000
Tank	1.0000	80.0	1.654	5.999	-3.000 (SB)	0.253	3.838
Tank	1.0000	50.0	0.379	10.841	0.000 (CL)	2.055	22.855
Totals for Miscellaneous			3.595	8.476	-1.381 (SB)	0.592	106.606
Full Harvest 2036-2040							
Rig			0.450	4.615	0.000 (CL)	5.000	0.000
Full Containers			31.350	4.257	0.000 (CL)	3.445	0.000
Full Drums			0.516	10.025	-0.668 (SB)	3.250	0.000
Totals for Full Harvest 2036-2040			32.316	4.354	-0.011 (SB)	3.464	0.000
Lightship			77.142	7.192	0.068 (PS)	2.251	
Deadweight			35.911	4.767	-0.148 (SB)	3.176	106.606
Displacement			113.053	6.421	-0.001 (SB)	2.545	106.606

Righting levers

Heeling angle	Draft	Trim	Displacement	KN sin(ø)	VCG sin(ø)	GG' sin(ø)	TCG cos(ø)	GZ	Area
(Degr.)	(m)	(m)	(tonnes)	(m)	(m)	(m)	(m)	(m)	(mrad)
0.0º (CL)	1.638	0.000	113.052	0.000	0.000	0.000	0.001	-0.001	0.000
-5.0º (SB)	1.634	0.055	113.052	0.830	0.222	0.055	0.001	0.553	0.024
-10.0º (SB)	1.622	0.186	113.052	1.646	0.442	0.057	0.001	1.147	0.098
-15.0º (SB)	1.588	0.360	113.052	2.395	0.659	0.057	0.001	1.679	0.222
-20.0º (SB)	1.524	0.582	113.053	3.031	0.870	0.057	0.001	2.103	0.388
-25.0º (SB)	1.436	0.896	113.053	3.458	1.076	0.057	0.001	2.325	0.583
-30.0º (SB)	1.244	1.178	113.053	3.625	1.272	0.056	0.001	2.296	0.786
-35.0º (SB)	0.936	1.198	113.053	3.625	1.460	0.054	0.000	2.111	0.979
-40.0º (SB)	0.600	1.177	113.053	3.593	1.636	0.052	0.000	1.905	1.154



Evaluation of criteria

IMO MSC.267(85) - Minimum design criteria applicable to all ships

International Code on Intact Stability (2008), Part A, §2.2 - §2.3

Description	Attained value	Criterion	Required value	Complies
Area 0º - 30º	0.7862 (mrad)	>=	0.0550 (mrad)	YES
Area 0º - 40º	1.1543 (mrad)	>=	0.0900 (mrad)	YES
Area 30º - 40º	0.3681 (mrad)	>=	0.0300 (mrad)	YES
Max. GZ at 30º or greater	2.296 (m)	>=	0.200 (m)	YES
Lower angle	30.0 (Degr.)			
Upper angle	90.0 (Degr.)			
Angle of max GZ	26.8 (Degr.)	>=	25.0 (Degr.)	YES
Initial metacentric height	6.077 (m)	>=	0.150 (m)	YES
Severe wind and rolling criterion (weather criterion)				YES
Wind silhouette:	Silhouette 2			
Wind pressure	51.4 (kg/m^2)			
Wind area	21.47 (m^2)			
Steady wind lever	0.000 (m)			
Deck immersion angle	28.02 (Degr.)			
Wind gust lever	0.000 (m)			
Ratio of areaA/areaB	0.541	<=	1.000	YES
Maximum allowed static heeling angle	0.0 (Degr.)	<=	16.0 (Degr.)	YES
Max allowed ratio static angle/deck immersion angle	0.000	<=	0.800	YES

