Concept study for offshore seaweed farming.

Design and feasibility study for large scale mechanized seaweed cultivation systems

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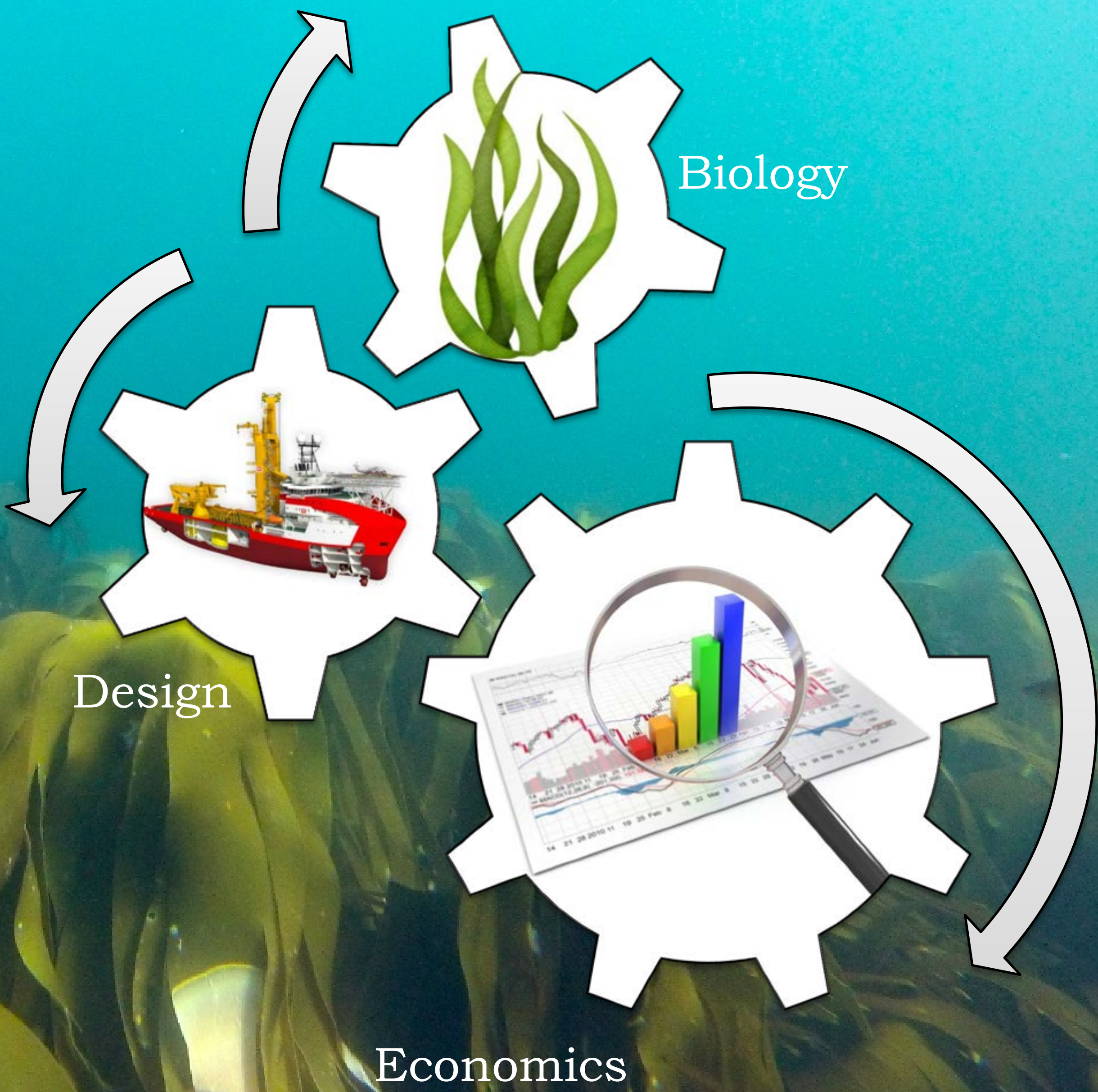

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Challenge the future

Concept study for offshore seaweed farming.

Design and feasibility study for large scale mechanized seaweed cultivation systems

By

G.J. Sijl

in partial fulfilment of the requirements for the degree of

Master of Science
in Marine Technology

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This thesis is confidential and cannot be made public until November 1st, 2020.

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Summary

Seaweed has been part of human consumption ever since humanity met with the oceans. As technology developed more applications for these macroscopic algae were discovered. Global population increased, technology advanced and people started to understand the lifecycle of seaweed allowing them to cultivate seaweed. Seaweed is currently cultivated in countries like China, Korea and Japan and is predominantly harvested manually. The seaweed industry has seen tremendous growth in the past two decades, increasing the call to scale up production by mechanization. Coastal sites are running sparse, and concentration of this industry has already caused major environmental problems.

The solution would be to move further offshore, at a larger scale, with mechanized cultivation systems being able to cope with adverse conditions. As maritime industry market leader, Royal IHC has been at the forefront of technological advancement in a multitude of maritime operating fields. With a continuous need to develop, Royal IHC, through MTI Holland, is investigating the possibility to add value to the development of technology and equipment to service the seaweed industry.

This thesis will present a market overview and research in various topics in order to evaluate the overall problem space. Based on the Integrative and Rational method, as proposed by Cross (2008), multiple design support tools are used to identify opportunities, clarify objectives and establish functions and requirements. The scope of the assignment has been closely adapted to current market needs: To develop aquacultural machinery able to service a demonstration farm (50 ha), able to demonstrate the economic feasibility of offshore cultivation. At the moment multiple pilot projects are run to demonstrate different cultivation techniques and offshore structures.

A process chain has been developed to determine the mission profile, task-related functions, and compile a list of objectives. Using a function modelling method these are further decomposed into sub functions. The functions are used to generate a set of requirements for the initial concepts.

Using state-of-art information on technology currently used in relevant industries, a global patent search and brainstorm sessions, a multitude of solutions were generated. These solutions are captured and organized in multiple morphological overviews. Selection criteria allowed a first filtering stage for most sub solutions and the remaining solutions provided enough information to develop four different concept designs. Using the weighted objectives method the designs where compared based on ten differently weighted objectives. The highest scoring concept was used to develop the final concept design. Using Autodesk Inventor the model was developed and partially engineered.

The machine is able to harvest line based substrates with different species of seaweed attached to a set of floaters. The design can be used on a number of different carrier vessels and is containerized to be transported and deployed worldwide. The design is able to harvest farm sizes of up to 100 ha, depending on patch configuration and vessel manoeuvrability. It is scalable since it uses basic design principles and parts that can be produced in most marine production facilities.

To aid in further design development and feasibility assessment of different cultivation scenarios, an exploitation model has been developed. Through optimizations on a multitude of scenarios the model proved to be an effective method to assist with design decisions, operations planning and concept feasibility.

With this thesis and the exploitation model, Royal IHC is prepared to lead development of products and services in this innovative market. Future industries and researchers will benefit from this basis for development in the North European Seaweed market.

Preface

This thesis concludes the Master Marine Technology at Delft University of Technology. Through the application of design, engineering and economics a maritime solution is presented to approach novel offshore seaweed cultivation opportunities.

During this Thesis it has become more and more come clear that designing new technology is an iterative process. Not all information is available in the beginning, yet some is necessary to make initial assumptions. Once the initial problem space is explored, solutions are generated and when evaluated, you often come to new insights that often raise more questions than it provides answers. At a certain point the literature doesn't provide the answers or ascertain made assumptions anymore and you are faced to get answers elsewhere.

Throughout my time at MTI Holland I've received much advice on how to approach this and this has sprouted many ideas and questions. I would like to thank all employees and fellow graduates, who were willing to help me in providing useful discussions and insights. In particular I'd like to thank Bernadete who has been a great help in acquiring the missing information and showing me the right direction.

I would like to thank MTI and IHC Holland as organizations to allow me time, energy and resources to participate in the Tour for Life. A life changing charity ride for Doctors without Borders that often consumed more time than was helpful to graduate within the acclaimed timeline. MTI has always supported me, even when I started with my current occupation, before finishing graduation.

I would like to thank professor Hopman, for his support, guidance and help along the way. I would like to thank all people in the industry who have helped me along the way through visits and feedback, especially Job Schipper from Hortimare and Sander van de Burg and Willem Brandenburg from Wageningen LEI and Wageningen UR. Their insights and spirits have helped me to continue the report and evolved the work to useful proportions for current and near future applications.

At last I would like to thank all the friends and family who believed in me and helped me continue finishing my work.

G.J. Sijl
Rotterdam, November 2015

Contents

1

Introduction

The sea is everything. It covers seven tenths of the terrestrial globe. Its breath is pure and healthy. It is an immense desert, where man is never lonely, for he feels life stirring on all sides. The sea is only the embodiment of a supernatural and wonderful existence. It is nothing but love and emotion; it is the Living Infinite.

Jules Verne, Twenty Thousand Leagues under the Sea

1.1 A call for sustainability

Earth's population is growing rapidly and with it, the demand for sustainable food sources. According to the World Bank, the world needs to produce at least 50% more food to feed 9 billion people by 2050 (Worldbank.org, 2015).With limiting freshwater supply and limited arable land, there is an increased need for alternative sources of protein (The Guardian, 2015). Not only food supply is threatened. With the depleting deposits of fossil fuels and the increasing amount of greenhouse gases in the atmosphere, more and more pressure is felt to increase sustainable sources of energy.

As Jules Verne writes in his novel, the ocean covers a large part of the planet's surface and its potential is still barely used. But the call for sustainability in exploiting the resources of the ocean is ever present, with problems such as overfishing, ocean acidification and other human interference. The sustainable cultivation seaweed could be the solution to solve protein shortage and energy deficits. This thesis hopes to add value to the discussion and development of a sustainable offshore seaweed farm and help Royal IHC identify the opportunities.

1.1.1 Seaweed cultivation

Seaweed or macroalgae have been harvested for centuries. Gathered from beaches and estuaries, early humans used seaweed for food and medicinal purposes. During the ages seaweed was used to facilitate the glass and iodine industry, and even helped early war efforts in the production of black gunpowder and fertilizers.

Due to increasing demands, the market has rapidly grown in the past decades. This, combined with a better understanding of the lifecycle, has led to a shift from harvesting wild resources to coastal cultivation, where today more than 95% of the harvested seaweeds are grown in cultivation systems (McHugh, 2003).

Nowadays seaweed is widely associated with the food industry, which isn't strange, knowing that 99% of the global production is currently designated for human consumption (FAO, 2011). However, due to the uncommon chemical composition of seaweeds, they serve many other purposes as well. It can be used to make gels out of hydrocolloids, such as agars, alginates and carrageenan; it can be used as fertilizer or feedstock for animals and recent developments in the bio-sorption of metals with the use of seaweeds, has already shown benefits in both aquaculture and industrial wastewater streams.

Because seaweeds are a rapidly growing product made out of valuable carbohydrates, there is also great potential in the form of bioenergy. It can be used as biomass feed in aerobic digesters or, through use of fermentation, extract the sugars to convert it to ethanol (Alexander, 2013). The added benefit of using seaweed for energy purposes, it that it does not compete with agricultural crops nor fresh water and agricultural nutrients.

1.1.2 Mechanized cultivation offshore

Even though the seaweed market continuous to increase, cultivated seaweed is still harvested manually in countries like China, Indonesia, Korea, and Japan. Few mechanized seaweed harvesters exist, and they are solely built for the harvest of natural seaweed. Furthermore coastal sites are running sparse, and concentration of this industry has already caused major environmental problems in the form of algal blooms (Liu, et al., 2010), affecting other coastal activities. The two concepts: Scale increase and the resulting demand for mechanisation, and the demand to investigate farming further offshore, make it interesting for a maritime vessel and equipment supplier like Royal IHC to investigate market opportunities.

In the past there have been a multitude of studies with regards to the cultivation of seaweed offshore, either close to the coast or at a large scale in large oceanological colonies in calmer parts of the world's oceans.

The first major attempts came as a result of oil crises during the 1970s. The basis for the development was a concept proposed by Howard Wilcox in 1968. It consisted of large, open ocean macroalgal farms as alternate sources of food, fibres, fertilizer, methane gas and other products. In late 1972, the U.S. Navy initiated an experimental program called Ocean Food and Energy Farm (OFEF) to explore the ocean farm project. Later the gas industry took over sponsor ship and started the Marine Biomass Program. Though the project provided several test sites and loads of research the project was terminated due to the decline in oil price in the 1980s (Chynoweth, et al., 2001).

The plans to harvest seaweed offshore came to a hold until the rapid growth in the market, combined with the increased demands in sustainable resources, sparked more interest in the subject again. This development boosted research projects in Europe (Reith, et al., 2005) (Bruton, et al., 2009) (Burg, et al., 2012) and in Japan (Aizawa, et al., 2007).

Still very little research has been done regarding the utilization of seaweed cultivation off shore (Roesijadi, et al., 2008). Most studies are techno-economic studies that form preliminary assessments of the possibilities of offshore cultivation. Most cases rely heavily on the work of the Marine Biomass Program. Often the recommendation is done to investigate the technological possibilities to carry out a project off shore. All the more reason to investigate further.

1.1.3 Assignment

As maritime industry market leader Royal IHC has been at the forefront of technological advancement in a multitude of maritime operating fields. With a continuous need to develop, Royal IHC, through MTI Holland, is investigating in the possibility to add value to the development of the seaweed industry. It is therefore that the following assignment was made:

Make an inventory of existing seaweed harvesting and processing technology and identify the bottlenecks for the harvesting of large volumes. Design a vessel that can collect and pre-process cultivated seaweed (water content after pre-processing to be defined later). For the main dimensions and boundary conditions, close cooperation will be required with ECN and NIOZ.

With the help of multiple stakeholders and experts in the field of biology, aquaculture, bioenergy and marine technology (WageningenUr, Hortimare, Nioz, ECN, IHC) and a study in the field of seaweed, technology the requirements for a mechanical cultivation platform were set. Several concept designs were developed based on these requirements.

It was through evaluations of the design and conversations with the industry that there was a heavy demand to develop a tool to gain insight in the operational aspects of the design. A model has been developed to evaluate farm and harvest designs, adding valuable parameters for further engineering and future designs. With this thesis Royal IHC has the basis to develop future designs and tools to assist stakeholders throughout the value chain.

1.2 Structure of the report

The structure of the report is based on the Integrative and Rational method as proposed by Cross (2008). A detailed description of the method used can be found in chapter 2. The method envelopes the first three steps of basic design, being: Exploration, Generation, and Evaluation. In addition chapter 2 clarifies the study objectives that lead to the report.

The first stage of design involves exploration of the problem space. This is separated into four different activities: Identifying opportunities, Clarifying objectives and Establishing Functions and Requirements.

Chapter 3 describes the opportunities of the seaweed industry. The first paragraphs introduces basic seaweed cultivation terminology, its reproductive cycle and the chemical properties that distinct different species and make seaweeds a valuable commodity. The second part denominates the current industry and the applications of seaweed, finishing with seaweed as an energy source in the form of biomass.

Chapter 4 is an evaluation of the market opportunities for Royal IHC. Through data from literature research, different scenarios are calculated with regard to the predicted end product and the scale of the farm. A choice is made in scale and scenario and with this the design objectives are clarified

Chapter 5 describes the value chain of seaweed cultivation and its related processes. Based on this information a function diagram is modelled to distinct the functions within various phases of production. This information serves to the development of design requirements in the same chapter and the morphological diagrams in the next.

Chapter 6 is devoted to the generation of ideas and the development of concepts. In this chapter the functions are fulfilled with different mechanics in through a depiction of current methodology and generation of new ideas, filtered through morphological overviews. Different concepts are described and evaluated based on weighed objectives and the winning design is explained. In order to further develop the product more data is needed.

Chapter 7 describes a model that serves as a tool to evaluate various system concepts with regard to cultivation platforms and production machines. It provides an effective method to assist with design decisions and operations planning and could prove the feasibility of a concept.

Chapter 8 contains three scenarios that are used to validate the model and assess different scenarios with regards to scale, cultivation techniques, and substrate and species selection.

Chapter 9 concludes the report, including recommendations for future research.

2

Study objectives and methodology

This chapter illustrates the objectives of the studies by identifying: initial research, the project domain and related boundaries. The methods used throughout this thesis are explained and their usage is motivated.

2.1 Study Objectives

The main objective of this thesis is to develop a design for a vessel or platform to carry out cultivation related tasks for an offshore seaweed farm. The main and most demanding task within this scope would be to harvest large volumes of seaweed in a limited amount of time. This requires a multidisciplinary approach, as it is important to understand its mission profile and what value it could add within the production chain.

2.1.1 Preliminary research

The cultivation of seaweed is an unknown field for a ship design student, so extensive research was required to gain more information. This was done through literature research and conversations with stakeholders. The research consists of a multitude of topics, all necessary to determine the design requirements for the harvester. Topics include:

- Biology, lifecycle, and selection of species;
- General applications of seaweed;
- Potential of seaweed as energy source;
- Cultivation of seaweed;
- Market development expectations.

The development of offshore seaweed farming is still very immature and current projects are still focusing on primary production development in the forms of species and substrate selection. Prototypes have been built on a pilot scale, not bigger then several hectares. Current research is done to determine growth rate and growth patterns as well as the survivability of the artificial substrates. The next phase in this research would be to start a demonstrations farm to provide a proof of concept. This in turn will define the viability, identify technical issues, and suggest an overall direction of next steps on seaweed cultivation offshore. Without a proof of concept, large investors will stay away. To add the most value to current development it is chosen to preliminary design for a demonstration scale farm (50-200 hectares). This choice will be illustrated in chapter 4.

2.1.2 Domain

This graduation project deals within the field of Ship Design, where the design and operation of marine systems is core business. The scope of the project is in the development of a one-off design for the cultivation of seaweed in an offshore environment. In the early stages of the design process for a new kind of vessel in a new market, it is important to understand the functional capacity required from a design through its mission profile. The mission profile of a vessel will define the required equipment and dimensions of the vessel in order to provide the required functions. For a seaweed cultivating vessel this mission equipment might vary from cultivating and harvesting mechanisms, to processing installations and cargo handling systems.

The definition of an accurate mission profile, the development of design requirements, the creation of a concept design and the evaluation will be of main concern during this research since these aspects are lying within the field of design.

2.1.3 Project boundaries

The first boundary has been set in the form of scale as mentioned in 2.1.1. Though this is a measurable there are many boundaries that envelope the project as a whole but aren't measurable. Since the idea is very novel it is important to determine the feasibility of a concept design as well as possible. Therefore the following boundaries have been set:

- Estimations in yield based on research;
- Estimations in process yields and their market value;
- Estimations in process costs within the value chain for the business case through discussions with specialists, literature and educated guess

2.2 Methodology

The structure of this thesis will follow the design methodology proposed by Nigel Cross in his book Engineering Design Methods (Cross, 2008). In addition processes will be used from the Delft Design Theory (van Boeijen, et al., 2014), Practical Ship Design (Watson, 1998), Engineering Design (A systematic approach) (Pahl, et al., 2007) and System Based Ship Design (Levander, 2009). To illustrate the choice for these methods an introduction to design methodology is given.

2.2.1 Design methods

There are a multitude of design theories, models and methods created to give guidance or improvements to the design process. These various design methodologies are often a study of how designers think and work and give structure to the different design processes.

It is important to have a defined design procedure that will deliver good solutions, since designers are responsible for the technical and economic properties of a product. It is also of commercial importance to have timely and efficient product development. Although extensive research has been done in the past, there is no single model which is conclusive about the ideal description of the design process (Clarkson & Eckert, 2005). Design methods can be classified in different ways:

- Stage-based vs. activity-based models;
- Solution-oriented vs. Problem oriented literature;
- Abstract vs. Procedural vs. Analytical approaches.

Since the problem in this thesis is relevant to a practical situation, it is wise to use a procedural approach to the problem. They are more concrete in nature than the abstract theories, typically incorporating a larger number of phases and focusing on a specific audience and/or industry sector.
Within procedural approaches there is a distinction between descriptive and prescriptive literature.

Descriptive models

Descriptive literature often resulted from studying design practice. Processes and procedures observed in industry form the basis of texts which are used for teaching, training and research. An example of a descriptive method is a simplified model from Cross (2008). This model is to illustrate the process derived from what designers have to do. The endpoint of the process is the *communication* of a design, ready for manufacture. Prior to this, the design proposal is subject to *evaluation* against the goals, constraints and criteria of the design brief. The proposal itself arises from the *generation* of a concept from the designer, usually after some initial *exploration* of the ill-defined problem space.

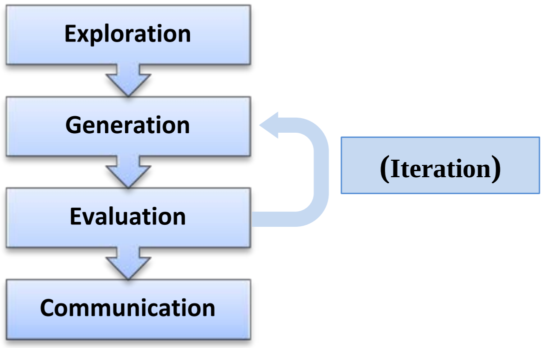


Figure 1 Simple four-stage model of the design process **(Cross, 2008)**

Prescriptive models

Prescriptive approaches recommend or prescribe guidelines, stages or techniques which, if implemented correctly are thought to improve performance in specific aspects of the product or project. A systematic approach is often a combination of both, combining both descriptive and prescriptive aspects and combining models and methods.

A comprehensive prescriptive model is the model used by the professional engineers' society, Verein Deutscher Ingenieure (VDI) which has produced VDI 2221 guideline: *systematic approach to the design of technical systems and products* (VDI-Verlag, 1993). The guideline aims for a general approach to design, applicable to a wide variety of tasks and different branches of industry. The general approach is divided into seven stages, correspondingly producing seven results (figure 2).

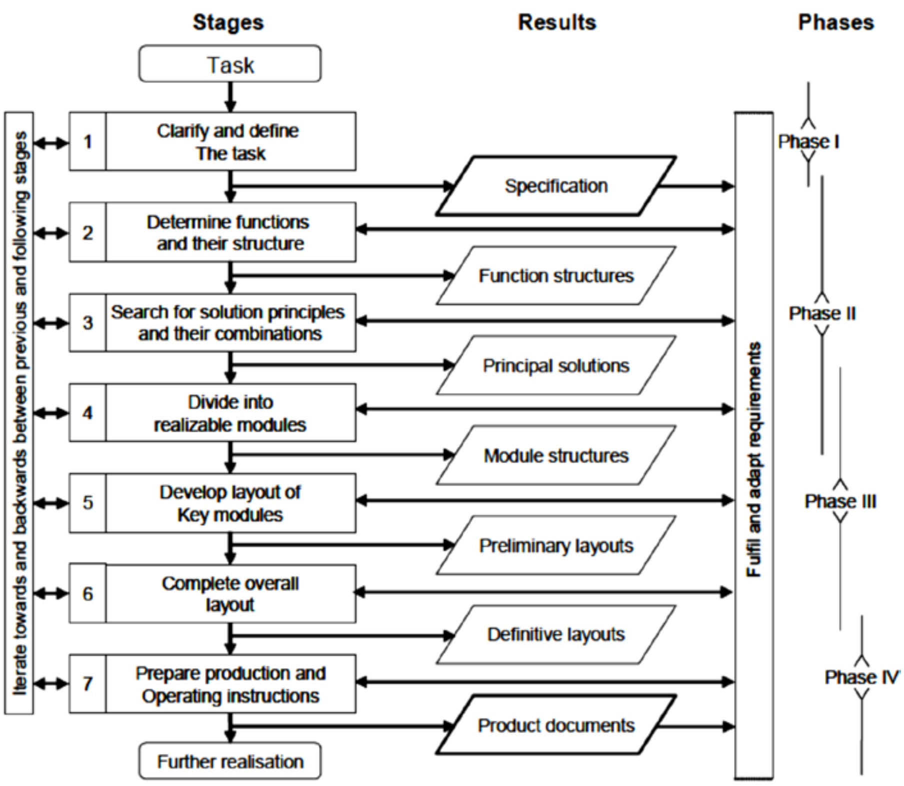


Figure 2 Guideline VDI 2221

In the guideline it is emphasized that several solution variants should be analyzed and evaluated at each stage, and that there is a lot more detail in each stages than is shown in the diagram. The general procedure of the guideline is to first understand the problem and break it apart in sub-problems. After which possible sub-solutions have to be found to, in the end, be combined in an overall solution.

2.2.2 Integrative and rational method

An integrative model is proposed by Nigel Cross (2008). He proposes that: "*it is not possible, or relevant, to attempt to analyse the problem ab initio and in abstract isolation from solution concepts; the designer explores and develops problem and solution together.*" Although there is a logical progression from problem to sub-problems and from sub-solutions to solution, there is always a relationship between the problem and the solution.

The model illustrates the nature of the design process, in which understanding of the problem and of the solution develops together. There is a certain progression in the design process, but with substantial periods of iterative activity in between the stages.

Cross proposes a rational method which encourages a systematic approach to design. It contains of eight design stages, covering the whole design process. The eight different stages are presented within the symmetrical problem/solution. In his book he presents examples of methods to use during these stages.

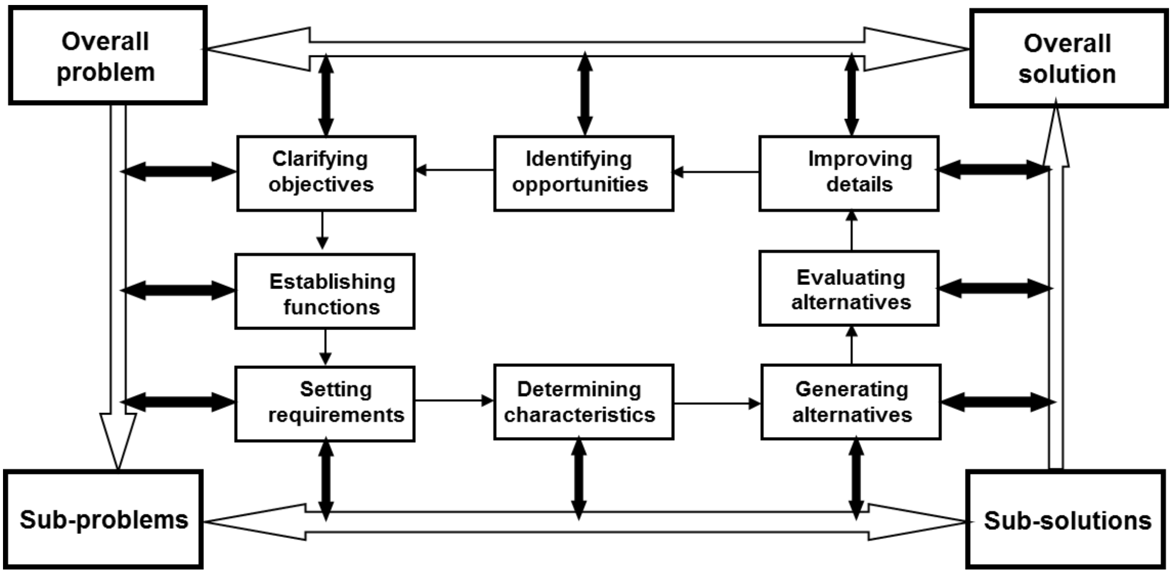


Figure 3 Eight stages of the design process positioned within the symmetrical problem/solution model

The eight stages will provide the backbone for the design of the seaweed cultivation platform. Each stage will be covered in the different chapters in this thesis as described in chapter 1.2.

2.2.3 Additional methods used

This section shortly describes additional methods used. Though less present than the method from Cross, they do provide an additional background when the mostly product design focussed method from Cross is insubstantial. The methods that Cross describes are also covered by Delft Design Theory (van Boeijen, et al., 2014). It uses different explanations and examples and as such help to understand the design theory better.

Engineering Design

Engineering Design (A systematic approach) (Pahl, et al., 2007) is an international reference on systematic engineering design in industry, research and education. It teaches the methods of engineering design as a condition of successful product development. It breaks down the design process into phases and then into distinct steps, each with its own working methods. It is a nice addition to the work of Cross and focuses more on the technical aspects of design, its working principles and functionality

Practical Ship Design

Practical Ship Design (Watson, 1998) covers a wide arrange of aspects of ship design. It describes a multitude of various merchant ships and naval ships and includes subjects as: concept design, detail design, structural design, hydrodynamics design, the effect of regulations, the preparation of specifications and matters of costs and economics. It is used as guidance where specific ship design issues are required.

System based ship Design

Traditionally ship design has been done according to the spiral model. First introduced by J. Evans (1959) it captures a sequential and iterative process to the design of a vessel. Kai Levander (2009) proposes a different method. His suggestion is to use a method that better supports innovation and creativity. The design work should start from the mission specified for the ship based on which a function description can be made; this is illustrated in figure 4. The function description defines all systems needed in the ship to perform the tasks demanded in the specified mission statement. A lot more can be said regarding this method and its development (especially regarding Offshore Supply Vessels), more information can be found in *System Based Ship Design for Offshore Vessels* (Vestbøstad, 2011) and *Modular approach to offshore vessel design and configuration* (Tvedt, 2012).

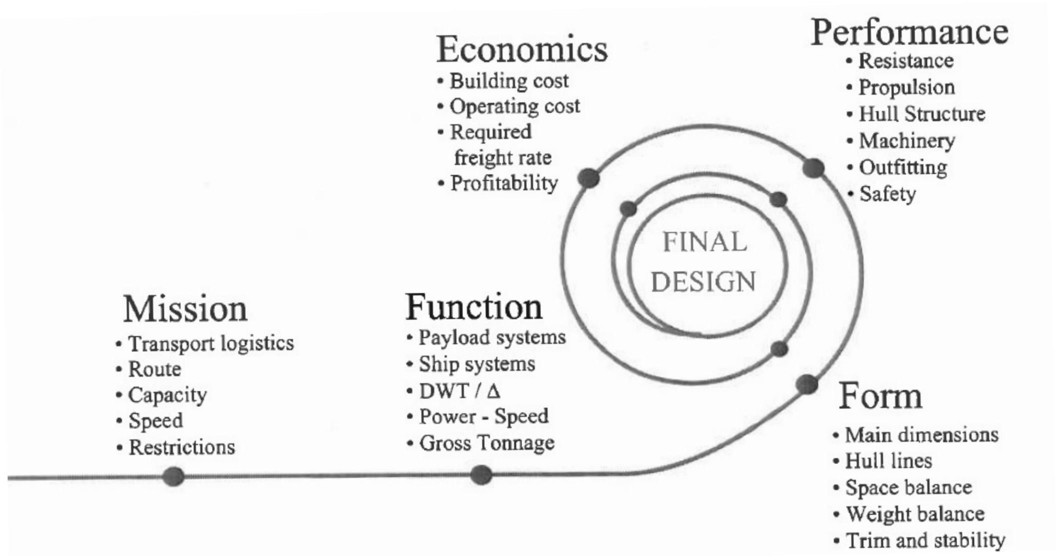


Figure 4 Open design spiral according to Levander (2009)

3

An overview of the seaweed industry

The first step in designing a seaweed cultivating machine is to determine the demand for such innovative cultivation methods. This is done based on market analysis and potential industry expansion. Aside from economical drivers in the industry, attention is given to illustrate the aspects of cultivating seaweed and its composition that add value to the commodity.

3.1 Biology of Seaweed

3.1.1 An introduction

Seaweeds are one of three groups of marine plants: microalgae, macroalgae and rooted plants. Microalgae can occur as phytoplankton in the open ocean and as benthic or sediment-dwelling forms; macroalgae, also known as seaweeds, are multi-cellular plants that generally anchor to hard surfaces, usually on the ocean floor; rooted plants root in soft substrates[1] that deliver nutrition to the plants. The main difference from rooted plants is that algae get their nutrition from seawater and not from the soil or sediment it is attached to. Seaweeds are not classified as true plants because they lack a specialized vascular system, roots, stems, leaves, and enclosed reproductive structures like flowers and cones. In order to grow, develop and reproduce seaweeds need sunlight, a carbon source, dissolved nutrients, dietary minerals (trace elements) and other compounds. Sunlight (Irradiation and Limpidity) and nutrients are major factors when it comes to rate of growth and production of biomass (Roesijadi, et al., 2008).

A typical seaweed contains a leafy blade or lamina (also referred to as the frond), the stem-like stipe, and the holdfast. The structure of the stipe varies among seaweeds; they can be flexible or stiff; solid or gas-filled; very long, short, or even completely absent. Some seaweeds have only one blade, which may be divided, while other species have numerous blades. In some species the blades also support the reproductive structures of the seaweed. Many seaweeds have hollow, gas-filled structures called floats or pneumatocysts. These help to keep the photosynthetic structures of the seaweed buoyant. Kelp, like the species shown in figure 5a, usually grows in 10 meters of water depth. The blades grow from the stipe and form a surface canopy with which they intercept light and nutrients. (Encyclopeadia Britannica, 2013)

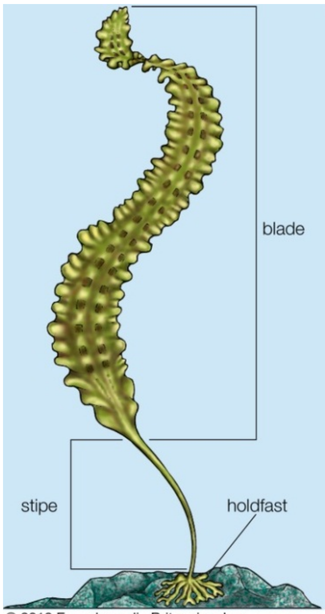


Figure 5a Structure of the kelp Laminaria agardhii (Encyclopeadia Britannica, 2013)

[1]Substrate: The surface or material on or from which an organism lives, grows, or obtains its nourishment

Because most seaweeds require a hard substrate to anchor their holdfast, their growth is restricted to shallow coastal waters, or areas where an artificial hard surface can be provided. There are exceptions, there are some species of seaweeds that are free floating. Most algae are small and delicate and only a few species, roughly one per cent, have any significant commercial value. (Zemke-White & Ohno, 1999)

3.1.2 Lifecycles of seaweed

A basic understanding to the diverse life cycles is important to gain knowledge in the way seaweed grows and reproduces. It can help facilitate improvements in cultivation practices and strain selection for desirable traits such as faster growth, resistance to environmental impacts and enhancing economically importance of products derived from seaweed.

The lifecycles of seaweed are complex and differ greatly between species. Species can be annual and perennial and can have sexual and asexual reproductive modes.

Perennial seaweeds live for many years, whereas annual live for only one year. Annual seaweeds generally begin to grow in spring, and continue throughout the summer. During powerful fall and winter storms the stipes and blades of seaweeds are often ripped off. If the holdfast manages to survive through the winter, new blades will begin to grow from it in the spring. Perennial species can also lose many of their blades, either during the winter or because of high temperatures in the summer months. This seasonality also influences their growth.

To illustrate the complexity of the lifecycle, a short description of the lifecycle of brown kelp will follow. Kelp begins as a microscopic spore in the various sporangia on the leaves of the seaweed. These spores which grow into a miniscule male or female plant called a gametophyte. These produce eggs and sperm, which fertilize and grow to form the large plants or sporophytes. The larger grown sporophytes release many more spores to start the process over again. The length of the lifecycle also differs. The lifecycle of giant kelp (*Macrocystis pyrifera*) is believed to be 12 to 14 months. (Bushing, n.d.). Figure 5b shows the lifecycle of kelp. (open stax college, 2013)

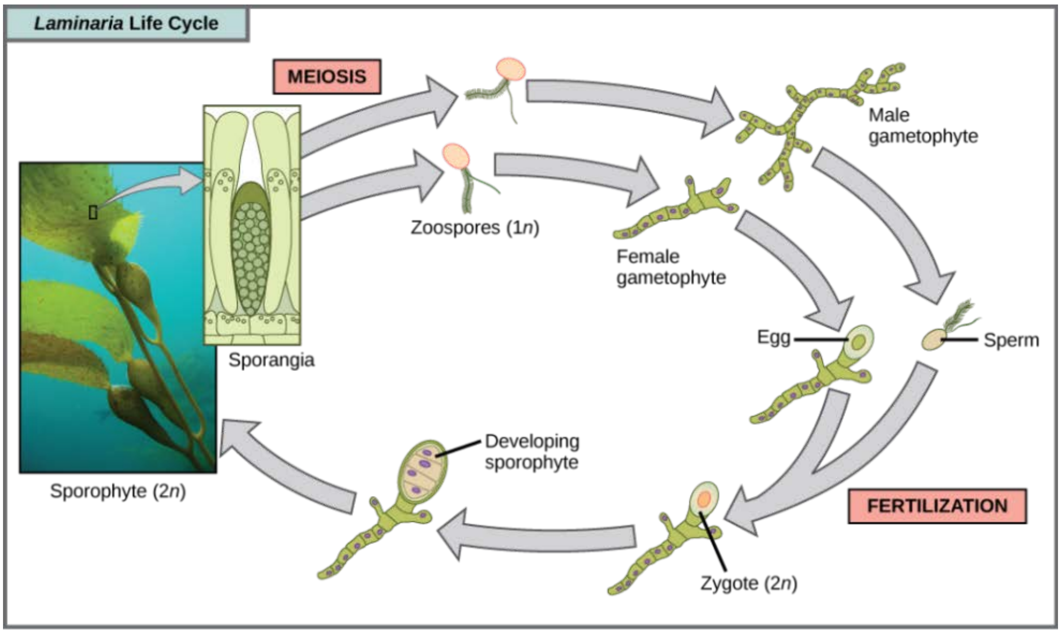


Figure 5b Lifecycle of kelp (open stax college, 2013)

3.1.3 Introduction to various species

This chapter elaborates on the specifics of the various candidate species based on the available research and the high growth potential (Burg, et al., 2012) (Holdt & Kraan, 2011). Though more species might prove valuable for open ocean farming, they are left out due to the scope of the research assignment.

Seaweeds are divided in three major groups based on their pigmentation: chlorophytes or green algae, rhodophytes or red algae and phaeophytes or brown algae. They are further classified through the differences in types of metabolic pathways, and the differences among the structural polysaccharides and essential pigments (Burg, et al., 2012). Their colour is defined by carotenoids that are stored inside plastids; the site of manufacture and storage of important chemical compounds used by the cell. Carotenoids are organic pigments that, amongst other uses, provide photosynthesis and are divided in two major groups: xanthophylls and carotenes. Both are large hydrocarbon chains with the difference that xanthophylls are carotenoids that contain oxygen molecules and carotenes are oxygen free.

Seaweeds can be found at different depths, and to distinguish the difference between these depths the sea is divided in zones (Figure 6). Since seaweed need sunlight, all algae grow in the euphotic zone, the zone sufficiently illuminated to permit photosynthesis by phytoplankton and plants. This is further divided in a few littoral zones. The littoral zone is the marine ecological realm that experiences the effects of tidal and long shore currents and breaking waves to a depth of 5 to 10 meters below the low-tide level, depending on the intensity of storm waves (Encyclopeadia Britannica, 2013).

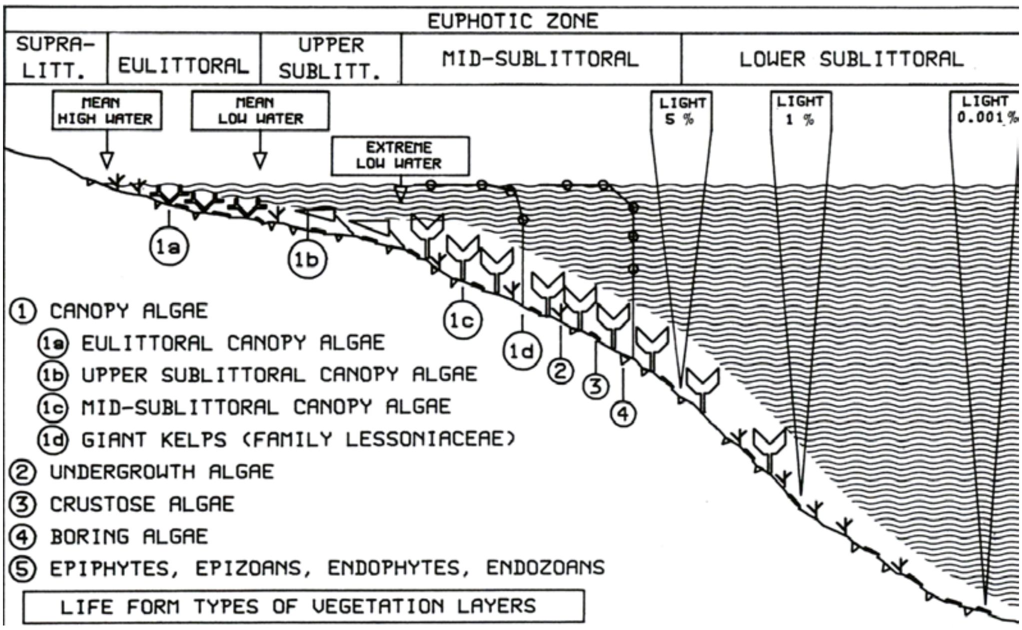


Figure 6 Algal life forms within the euphotic zone. (Lüning, 1990)

Brown Seaweeds

Brown seaweeds have a dominant xanthophyll pigment, called fucoxanthin, as their main pigment for capturing photons. This pigment masks other pigments as chlorophyll, beta-carotene and other xanthophylls, hence the dominantly brown or olive-green colour. Brown algae, can grow deeper than green algae because their pigments are more efficient in absorbing the wavelengths of light not filtered out by the water column.

There are roughly 1800 known species of brown algae or Phaeophyceae, the class of brown seaweeds (Guiry, 2014). They vary in a range of sizes and forms. The smallest algae grow as threadlike cells of only a few centimetres long, while the largest species of kelp can grow up to 45m in length. The forms vary from small crust like cushions to leafy, free floating mats. Some species have single shape leaves, where others have blades that divide into multiple ends.

Red Seaweeds

The red colour of these algae results from the pigments phycoerythrin and phycocyanin; these mask the other pigments, Chlorophyll beta-carotene and a number of unique xanthophylls. The main reserves are typically Floridian starch, and floridoside; true starch like that of higher plants and green algae is absent. The walls are made of cellulose, agar and carrageenan, both long-chained polysaccharides that are commercially used (Guiry, 2014).

There are currently roughly 6400 species known of Red Algae or Rhodophyta. Red algae such as Dulse (Palmaria palmata) and laver (Nori/Gim) are a traditional part of European and Asian cuisines. They are also used to make products such as agar, carrageenan and other food additives. Compared to other classes of seaweed, red seaweeds have a high protein content.

Green Seaweeds

Green algae have chlorophyll as the main light absorbing pigments and are typically found in intertidal, shallow water zones.

More information on de different species can be found in Appendix A.

3.1.4 Composition

The chemical composition of seaweeds is different from terrestrial biomass. Seaweeds have high water contents that could be as much as 94% (Holdt & Kraan, 2011) (percentages given are based on weight). Aside from high moisture content, seaweeds also contain a lot of minerals and trace elements in the form of ash. Though, like other plants, seaweeds contain nutritional elements such as proteins, lipids, carbohydrates, vitamins and minerals, the content of these elements varies depending on season and the area of production. These seasonal and environmental variations in the composition of seaweed make generalizations impossible (Holdt & Kraan, 2011).. In table 1 there is an overview of the chemical composition per seaweed species.

Protein

The average protein content of dry macroalgae is approximately 15 % in brown algae and 35 % in red and green algae species (Burg, et al., 2012). Proteins are large molecules that consist of one or more chains of amino acids and perform a multitude of functions within living organisms. Some seaweeds might prove a potential source of food proteins, due to their high protein level and their amino acid composition. The protein level correlates with the amount of nitrogen present in the environment, which changes seasonally. (Fleurence, 1999).

Polysaccharides

The polysaccharide content of macroalgae is between 15-65% of dry seaweed. The polysaccharides are structural components in the cell wall and act as energy storage molecules for growth during winter. (Burg, et al., 2012). Most specific to seaweed are storage polysaccharides, which include laminarian, mannitol, carageenan and alginates. Laminaria species contain approximately 55% (dry) carbohydrates laminarin and mannitol (Guiry, 2014). The peak time for laminarin and mannitol production is during summer and autumn, decreasing throughout winter.

Lipids

Macroalgae lipid are low and vary between 0.2 and 4% of dry seaweed. Species found in temperate climates mainly consist of polyunsaturated fatty acids (PUFAs) with Omegas 3 and 6, making them useful for human food and supplements.

Phenol

Plants normally contain two types of phenol; these are hydrolysable tannins and phenylpropanoids (lignin). Lignin provide a defence against predators (microbial and herbivores) and UV light. However macroalgae, particularly sub-tidal species do not contain lignin since they require less protection from UV light underwater. Brown algae contain phlorotannins, a type of phenol, which is exclusively found in these genera, constituting 1-20% of the dry weight. Their main task is to precipitate proteins from solutions. Polyphenols are also present, particularly in the outer tissues of brown algae, where they are in greater abundance than in the remainder of the plant. These compounds provide a low-level immune system or bacterial defence by intercepting, binding and releasing toxic heavy metals (Alexander, 2013).

Minerals

Seaweeds are rich in minerals, which relate to a high ash content between 10 and 40%. That is 5 to 10 times higher than in terrestrial plants. There is a high level of sulphates and seaweeds are rich in iodine, potassium, sodium, calcium, magnesium, phosphor, iron and zinc. Macroalgae have the ability to biosorb; therefore their metal contents reflect the background levels of the surrounding environment. These metals come from two sources, which are: natural reserves from soil leaching, rock weathering and volcanic activity, and human activity such as mining, fossil fuels, waste disposal and other industrial applications (Alexander, 2013).

Fish farming is another source of marine metal, releasing zinc, copper and cadmium. This has led to the proposed integration of macroalgae and fish farming facilities, where the macroalgae are fed the excess nutrients from fish excrements.

Table 1 overview of substances per seaweed species (Holdt & Kraan, 2011)

Group (phylum)	Genera	Moisture [%]	Ash [%]	Protein [%]	Lipids [%]	Polyssacharides [%]	Dietary Fibers [%]
Brown Algae	Laminaria digitata	73-94	15-45	3-21	0.3-2.1	38-61	36
	Saccharina latissima	73-94	15-45	3-21	0.3-2.1	38-61	36
	Ascophyllum	67-87	18-27	1-12	1.2-4.8	42-70	38
	Fucus	68-84	19-30	1-17	.5-3.1	62-66	
	Sargassum	61	14-44	9-20	.5-3.9	4-68	49-62
Red Algae	Palmaria palmata	84	12-27	8-35	.2-3.8	38-66	
Green Algae	Ulva Lactuca	78-80	19	24	.3-1.6	15-65	38

3.1.5 Species selection requirements

As mentioned, species of seaweed are diverse and not all species are suited for open ocean seaweed farming with a mechanical harvester. In 1979, as part of the Marine Biomass Program there has been a comparative assessment of marine biomass materials to select suitability for open ocean farming. Candidate species are evaluated against a set of desired criteria. Roesijadi, et al. (2008) describe a set of criteria for specie selection for methane gas:

- *“Organic matter yield per unit area, annual;*
- *Growth sensitivity to plant spacing;*
- *Dependence on substrate and substrate depth, or free floating;*
- *Susceptibility to disease, grazing and epiphytes;*
- *Simplicity with which a species can be propagated;*
- *Nutrient requirements;*
- *Ability to take up and store nutrients for subsequent use;*
- *Harvestable by part-cutting rather than removal of the whole plant;*
- *General robustness – tolerance to variable physical conditions;*
- *Water and ash content;*
- *Calorific content, and yield of methane on digestion;*
- *Bound nitrogen (protein) concentration and extractability;*
- *Concentration of other co- and by-products of value;*
- *Variability in composition, e.g. with season;*
- *Sulphur concentration (high S result in high H2S in the digester gas, a major issue).”*

These are but a few different selection criteria for offshore cultivation. Additional criteria are required when environmental conditions vary and are also dependent on the end product of seaweed e.g. for cultivation in the North Sea there is a tendency to focus on endemic species. In the past, the introduction of alien seaweeds has had adverse effects on the ecosystem. The selection of species is still under development. Starting point for this research is the cultivation of brown seaweeds.

3.1.6 Cultivation parameters

Based on the biology, lifecycle and specie selection a set of cultivation parameters can be established. In their report *Worldwide potential of Aquatic Biomass* Florentinus et al. (2008) define a set of most cultivation parameters divided in two groups:

- Primary growth parameters: have been covered in the introduction and consist of: Irradiation, Temperature, Nutrients and Limpidity. All affecting specie growth and seasonality

- Cultivation parameters: determine technical feasibility table 2.

The clarification of the parameters and parameter selection follows in their report. The decision to cultivate in a certain area is left outside of the design scope. In chapter 4 analysis is done to illustrate initial markets served. In chapter 5 the parameters are used to determine functional requirements for the design.

Table 2 Cultivation parameters from Florentinus et al. (2008)

Parameter	Description
Sea conditions	currents, undulation, sea quakes, water depth, but also the general weather conditions are concerned in this parameter. Rough sea will hinder cultivation and harvesting. Depending on the chosen technology, it can cause severe damage to the cultivation system.
Substrate presence	to fix the cultivation systems and for anchorage of seaweeds.
Spatial planning	the sea harbours many functions: habitat of many species, nature, transport, fishery and recreation. The development of cultivation areas will have its influence on these pre-existing functions and will compete for space.
Control	Control is defined as the degree of being able to influence and monitor your biomass cultivation system, like the amount and composition of nutrients. A closed system has the highest control possibilities, whereas an open system has the lowest.
Logistics	Areas near the coast generally have better accessibility to conversion units for the biomass and a lower transport requirement for operation and harvesting.