The condition complies with the stability criteria

J Resistance Calculation with Guldhammer Harvalds Method

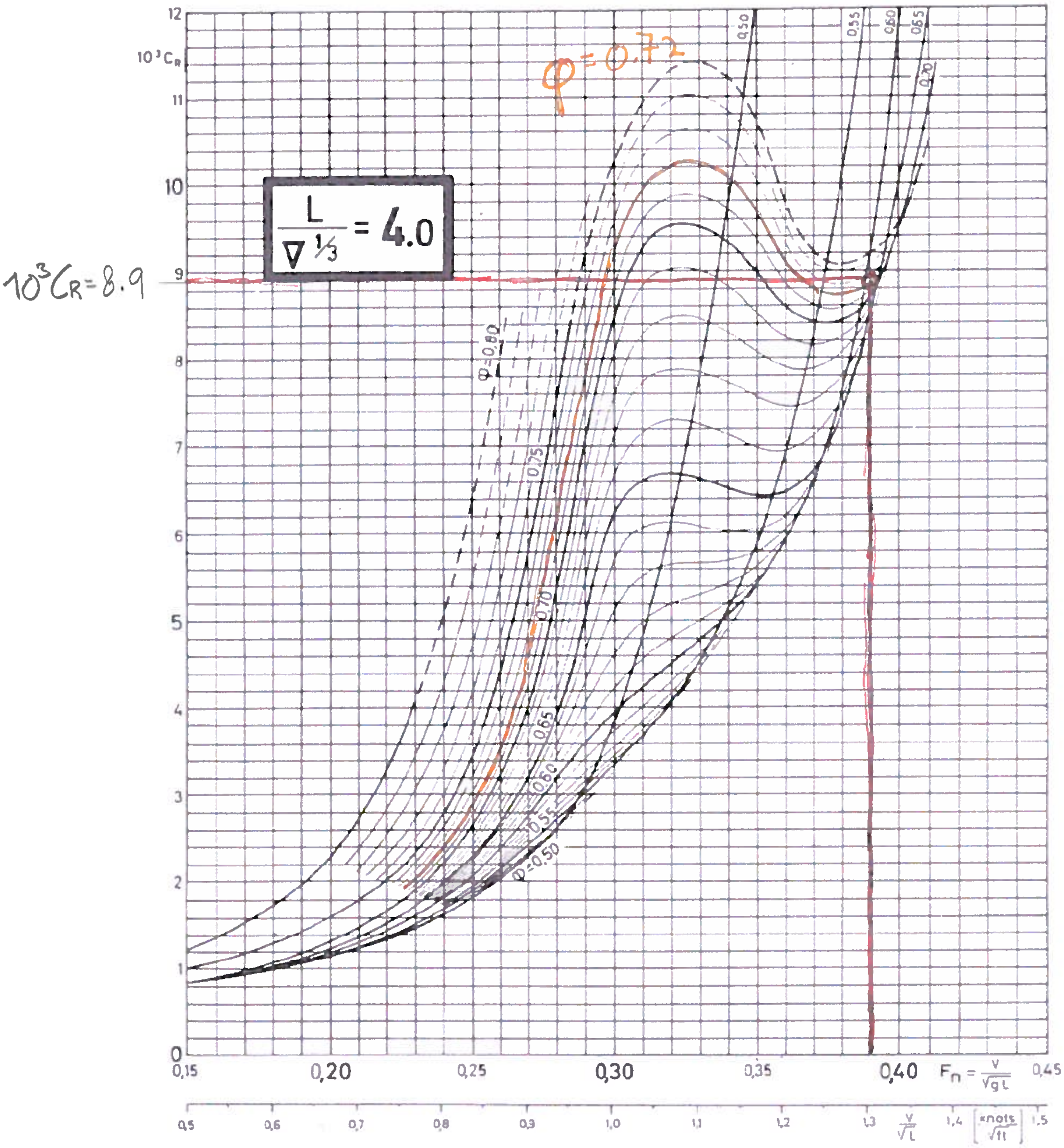


Figure 5.5.5. Residuary resistance coefficient versus speed–length ratio for different values of longitudinal prismatic coefficient. $L/\nabla^{1/3} = 4.0$.

$\varphi = 0.7199 \approx 0.72$

$F_N = \dfrac{9.05144}{\sqrt{9.81 \cdot 14.75}} \simeq 0,39$

$\dfrac{14.75}{665^{1/3}} = 3.64$

Assuming correction of +1.0 for wrong $\frac{L}{\nabla^{1/3}}$.

$10^3 C_R = 9.9$

$$C_F = \frac{0.075}{(\log(R_N)-2)^2} = \frac{0.075}{(\log(5{,}75\cdot 10^7)-2)^2} , \quad 10^3 C_F = 2{,}261$$

$$R_N = \frac{V \cdot L}{\nu} = \frac{9 \cdot 0{,}5144 \cdot 14{,}75}{1{,}1883 \cdot 10^{-6}} = 5{,}75 \cdot 10^7$$

ν - Kinematic viscocity

$\nu = 1{,}1883 \cdot 10^{-6}\, m^2/s$

Guldhammer Harvalds method for one hull. Assuming a scaling factor of 2.2 for catamaran power.

$R_T = 11.1\ kN$

$P_B = 284\ kW$

$P_D = 277\ kW$

$$\frac{B}{T} = \frac{4\,m}{1{,}88\,m} = 2{,}13 \neq 2{,}5$$

B/T correction: $10^3 C_R = 9.9 + 0.16 \cdot (2{,}13 - 2{,}5)$

$10^3 C_R = 9{,}84$

$L = 14{,}75\,m < 100\,m$

$10^3 C_A = 0.4$

$$C_T = C_A + C_F + C_R = (0{,}4 + 2{,}261 + 9{,}84) \cdot 10^{-3}$$

$10^3 C_T = 12{,}5$

$$R_T = C_T \cdot \frac{\rho_{SW}}{2} \cdot V^2 \cdot S = 12{,}5 \cdot 10^{-3} \cdot \frac{1025}{2} \cdot (9 \cdot 0{,}5144)^2 \cdot 81{,}01$$

S - wetted surface, $S = 81.01\,m^2$

$R_T = 11125{,}12\ N$, $R_T \simeq 11{,}1\ kN$

$P_E = R_T \cdot V = 11125 \cdot 9 \cdot 0{,}5144 \Rightarrow P_E \simeq 51{,}5\,kW$

P_E - Towing power

P_B - Engine power

P_D - Power delivered to propulsion system

Assume $\eta_T = 0.4$

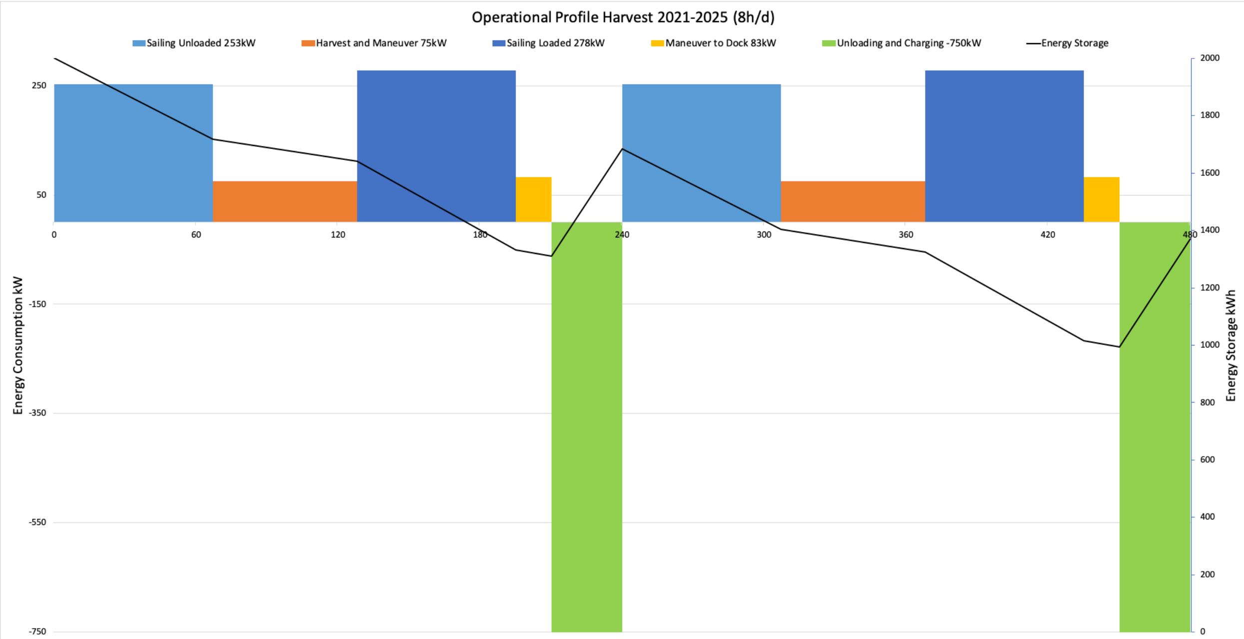
$$P_B = \frac{P_E}{\eta_T} = \frac{51{,}5 \cdot 10^3}{0.4} , \quad P_B \simeq 129\ kW$$