3.2 Market analysis

3.2.1 Current applications

Food

Of all the current applications the food market is far out the largest application of seaweed, with 99% of the total tonnage (FAO, 2011). The historical use of seaweed has been traced back to the Neolithic. Remains of species of marine algae were recovered from human artefacts at the Monte Verde archaeological site in Chile and were dated back to 12,000 BC (Dillehay, 2008). The findings indicate that inhabitants used seaweed for food and medicine which they gathered from distant beaches and estuarine environments. Currently the main market for seaweed focusses on Asia, where Japan, China and the Republic of Korea are the largest consumers of seaweed as food (McHugh, 2003).

Hydrocolloids

The second largest use of seaweed is the production of hydrocolloids, with a sales volume of 86,100 tonnes in 2009. The growth of the market has been relatively slow with only 19% in between 1999 and 2009 (Bixler & Porse, 2011). Hydrocolloids are non-crystalline substances that are constructed of large molecules that dissolve in water to give a thickened (viscous) solution, or gel. They are used in various industrial and food applications as a stabilizer and emulsifier (e.g. EU additives E400-409). The three main hydrocolloids found in seaweed are agar, alginates and carrageenan.

Agar has been mainly used as an ingredient in desserts and as a solid substrate to contain culture medium for microbiological work.

Alginates are extracted from brown seaweeds and form a viscous gum through binding with water. When it is extracted it absorbs water quickly and is able to absorb 200-300 times its own weight in water. (Rowe, et al., 2009). This makes it useful as an additive in dehydrated products such as slimming aids and in the manufacture of paper and textiles. Other uses are in the food industry, for thickening soups and jellies, as well as an impression-making material in dentistry, prosthetics and life-casting.

Carrageenan is mainly used in diary and meat products due to their strong binding to food proteins.

Feedstock

The use of seaweed as feedstock for animals has been used in the past, yet only on a small scale. Seaweed is known to be grazed by animals such as cattle and sheep that live in coastal areas. Nowadays, seaweed is dried and milled to produce a fine seaweed meal. The animals benefit from the seaweed due to the useful amounts of minerals, trace elements and vitamins that it contains. However, most of the carbohydrates and proteins are not digestible, therefore only small amounts of seaweed are used to supplement normal animal feed. Most research of seaweed as a supplement in animal feed has given promising results. Various tests on livestock and fish has proven beneficial in the form of growth rate, feed efficiency and pigmentation. (Holdt & Kraan, 2011) In 2003 approximately 50000 tonnes of wet seaweed was harvested for the production of animal feed. (McHugh, 2003)

Fertilizer

Seaweeds have been used as fertilizer along the Atlantic coast of Europe for centuries. In France, for example, coastal populations exploited algae for soil improvement. Men collected algae from the sea with large rakes and women gathered seaweed that was washed ashore during storms. To preserve the seaweed they were dried on dunes so that it could be used year-round. (Mesnildrey, et al., 2012). The contents of fibre act as a soil conditioner and assist moisture retention, while the mineral content is a useful fertilizer and source of trace elements. In the early twentieth century, a small industry developed based on the drying and milling of mainly storm-cast material, but it dwindled with the advent of synthetic chemical fertilizers. Today, with the rising popularity of organic farming, there has been some revival of the industry, but not yet on a large scale. (McHugh, 2003)

Cosmetics

The Cosmetic products associated with seaweeds are usually creams and lotions where a hydrocolloid made of seaweed has been added. Alginate and carrageenan improve the skin moisture retention properties of the product. Pastes of seaweed, made by cold grinding or freeze crushing, are used in thalassotherapy, where they are applied to the person's body and then warmed under infrared radiation. This treatment, in conjunction with seawater hydrotherapy, is said to provide relief for rheumatism and osteoporosis. (McHugh, 2003)

Medicines

The medicinal uses of seaweed date back to the use of seaweed as food (Dillehay, 2008). Since then many claims have been made for the benefits of seaweeds on human health. It has been suggested, that seaweeds have curative powers for a multitude of diseases such as tuberculosis, arthritis, colds, influenza and many more. Many of the reported medicinal effects of marine algae, however, have not been substantiated. (Guiry, 2013)

Seaweeds are rich in polysaccharides that could potentially be exploited as prebiotic functional ingredients for both human and animal health applications. Prebiotics are non-digestible, selectively fermented compounds that stimulate the growth and/or activity of beneficial gut micro biota which, in turn, confer health benefits on the host. (O'Sullivan, et al., 2010)

Chemical Applications

Seaweed has been used in chemical processes for over centuries. From the 17th century onwards seaweed was burned for their alkaline ash. The ash from seaweeds contains Soda and Potash and was used in the glass and soap industry. When production of soda was no longer viable, the iodine extraction from kelp

arose. Iodine is used in medicines and the photo industry. Cheaper mineral deposits were later imported from Chile and by 1900 the industry was petering out. (Biomara, 2014)
Current production processes of chemicals from seaweed focus on hydrocolloids and colorants. The dyes and colorants, are currently used in food coloring, clothing, pharmaceuticals, cosmetics and paper industry.

IMTA

IMTA or Integrated Multi-Trophic Aquaculture is a way of combining different aspects of aquaculture. It is the integrated culturing of fed species, such as finfish, inorganic extractive species such as seaweeds and organic extractive species such as suspension and deposit feeders. The by-products of one aquatic species acts as a fertilizer or food source for another. The potential benefits of such a balanced ecosystem approach are:

- Capability to remediate nutrients from excretion and feed waste;
- Several mutual benefits to the cultured organisms;
- Economic diversification by producing multiple value-adding marine crops;
- Increased profitability per cultivation unit for the aquaculture industry.

As a result of a rapidly growing aquaculture industry, several rules and guidelines will be introduced with regards to the wastes produced by aquaculture. Using appropriately selected seaweeds as renewable biological nutrient scrubbers could be a cost-effective means for reaching compliance (Chopin, et al., 2001).

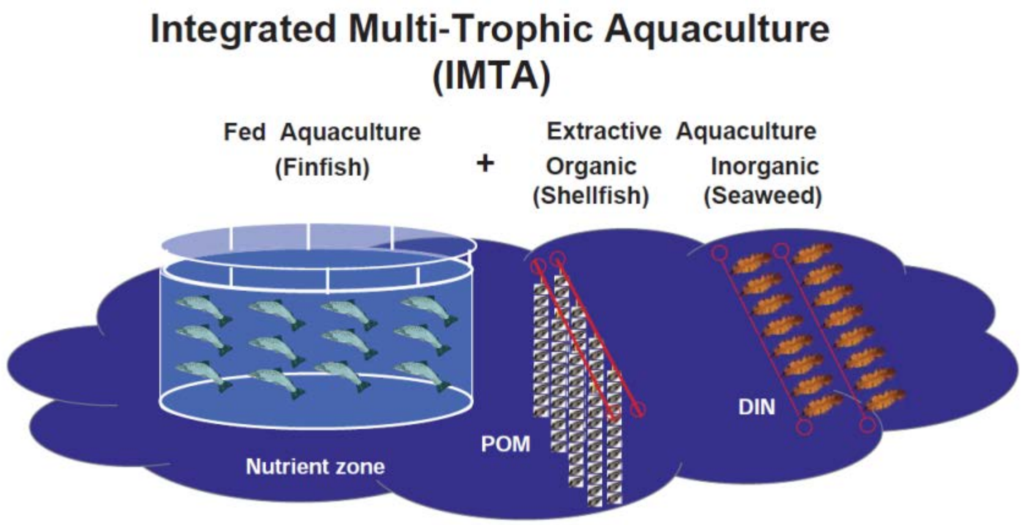


Figure 7 Example of IMTA (Barrington, et al., 2009)

3.2.2 Future applications

Pigments in Solar Cells

Chlorophylls based-dyes obtained from seaweeds can be used in dye-sensitized solar cells (DSSC). A DSSC is a low-cost solar cell, based on a semiconductor formed between a photo-sensitized anode and an electrolyte. It is simple to make using conventional roll-printing techniques, is semi-flexible and semi-transparent which offers a variety of uses not applicable to glass-based systems, and most of the materials used are low-cost. (Calogero, et al., 2014)

Bio sorbent in waste water

Studies have showed that seaweeds possess high metal binding capacities, through the high presence of polysaccharides (Romera, et al., 2007) (Davis, et al., 2003). Seaweed could prove a technically feasible solution to filter heavy metals (e.g. lead, copper, cadmium, zinc, chromium, etc.) from industrial wastewater flows. Heavy metals are discharged into environment from various industries, such as textile, plastics, mining, metallurgical processes, etc. Heavy metals are toxic even at low concentrations and since they are non-biodegradable, their threat is multiplied by accumulation in the environment through the food chain.

Chemical Products

Aside from the chemical products mentioned before, future applications of chemicals depicted from seaweeds might be in the form of bio plastics, polyesters and platform chemicals such as xylose and glucose. (Hal, et al., 2014). The use of a bio-refinery to extract these chemicals is currently being researched.

3.2.3 Market and expectations

In the past 60 years the farming and gathering of seaweed has expanded exponentially. The FAO Fisheries and Aquaculture department provides data on the amount of seaweed harvested and the value of seaweed. Their data shows an annual volume increase of 9.5% in the 1990s and 7.4% in the 2000s. The total production increased from 3.8 million tonnes in 1990 to 19 million tonnes in 2010 (FAO, 2012). The continuous trend in these figures, combined with a growing world population the market is expected to further grow. In the past decades the production also shifted from natural sources towards cultivated sources. Nowadays merely 4.5 % is harvested from the wild. The estimated value of farmed aquatic algae in 2010 is US$ 5.7 billion. There are only several species that dominate the algae production, see Figure 8.

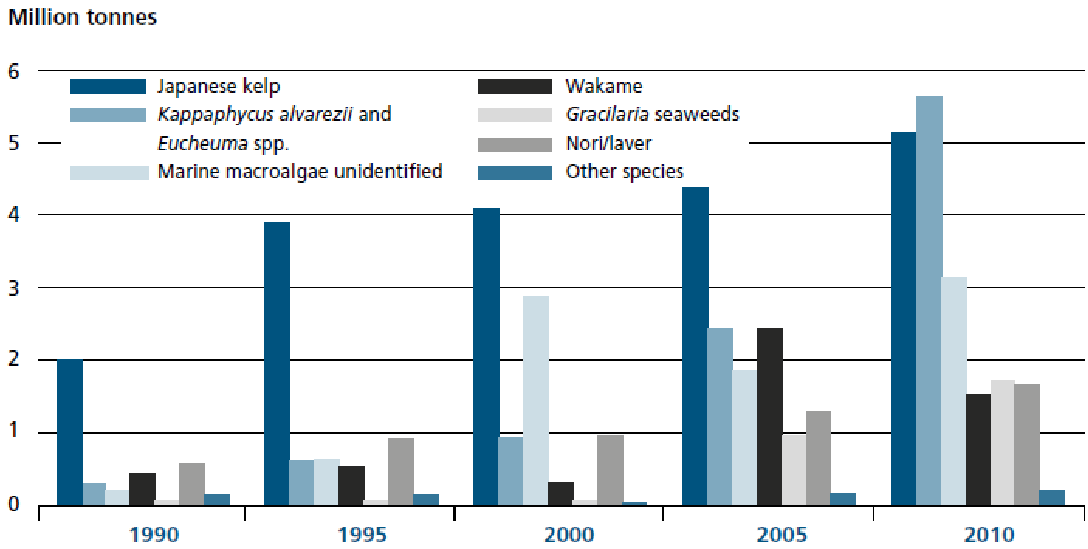


Figure 8 World production of farmed aquatic plant (algae) by major species or species group (FAO, 2012)

The ‘other species’ in the figure are marine macroalgae species farmed in small quantities and microalgae cultivated in freshwater. The production increase is most obvious in the farming of Eucheuma seaweeds. According to the FAO the 2000 production value for unidentified marine macroalgae in the figure contains a significant portion of wakame, which was not separately reported by the main producer. The cultivation of aquatic algae has only been recorded in 31 countries and territories. As shown in table 3 only 8 countries provide for 99.6 per cent of the global cultivated algae production, whereby china provides more than half the world’s production.

Table 3 Country production of macroalgae in 2010 (FAO, 2012)

Country	Production (x1000 tonnes)	Percentage
China	11 100	58.4%
Indonesia	3 900	20.6%
The Philippines	1 800	9.5%
The Republic of Korea	902	4.7%
People's Republic of Korea	444	2.3%
Japan	433	2.3%
Malaysia	208	1.1%
Tanzania	132	0.7%

Effects of a rapid growing industry

The rapid expansion of the industry has resulted in a boom of human coastal activity in the Asian continent. Since cultivation is still done manually this has increased welfare along the coast. Cultivation is often concentrated in certain areas along the coast line, where conditions are beneficial to cultivation. This concentration does also have a detrimental effect on the biological activity in this zone which spreads out along the coastline. It has been confirmed that aquaculture rafts in concentrated cultivation areas have acted as nursery for macro algal blooms, resulting in what is called a 'green-tide' affecting coastline and resulting in major clean-up operations (Liu, et al., 2010). Moving offshore could decentralize cultivation and less coastal interference.

European growth

The European seaweed market is small compared to the rest of the world. The majority is harvested from natural populations in mostly Norway, Ireland and France. Based on figures from the Danish Technology Institute (Svane Bech, 2012), the total production in 2008 was 226200 tonnes. With limitations in natural resources this isn't expected to grow soon. There is however an increasing interest in cultivation. Taking the Netherlands as an example, the last couple of years there has been a rapid growth in the consumption of seaweed products, and this growth is expected to continue (Burg, et al., 2014). Most of it is still imported from Asia, but locally produced seaweed could increase sustainability and better monitoring of product quality. A large step is to be made, if seaweed is to become a common commodity in everyday consumption.

More details of applicable production markets follow in chapter 4 *Analyzing market opportunities*.

3.3 Seaweed as biomass

One of the biggest potential of seaweeds could be the supply of biomass for energy production. It is possible to produce methane through anaerobic digestion or ethanol through fermentation. In this paragraph an overview is presented containing the demand for sustainable fuels, the required production processes specific to seaweed and possible constraints or hurdles.

3.3.1 Demand for sustainable energy sources

There are numerous predictions on energy demand in the next 30 to 40 years, and they are far from uniform. However, most predictions show that energy demand is rising in the near future. Some reports suggest that energy supply will stabilize after 2020, others predict a doubling of the demand from 2000-2050. Some reports also proposed scenarios to decrease demand which could result in a drop of energy demand around 2025 (WWF, et al., 2011). A number of scenarios are displaced in figure 9, with the side note that the top three lines are primary energy and the bottom lines are final energy demands (with losses).

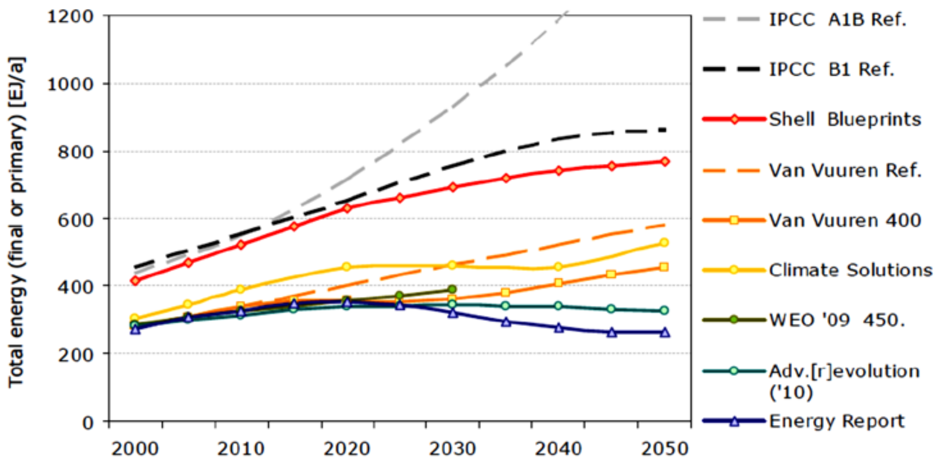


Figure 9 Comparison of global energy demand according various future energy scenarios

The predicted rise in energy demand also raises questions on how to fulfil future energy demand. With the depleting deposits of natural fossil fuels and the increasing costs to develop new deposits added with the increasing amount of greenhouse gases in the atmosphere, more and more research is done to increase sustainable sources of energy. The increase of greenhouse gases has already raised the global average surface temperature and the global average sea levels, with additional consequences to meteorological patterns (IPCC, 2007) and is most likely to cause the extinction of certain plant and animal species in the future (WWF, et al., 2011).

3.3.2 The potential of biomass as energy source

Most bioenergy systems contribute to climate change mitigation if they replace traditional fossil fuel use and if the bioenergy production emissions are kept low. It has the potential to lower greenhouse gases, provided there is enough regrowth to absorb the CO_2 released and good management practices are applied. The savings are also impacted by nitrous oxide emissions from feedstock production and use of fossil fuels during biomass conversion.

In their report Renewable Energy Sources and Climate Change the IPCC presents an overview of lifecycle GHG emissions from modern bioenergy chains compared to fossil fuel energy systems (2012). This overview can be found in appendix B.

Looking closer at the use of renewable Biogas for the use of transportation and the production of electricity, savings can be obtained ranging from we can see a total in savings between 350 g CO_2 eq/ MJ or 85% compared to coal and 200 CO_2 eq/ MJ or 80% compared to oil. The report does warn the reader that the ranges are very approximate and comparable or increased emission reductions relative to crop biodiesel could be achieve through successful R&D and commercialization. Even though a lot of research still has to be done, in 2009 biofuels already accounted for 3% of the global road transport fuel demand. By the end of 2009, the annual production of ethanol has was 1.6 EJ (76 billion litres) and the annual biodiesel production was 0.6 EJ (17 billion litres). This rise is only expected to continue and is projected to increase eight-fold from 2008-2035. Currently USA and Brazil dominate the biofuel market with a production of 43,139 (46%) and 28,542 (31%) million litres per year respectively. (IPCC, 2012)

3.3.3 Challenges with the use of biomass as energy source

Even though the use of biomass is beneficial in the reduction of greenhouse gases, there have been questions whether the use of increased use biofuels is really beneficial to the planet. Unsustainable production could have a devastating impact on social and environmental systems. There are some applications where bioenergy is currently the only suitable replacement for fossil fuels (transportation applications which use fuel with high energy densities and heavy industry applications such as steel manufacturing). For the other applications it is important to appraise the production chain.

Areas of concern are (IPCC, 2012):

- Global, Regional and offsite environmental effects;
- Local and onsite environmental effects;
- Technology;
- Human Rights and working conditions;
- Food security;
- Land and property rights;
- Participation and well-being of local communities.

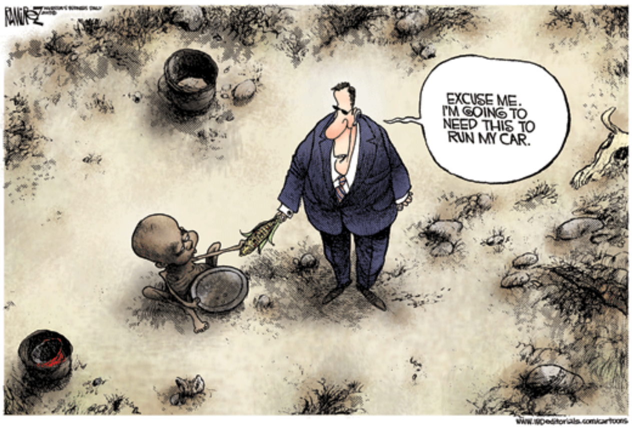


Figure 9 Illustrating the discussion over potential impacts as result of increased biofuel use.

To distinguish the environmental and sociological impacts biofuels are commonly divided in different generations (Mullan, et al., 2009):

- First Generation biofuels are produced directly from food crops by abstracting the oils for use in biodiesel or producing bioethanol through fermentation.
- Second Generation biofuels have been developed to overcome the limitations of first generation biofuels. They are produced from non-food crops such as wood, organic waste, food crop waste and specific biomass crops.
- The Third Generation of biofuels is based on improvements in the production of biomass. It takes advantage of specially engineered energy crops such as algae as its energy source. The algae are cultured to act as a low-cost, high-energy and entirely renewable feedstock.

It is hard to classify seaweed within this spectrum. On one side seaweed could be a valuable resource and could therefore be classified as a first generation fuel. While specially engineered seaweed production could be classed as a third generation. Because seaweed would not compete with arable land and freshwater supply seaweed could be classed as a third generation fuel

3.3.4 Seaweed as fuel, sooner or later?

The question that often arises is if seaweed's could be feasible as a resource for energy. Multiple studies regarding the technological and economic feasibility show that there are several challenges for feasible cultivation of seaweed (Alexander, 2013)**,** (Roesijadi, et al., 2008) (Burg, et al., 2012).

There are numerous processes to convert seaweed into valuable sources of energy. Some of these processes are already used on industrial scale with other feed stocks, while others have only taken place in laboratories on a pilot scale. An overview of the various conversion processes can be found in appendix C.

In line with the assignment, a review of the two most technically feasible conversion routes are presented. The most detailed and researched are the conversion to methane through anaerobic digestion and the conversion to bioethanol through fermentation.

Anaerobic digestion is currently the most technically established route for marine biomass and operates at a range of scales. The process and feedstock pre-treatment are relatively simple, which is technically attractive for the use of a novel feedstock.

Bioethanol has been investigated, and has huge potential in the transport sector. There are ideas of combining few of these processes in bio-refineries. Further research is needed to find the most beneficial conversion process. Some reports exclude the mono specific use as a valuable option and suggest that a bio refinery would be the only feasible way of conversion. The remaining technologies (particularly liquefaction) have potential and may form part of a wider assessment at a future date, when resources allow.

The economic investigation of these conversion routes is recorded in chapter 4.2.

3.4 Synopsis

Seaweed can be cultivated for a wide array of products. Its complex lifecycle does make it hard to cultivate and requires advanced techniques. The seaweed market is rapidly growing and predicted to grow in the future, the need for mechanization and sustainable production is present. Seaweed can be converted to various sources of energy. Through different processes seaweed can be converted to gas or ethanol. More information is required to see whether it is an interesting moment to start in the market. It is clear that there are specific advantages that seaweed over other land based crops:

- Seaweed productivity can offer high biomass yields per area of cultivation (U.S. DOE, 2010);
- Seaweed cultivation strategies can minimize or avoid competition with arable land and nutrients used for conventional agriculture.
- Cultivation of Seaweed is not dependable on freshwater, reducing competition for limited freshwater supplies.
- Seaweed can recycle carbon from CO^2-rich flue emissions from stationary sources, including power plants and other industrial emitters.
- Biomass from seaweeds are compatible with the integrated bio refinery vision of producing a variety of fuels and valuable co-products.
- Reduce eutrophication and acidification of seas through strategic positioning of production facilities because nutrients are taken up during growth and removed by harvesting the seaweed.
- Help in combatting overfishing and subsequent decline of fish stocks as seaweeds can be used as an alternative source of marine protein in fish feed.

4

Analysing market opportunities

A big part of successful upcoming technology is that it fulfils a certain need and it is feasible to develop. This chapter illustrates the parameters that affect feasibility and analyses value and yield in order to determine the initial market strategy and application. Based on these parameters the design scope is created.

4.1 Development decisions

The location and established product chains have a large effect on the development of a concept. The cultivation parameters in chapter 3 will help to decide a correct location for the farm, but do not provide answers in development of equipment. There are several trains of thought when it comes to implementation of the concept.

4.1.1 Scale and scope of production

Three main cultivation scenarios can be identified based on their scale and development expectancy.

Large scale open ocean seaweed farms are often discussed with regards to production for energy. As there are many unknowns with regard to the cultivation parameters and the comparatively huge scale requires large investments it is expected that this development will not start for at least another 10 years. Therefore it is not interesting to look into this scale, other than making predictions based on small scale development. This leaves two other options:

On one end there is the notion that the focus needs to be on European centralized development, aiming for sustainable offshore farms on the North Sea or along the Atlantic or Mediterranean coast. Using collective data developed from collaborative pilots and laboratories new concepts for farms are established, that are to be served by technologically advanced machinery. Once proven successful in the North Sea the market can expand to other areas in the world.

On the other end there is focus on existing production facilities in Asia. By improving/mechanizing current farms, information can be gathered necessary for production and development can be sped up through knowledge and experience, through longer and or larger exposure. Once established the cultivating machine can be scaled up and prepared to be used offshore. There are several advantages in choosing this option:

1. The production and distribution chain is known;
2. The focus off research can be solely focussed on harvesting equipment, instead of taking in account specie selection, cultivation methods and processing
3. There is a high market share potential; A lot off established farms, often based on similar configurations.

4. Calmer environment and shallow water, allowing longer continuous tests and reduces additional assets
5. A lot of knowledge has already been acquired, which could be beneficial when starting in Europe
6. Instead of aiming for sustainability here, it is possible to increase sustainability of existing farms
7. Less dependency on other parties when it comes to knowledge sharing or collaboration
8. Direct test environment
9. Initial mechanisms and ideas could be patented or licensed from an early stage

Disadvantages

1. Shipping costs of prototypes.
2. Cultural effects of mechanization, people losing jobs/dependency.
3. Less secure environment with regards to product infringement. Small ‘low’ tech equipment in higher quantities is easier to copy/produce.
4. Gaining access to resources / establishing yourself

In conversations with MTI Holland, social acceptance, availability of resources, knowledge institutes and funding, were key elements in choosing for European coordinated development. Since a lot of development, focusses on North Sea cultivation, it has been decided to design for pilots in the North Sea Area.

4.2 Cultivation parameters

In this paragraph the economic opportunities are discussed. The two main aspects are therefore the projected yield and size cultivation site in combination with the expected economical outcome. Based on conversations with various stakeholders, the offshore cultivation of brown seaweeds currently has the most opportunity to succeed based on the growth rate and survivability.

4.2.1 Expected yield

The expected yield of seaweed varies in different research reports. While comparing research it is important to identify method of yield measurement, especially when taking into account the high water content water of seaweed (73-94% for the species Laminaria digitata and Saccharina latissima (Burg, et al., 2012)). The water is not used in most processes (with the exception of anaerobic digestion and possible fresh water extraction) and is therefore mostly obsolete. There are usually three ways of describing the annual yield of seaweed:

- Wet tonnes per hectare [t/ha wm];
- Dry tonnes per hectare [t/ha dm];
- Dry tonnes (ash free) per hectare [t/ha af]; the mass of dry seaweed without ash content.

The assumption is made that all the articles refer with tonne, ton, or t, as metric tonne or 1000kg (and not to 2240 lb. or 2000 lb.). Based on information from the different reports, together with the interview held at Nioz (K. Timmermans 2013, pers. comm., 22 November), table 4 was made. From the table we can determine that a safe estimate would be 20 t/ha dm in natural conditions.

Table 4 Expected yield of offshore Laminaria cultivation

Species	Source	Expected yield
Laminaria digitata / Saccharina latissima	(Burg, et al., 2012)	15 t/ha
Laminaria digitata	(Reith, et al., 2005)	20 t/ha
Laminaria digitata	(Buck & Buchholz, 2004)	20 t/ha
Laminaria digitata	Klaas Timmermans (Nioz)	20 t/ha
Laminaria digitata	(Florentinus, et al., 2008)	30 t/ha

There are various method's to increase the yield. One would be through the addition of nutrients, other factors would be the increase of plant density. The latter could be increased by cultivating seaweed in various layers, at different heights. The expected yield of 20 t/ha could potentially increase to 50 t/ha (Reith, et al., 2005). There is however, a lack of definitive data for seaweed cultivation, the verification through different pilot projects is necessary and is an important success-factor for economical production. Furthermore the increase of density might not always lead to increased yield, since sunlight might deprived the amount of necessary sunlight (W. Brandenburg 2014, pers. comm., 26 Oct.).

4.2.2 Expected commodity value

With the predicted yield it is possible to convert this into a specific value per hectare, which can be used to determine the earnings of a seaweed farm. Unfortunately there is no extensive market research done in the past decades that could help determine the price for offshore seaweed. A solution must be found through estimations from different literature.

There are various methods to determine the price of seaweed. Looking at the total annual production of all brown seaweeds (7,149,719 ton, 2011), and a total value of those seaweeds ($ 1.064 billion), the average value of seaweed is $ 149.-/t wm. (FAO, 2011). Since most seaweed is cultivated for the food industry this price could be used to determine the value for food and to be able to see whether offshore cultivated seaweed could compete with the existing market. Compared to other food sources like rice, averaging at $ 420.-/t, and soy, averaging at $ 550.-/t (World Bank, 2013), the price of dry seaweed $ 745.-/t dm (80% water) is still significantly higher. Whether this is a fair comparison is unsure especially since food prices have fluctuated over the past decade and are still rising. (Wenzou, 2013).

The value of seaweed is however very dependent on the end product. The average price, as presented by the FAO only acts as a rough estimate. Wageningen UR (Burg, et al., 2012) carried out a feasibility study with other end products in mind. Using the value of end products and the expected conversion rate from seaweed dry mass, to the weight of the end product. It led to the following table:

Table 5 Predicted value of seaweed applications (Burg, et al., 2012)

Product	Economic Feasibility	Processing	Value [€/t dm]
Hydrocolloids	Possibility for Alginates	Cleaning, production	333-1250
Feed	Low	Cleaning, drying	0-121
Chemicals	Possibility to produce certain chemicals	Bio refinery	114-606
Biofuels	Low	Anaerobic digestion or fermentation	3-30

A small side note is that the Hydrocolloids markets are relatively small and haven't seen rapid growth in the past years (Bixler & Porse, 2011).

Based on this data alone it is possible to conclude that the market for human consumption and additional sources of hydrocolloids are most interesting to develop. However more research needs to be done to see whether this conclusion is justified.

A closer look at biofuels

The economic feasibility of biofuels are low in the report presented by Wageningen University (Burg, et al., 2012), and with a value of € 3-30/t dm, the conversion of seaweed to biofuels can't be very profitable. They based their information on the report from ECN in 2005, that looked at feasibility of using seaweed in combination with offshore wind farms (Reith, et al., 2005), that included investments and operational costs based upon cost estimates of bio ethanol from roadside grass.

These investments and costs are not calculated as they did with the chemicals and the hydrocolloids, which are directly converted with the conversion rate and the market value. Furthermore the price for ethanol in the report from Reith is not consistent. In table 4.1 of the report, the chemical conversion value, also used in the report from Wageningen, is based from a report from the NREL (National Renewable Energy Laboratory) from 1999. It gives a market price for the chemical conversion value in the report from ethanol of $ 333/t or, with a conversion of 0.79 g/cm³ (IFA, 2013), $ 0,263/l. While in Table 4.6, where they do a prediction of the total costs involved they use an ethanol price of € 0.40/l.

Also the energy price they used was € 27/MWh. Looking at the Amsterdam Power Exchange or APX, the stock market for over 60% of the Dutch energy trade, we can see that the average monthly prize varied between € 43.48/MWh and € 58.52/MWh from 2011 till 2013, and averaged € 50.63/MWh in that same three year period (APX Group, 2013).

The market price for ethanol is quite volatile, based on data from trading economics (Trading Economics, 2013), the prize of Ethanol averaged 2.3 $/Gal in the past 8 years, with a low of $1.2/Gal and a high of $ 5.0/gal. In the last year it averaged a growth of 4.94% and the current price (dec 2013) is $ 2.55/Gal. The average price of $ 2.3/Gal, using a conversion rate of 1.35$/€, is equal to € 0.45/l, which is slightly higher than data from the report. Using this data we can now investigate the potential value of seaweed per ton.

In various reports the average expected conversion rate from seaweed to ethanol is between 255 kg/ton dm (Reith, et al., 2005) and 281 kg/ton dm (Wargacki, et al., 2012). Using an estimated conversion ratio of 275 kg/ton and the density of 0.79 kg/l (WolframAlpha, 2014), from 1 ton of seaweed dm we can get 348 l of ethanol. With the price of € 0.45/l, this results in a price of € 156.60/t. dm seaweed.

Using anaerobic digestion technology to create methane, we use the wet mass of seaweed during the process. The used yield is based on table 4 (Reith, et al., 2005) with an average of 0.27 m3/kg per versatile solids. Since versatile solids are roughly 75% of dm, the yield for dry mass would be 0.2025 m3/kg or 202.5 m3/t. There are some losses due to heating of the digester, but none of the processes above are calculated with process costs, therefore it is neglected for the current comparison. The calorific value of methane is 37 MJ/m3 (WolframAlpha, 2014) which is equal to 0.0103 MWh/m3 or 2.081 MWh/t. However the conversion to energy is decreased due to the efficiency of a gas engine with a maximum efficiency of 40% (Reith, et al., 2005). Decreasing the converted energy to 0.833 MWh/t with the current energy prices this results in a value of €42.14/t. Since this is already converted from chemical to electrical energy the comparison might not be completely fair. Using prices of the European gas market at a high prediction of € 0.25/m3 (Ministerie van EZ, 2013) the return would be € 50.63/t.

Based on the value it could be concluded that the conversion into ethanol would be more profitable. However due to the complex nature of the conversion route, anaerobic digestion is often mentioned as the preferred conversion method. In their report, *Macroalgae-Derived Biofuel: A Review of Methods of*

Energy Extraction from Seaweed Biomass Milledge et al. (2014) mention one of the major limitations of seaweed as bioethanol feedstock to be: “The lack of “tractable microorganisms” that can efficiently convert the monosaccharides derived from seaweed into ethanol”. In her dissertation, *Novel biomass conversion routes*: *ammonia from biomass, and marine macroalgae for energy,* S. Alexander (2013) proposed the use of anaerobic digestion as it is currently the easily the most technically established route for marine biomass and operates at a range of scales. The process and feedstock pre-treatment are relatively simple, which is technically attractive for the use of a novel feedstock.

With a predicted value of around € 50/t for anaerobic conversion and € 150/t for bioethanol, even without the additional conversion costs and technical issues, it can be concluded that the use of seaweed as feedstock for biomass is not economically preferred when compared to the food market. With predicted harvesting costs expected of at least € 600/t (see 4.1.3) it is not feasible to cultivate seaweed for the production of biomass. This conclusion is also in line with the conclusion from Alexander (2013), where seven scenarios, which varied the scale and production technique, were investigated to determine the most suitable scale of operation for the UK. Even the most optimal scenario resulted in a required energy price six times higher than the current applied tariff. It is therefore decided not to pursue any cultivation technique optimized for energy production.

A closer look at human consumption

One of the more profitable markets would be the use of seaweed in food products (Burg, et al., 2014). In the previously mentioned report from WageningenUR (Burg, et al., 2012), there is little to no information available with regards to production for human consumption, so this was excluded from their feasibility study. According to the BIM (Irish Sea Fishery Board) in 2009, good quality, dried, Laminaria was typically wholesaling at €10/kg to €16/kg for bulk quantities and retailing at about €2.99/50g to €4.80/40g (Walsh & Watson, 2013). This is however based on a very small niche market. Earlier market research on the potentials of seaweed farming in Canada (Ference Weicker & Co, 1995), recommend focusing on species that currently form a large part of the food market (nori, wakame, kombu). Looking at brown seaweeds, in the early nineties the costs for these products were already estimated at € 3.7/kg (Kombu) and € 3.5/kg (Wakame) respectively (based on $-€ conversion rate of 1.35). Based on statistics from the FAO prices in 2012 market prices were $55/t wm (Kombu) and $453/t wm (Wakame), once again showing difficulty in predicting the value (FAO, 2012).

A more detailed market study is needed to predict whether it is possible to compete with the Asian seaweed market in Europe. Environmental research is necessary to predict the effects of cultivating non endemic species in the North Sea area. If the European seaweed market is to develop, more information is necessary on the Asian production chain, to see whether it is possible with Asian producers. Based on the above mentioned prices and the world average, the prediction is that the early farms will be able to sell their products for € 2.5/kg. As the scale of the market increases and technological advancements in cultivation techniques continue this is expected to drop to € 1.5/kg.

Synopsis

Judging the different price/ton values it is clear to see that producing seaweed for the food industry is much more beneficial when compared to production for energy. With such a low feedstock value the question rises whether it will ever be justifiable to harvest seaweed for energy consumption alone. The fact that production processes still have a long way to go does not help that either. Therefor the main focus of the seaweed industry should be on the production for human consumption. If part of the harvest doesn’t meet food quality standards it could be used for animal consumption, chemicals and hydrocolloids.

4.2.3 Expected offshore production Costs.

The following costs (table 6) are based on predictions by Wageningen UR (Burg, et al., 2012) on a 10,000 ha farm and communications with J. Schipper (J Schipper 2014, pers. comm., 14 Feb) with regards to his predictions on a 50 ha. farm. Both mention the difficulty in predicting the costs for the cultivation of seaweed. Based on conversations with Mr. van de Burg (S vd Burg 2014, pers. comm., 29 July) it was especially hard to predict the costs of acquiring of young seaweeds to plant and the actual harvesting costs.

Table 6 Predicted Seaweed Cultivation Costs

Costs (€ per ton DM)	10,000 ha					50 ha
	Scenario	Per ha	Lifespan	Per year	Per tonne	Per tonne
Investment in systems	Low	50,000	10	2,500	250	150
	High	150,000	10	7,500	750	350
Seedlings	Low	13,000	1	13,000	650	250
	High	13,000	1	13,000	650	400
Labor		300	1	300	15	
Deployment						50
Harvesting					104	100
Management and Licenses.						50
Total	Low				1019	600
	High				1519	950

The price of the seedlings is high in the predictions from Burg, et al. (2012). In conversations with him he mentioned how this price was calculated based on previous bought seedlings from Hortimare. Based on conversations and presentations of J. Schipper this price can be much lower, certainly when scale increases. Both estimate the Harvesting costs to be around € 100/ton. This estimate will be used in future evaluations of harvesting concepts. With the predicted total cost between € 600 and € 1500/ton it can be concluded that the focus should be on high class products such as human consumptions, chemicals and hydrocolloids.

4.2.4 Time scale and development

The current seaweed market in Europe is very small; the reason that is hard to predict the value is a direct result thereof. As mentioned before, market research is necessary to clarify the values and risks involved with increased cultivation in the North Sea. Even though thorough predictions are not present it is valuable information for future designs. After discussion with several stakeholders and analysis together with B.G. Castro, a development path was established and is presented below in Figure 10. The development path from the current situation (establishment of pilot farms) is described, with the expected turnover and the estimated probability of future scenarios, based on revenues and risks. These are rough estimations, to give an indication of the turnover dimensions and the increase of scale, leaving room for discussion.

2014-2017: IMTA pilot 8 ha (100% Probability)
The implementation will be tested in pilots of 8 to 50 ha in size. Possible start up locations are aquaculture sites in semi sheltered waters such as: Norwegian Fjords or Scottish Firths, in the cooler regions of the Atlantic Ocean and North Sea Area. Expected turnover of seaweed to be 400 k€/year (160t @ € 2.5/kg) and about 50 k€/year for the harvesting party (dealing with deployment and harvesting) of an 8 ha seaweed farm.

2017-2025 Commercial demonstration farms of several hundred ha, 2 to 5 of aquaculture firms adopt IMTA (80% Probability)

Once the pilots have proven to be profitable throughout the chain and the technology is scalable and proven through several pilot projects, the next step is adoption by other aquaculture firms, often holding multiple fish farms. Turnover of up to 24 M€/year (12k t @ 2€/kg) can be expected if roughly 10 Norwegian salmon farms use the system. Depending on the available area and the size of the fish pens, farm sizes are estimated up to 100 ha. This would generate a revenue of 2.5 M€/year to the harvesting party.

After 2025 IMTA's go full commercial scale (scenario 1, 50% Probability)

The technology has taken over more than half of the aquaculture sites in Northern Europe and seaweed is accepted as a genuine commodity in the European food market. The increased demand for protein forces aquaculture industries to venture off offshore and full scale commercial applications of 500 to 2500 ha plots emerge along the North Sea coast. Estimated turn overs of up to 60 M €/y (50k t @ 1.5 €/kg) turnover is expected for an area of 2000 ha. At this moment technology starts to spreads to other continents and specialized harvesters operate year round due to seasonal differences throughout the world. (Visually represented in ch 8.4, in the introduction of scenario C)

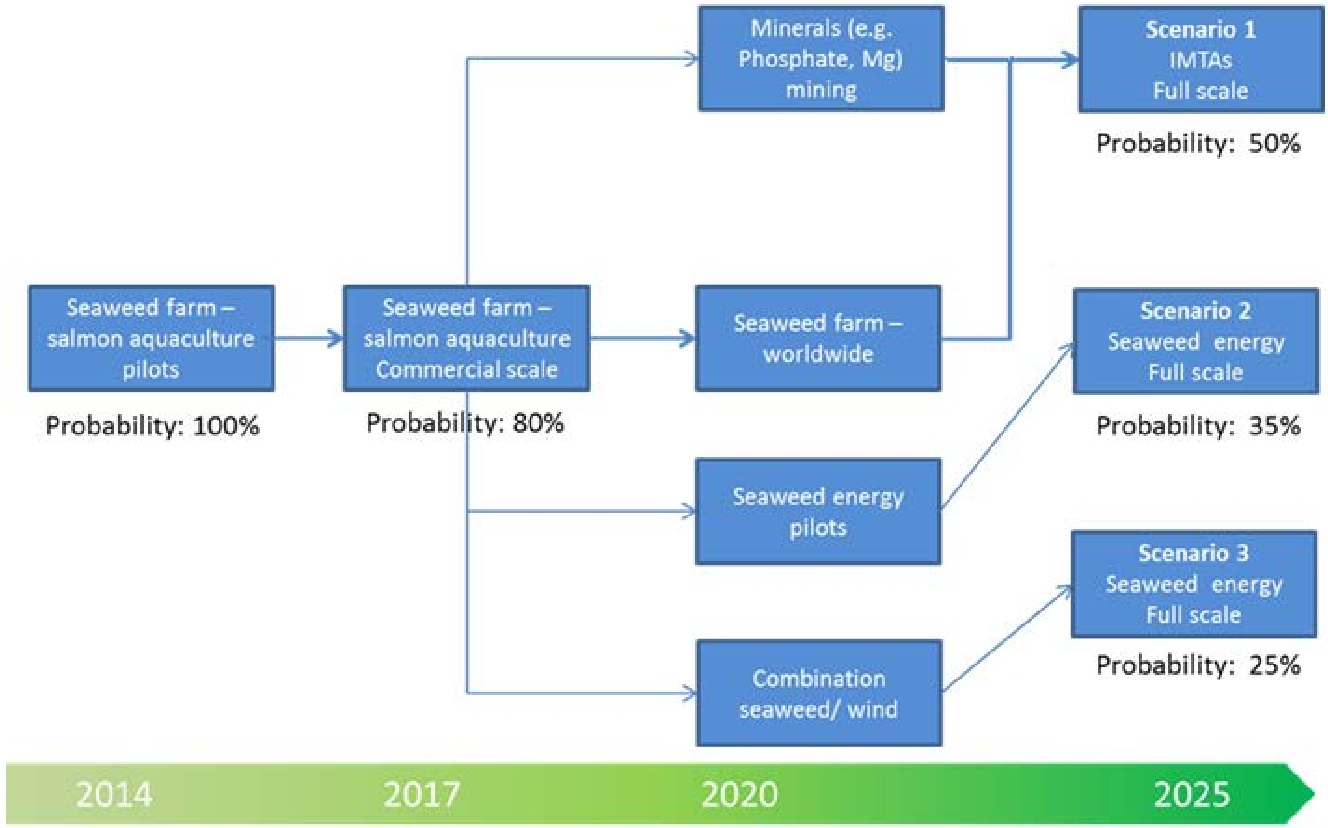


Figure 10 Prediction of market growth

Other possible scenarios are:

Scenario 2: A separate introduction of off shore seaweed farms (not in combination with aquaculture), if for e.g. environmental reasons the up-scaling of IMTA sites cannot be achieved;

Scenario 3: Combination with offshore wind/solar farms, where parts of the infrastructure can be shared.

Both alternative scenarios are considered now less promising than scenario 1, as it is the more profitable, so the probability is presented lower. Another possible combination shown separately is the exploration of seaweed for minerals. The bio sorbent capabilities of seaweed could benefit deep sea mining activities of phosphate reserves and other heavy minerals by filtering effluent streams at the water surface.

Scenario 1 is considered now the most likely as it is the most sustainable scenario (People-Planet-Profit). It generates the most revenues as the integration in IMTA systems takes advantage of the full value of the seaweed in the environmental chain: impact remediation, food, chemicals and biomass. The IMTA business case in Norway is currently considered commercially feasible (J Schipper 2014, pers. comm., Feb 16)

4.2.5 Synthesis

As mentioned in the report by Burg, et al. (2012), it is too early to draw conclusions on the economic viability of offshore seaweed cultivation on the North Sea. There are many uncertainties with regards to possible revenues and consumer demand. The use as feedstock for biomass is unlikely in the near future, as the expected costs far exceed the predicted returns. The most promising application is for human consumption with rest products going through bio refineries where seaweeds are refined into a range of products such as alginates, chemicals and feed additives. The question remains if it is than still possible to compete with other producers around the world. Following the predicted development path, the combination of cultivation of seaweed in conjunction with aquaculture deems to be the most sustainable option. The combination with sheltered waters and advancing aquaculture technology makes this the most valuable option to develop new technology and introduce mechanical harvesting techniques. This variant is chosen as the starting point for the design investigation.

4.3 Design Brief

Based on the analysis of the market opportunities the offshore cultivation of seaweed present a feasible solution for a sustainable source of protein for both human consumption and alternatively as protein source for animals in combination with other products from bio refineries. There are still a lot of knowledge gaps before it can be deemed fully commercially viable, one of them being the expected costs and technology for the offshore cultivation operations.
A great way to overcome these knowledge gaps is a design study for a concept harvester. Through the iterative process of system based ship design more knowledge is gained increasing accuracy in future feasibility and design studies. In this chapter the design brief of such a concept is presented based upon the opportunities and analysis. The next chapter will elaborate more on the mission profile and functionalities of such a design.

4.3.1 Summary

The design brief can be summarized in terms of the design goal, context, constrains and criteria.

- Goal: A concept design of a platform to cultivate seaweed at sea.

- Context:
  Seaweed is a proven source for aquaculture feed additives, and a sustainable alternative for land-based protein production. Seaweed or macro algae could in addition be used as a suitable source for a range of chemical products and secondary energy carriers. With increasing consumer consumption it could be used to serve as a sustainable food source.

- Initial Constraints:
  - Profitable within the value chain
  - Safe
  - Easy to operate, easy to install
  - Able to scale up.

- Criteria:
  - Scale of the platform should cohere with market expectations.
  - Should be able to deploy and harvest ‘large’ volumes of seaweed in restricted times due to seasonality.

- Approach:
  - Investigate the possibilities of a mechanized seaweed cultivating system within the value chain of seaweed production. Identify the various tasks that need to be fulfilled by a vessel for large scale cultivation. (Mission Profile)
  - Determine which tasks should be carried out by a vessel and design a concept that can carry out these tasks. (Ship Functions)
  - Determine the feasibility of the concept and evaluate its potential within a commercial large scale seaweed farm. (Form, Performance and Economics).

The remaining constraints and criteria will follow through clarification of design objectives after investigation of the process chain and through the establishing of functionalities. This will ultimately lead into design requirements.

4.4 Design investigation for Seaweed Cultivation in Norway

According to the Food and Agriculture Organization of the United Nations (FAO) aquaculture is the fastest growing food producing sector in the world, with an annual increase of 6.3% in the last decade (FAO, 2012). This rapid growth has led to both an increase in demand of fish feed and in negative ecological effects near existing aquaculture sites. A possible way to increase the sustainability of marine aquaculture is to combine fed aquaculture species, such as finfish, with other extractive species, such as seaweed and shellfish, also known as integrated multi-trophic aquaculture (IMTA). IMTA provides potential economic, societal and environmental benefits, including the recycling of waste nutrients from and the production of crops of commercial value.

The Norwegian aquaculture sector is looking for solutions to integrate IMTA systems and has started collaboration with Hortimare (J. Schipper 2014, pers. comm., Feb 16) to start cultivating seaweeds on artificial substrates in the vicinity of salmon pens. At the same time MTI Holland is investigating the collaboration of IHC Merwede in this upcoming market to provide maritime knowhow and solutions for concepts of offshore structures and a potential harvesting platform.

The potential of growing seaweed near a fish farm are large. Several studies have shown increased growth rates of seaweeds near salmon pens compared to monoculture species (Handå, et al., 2013) (Troell, et al., 2009). An average aquaculture site in Norway, consisting of 1500 tons of salmon could provide enough nutrients to feed 30k tons of seaweed annually. 30k tons of raw seaweed requires 150 ha of seaweed farm (Calculation in appendix C). With an approximate market value of € 250,- per ton after processing and a production of more than 1 million tons of salmon annually, the potential is there to take part in this vastly growing industry.

To determine the benefits on a large scale Hortimare is looking to develop a 50 ha seaweed farm within the next two years. However there are still questions regarding the harvesting of such a large volume.