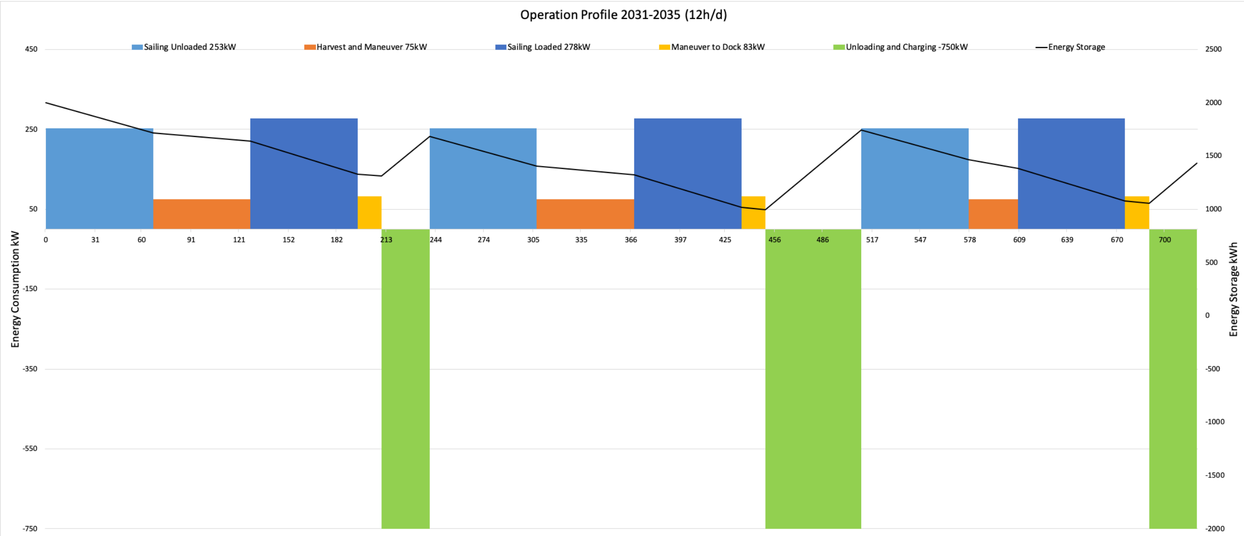
Assume $\eta_M = 0.98$

$$P_D = P_B \cdot \eta_M = 129 \cdot 10^3 \cdot 0.98 , \quad P_D \simeq 126\ kW$$

K Operational Profiles 2021-2040

The opertional profiles for 2021-2040, showing the energy consumption of different operations as bars with axis on the left-hand side. The remaining energy storage is indicated with the black line, which has axis on the right-hand side. The numbers on the horizontal axis indicates minutes after initiation.