4.4.1 Analysis

Bio refinery proposition

Even though analysis has proven that human consumption is proved to be the most feasible option. The business case from Hortimare is based on the extraction of protein through a bio refinery. This as an incentive to aquaculture firms to provide a sustainable source of fish feed. The value of different end products from the biorefinery is shown in table 7. The table is based on conversations with Hortimare and are adjusted based on market expectancies.

Table 7 Value per ton of Sachharina latissima

Value per ton (Saccharina latissima)				
Category				
Food	Protein	12%	€2000,-	€ 240,-
Chemicals	Phycocolloids	20%	€3000,-	€ 600,-
Energy carriers	Biomass	26%	€570,-	€ 148,-
Ash/Minerals	Potash(9,5%), Jodium(0,45%)	32%	€130,-	€ 42,-
Losses		10%		
		100%		€ 1030,-
Service	Best management practices			€ 25,-
	Subsidies			€ 25,-
Total				€ 1080,-

Based on the expected costs (4.1.3), this is not a very lucrative proposition, especially when the processing costs are still largely unknown. The processes in a bio refinery are still being investigated and are in a very infantile state. Perhaps subsidies and cooperation with different business partners within the chain presents this to be a better opportunity to develop their cultivation technology. Either way demands from both the food industry as the chemical industry insist on a high quality product. The definition of this is described in the next section.

Demands of the food industry

From conversations with different organisations the following demands would have to be met with regards to the harvested seaweed:

- When dried the allowed water percentage should be between 10 and 12%.
- The fronds should be free of any shellfish, either aquatic shelled molluscs (e.g., an oyster or cockle) or a crustacean (e.g., a crab or shrimp), especially one that is edible. This to prevent allergic reactions from people with shellfish allergy.
- The amount of heavy metals absorbed by the seaweed should be kept to a minimum. The bioremediation of seaweed could help to clean river outflows, although this seaweed might not be used for human consumption. More information on potential hazards and legal framework can be found in Chapter 6 of the Triple P report (Burg, et al., 2012).
- The level of nitrates should be checked, and should be low.

- For the highest quality on the market, certainly for the food industry it is recommended that the fronds are to be intact.

These demands will be incorporated in the design brief.

Swot analysis

A SWOT analysis is a commonly used strategic planning tool to review Strengths, Weaknesses, Opportunities and Threats. The table below (8) presents a SWOT for european offshore seaweed cultivation. This analysis is based on the work of B. Lee (2010) and numerous conversations with stakeholders. Lee's report and analysis, *Cultivated Seaweed and Seaweed Industry Development in Australia*, has been established to support the development of the Seaweed Industry in Australia.

Table 8 SWOT Analysis North Sea offshore seaweed cultivation

Strengths	Weakness	Opportunities	Threat
Existing nutritional knowledge for endemic seaweeds Focus upon cost of Production Focus upon cultivated seaweeds with high commercial value Quality of European cultivated seaweed Growth of aquaculture industry in North West Europe Location of aquaculture pens often calmer waters than offshore	Limited marketing experience Lack of strategic market research Understanding of product market requirements especially for human consumption and animal/aquaculture feeds Lack of market education about North Sea seaweeds Limited knowledge on cultivation techniques Understanding of processing and packaging needs Limited knowledge on various processing methods	Growth in trends for functional foods and health Increased consumer interest in the potential health benefits associated with dietary intake of seaweeds Global growth of the seaweed industry and its multiple markets Potential for seaweed to be cultivated in integrated aquaculture systems	Consumer non-acceptance of North Sea grown seaweed Rudimental industry Product competition from imports (wild harvest and cultivated) Exceeding costs of artificial substrate Biosecurity risks for stand-alone or integrated aquaculture systems Pests and diseases

4.5 Conclusion

In the previous chapter it was already established that seaweed cultivation is a growing market and that it can be used in a vast array of production processes. In this chapter, through analysis, the notion can be portrayed that there is potential to join the industry in with novel production techniques and innovative cultivation methods.

However there are severe knowledge gaps in different aspects of offshore cultivation. Starting at the initial stage of cultivation it is very hard to predict expected costs of young sporophytes, and specie selection. Cultivation techniques are still under development and offshore pilots are undertaken to learn the effect of adverse conditions on the construction and yield predicaments. There is little information on the effects of mechanization of cultivation processes and when it comes to the potential product market and value there are still a lot of unknowns. This is not new in product development and a concept design study could help to fill out a few of these gaps.

There are also a few conclusions that can be drawn. The food market, with its high value and growing market, is the most logical market to produce for. There are little to know product costs and the supply chains are already mostly established with other marine products or imported seaweeds.

Both bio refineries and energy processes are a long way from being commercially feasible. The bio refinery is however commercially attractive even though it will still be hard to break even. The production for Energy alone seems like a bridge to far. Multiple reports illustrate this to be more of a pioneering dream than a hard reality. The increased costs compared to other 'green' alternatives, will result in slow development due to the lack of investors. Perhaps a change in the perception of single product chains should also be changed to achieve the optimal value for seaweed and avoid losses due to quality control.

Based on expected development paths the increased yield and bioremediation around aquaculture sites seems like the most probable development direction. The added fact of calmer waters and increased interest from this sector makes development in this direction even more attractive. Alternatives might be in mechanization of existing farms in Asia but this is left out of the scope of the assignment.

To increase development a proper market research is highly recommended. If investors could be informed with accurate data and clearly identified risks it might become easier to get the necessary research budget. An open information stream between the different actors throughout the production chain is necessary to eradicate the knowledge gaps as quickly as possible.

Through the design concept an attempt is done to fill in a few of the gaps and increase understanding of mechanized offshore cultivation.

5

Mission profile analysis

"It is most important that the objectives which a new design is to meet should be stated in a way that does not rule out any possible solution. It is only too easy when setting requirements to have a particular type of design in mind and write terms of reference in a way that leads to a solution along these lines but excludes some other equally good or better answer. Objectives should be set at their most desirable level even if their attainment seems unlikely or impossible. This will stretch designers and may cause them to come up with novel ideas that are ahead of any current solution." (Watson, 1998)

5.1 Introduction

As stated by Watson (1998) above it important to define a set of objectives that are clear and yet open enough to not rule out any solution. This is often needed to improve on current solutions and think out of the box. Offshore cultivation of seaweed is a novel design that is based on both the mechanical harvesting of natural seaweed and the manual harvesting and cultivation. In this chapter the objectives are developed based on selections of processes within the value chain. These selected processes form the basis of the mission profile. The main functional tasks can be extracted from this mission profile. Based on these objectives the main functions are selected and divided in sub-functions. With the IDEF0 function modelling method these functions are structured. The parameters belonging to the sub functions form the basis of the design requirements. These requirements and functional tasks form the basis for the design concepts in chapter 6.

5.2 Forming objectives through process selection

The aim of this section is to clarify design objectives and sub objectives. With the relatively vague design brief there is not a complete and clear statement of design objectives. The initial and interim objectives may change, expand or compact, or be completely altered as the problem becomes better understood and as solutions and ideas develop. This iterative system is used as well, since the initial objectives were not sufficient to select and weigh the different designs.

To come up with an accurate value chain various existing chains have been studied and conversations have been held with various stakeholders (NIOZ, ECN, Hortimare, WageningenUR). This was sufficient to develop the functional tasks. Alternate chains could be developed in the future with other stakeholders. Additional potential stakeholders could either be external (i.e. governments, NGOs and others) or internal (i.e. universities, research institutes, storage operators, transporters, processing plants, biofuel refineries, distributors, the end user and the parties that are responsible for the disposal of biofuels).

The following session contains literature studies into the various chains of seaweed cultivation (value and process chains) and expresses a potential process chain based on conversations with research institutes, seaweed experts and the design brief.

5.2.1 Process chains in literature

Most cultivation chains in recent studies are based on using seaweed as a feedstock for energy applications. Though this was already deemed unfeasible in chapter 4, it does intend to cultivate seaweed on a larger scale and forms a solid basis for large scale conversations with other end products in mind.

In her master thesis Herfst (2008) describes a value chain for a large open ocean algae field. She uses the ethanol process of sugar cane from Hamelinck, et al. (2005) and the gasification of rapeseed and palm oil from Faaij (2006) to form the basis of her processing chain. This is later combined with a flowchart from a simulation from Aresta, et al. (2005) and interviews with government bodies, NGOs, energy companies, research institutes, universities and companies within the port of Rotterdam. Herfst's value chain describes the process of cultivating seaweed from the transport of seedling material to the disposal of biofuel.

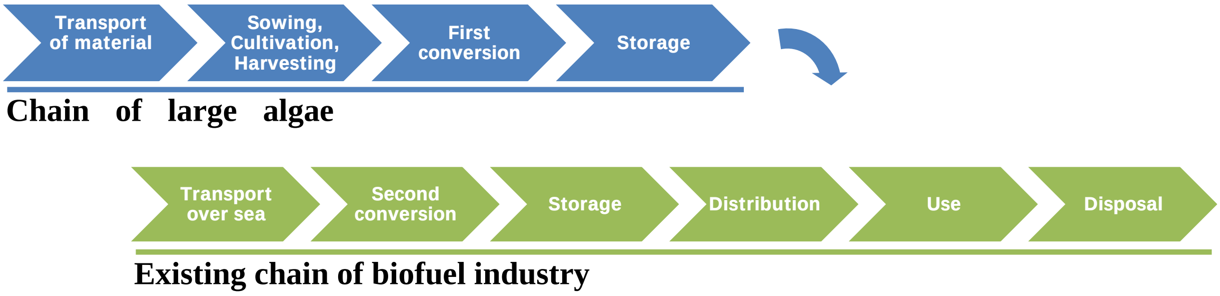


Figure 11 Conceptual chain of large algae field project (Herfst, 2008)

She placed two remarks with her concept chain: "*First of all, as long as one does not know what the final products of the algae conversion are, it is impossible to define the conceptual chain in detail. Secondly, the conceptual chain can change during the design process. Therefore, the conceptual chain presented above must be viewed as just one of a range of possible chains for this project*".

The various process systems have also been discussed in the recent lifecycle assessments. Dave, et al. (2013) describe the process of anaerobic digestion of seaweed combined with a CHP-plant (Combined heat and power). Their techno-economic assessment covered the mass and energy balance of the entire process followed by the economic feasibility. Alvarado-Morales, et al. (2013) have made a lifecycle assessment of biofuel production from Laminaria Digitata. They describe the process in the initial stages of the farm, from the collection of fertile seaweeds, the development of the culture in the laboratory and the grow-out phase all the way to the production of biogas and bioethanol. Langlois, et al. (2012) discuss the life cycle assessment of anaerobic digestion of seaweeds. In her assessment she compares a single cycle purely for the production of biogas, with a chain that starts with the extraction of alginates, whereby the residues are used for biogas production. An overview of this process can be found in appendix D.

5.2.2 Proposed process chain

Selecting the Business Case

In order to select the correct processes for the mission profile a case is developed. Based on the conclusion from chapter 4, the collaboration with aquaculture is chosen to develop the first concepts for. This case is based on the proposition that a company develops several patches around multiple aquaculture pens in Norway, similarly to the development of Hortimare BV. The Norwegian aquaculture sector is concentrated along the Atlantic coast of Norway. Most pens reside in fjords, several miles from the coast line, providing shelter from North Atlantic waves and winds. One of these regions is the Sogn og Fjordane district in Norway (see figure 12). Hortimare is active in this area and is situated in Hardbakke (black dot).

Currently they have a 3.5 ha farm for testing and this is all harvested manually. The area consist of many fish farms, as can be shown on the attached nautical chart in appendix E. The closest large basin of water is the Sognesjøen which serves as an entrance from the North Sea on the west to the Sognegfjord at the eastside. The closest large harbours are Mongstad (20 nm) and Bergen and Florø (both roughly 40 nm away). Hortimare is planning to construct several seaweed farms with a total size of 50 ha.

Figure 12 Hardbakke Area, Norway

Though the previous process chains describe the cultivation and processing of the seaweeds, it often lacks the significant necessity for the farm and its related infrastructure. Activities as the installation and maintenance of the farm and other related processes are often neglected, while the tasks could be carried out by the same device. The design brief states to focus on the offshore cultivation of seaweed, which also includes ensuring that it can be attached to something offshore. The proposal is therefore to look at the two operations:

- The construction, installation and maintenance of an offshore carrier, able to keep position and depth while withstanding the environment;
- The cultivation of the seaweed attached to an offshore carrier.

Before viewing the proposed chain, we first need to define the following terms:

Carrier – The offshore structure moored at sea, able to attach substrates of seaweed to;
Substrate – The artificial base (line, net or cloth) used to attach and grow seaweed on. The substrate is attached to the carrier;
Cultivator – Machine designed to cultivate seaweed. In this report the design concept;
Platform – The overall combination of offshore equipment including cultivator, carrier and substrate.

Offshore carrier

Before cultivation can take place the offshore carrier needs to be built. Based on the design of the carrier and the choice of substrate, this would require installation of mooring systems and floatation devices. Due to the adverse conditions the carrier requires maintenance and if necessary, repairs. The expected process can be found in the Off-Shore project development section of the value chain in appendix D. The design and ideas of the carrier and the substrate are still under development (see 6.1.3). Figure 13 illustrates a concept with a moored carrier system using floatation devises and a line substrate.

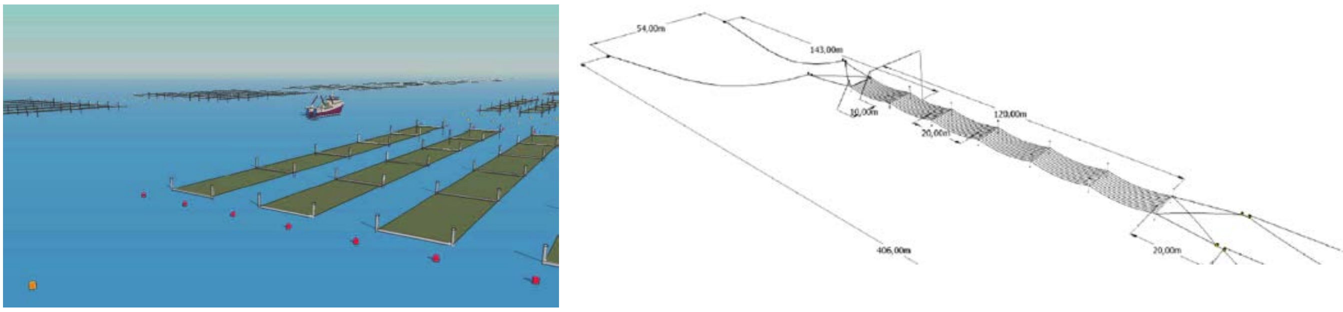


Figure 13 Example of an offshore farm [L] and its carrier structure [R]

This example is created by Hortimare BV. in close cooperation with Bakker machinefabriek. A pilot system has been tested on the North Sea. Yet it is still far away from commercial use.

As with other offshore installations (wind turbines and offshore oil and gas installations) the installation of equipment offshore often requires specialized vessels. The question is whether the cultivator should be able to carry out these tasks or not. In order to evaluate the options, table 9 illustrates the advantages and disadvantages of installing additional installation equipment. In addition similarities from other industries are mentioned.

Table 9 Advantages and disadvantages of adding construction functionality to a cultivator

Advantages	Disadvantages
Additional construction equipment can be optimized on the carrier. Decreasing construction time. Construction systems could show similarities with cultivating systems. Maintenance and repair could be carried out by the cultivator	Additional space requirements. Requirement for additional trained personnel. The occurrence of installing is limited making the additional equipment obsolete for a large part of the time
Industry Similarities	
Separate construction / operation	Joined construction and operation
Offshore Wind Offshore Aquaculture Offshore Oil and Gas Dredging industry (Rigging of discharge lines)	Fishing industry

In the original graduation assignment it was not required to look at the construction of the offshore carrier. It does however influence the design in multiple ways. It affects the design of the cultivation system as well as the choices for added equipment for construction and maintenance tasks. With the predicted market growth and the installation of multiple farms in the foreseeable future it could be useful to install this equipment on board. However, due to the uncertainty of the final carrier design, it is hard to jump to this conclusion. The fact that the carrier design is not yet determined makes it hard to determine the requirements for construction. The assumption is therefor made that the construction will be outsourced and that the carrier construction is at location before the cultivation starts.

Offshore Cultivation

The cultivation of seaweed is the second process required to farm seaweed. The illustration on the next page contains the various stages within the production cycle and is based on the previous value chains and the LCA's. There are three stages throughout the process. The chain starts at the Nursery, where natural seaweed is reproduced, attached to substrate lines and developed in tanks until they are strong and large enough to deploy at sea. The substrate material with the young sporophytes (nonsexual phase (or an individual representing the phase) in the alternation of generations) is transported to the farm site where it is deployed on the carrier.

Once the seaweed is fertile and fully grown, it is harvested and transported to an offload location. At the location it is processed, or transported to different process sites to be developed into the required product. The proposed cultivation process is illustrated in Figure 14. In the next paragraph this process is converted into sub functions using the IDEF 0 function modelling method.

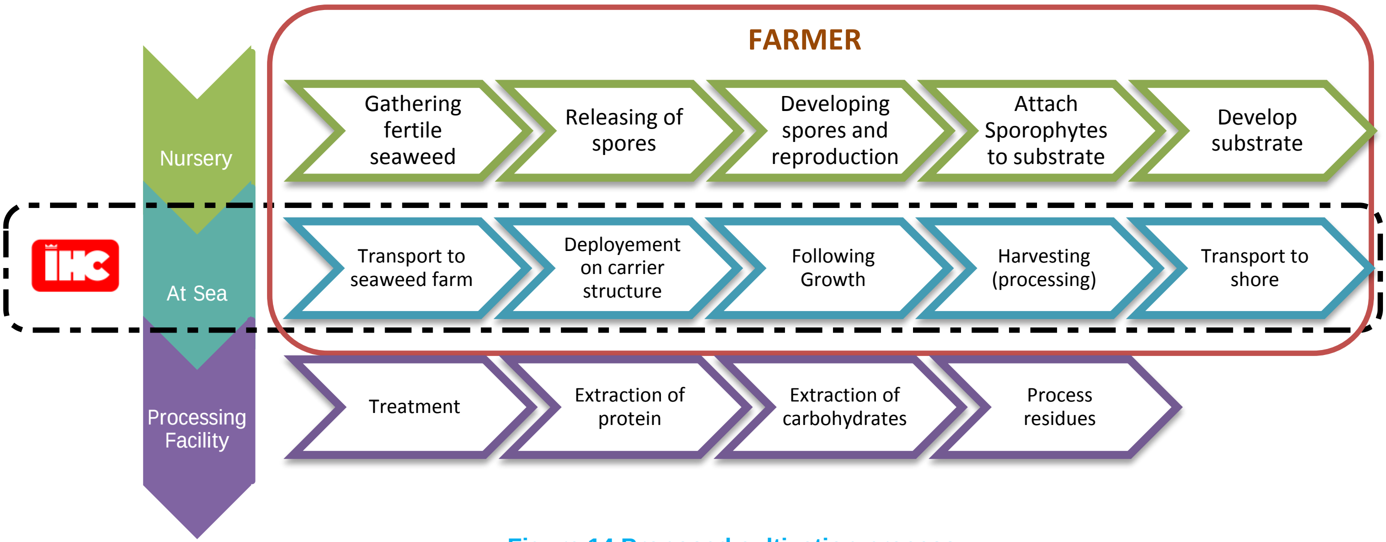


Figure 14 Proposed cultivation process

The original assignment describes a vessel that is able to harvest and pre-process seaweed. Looking at the process overview, there are a multitude of different tasks to be carried out at sea. Based on information from Hortimare, during the growth period at sea, only regular checks have to be carried out. This can be done by any vessel, and does not require much effort. Therefore the main processes of interest are the transport, to and from the farm, deployment and harvesting.

5.2.3 Objectives

Coming back to the design brief from chapter 4, the initially vague design brief has been narrowed down to various stages in a process chain. In this section the various objectives from the design brief and the processes are listed and an objective tree is made to illustrate the objectives. Cross (2008) describes this procedure in chapter 6 of his book:

1. Prepare a list of design objectives. These are taken from the design brief, from questions to the client and from discussions in the design team.
2. Order the list into sets of higher-level and lower-level objectives. The expanded list of objectives and subobjectives is grouped roughly into hierarchical levels.
3. Draw a diagrammatic tree of objectives, showing hierarchical relationships and interconnections. The branches (or roots) in the tree represent relationships which suggest means of achieving objectives

The list of objectives have been discussed with IHC Merwede and the important factors can be found in Appendix R. The objectives will later be used to evaluate the various concepts in chapter 6.

5.3 Defining functions

5.3.1 Function modelling method

Function analysis is a method for analysing and developing a function structure. A function structure is an abstract model of the new product, without material features such as shape, dimensions and materials of the parts. It describes the functions of the product and its parts and indicates the mutual relations. The underlying idea is that a function structure may be built up from a limited number of elementary (or general) functions on a high level of abstraction (van Boeijen, et al., 2014).

The functions are described using the IDEF0 processing method. IDEF is a method designed to model the decisions, actions, and activities of an organization or system. This method is chosen due to its simplicity in displaying the functions of a complex system. IDEF0 is useful in establishing the scope of an analysis, especially for a functional analysis. As an analysis tool, IDEF0 assists the modeller in identifying what functions are performed, what is needed to perform those functions, what the current system does right, and what the current system does wrong.

The "box and arrow" graphics of an IDEF0 diagram show the function as a box and the interfaces to or from the function as arrows entering or leaving the box. To express functions, boxes operate simultaneously with other boxes, with the interface arrows "constraining" when and how operations are triggered and controlled. The basic syntax for an IDEF0 model is shown in the figure below.

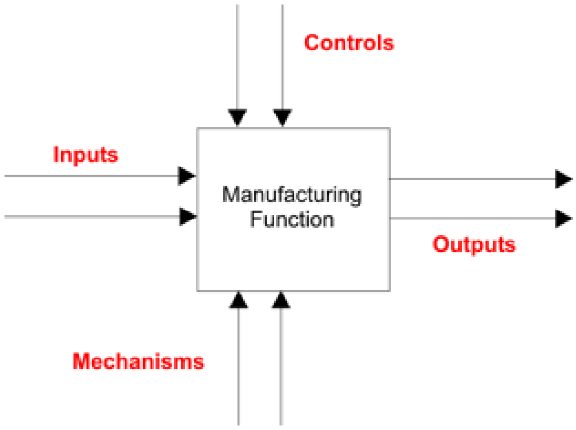


Figure 15 IDEF0 Box and Arrow Graphics

The IDEF0 language semantic is based on five major concepts:

- **Activities** are the functionalities of the system.
- **Inputs** are elements to be processed by the activity (e.g., files, documents, raw materials, products).
- **Controls** are elements like laws, policies, standards, and unchangeable facts of the environment. They control, direct, or force the execution of the activity but are not modified by it.
- **Outputs** are elements produced or modified by the activity (e.g., data, materials, products).
- **Mechanisms** are means to execute the activity. They are resources (human or material) that are used in bringing about the intended goals of the activity.

Box and arrow segments are combined in various ways to form diagrams. The boxes in a diagram are connected by sequences of arrow segments. IDEF0 models are hierarchically arranged IDEF0 diagrams.

Unlike every other diagram in the model, the top-level diagram (context diagram, numbered A-0) contains only one box. This box represents, at the coarsest granularity, the single high-level activity that is being represented and decomposed in the IDEF0 diagrams. The parent–child relation holding between two diagrams signifies that the parent node is the decomposition of a box in a parent node. A decomposition of a box is a diagram that represents a finer-grained view of the function. Diagrams are numbered. Figure 16 illustrates this hierarchical decomposition.

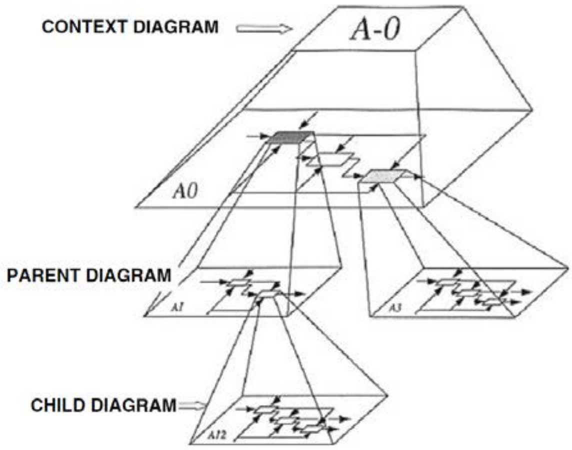


Figure 16 IDEF0 hierarchical decomposition of boxes and diagrams

5.3.2 Context diagram offshore seaweed cultivation

As mentioned, there are various chains published for the use of a seaweed farm and its relevant processes (Herfst, 2008) (Langlois, et al., 2012). Although applications differ, they form a solid start in determining the various functions within the process chain. This has also been the reason the process chain is separated from the cultivation chain. It is possible that some processing might be part of the harvesting process, depending on time and volume constraints, for now however; it is decided to leave that out of the design scope.

To complete the process chain the installation and maintenance of the offshore carrier is also described. The following IDEF0 diagram (figure 17) acts as context diagram in the model. The cultivation of seaweed (A0) is the main manufacturing function, where seaweed forms the output of A0 and the input for processing function (B0). The infrastructure (C0, carrier and terminal) and the work platform form the mechanisms to make A0 possible. The work platform can be used as mechanism in all main functions, yet mainly for A0.

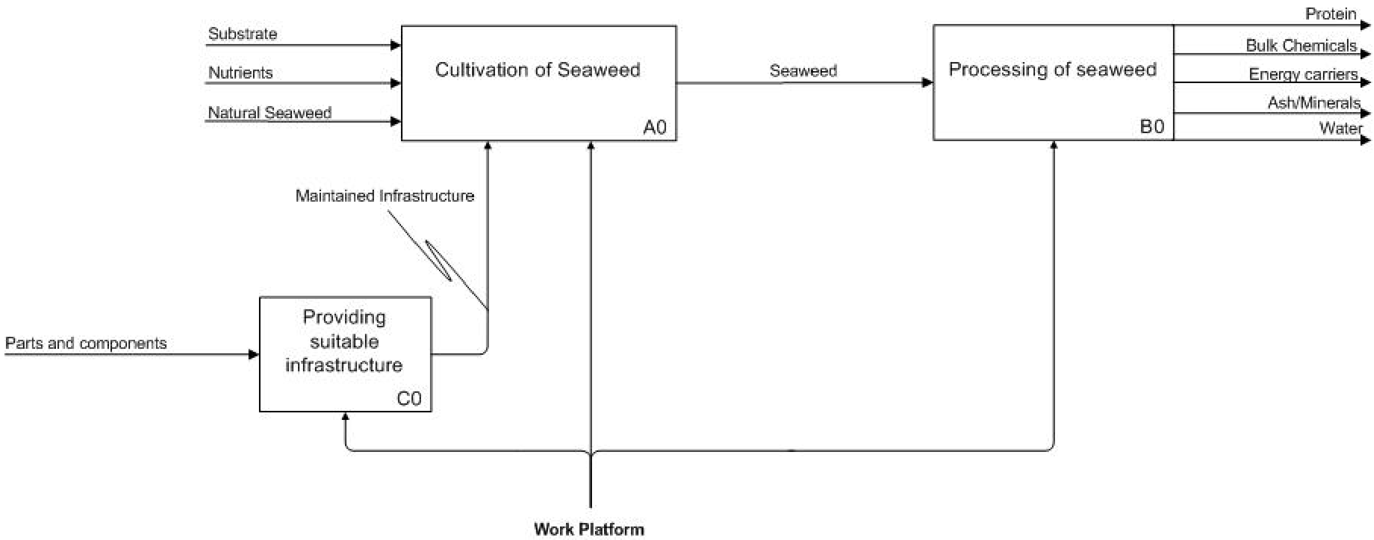


Figure 17 Overall Production Diagram

Though the overall functions of both the installation (B0) and processing (C0) have been analysed this report will not further elaborate on modelling of these processes. Recommendations and references have been mentioned if modelling is necessary in future design evaluations. The next section illustrates the various parent processes of seaweed cultivation and describes the parent processes of deployment and harvesting. A complete diagram of all other processes can be found in Appendix E. To increase clarity most of the diagrams are simplified, leaving out the mechanisms and control mechanism for the activities. As discussed in 5.2.2 the main processes of interest are: deployment, harvesting and transport, and the mechanism executing these functions will be accomplished by the concept. In chapter 6 the mechanisms for the sub functions will be further explained.

5.3.3 Cultivation methods and parent functions

An important aspect of the entire process chain is the used cultivation method. Some seaweed can be cultivated vegetatively, where other species need to go through a separate reproductive cycles, often involving alternation of generations. In the next section the differences are elaborated.

Vegetative cultivation

In vegetative cultivation small pieces of seaweed are taken from either natural sources of previous harvests and are deployed at sea. Once fully grown, harvesting commences by either removing the entire plant, or by removing most of it, leaving a small piece on the substrate that will grow again. When the whole plant is harvested, small pieces are cut from it and used as new feedstock for cultivation.

Reproductive cultivation

Cultivation involving a reproductive cycle, with alternation of generations, is necessary for many species; for these, new plants cannot be grown by taking cuttings from mature ones. This is typical for many of the brown seaweeds. Natural spore-recruitment and induced spore-shedding in hatcheries are two methods are being practiced in the production of sporophytes from spores:

Natural spore recruitment

In the natural spore recruitment method artificial substrates are anchored among dense populations of seaweed. These are left in the area to allow the naturally shed spores to settle on them. The seeded substrates are then transferred to the culture sites for outgrowing.

Hatchery production

In a hatchery mature seaweed is prepared to release spores, which are further developed and reproduced into new sporophytes under controlled conditions.

Based on conversations with Hortimare (J Schipper 2014, pers. comm., 14 Feb) it is hard for seaweed on substrates to regrow and or reproduce. In a technical report of the FAO, McHugh states that none of the usual seaweeds for alginate production are cultivated (McHugh, 2003). These include the brown marine algae species that grow natively in the North Sea area and are planned to be cultivated. They cannot be grown by vegetative means, but must go through a reproductive cycle involving an alternation of generations. Therefore it is not possible to cut the seaweed off and leave the rest in the water for a next season. In addition, there is much interest in strain development of different seaweeds to improve and control the growth and substance of seaweeds. Hatchery production will therefore be the starting point of seaweed cultivation.

Parent diagram

The cultivation of seaweed can be described in the following four processes: Development; Deployment; Following growth; Harvest. These are also illustrated in Figure 18 on the next page.

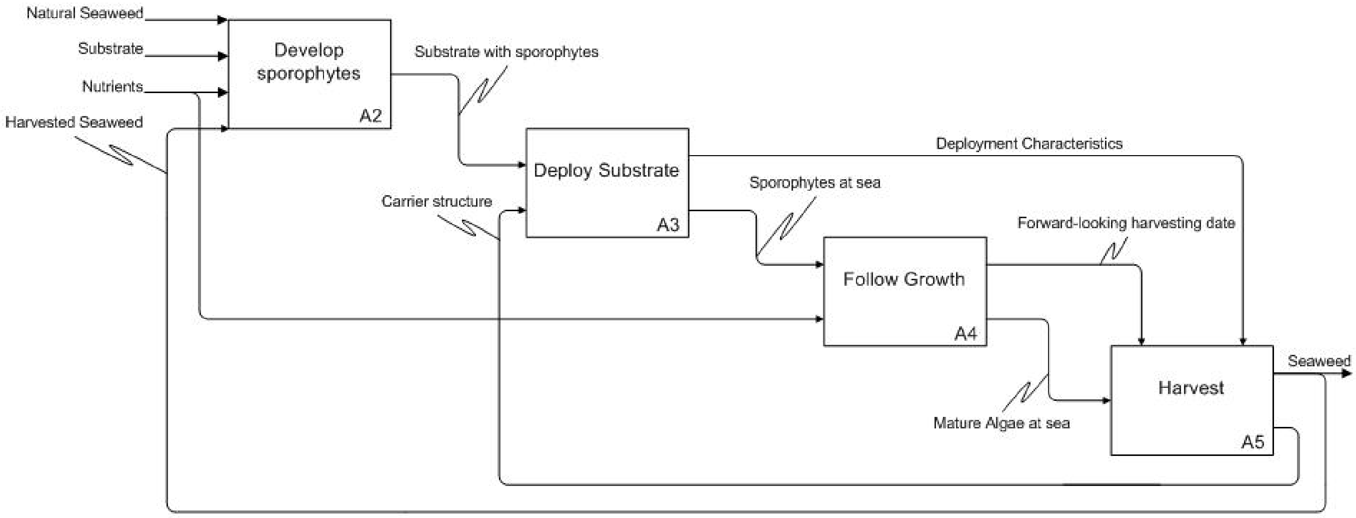


Figure 18 A0 Cultivation of Seaweed

In short, it starts with the development of new sporophytes (A2), these are young seaweeds developed in a nursery from natural or harvested mature species. The sporophytes are attached to a substrate, developed and deployed at sea on a carrier structure (A3). Once at sea the seaweed will grow and develop further. During this growth the conditions and growth rate are monitored (A4). Once the seaweed has matured and conditions are good for harvesting the seaweed is removed from the carrier structure (A5) and ready for further processing (B0).

5.3.4 Development of sporophytes

The development of sporophytes in a nursery is described in five different stages. Alvarado-Morales, et al. (2013) describe this phase in six different steps, separating the development of the spores and their reproduction. Most information is based from their analysis of using Laminaria Digitata. It starts with the the collection of fertile species to be used in the nursery, or laboratory (A21). As both Laminaria Digitata and Saccharinna Latissima have similar growing patterns, these can be collected between October and May. After the first season it is also possible to reuse the sporophytes from the harvested stock (Langlois, et al., 2012). The gathered mature species have blades that bear sporangia, also known as sporophylls. These sporangia are cases or sacs where spores are produced. In a nursery these sporophylls are prepared for the release of spores under controlled laboratory conditions (A22).

The culture of spores are further developed and after a certain period reproduction occurs. The spore solution is filtered and the filtrate is mixed with strain nutrients and seawater in inoculating flasks (A23). After a certain period reproduction is induced by manipulating the temperature, irradiance and photoperiod for about 8 days, until new sporophytes are developed.

Once reproduction has finished, the small developing sporophytes are being attached to a substrate (A24). This could either be a small culture line, or a different form of attachment surface (net/sock). The substrate is then placed into culture/nursery tanks to further develop (A25). This development is necessary to ensure the holding strength of the sporophytes. Nursery plantlets on string of 0.1–0.5 cm in length are ideal to be deployed at sea (Alvarado-Morales, et al., 2013).

5.3.5 Deployment at sea

After the substrate has been developed in the laboratory it needs to be deployed at sea. Before the substrate is being transported to the cultivation site it needs to be prepared for transport (A31). Depending on the deployment method there are various ways to store and conserve the sporophytes on the substrate. Preferably the substrates need to be submerged in seawater, to mimic conditions from the nursery (J Schipper 2014, pers. comm., 14 Feb). After the preparations the substrates are being transported to the site of the farm (A32). The frequency of the loading and transport depends on: the size of the farm, the distance between the farm and the loading port, the carrying capacity of the work platform, and the loading and deploying characteristics.
Once the platform arrives at the farm site it deploys the substrate and attaches it to the carrier (A33). There are multiple ways to attach the substrate to the carrier, and also multiple ways to design the carrier. Once it is attached to the carrier structure it needs to be secured to withstand the forces of the environment (A34).

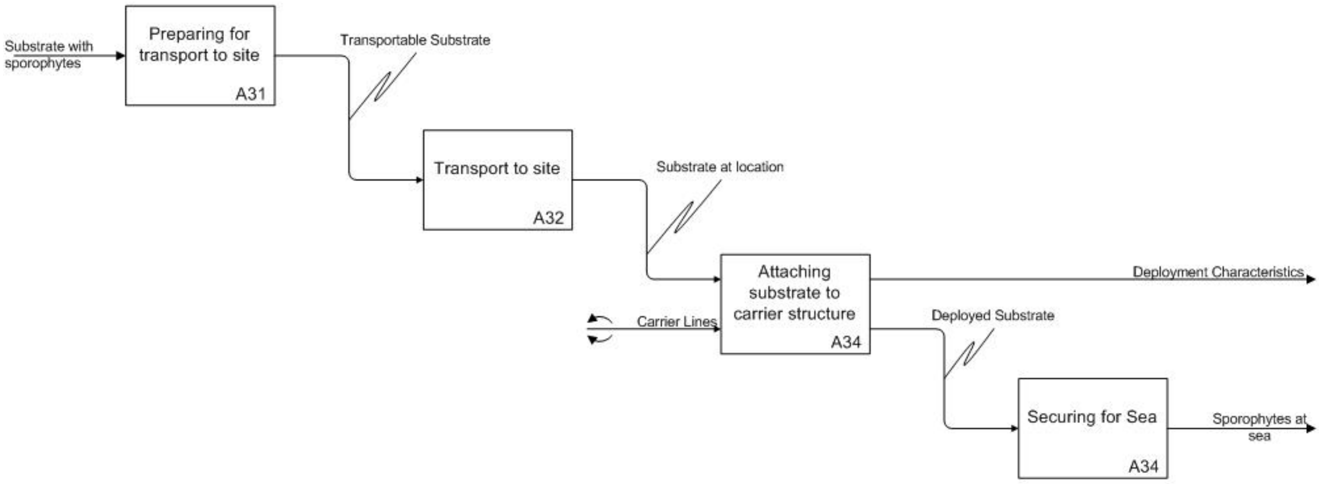


Figure 19 A3 Deployment

5.3.6 Monitoring growth

During the growth of the various sporophytes the growth has to monitored and assisted when necessary (A4). This is expected to be carried out once or twice a month (8-12 times per grow out period) (Alvarado-Morales, et al., 2013). Careful measurement of the environmental qualities and the state of the seaweed is necessary, especially in the first years, to ensure sustainable growth. In case of integration with IMTA, the effects of wastewater mitigation needs to be measured to ensure the beneficial effects. Taking samples and observing growth will also give more information in precise prediction of harvesting dates.

Next to natural growth, it can also be strongly influenced by pests. These can affect the yield and survivability of plants under cultivation. We distinguish three pests with seaweed:

- Colonization of seaweed fronds by microalgae and smaller seaweeds (Epiphytes)
- Predation (Grazing)
- Diseases

An Epiphyte is any plant that grows upon or is in some manner attached to another plant or object merely for physical support. Epiphytes are primarily tropical in distribution and are often known as air plants because they have no attachment to the ground or other obvious nutrient source. They obtain water and minerals from rain and also from debris that collects on the supporting plants (Encyclopeadia Britannica, 2013). Seaweed fronds provide an excellent substrate for epiphytes and encrusting organisms to grow. The epiphytes tend to shade the seaweed fronds from sunlight, thereby reducing the overall farm productivity. It is predicted that large algal farms with fast growing kelps are less likely to suffer severe productivity losses from epiphytes (Roesijadi, et al., 2008).

Herbivores can also have a devastating effect on seaweed populations. Yet in many communities algae and herbivores coexist. Larger farms are less likely to suffer widespread losses as overall plant productivity will greatly exceed grazing demand, and the damage from grazing will become negligible.

Intensive farming of seaweeds, like any domesticated crop, can encourage disease organisms to flourish. The greater the number of farms and concentration of plants, the greater number of diseases may be found. Disease has occasionally been widespread in Chinese Laminaria (kelp) farms, reducing yields in various regions of China (FAO, 1989). Major diseases, including cause, are displayed in table 10:

Table 10 Major diseases correlated to kelp cultivation (Roesijadi, et al., 2008)

Disease	Cause
Environmental etiology[1]	
Green rot disease	Poor illumination
White rot disease	Change in transparency + insufficient nutrients
Blister disease	Freshwater mixing with seawater after heavy rainfalls
Twisted blade disease	Excessive illumination
Pathogenic etiology	
Malformation diseases	Hydrogen sulfide + sulfate reducing and saprophytic bacterial, e.g. Macrococcus
Sporeling detachment disease	Decomposing Pseudomonas bacteria
Twisted frond disease	Mycoplasm-like organisms

5.3.7 Harvest

When the seaweed is fully grown it is time to harvest. Harvest time is mainly based on the thickness of Laminaria fronds. Thickening, in turn, is directly related to the time of deployment and to light conditions at the farm site. Early deployment allows a longer grow-out period, resulting in good rate of blade thickening. Late deployment delays blade thickening.

During the mature sporophyte stage, growth in length of the blades stops and the tips of blades may even deteriorate, causing blades to shorten somewhat. Even though plants become shorter in length, however, they continue thickening and thus adding biomass. Length is not a criterion for timing of harvests. The main criterion is blade thickening (FAO, 1989).

Harvest of seaweed requires sound organizational planning. In China it usually takes about 40 days and often requires employment of additional temporary manpower. Timing must be accurate to prevent loss of biomass as summer water temperatures rise.

If harvest is too early there will be a decline in yield and in quality of Laminaria because the firm and light brown fronds will contain too high water content. On the other hand if harvest is too late, Laminaria fronds will deteriorate and plants will be invaded by many different species of invertebrates, such as bryozoan (moss animals) and barnacles. Harvest time must be accurately timed to obtain highest yield and best quality product.

During harvesting the seaweed has to be removed from the carrier structure (A51). Since we make use of a hatchery the entire plants can be removed. After collection of the seaweed it is important to remove any fouling or marine life attached to the seaweed (A52). When the seaweed is cleared of any impurities it can

[1] Etiology : The study of the causes of diseases

be processed before storage and transport. The harvested seaweed on average contains 85% water, and this might even increase due to additional water during the harvesting process. Depending on the processing method, either the water is unnecessary, or can be used for further processing (Alginate). The question remains whether it is beneficial to transport the additional water. If the water is to be separated from the harvested material a drying or extracting mechanism should be installed. Once the seaweed has been pre-processed it is transported ashore for further processing.

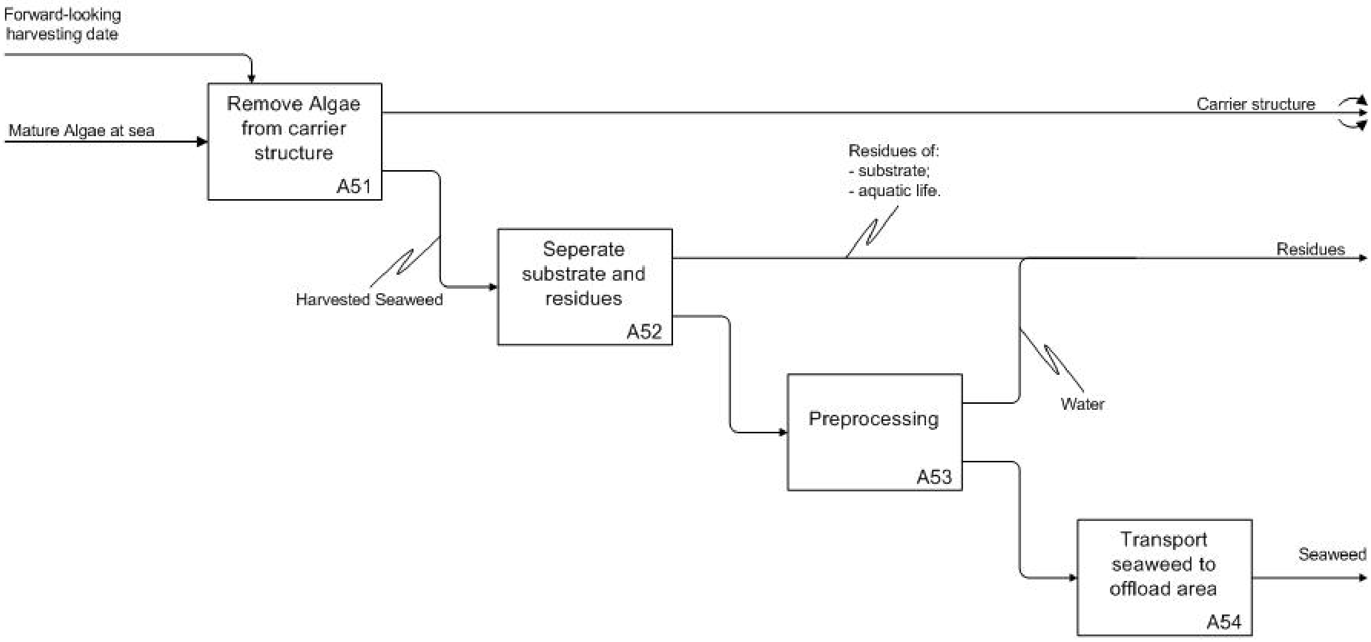


Figure 20 A5 Harvesting

To elaborate on the required functionality with regard to the concept design, the removal of algae and the separation of substrate and residues is further divided in additional sub functions (see table 11).

Table 11 Sub functions of harvesting

A51	Remove Algae from carrier structure
A511	Approach seaweed with removal mechanism
A512	Adjust removal mechanism to correct position
A513	Lift/Queue/Grab seaweed to removal mechanism
A514	Remove seaweed from substrate
A515	Collect harvested seaweed
A516	Transport seaweed to separation stage

A52	Separate substrate and residues
A521	Sift/Separate material/substrate/fauna
A522	Clean harvested material
A523	Inspect/monitor quality
A524	Store seaweed for transport / Send to pre-processing

5.3.8 Processing and handling

As discussed before the process will not be a part of the functional capabilities of the concept design. There are two questions with regards to processing that do arise from the processing. 1: The effect of the subsequent process has on the product that needs to be delivered (dry vs. wet) (whole vs. chopped) (rinsed vs. raw). 2: if the concept needs to be scaled up, how would this influence the possibilities to process the seaweed on board? E.g. A longer distance between farm and shore might make it more worthwhile to invest in a drying mechanism to reduce cargo space and increase preservability. On the following pages these possible processing steps are illustrated.

As described in the previous section before seaweed is processed it needs to be either wet or completely dry. Wet seaweed is required in the alginate industry (McHugh, 2003) and during the conversion of seaweed to methane gas through anaerobic digestion. In most other cases, especially food, it needs to be as dry as possible. Most totally-dried sea vegetables stay nutritionally and medicinally secure for a multitude of years (FAO, 1989). The minerals do not degrade; the phycocolloids slowly fragment over years; the pigments slowly fade, especially the chlorophylls; fats slowly become rancid; proteins fragment slowly to polypeptides and amino acids.

Proper storage ideally means that the seaweed is stored in air-tight waterproof opaque containers (not paper or plastic bags) at temperatures less than 70 degrees F, in the dark. The advice from the FAO is to not store dried seaweed in a refrigerator or near sources of strong odours. Dried sea vegetables are very odor-absorptive. They also tend to be aggressively hygroscopic, (they absorb water from the air) which is why dry storage is essential.

In most seaweed producing countries there are two main kelp processing methods for food: drying and salting. Choice of which method to use depends on availability of manpower and weather conditions. Weather is the critical consideration since most drying is done outside. Rainy or cloudy days will delay drying and cause deterioration in product quality. In order to prevent delays in harvest, salting may be required to preserve kelp product so that it can be dried when weather conditions improve.

Both fresh-drying and salt-drying of Laminaria are done by laying out fronds in the sunlight on the drying-ground area. Fresh-drying is low cost, produces good quality product, and is a simple work procedure. In addition the seaweed could be dried in steam-heated drum dryers (Booth, 1956).

In northern China, harvested kelp fronds are arranged on the drying area so that all plants are parallel to one another, with holdfasts pointing in the same direction. Holdfasts are cut off either when plants are fresh or after they have dried. In sunny weather, drying may be completed in 5–6 hours. In southern China, harvested kelp culture ropes are laid across bamboo poles so that fronds can hang in the air for drying. This method yields a clean product, free of debris, but is somewhat slower in drying plants than the method of laying plants flat on the ground.

Salting is done by two methods: (a) harvested plants may be soaked in a brine solution for a few minutes, or (b) harvested plants may be stored by packing them in layers with salt scattered between the layers. The salted and stored plants can then be dried after harvest is completed. Whenever possible, fresh plants should be dried first. Salted plants can then be dried as time and weather conditions permit.
The problem with the salt-drying method, however, is that salting produces a lower quality product, by destroying some of the nutrient value in kelp blades. Salted fronds are not suitable for extracting iodine, mannitol and algin, which are the main products desired from processing. Also, cost of processing is increased because of the additional labour required for the salting procedures. Salted product can be processed into products for human consumption but cannot be made into lameal (Laminaria meal) for livestock fodder.

Once the seaweed has been dried it can be used for further processing. The required processing is heavily dependent on the business case. The parent diagram from B0 processing will be based on the bio refinery principal from Alvaro-Lopez (López-Contreras, et al., 2012) which requires dried seaweed. Seaweed is comminuted in smaller uniform particles (B2), after which it is processed either through fractionation and/or hydrolysis(B3). This first step extracts the protein, used as feedstock for the salmon. After which the remainders are fermented and/or fermented to extract bulk chemicals, sugars or alginates.

Since the design brief mentions multiple uses (see 2.5.2) and food is often given as the most economical promising product (Burg, et al., 2014). It is important that the product is clean and the leaves are in one piece. Later processing could still chop or dry seaweed.