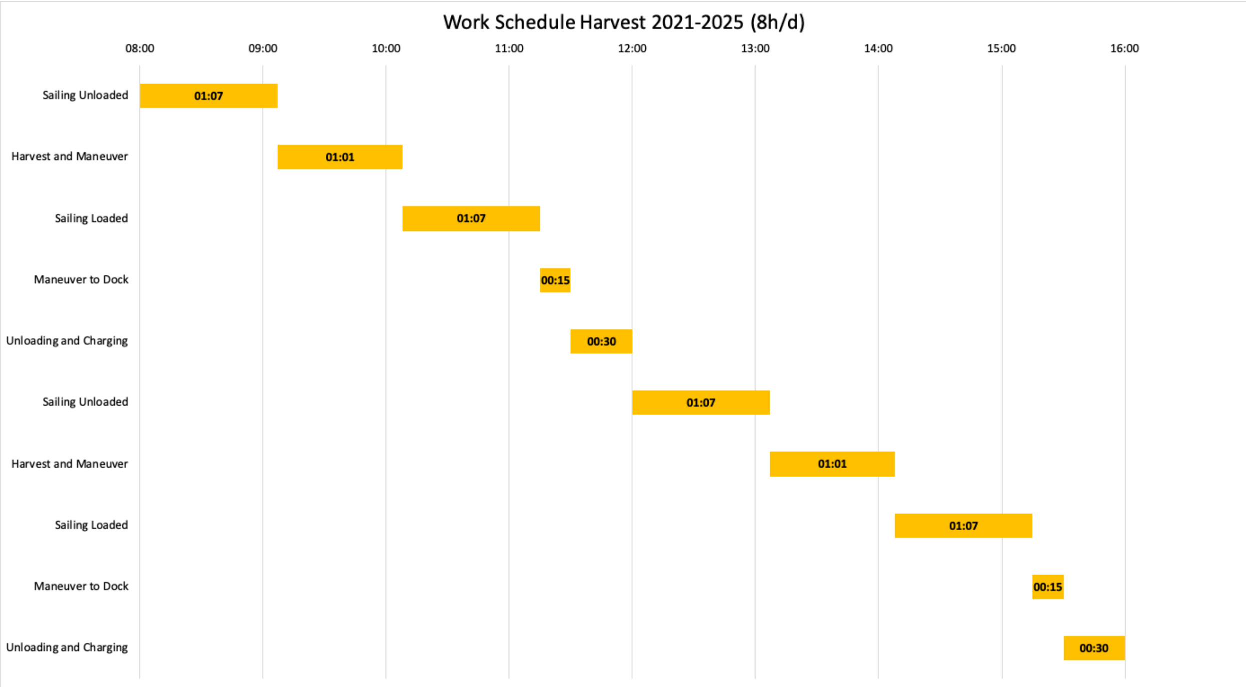


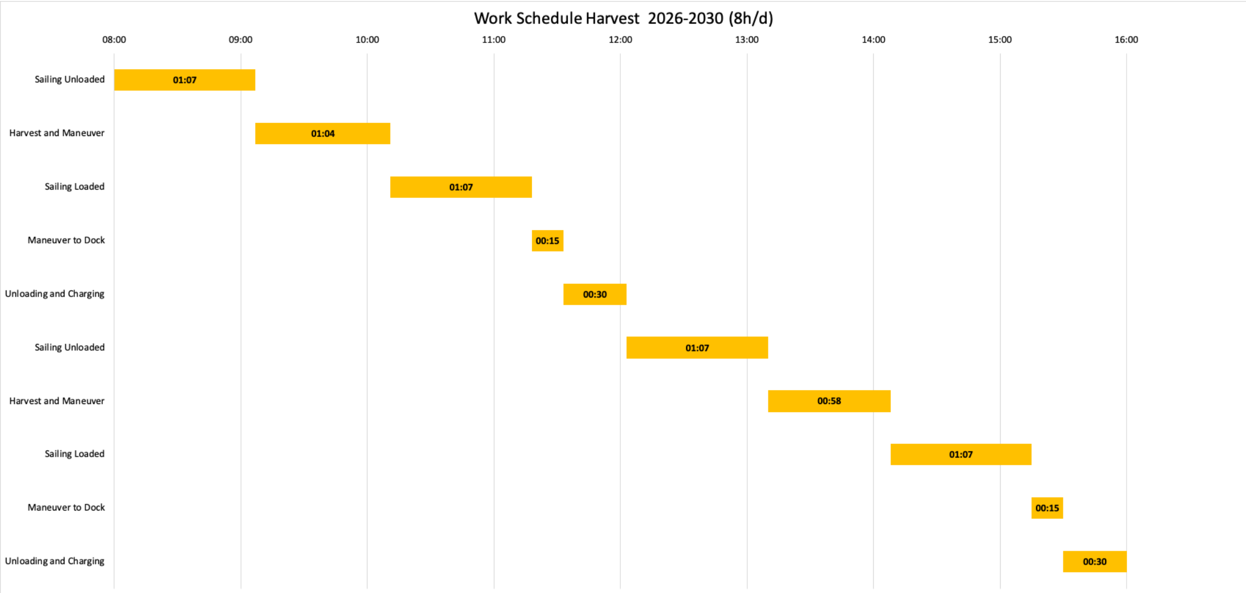

Operation Profile 2031-2035 (12h/d)
Sailing Unloaded 253kW
Harvest and Maneuver 75kW
Sailing Loaded 278kW
Maneuver to Dock 83kW
Unloading and Charging -750kW
Energy Storage
Energy Consumption kW
Energy Storage kWh