5.3.9 Carrier installation

The process of constructing an offshore seaweed farm has not been described in detail in literature. Often concept designs are mentioned, yet often they lack the process plans of constructing such a structure. With little reference material from the seaweed industry, it is necessary to look at other industries involved in constructing large structures in the open ocean. Large projects can usually be found in the offshore industry, with regards to production platforms and offshore wind farms. To evaluate these processes information is used from various reports:

- General report of the Offshore Wind farm Egmond aan Zee (NoordzeeWind, 2008);
- Case Study: European Offshore Wind Farms - A Survey to analyse Experiences and Lessons Learnt by Developers of Offshore Wind Farms (Gerdes, et al., 2008);

The seaborne operations that bare close resemblance with the offshore industry are:

- Installation and commissioning;
- Full operation;
- Dismantling.

The process diagram C0 in appendix E covers the function overview during this process.

5.3.10 Required Functions for Cultivation concept

The Functions for the required platform can now be illustrated through a function tree. As in the work of Levander (2009), the functions are divided in ship functions (common function necessary to operate the vessel) and task related functions based on the mission profile. The functions are sorted on process types and their relevant domain within the process. Notation o stands for optional, these are functions that can be added to other designs, but will not be used in current concepts.

Table 12 Function tree

Function type	Process type	Domain	Functional Requirements	Optional functions
Ship functions	Common functions		Structural	
			Propulsion & Manouevring	
			Crew Facilities	
			Service Facilities	
			Technical systems in accomodation	
			Tanks and Voids	
			Outdoor Decks	
Task related functions	Farm functions	Constr.	Preparation	o
			Placement	o
			Construction	o
			Completion	o
		Maint	Inspection	o
			Repairs/Refit	o
		General	Transport and storage	o
			Manouevering/Station keeping	o
			Towing capabilities	o
	Seaweed functions	Deploy	Preparation	
			Placement	
			Securing	
		Cultivate	Inspection	o
			Pest control	o
			Fertilize	o
		Harvest	Removal	
			Collection	
			Sifting	
		Process	Dewater	o
			Wash	o
			Dry	o
			Cut	o
			Press	o
		Trspt	Storage	
			Climate control	
		Gen.	Manoeuvring / Station keeping	
			Towing capabilities	

5.4 Determining functional requirements

With most functional specifications set in paragraph 5.3 it is necessary to further specify the requirements. This will help to set certain limits and constraints to the design. One of the most important limits is that of costs: what are the expected production costs and what is the client willing to pay for. Other common limits in shipbuilding are dimensions, speed, installed power and safety or statutory requirements.

Objectives and functions are statements of what a design must achieve or do, but are not normally set in terms of precise limits, which is what a performance specification does. In order to specify limits it is important to look at the design brief and identify the required operation.

With the selected case it is possible can make assumptions of requirements. A transport model will later be used to determine the required capacities and speed. The environmental and marine conditions are used to further specify the limits of the vessel.

The cultivator will be operating within the Norwegian Fjords and near the North Atlantic coast of Norway. The deployment is expected to be in October and November. And Harvesting is expected in May and June. The following specifics are required to determine requirements for the vessel.

5.4.1 System parameters

The plan is to cultivate the seaweed close to salmon pens on parallel line systems. Literature is divided when it comes to the yield in meters for a line system (see table 13).

Table 13 Yield and blade specifics brown seaweeds

Source	(Peteiro & Freire, 2009)	(Peteiro & Freire, 2009)	(Maeve Edwards, 2011)	(Handå, et al., 2013)	(Burg, et al., 2013)	(Pers. Comm. Job Schipper)
Species	Sach.	Sach.	Laminaria.	Sach.	Not Defined	Sach.
Months	Dec-Apr	Feb-May	Oct-May	Aug-June		Nov-May
Cultivation length	107 days	98 days				± 180 days
Front weight [gr]	103.9 ± 11.8	65.9 ± 28.6				
Front Length [cm]	145 ± 13.4	100 ± 16.8	± 90	135 ± 7		
Yield [kg/m]	11.7 ± 0.9	6.2 ± 1.5	7.5 ± 0.5		3-12	12-18

Assuming that seaweed is cultivated on a line structure this would mean that the total length of line to be harvested would be around 850 km. (10000[t seaweed] / 11.7 [t seaweed/km line]). This is roughly 17 km line per 1 ha. Due to the seasonal requirements of the harvest, harvesting of the entire plot should be done within a month. Having an approximate of 20 working days to harvest, the following minimum harvesting rates are required: 500t/day or 42.5 km/day.

To accomplish this distance of lines per day the operating speed could be enhanced by being able to process multiple lines at once. The sizes of seaweed the harvesting device should be able to remove could differ between 20 and 200 cm. Since it is still unknown what species could be optimally harvested, the harvesting device should be able to cope with different species of brown seaweeds Laminaria digitata and Saccharina latissima.

For optimum growth rates of Saccharina latissima, Handå et al. (2013) suggest the depth of the seaweed lines to be between 5m and 8m of water depth. If the height is not alterable the system should be able to work at these depths.

5.4.2 Ship related function requirements

To accomplish the common ship functions (Levander, 2009), the following facilities have to be part of the design:

- Crew and service facilities, to facilitate the crew during daily operations (galley, restroom, messroom) or berths (depending on operational profile).
- Navigation equipment and facilities, to provide safe navigation and manoeuvring
- Machinery
- Technical systems, in addition to common facilities, this is also to provide additional power to the harvest and deployment equipment.
- Outdoor decks, in addition to common functions (anchoring, mooring, lifesaving equipment) adequate space to support harvest and deployment equipment.

Though these are necessary for any cultivator to fulfil its functions it is heavily dependent on the operational profile and the design of the harvest and deployment equipment to quantify the requirements. This is also part of the iterative design process. Since the task related function requirements are the primary objective, the ship related functions are secondary, and thus will be filled in when the primary requirements and parameters have been set.

5.4.3 Condition based requirements

The following requirements are derived from operating in the proposed cultivation environment.

Route
The Route is an important factor in the process since it is the connection between the farm and the offloading harbour/station. Furthermore it determines possible dimensional limitation, for example due to bridge heights, narrow passages or locks, and time constraints due to speed limitations or at the harbour, a movable bridge or a lock.

Weather and oceanographic phenomenon
Another big influence on the operation is adverse weather and currents. High wind speeds may halt harvesting or offloading operations and high waves may hinder transport speeds; while oceanographic phenomenon like currents, also affect transport speeds and harvesting and position keeping at the farm.

There are numerous sources with regards to weather and oceanic data. This data often applies to either large harbours in the vicinity of the farm plots, as well ocean based meteorology stations like weather buoys. That being said, the conditions within the fjords are usually very local and could only be attained through local measurement studies. Since these conditions do affect the design a short overview will be given with regards to the possible data. However, due to the conceptual nature of the design and the fact that IHC would predominantly focus on a design that can be used in other environments as well, the designs will not be checked on conformity with these local requirements.

Daylight
Depending on the operational profile during harvesting and deployment, work either has to be carried out during daylight, or both during day and night time. This will affect speed of manoeuvring and monitoring of the harvesting operation. Based on the time constraint of the harvest that the operations will have to be carried out 24 hours per day. This should be taken into account during the design phase. The exploitation model in chapter 7 could determine whether daylight hours are sufficient for the required harvest window.

Wind
There are two operational situations that influence the operations. One is the deployment or harvest at the farm site and the other is the transport overseas to an offloading harbour. Therefor it is determined that two wind speed limitations should be used. As an example local airport data is used to show annual wind expectancy. Based on operational availability, you can determine your design limits and vice versa.

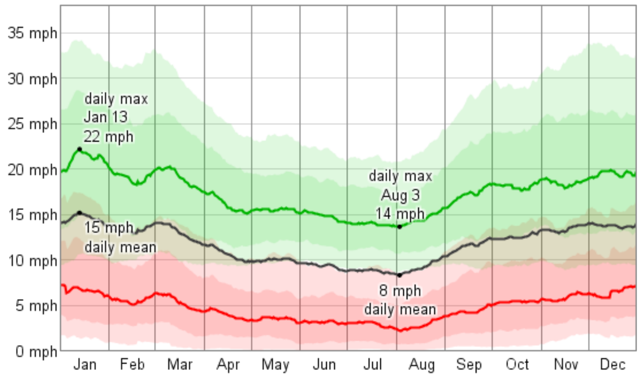


Figure 21 The average daily minimum (red), maximum (green) and average (black) wind speeds for Florø

Waves
Waves are a big factor on both the operational aspects of the farm, as well as its survivability. An offshore farm in the North Sea should be able to withstand 6 meter high waves, where in the fjords, due to the sheltered conditions, the sea state is expected not to exceed state 3 or slight seas (0.5-1.25m). That is one of the predominate factors to focus on seaweed production within the fjords.

To determine local wave and wind data at sea or near the coast, mariners often use Nautical Pilots provided by hydrographic services. These also include swell predictions, which are often very seasonal. If this is inconclusive additional hydrographic information needs to be obtained, as an example the wave height could be found from the Sognefjorden Feasibility Study of Floating Bridge (Statens vegvesen, 2013), where the yearly maximum expected significant wave height of wind generated waves does not exceed 1.1 m.

Currents
Currents have a large effect on the layout of the farm. Not only has the drag to be minimized, but currents also bring nutrients onto the fronds. Offshore, currents are often easy to predict. Platforms and oceanographic buoys provide continuous data on the current conditions. Closer to the coast this changes. In general the tidal currents along the western coast of Norway are very much influenced by the winds and floods; influencing the general flow along the coast. Looking more locally, the outward current in Sognefjorden will increase significantly during the snowmelt period and during periods of heavy precipitation, which is strongest on the N side of the fjord. To determine local currents information could be gathered from local fisherman or other authorities, or measurements are required at the possible farm locations.

Regulations
As with all vessels sailing in Norway, the cultivator should comply with statutory laws. Depending on the selection of classification society, additional class regulations may have to be met. Since it is still unknown what the design will be, this is not further detailed.

5.4.4 Table of requirements

A summary of general design requirements is given in Table 14. It can be noted that this initial set of requirements are still recommendations, since details of the farm layout, location and configuration are estimated. This does however allow a large variety of design solutions. It is therefore decided not to elaborate on more detailed requirements, especially since more specific requirements are generated in the model, based on differences in configuration. As mentioned before the Sailing Area requirements are taken into account developing the concepts, but will not be used in evaluation of the design.

Table 14 general design requirements

Demand	Specifics	Description	Demand	Wish	Value	Unit
Capacity	Total capacity	The expected total capacity needed to be harvested in one season	x		10000	T
	Total days	The total maximum days of harvesting	x		20	days
	Minimal daily Capacity	The minimum capacity per day	x		500	T/day
Sailing Area	Sea keeping Transport	Minimum sea state		x	>4	Sea state
	Sea keeping operations	Minimum sea state		x	>3	Sea state
	Wind operations	Minimum wind force limit operations		x	5	Beaufort
	Wind transport	Minimum wind force limit for transport		x	7	Beaufort
Deployment	Deployment Capacity (lines)	Preferable similar to harvest capacity to ensure product equality		x	42.5	Km/day
	Seedlings	Seedlings not to be affected by transport and deployment	x			
Harvesting	Species	The module should be able to cope with different species of brown seaweeds.		x		
	Size of seaweed	The frond sizes the harvesting device should be able to process.	x		20-200	cm
	Max Yield of seaweed	Max Yield per meter line	x		15	Kg/m
	Quality	Food grade: - Means to inspect - Removal shellfish - Preferred: fronds to be intact	x			
	Multiple lines	When using a lined system, to enhance operating speed, multiple harvesting lines are to be processed at once		x		
	Depth	Depth of lines should either be variable or harvesting needs to be done at 5-8m. depth		x		
	Quantity	Losses during harvesting to be minimized.		x		
	Manoeuvrability	Manoeuvrability to be optimized on farm configuration and harvest methodology		x		
Transport and storage	Quality	Quality and composition not to be affected by temporary storage and transport time.	x			

5.5 Conclusion

With information from different stakeholders and literature it is possible to develop a probable process chain for offshore seaweed cultivation. Though it is noticed that the installation and maintenance of the carrier structure is often left out of the process chains, it is easy to see why. There is still large uncertainty with regards to optimal substrate designs, and its related longevity. It is therefore hard to predict the required functionality of a vessel. Using the process chain as the culmination of activities, the ones necessary for the design can be selected and used to create a list of objectives. Since most objectives where still relatively vague a function analysis was done to establish the functions required.

The main functions selected to be part of the design are: the deployment, harvest and transport between the farm and the offload destination. With the use of a function modelling method the functions have been hierarchically decomposed in sub functions, increasing understanding in the process and the requirements. Based on the selected business case in relation with other aquaculture activities a set of parameters have been established. This resulted in a set of primary requirements.

Since the harvesting of seaweed at this required scale is relatively new, it is hard to come up with a list of detailed requirements. Additional calculations, combined with information from chapter 4, will help improve the set of design requirements. Yet to fully be able to calculate the requirements from the process chain it is important to know which systems will be used to full fill those functions. In the next chapter design concepts are introduced that will determine which set of requirements are important.

6

Concept development

6.1 Introduction

The next phase in the integrative model is to determine the characteristics and generate alternatives. In this chapter the characteristics are determined based on current technology and requirements from the previous chapter. The alternatives are generated both through functional sub-solutions in morphological overviews, and concept solutions based on the evaluation of the morphological overview. The generation of solutions is considered the essential and central aspect of designing, since the whole purpose of design is to make a proposal for something new, that hasn't existed before.

With such a broad design scope and range of requirements the design of a seaweed platform is largely based on variation or modification from exciting machines. In particular the reordering or recombination of existing elements. Hereby predominantly focusing on generating designs based on theoretical design requirements. This is done because of two things:

- To allow a lot of alternative solutions and ideas. A lot of the specific parameters are left out.
- With a preliminary design decision it is easier to find out the necessary parameters to model.

In the next chapter (7) specific parameters are introduced to further define the design specifics and further evaluate concept designs.

6.2 Gathering Information on harvesting systems

A way to start generating probable solutions is to look at the history of the industry, as well as developments in similar industrial fields. In this paragraph the history of mechanical seaweed harvesting is presented.

6.2.1 History of mechanical harvesting

The first mechanized seaweed harvester dates back to the First World War, where in Southern California giant kelp (*Macrocystis pyrifera*) was harvested to produce valuable chemicals. During the war Germany had placed an embargo on potash, an organic compound that is a major component of most plant fertilizers. The lack of Potash would severely hurt the agricultural sector in the US, since they were the world's largest consumer of potash fertilizers at that time. Next to the demand for Potash there was a need for alternative sources for the production of acetone and butanol. This was mainly used for the production of cordite (smokeless gunpowder), primarily used by the British navy. At its peak the total production was 400.000 ton annually and several related industries where setup (Roesijadi, et al., 2008). Long before the war, seaweed was harvested manually and it was only in 1913 that the first successful mechanical harvester was built by the Pacific Kelp Mulch Company. It consisted of a flat-decked barge, fitted with a conveyor-belt device that stretched across the front of the barge down to a depth of 4 feet beneath the water surface. This design was later copied by other companies. After the war the embargo on Potash lifted and it was no longer viable to continue harvesting, despite the successful development of new processing techniques. (Neushul, 1989)

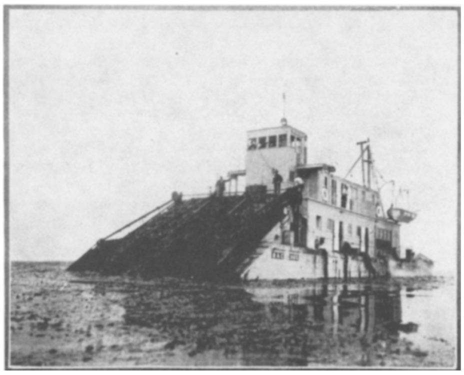


Figure 22 The Bacchus(1916), a $75,000 harvester operated by Hercules Chemical Co.

In Norway, kelp was used in agriculture as feedstock and soil conditioner. In addition to collecting drifting kelp, L. hyperborea and L. digitata were harvested from small open boats using cutting blades on long poles. In 1961, a new alginate production plant was built in Haugesund, Norway, and the need for raw material increased. As the Norwegian economy grew and developed, labor costs made manual harvest inadequate due to rising costs and decreasing desire among coastal people to do this very physical intensive work. In 1963, the alginate industry developed mechanized harvesting by creating a sled/trawl to be towed behind boats. The initial system had a blade to cut stipes, leaving the holdfast.
The first purpose-built boat for L. hyperborea harvesting, or seaweed trawler, was launched in 1969. However, small fishing boats remained in operation until the mid-1970s. The trawl saw developments over the years whereby the main difference was done by eliminating the front cutting blade, leading to whole-plant harvesting. This meant including the holdfast, but leaving small plants, especially juvenile of 20 cm or less. (Vea & Ask, 2011)

6.2.2 Analysis of Existing Technical Systems

Part of the assignment was to investigate in current harvesting methods. Currently there are several different methods to harvest seaweed from natural resources. These are based on two basic removal principles, either cutting or pulling. The seaweed is then transported to a storage space, where it is stored for further transport.

Conveyor cutter

The harvesting system used during the First World War is still commonly used today, be it mainly for the removal of weeds in harbours and waterways. The first harvesting barges carried the cutting apparatus at the bow of the vessel. Later designs moved the cutting apparatus to the stern of the vessels and, proceeding in reverse when operating in a kelp canopy. Cutting is accomplished by reciprocating blades attached to a horizontal bar that is lowered to a fixed depth of 1.2 m below the waterline. Cut ends of the kelp fronds are carried against a conveyor belt just behind the cutting bar. The cut kelp is carried up on the belt over the bow, and deposited in an open hold that extends for most of the barge's length. A mechanically driven steel claw or grapnel is used to distribute the cut kelp evenly throughout the hold. Typical harvesting vessels may load several hundred wet tons of kelp per trip. Cameron (1915) described a harvesting vessel of his day in considerable detail (Figures 23). The essential features of a kelp harvester, as described above, were fully developed even then. (Doty, et al., 1987)

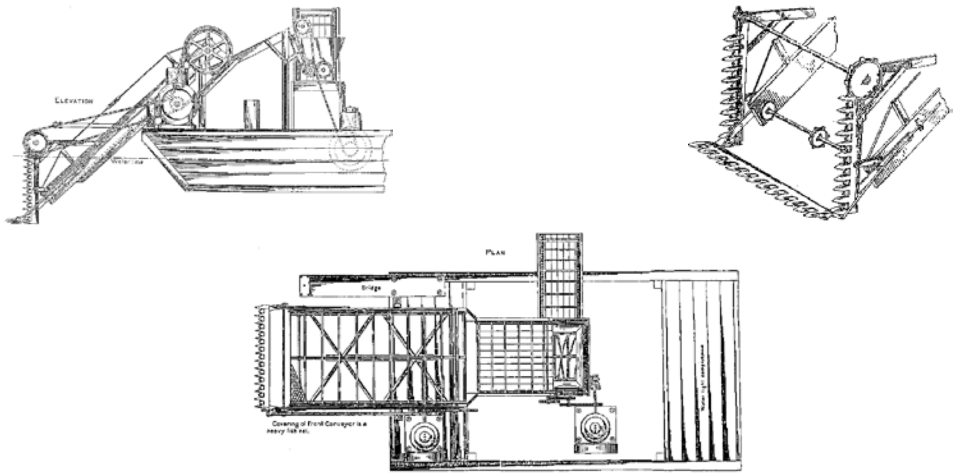


Figure 23 Harvesting mechanism of a kelp harvester. [L] side view of bow section; [R] Perspective view of the cutting apparatus; [C] top view of harvest arrangement

Suction Harvester

Developed around 1985 the Norwegian suction/cutter harvester is approximately 5m long, 2.2 m wide, and 2.3 m high. The vessel is propelled by water jets near the stern which allow for high manoeuvrability. A bladed impeller at the end of 25 cm diameter steel suction pipe simultaneously draws up and cuts shoots. The operator hydraulically controls lifting and lowering of the suction head. Water and cut shoots are discharged into a net bag of approximately 1 t capacity. The full bag is ejected and towed behind the vessel or moored together awaiting a collecting vessel. (Doty, et al., 1987)

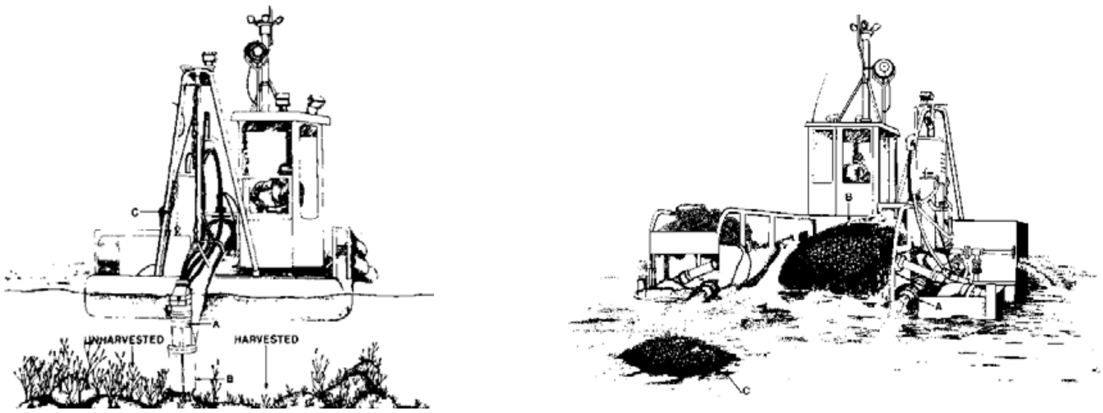


Figure 24 Front and rear view of a Norwegian suction cutter Ascophyllum harvester

Pulling systems

Scoubidou

The scoubidou system is used for the commercial harvest of wild Laminaria digitata in France. It is a 2 to 4 meter long steel bar with a spiral curved iron hook or sickle at the end which is suspended from a hydraulic arm mounted on a boat. It is lowered into the thickest part of the Laminaria digitata forests and then rotated or twisted, gathering the stipes, one could make a similarity with spaghetti on a fork. The hook is winched inboard using the hydraulic arm, and the plants are stored on board. The scoubidou can pull up about 10 kg per extraction, which takes about 30 seconds. Using this method harvests averaged 1.5 to 2 tons wet weight per boat per day. (Seaweed Industry Association, 2014)

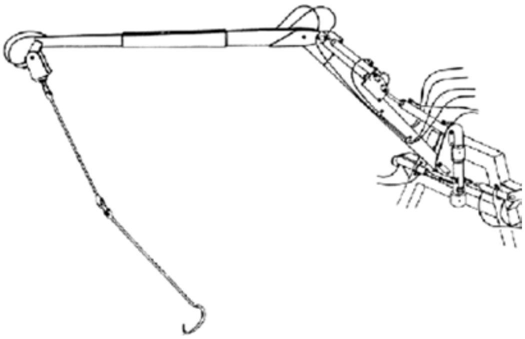


Figure 25 Scoubidou harvesting system

Rake

Figure 26 Seaweed Dredge

The Icelandic company Thorverk uses a coaster equipped with a large rake to harvest natural fields of Laminaria digitata. As can be seen in figure 26 the rake is attached to a crane on the side of the vessel. The forward movement of the vessel causes the rake to get stuck underneath the fronds and thus is pulls out the entire frond loosening the holdfast.

Weed harvesters

There are a multitude of aquatic weed harvester designs. These is one design in particular that differs a lot from the above mentioned systems and could be worthwhile to investigate as an alternative. The Versi-Dredge from IMS dredgers is normally used for dredging in canals, lakes, and marinas where maneuverability in confined areas is an issue. By interchanging it regular cutter head with the weed master cutting head it converts to a weed harvester. The Weedmaster has been designed to work in several types of aquatic plants including: floating vegetation such as hyacinths, submerged vegetation such as milfoil and hydrilla, and emergent / rooted vegetation such as cattails and reeds.

Most weed harvesters cut the weeds down to a max depth of 6 ft. (1.8m) and store them in a hopper which must be periodically emptied on shore. This requires unloading barges or pier / shore conveyors which increase labor and diesel fuel costs. The Weedmaster is much more efficient because it chops the weeds into 3-5 inch (76-127mm) pieces and pumps them to the shore, up to 1km away, using the dredge pump.

This system could provide multiple solutions to the design problem. The high seasonality of the seaweed farm only requires the harvesting system one month of the year. The costs of a conversion are in this case much lower than a complete new vessel.

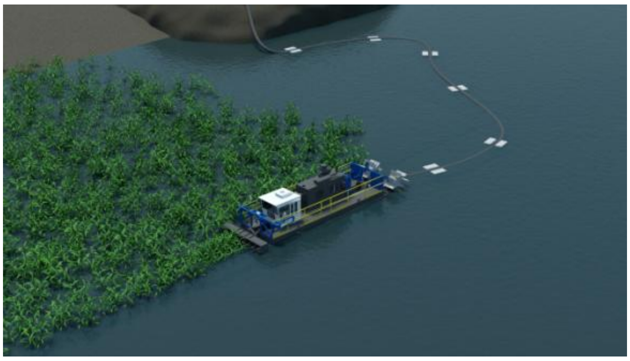


Figure 27 IMS Versi dredge in combination with weedmaster (IPS, 2014)

Next to the weed harvester there have been several concept designs by different organizations. Though these may give hints on future harvesting designs these are often more of an artist impression than a design. Other sources of input for the various solutions would come from other industries such as farming, dredging, oil recovery and aquaculture industries.