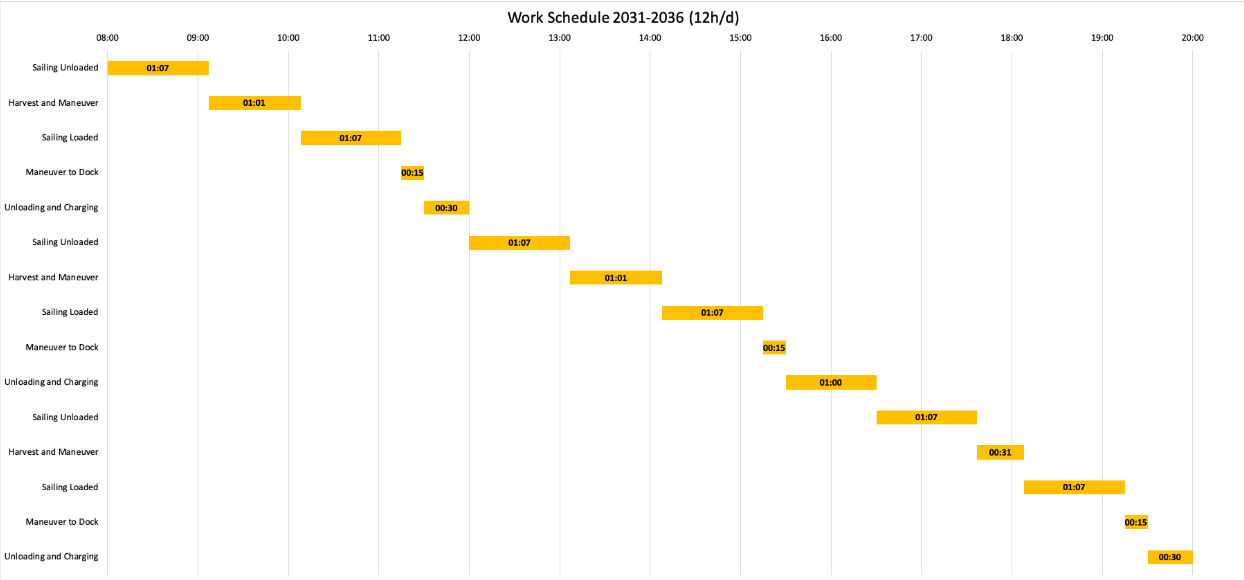

Operation Profile 2036-2040 (24h/d)
Sailing Unloaded 253kW
Harvest and Maneuver 75kW
Sailing Loaded 278kW
Maneuver to Dock 83kW
Unloading and Charging -750kW
Energy Storage
Energy Consumption kW
Energy Storage kWh

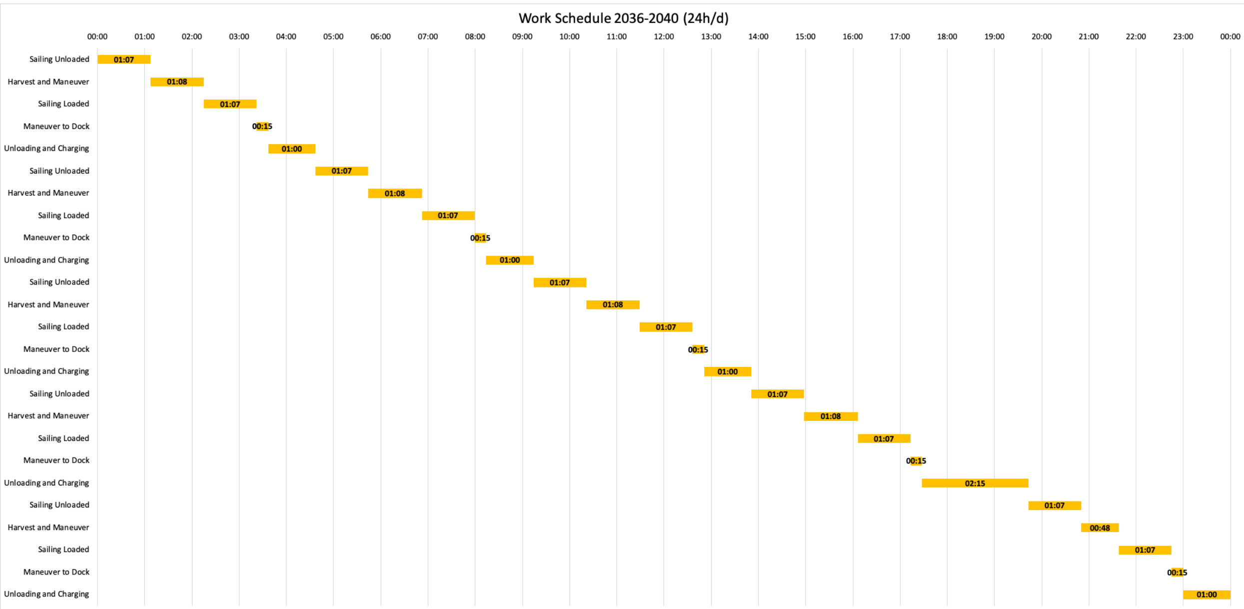
L Work Schedule 2021-2040

The work-schedule for the vessel and crew during operation in 2021-2040. The numbers on the top indicate the time of day. The numbers in the bars indicate the length of the operation, which is explained on the left-hand side.






Work Schedule 2031-2036 (12h/d)
08:00
09:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
Sailing Unloaded
01:07
Harvest and Maneuver
01:01
Sailing Loaded
01:07
Maneuver to Dock
00:15
Unloading and Charging
00:30
Sailing Unloaded
01:07
Harvest and Maneuver
01:01
Sailing Loaded
01:07
Maneuver to Dock
00:15
Unloading and Charging
01:00
Sailing Unloaded
01:07
Harvest and Maneuver
00:31
Sailing Loaded
01:07
Maneuver to Dock
00:15
Unloading and Charging
00:30


Work Schedule 2036-2040 (24h/d)
00:00
01:00
02:00
03:00
04:00
05:00
06:00
07:00
08:00
09:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
22:00
23:00
00:00
Sailing Unloaded
01:07
Harvest and Maneuver
01:08
Sailing Loaded
01:07
Maneuver to Dock
00:15
Unloading and Charging
01:00
Sailing Unloaded
01:07
Harvest and Maneuver
01:08
Sailing Loaded
01:07
Maneuver to Dock
00:15
Unloading and Charging
01:00
Sailing Unloaded
01:07
Harvest and Maneuver
01:08
Sailing Loaded
01:07
Maneuver to Dock
00:15
Unloading and Charging
01:00
Sailing Unloaded
01:07
Harvest and Maneuver
01:08
Sailing Loaded
01:07
Maneuver to Dock
00:15
Unloading and Charging
02:15
Sailing Unloaded
01:07
Harvest and Maneuver
00:48
Sailing Loaded
01:07
Maneuver to Dock
00:15
Unloading and Charging
01:00

M Capital Expenditure Calculations

The CAPEX calculations. Cost-numbers are somewhat based on Amdahl et al. (2015).

Cost Element	Unit Cost		Quantity		Cost	
Steel	35000	NOK/ton	52	tons	1,8	MNOK
Main Machinery	3000	NOK/bhp	670	bhp	2,0	MNOK
Auxilliary Machinery	1500	NOK/bhp	670	bhp	1,0	MNOK
Crew Equipment	500000	NOK/crew	3	crew	1,5	MNOK
Other Equipment	6500	NOK/m^2	150	m^2	1,0	MNOK
Autonomous System	10	% of Sum	7,3	MNOK	0,7	MNOK
Total Vessel Cost					8,0	MNOK
Administrative	12	% Vessel Cost	8,0	MNOK	1,0	MNOK
Engineering	12	% Vessel Cost	8,0	MNOK	1,0	MNOK
Financial	6,0	% Vessel Cost	8,0	MNOK	0,5	MNOK
Wharf Profit	6,0	% Vessel Cost	8,0	MNOK	0,5	MNOK
Total Build Cost					11,0	MNOK

Sigmund Nilsen Myhre

Autonomous Low-Emission Kelp Farm Vessel Design

NTNU
Norwegian University of
Science and Technology