6.2.3 Conceptual Ideas

The harvest of seaweed has spiked interest in the last years resulting in several conceptual designs. ECN has come up with a netting system submerged from floating flexible tubes (Lenstra, 2012). The floating tubes form lanes that can be followed by a harvester. Similar to a combine harvester it discharges the yielded produce in a separate transport vessel sailing along the harvester (figure 28).

OceanFuel is a company involved in an international program to aid the development of advanced technical textiles in order to demonstrate the technical and economic feasibility of open sea cultivation. In their brochure they describe a multi-layered harvesting system with a ROV-like suction device that is able to harvest multiple layers with different species year round (OceanFuel, 2012). Though the use of multi layered columns is highly debatable do to the severe lack of sunlight due to intensive cultivation in the top layers (pers. Comm. W. Brandenburg) The Idea of a remote operated harvesting system might prove valuable.

Wärtsilä is a global leader in complete lifecycle power solutions for the marine and energy markets. The company has designed ship concepts to envision vessels that could feature in three different scenarios presented in the company’s Shipping Scenarios 2030 published in the autumn of 2010. In one of their scenarios, the Open Oceans scenario, climate change is perceived as an opportunity to develop sustainable solutions, including the harvest of seaweed. Their design involves an autonomous sailing harvester that can load and offload barges that can be sailed to production facilities ashore.

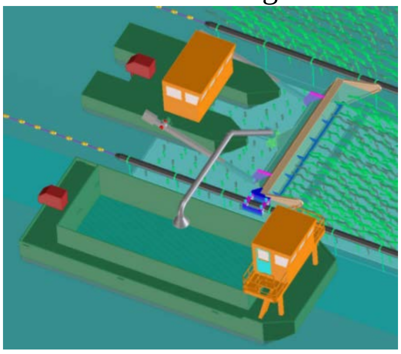


Figure 28 Concept by ECN

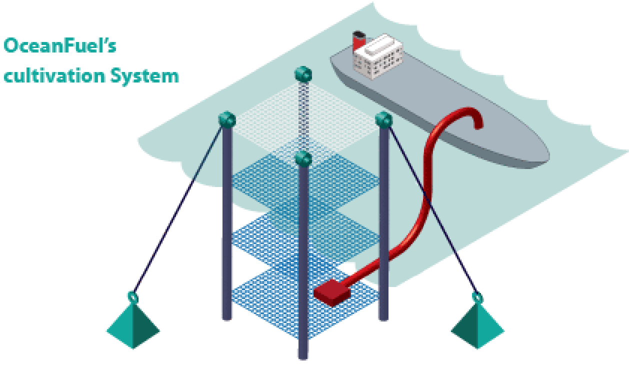


Figure 29 Ocean fuel Concept

Figure 30 Wärtsilä’s Algae harvester

6.2.4 Patent exploration

Another good way to gather information on harvesting systems is the exploration for patents in various patent databases. A patent search has been carried out to see what technology is already part of intellectual property, in addition this would later define the novelty of the idea.

The patent search was carried out by M. Klapwijk and M. Slagmolen, two honors students from the TU Delft, and later verified by MTI's IP department. Two programs where used to search for patents. The program Espacenet (Espacenet, 2014), allows searching for patents, without having to pay for a license. This is made it an easily accessible tool to allow for initial searches. At a later stage the program Orbit was used to find patents (Orbit, 2013). Orbit offers more options to search, e.g. the possibility to search for similar patents. This made it possible to get a lot of patents concerning the same subject quickly. Nearly all patents could be found in both databases.

An initial search resulted in a list of 89 patents concerning cultivation of seaweed. This were patents concerning seaweed harvesting, planting, process technology and complete integrated systems. From this list the relevant patents have been determined, resulting in 20 relevant patents concerning harvesting and cultivation platforms.

The history of harvesters is backed up in the patent database, with the first seaweed harvesting patents are published from up to a hundred years ago. Older patents refer to harvesters to remove unwanted seaweed from the surface of the water. Most of the patents are found in South-Korean, Chinese or Japanese databases. The relevant patents have been integrated in the morphological overviews. The list of patents can be found in Appendix H.

6.3 Gathering information on Cultivation Substrates

6.3.1 Confined waters

As explained in the introduction most cultivation is done in confined waters. The nature of these systems are low tech, and usually do not need to withstand a lot of forces from the ocean.

Kelp rafts

Traditionally, in Asia, kelp (Kombu or Lamaria Japonica) was harvested from natural beds in South Korea and Japan. The naturally growing plants grow biennial and could be harvested after 20 months. Hooks with poles where used to gather the seaweed by twisting it and removing it from the bottom. With a growing demand, around the 1960s attempt where made to develop artificial cultivation methods, however the biennial cycle made production costs too high. In the 1950s forced cultivation was developed and in the 1970s it made its way to Japan, reducing the cultivation period to one year.

There are two basic types of rafts where the young sporelings are attached to before going to sea (Tseng, 1987). The first type is called single-rope or hanging-kelp rope rafts. It consists of a floating line kept buoyant with several floats fixed every 2-3m. each end is anchored with a wooden peg, driven in to the sea bottom. At every 50 cm ropes with young sporelings are attached which are roughly 2m long and held down with a weight. The ropes are laid out roughly 10m apart to allow passage of small boats.

The second type is often referred to as double raft or horizontal line raft. Here three long ropes with floats attached are laid out parallel, about 5m apart. Short ropes with young sporophytes are tied across two ropes so that the ropes are more or less horizontal. This arrangement allows a better light exposure for each sporophyte, in comparison with vertical lines. Which increases overall growth rate.

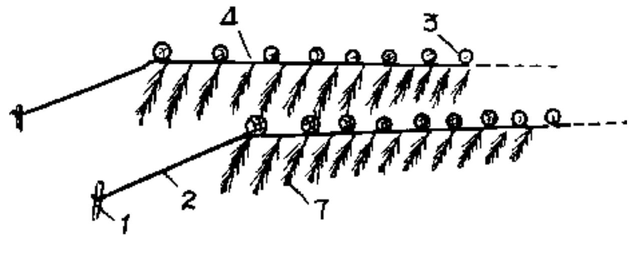


Figure 31 Two basic single line hanging kelp cultivation methods (Tseng, 1987)
1. Wooden peg (anchor) **2. Anchor line**
3. Float **4. Floating Line**
7. Vertical line with sporophyte and weight

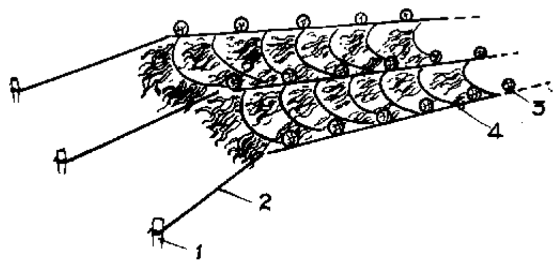


Figure 32 Double line floating rafts (Tseng, 1987)
1. Wooden peg (anchor) **2. Anchor line**
3. Float **4. Floating Line**

Nets

Nori or Porphyra has a different cultivation method. Although the aim is to cultivate brown seaweeds, a lot can be learned from the way Nori is cultivated. Mollusk shells are deliberately placed underneath existing Porphyra, which spores settles on the shells. These spores develop another form of algae which settle into the surface of the shell; also called the conchocelis stage. Seasonal changes make these algae form their own spores and these develop into Porphyra or Nori. During this period nets are placed above the mollusk fore the sporophytes to attach to. The nets are placed in intertidal zones, where they are left above the water for several hours each day. Though Nori can survive this dry period, its pests cannot and usually die

Figure 33 Net cultivation of Porphyra (McHugh, 2003)

Ponds

Some seaweeds, like those used to produce agars are cultivated in ponds. It is less labour intensive than rope farming and has been quite successful. Ponds are normally not larger than one hectare. Pieces of fresh seaweed are scattered into the ponds evenly and allowed to sink to the bottom. Since the seaweeds are not attached a pond should preferably be in a calm area with little winds and current. Ponds need access to both fresh and salt water so that the salinity can be adjusted. The water is usually changed every 2-3 days, often done through tidal flows with gates to control the flow. A pond is a method that could be artificially copied offshore in the use of floating vessels or containers.

6.3.1 Offshore

Concepts

Ever since the start of the Marine Biomass Program the idea of large scale offshore farms have challenged engineers and designers to develop a safe and stable platform to cultivate seaweeds on. In Appendix I a few of these designs are presented with a short description on their origin and how they are supposed to work.

Prototypes

The step from the drawing board to the field usually takes a while. Construction offshore is expensive and difficult. The first prototypes where part of the Marine Biomass Program. A total of three prototypes where made with various results. Though the seaweed was seen to be growing in offshore conditions, there were often external factors that affected the success of the prototypes. While the prototype was able to withstand a severe strorm, it was detected that the seaweed could not and had been ripped off.

Figure 34 Illustration from a prototype in the Marine Biomass Program (Popular Science, 1981)

Looking at the Northsea, research started in the mid-1990s where scientists at the Alfred Wegener Institute for Polar and Marine Research did several experiments with different offshore farm layouts, both investigating hydrodynamic forces of offshore cultivated Laminaria (Buck & Buchholz, 2005), as well as tests and developments of new system designs (Buck & Buchholz, 2004).

Part off the research was also a system test with various configurations in the German North Sea area near Helgoland. Part of these test were based on existing techniques: long line systems, ladder constructions and a Grid design, yet they also tested a new design named the offshore-ring. In their experiments the ring was deemed superior to the other designs based on rough weather resistance and ease of handling. Though their system worked, it must be said that there were problems with the designs of the comparative system as well as high costs for both construction and handling of the system itself.

In the Netherlands there has also been an increased interest in offshore seaweed cultivation along the Dutch coastline.

Several test modules have been launched in the past years to investigate the possibilities to cultivate Dutch seaweed. In March 2012 Ecofys, in collaboration with ECN and several other partners in a consortium tested a netting system. The goal was to test the reliability of the system and verify whether it was possible to cultivate seaweed on the design at open sea. A lot was learned from the system and currently Ecofys joined Hortimare and ATO to setup the North Sea Farm foundation (stichting de Noordzee boerderij).

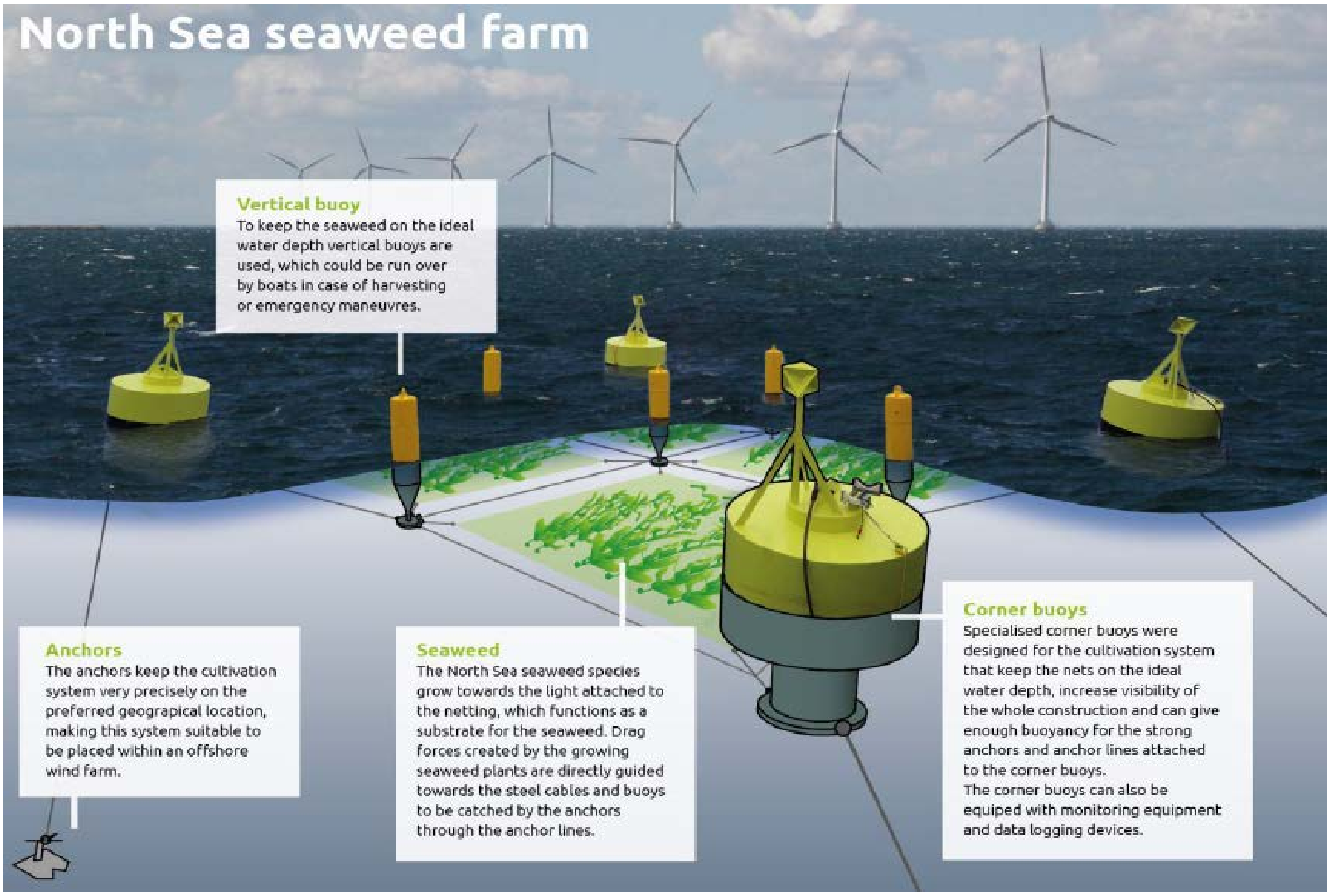


Figure 35 Info graphic of the pilot project from Ecofys (Ecofys, 2009)

Hortimare has been mentioned as a company before, and they also tested their H-frame design in the North Sea at the same time as Ecofys. Their design consisted of several ‘refloatable’ H-frames that would act as floaters between a set of lines. Holes and compartments in the H-frames would make it possible for the frames to lower itself in case of increased wave heights due to severe weather. An illustration of their system can be found in Figure 13 on page 46.

Based on all the various past projects, each design has its advantages and flaws. There is no uniform consensus on what seems to be the best approach when designing a new farm. And even now new opportunities are being looked at, such as the use of advanced fabrics as substrate (At~Sea project), or the use of membrane enclosures such as used in NASA’s omega project (NASA, 2012). Integrating the substrate design with the harvester design appears to be a valid point of research based on most of the project reports. Most of the ideas used are dissected in the various morphological overviews that follow in chapter 6.5.

6.4 Brainstorm

On the 30th of April 2014 a brainstorm session was held at MTI Holland BV to develop ideas and consider design options for a seaweed cultivation platform. During the meeting the following participants where present:

Name	Company	Function
Prof. J.J. Hopman	TU Delft	Professor Ship Design
Maarten Klapwijk	TU Delft	Student
Jochem Sijl	TU Delft	Graduate student
Job Schippers	Hortimare	Director
Mark Aelmans	MTI Holland B.V.	Project manager R&D
Stephan Hannot	MTI Holland B.V.	Senior project manager R&D
Vincent van Dijk	MTI Holland B.V.	Project manager R&D

The session was divided in two parts. The first part of the session consisted of an introduction into the seaweed market and a problem definition followed by a creative thinking session. During this session, participation were asked to present ideas for equipment/ work procedures in four different categories: farm infrastructure, seeding/deployment, harvesting and transport. The ideas were discussed afterwards and new ideas and combinations arose from the discussion.

After the creative thinking session several existing ideas were presented including concept designs for seaweed farms and seaweed harvesters. A brief concept, already formed in the previous months, was discussed and bringing forward the possibilities and challenges for this concept and within the business case.

Universal agreement was reached in the following:

- Due to the seasonality of the cultivation of seaweed and the relatively small quantities of a farm plot, a solution should be in the form of a cultivation module other than a specialized cultivation vessel.
- The concept presented could prove a viable working concept.
- Ideas presented during the creative thinking session could provide extra benefits for the concept design and should be taken in to consideration.

The Ideas from the session are summarized in Appendix H.

6.5 Morphological overview

To structure the information from the brainstorm session and other ideas that could solve some of the design processes a morphological overview is made. The morphological chart helps to identify novel combinations of elements and components. The main aim of this method is to widen the search for possible new solutions.

In order to present the various design decisions in a more legible way three separate Morphological overviews have been made. Although this increases the possible design choices, a clear distinction can be made on the level of decision making. The overviews are separated as follows:

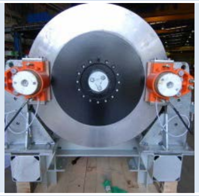
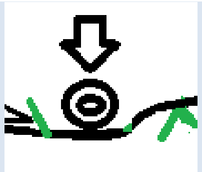
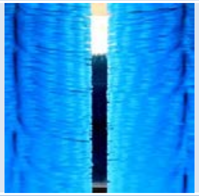
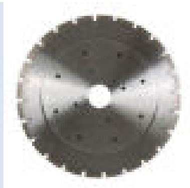
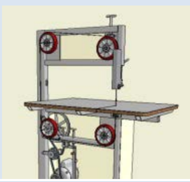
- **Overall design decisions.** These are decisions based on the generic description of the system. These can be found in the parent diagrams of the process chain. Choices are basic interpretations of solutions to the complete system, such as which carrier system and layout to use, as well as the seeding or deployment mechanism.

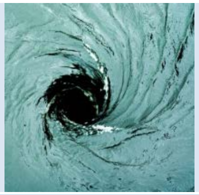
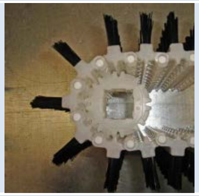
- **Harvesting system.** The harvesting overview present overall solutions for the functions as presented in parent diagram 5.1.1 of the process drawings. Examples are methods to adjust the harvesting device to the line and ways to remove the seaweed from the lines

- **Carrier system.** The carrier system presents an overview of solutions based on the different functions related to the carrier structure. Since these are not mentioned earlier the following overview presents the following decisions: Anchoring, Mooring, Mooring configurations, Substrate separation, floatation, attachment and deployment.

The overviews are presented in with illustration as well as short descriptions. Due to the scope assignment the harvester overview is presented on the next two pages. The other two overviews can be found in Appendix K.

Table 15 Morphological overview harvesting systems

Node	Process	A	B	C	D	E	F
A511	Approach seaweed with removal system (also main method to travel along/through seaweed)						
		Winch	Grip	Forward motion	Thrust		
A512	Adjust removal system to harvest position						
		Motion Compensated Line	Dynamic hydraulics	Propulsion	Static Shipboard crane	guide rail on reel or substrate	
A513	Lift / Queue or Collect Seaweed						
		Push down substrate	Positive suction	Brushes	Air bubbles	Roller	
A514	Remove Seaweed from carrier						
		Water jets	Hor. Rolling blades (lawnmower)	H. spinning blades	V. spinning cord (trimmer)	Reciprocating blade	Cable stripper
							
		Band saw	Laser	Strong suction	Pull with brushes	Pull with rollers	

A515	Collect removed seaweed						
		Suction	Forward motion	Brushes	Rakes	Collection tray	Water Pressure
A516	Transport						
		Archimedes wheel	Conveyor belt	Brushes	Pump		
A521	Sift/ Seperate						
		Sifting belt	Sifting drum	Centrifuge			
A522	Clean						
		Water Wash	Steam				
A521	Inspect / monitor						
		Visual	Moisture sensors	Flow sensors			

6.5.1 Initial Evaluation

Selecting solution variants

Now that all combination of ideas are captured, it is clear that the number of solutions are unattainable. Therefore the number of solutions need to be reduced, without eliminating valuable working principles. While there isn't a safe procedure, the use of a systematic and verifiable selection greatly facilitates the choice of promising solutions from a great number of proposals.

Due to the complexity of the carrier system it is decided that selection will not be done on the carrier systems. The ideas that evolve from the selection could use a variety of different carrier systems. It is determined that it will act as guidance.

Based on the information from *Engineering Design* (Pahl, et al., 2007) the selection procedure consists of two steps, elimination and preference. First, all unsuitable proposals are to be eliminated. If there are still too many solutions, those solutions that are patently better should have preference.

Since there are a lot of solution proposals a selection chart has been made. Based on *Engineering Design* solutions should only been pursued if the following criteria are met:

The solution should:

- be compatible with the overall task and with one another (Criterion A);
- fulfil the demands of the requirements list (Criterion B);
- be realizable in respect of performance, layout, etc. (Criterion C);
- be expected to be within permissible costs (Criterion D).

Unsuitable solutions are eliminated in accordance with these four criteria applied in the above sequence. Since there were still too many solutions two additional criteria were used:

The solution should:

- Be preferred in the industry (Criterion E);
- Be constructed or made of proven technology (Criterion F).

These added criteria eliminated quite a few solution, yet still leaving a lot of possible opportunities available. The selection charts can be found in the Appendix M.

Evaluation of systems

Based on the selection charts the following solutions have been selected to make combinations from:

Table 16 Solution selection system design

No.	Function	Options
1	Carrier system	A (Lines); B (Netting)
2	Layout	A (Rectangular patches); D (Single lines)
3	Collection and storage	A (Drums); F (Hold)
4	Transport system	A (Ship's Hold); B(Tug and Tow)
5	Seeding mechanism	F (Nursery)
6	Deployment	B (Towing out); C (attach a line)
7	Harvesting arrangement	A (specialized vessel); B (Harvesting with module)
8	Harvesting position	All; Above and below water and on deck
9	System position	A (Sail over); B (remote device); D(Sail underneath)

Table 17 Solution selection harvest design

No.	Function	Options
1	Approach Seaweed	A (Winches); C(Forward motion)
2	Adjust removal system	D (Crane); E(Guidance system)
3	Lift/Queue/Collect	C (Roller); E (brushes)
4	Remove	E (reciprocating blades); G (band saw)
5	Collect	B (Forward motion); D (Rakes); E (collecting tray); F (Water pressure)
6	Transport	B (conveyor)
7	Filter	A (sifting Belt)
8	Clean	A (water)
9	Inspect	To be determined later (out of scope)

Even though the selection is based on a set of criteria, it doesn't mean that the list is final. Improvements in technology and combination of ideas using different options might be possible to come up with a better overall design.

The next step will be to generate concepts based on the selection, which will be done in chapter 6.6.

6.6 Concept designs and evaluation

Now that the selection of options has been narrowed down it is time to think in concepts. The reason not all methods have been eliminated to a single option is to evaluate combinations of functions and systems better.

With regards to the concept it is important to keep the following in mind (Cross, 2008):

- Only combine compatible sub functions.
- Only pursue solutions that meet the demands of the requirements list and look like falling within the proposed budget
- Concentrate on promising combinations and establish why these should be preferred above the rest.

To evaluate the design concepts they are evaluated using the weighted objectives method, based on an overall value per design concept. The Weighted Objective Method assigns scores to the degree to which a design alternative satisfies a criterion. However, the criteria that are used to evaluate the design alternatives might differ in their importance. For example, the 'cost price' can be of less importance than 'appealing aesthetics'. The evaluation of the weights is done in chapter 6.5.3.

6.6.1 Concept 1: Sailing underneath the seaweed patches

The first idea was to sail underneath the seaweed in order to harvest and deploy it. The idea to sail underneath or above the substrate is advantageous to sailing parallel to a substrate, because it doesn't limit the area of the substrate and there is no requirement for additional space in between different seaweed patches to sail through.

The decision to sail underneath the substrate as opposed to sailing underneath the substrate can be is based on the following pros and cons:

Pro's from sailing underneath the substrate:

- More controllable cutting process in terms of guidance and visibility
- Easier to transport the seaweed to its containment on board or on another vessel. (Under water requires pumps)
- Avoid complexities with regards to propulsion and possible damage to substrate and yield
- Easier to make as conversion of smaller vessels, pontoons.
- Avoid draft limitations

Cons

- Could prove more difficult to Scale up the process
- Flexibility of working with different systems (limited to lines, or small patches of nets/sheets)
- Need to lift the seaweed and position the harvester underneath the lines calls for additional time
- Increased tension on the lines (could be controllable)
- Demands for a low platform

The following choices have been made with regards to the morphological overviews:

Table 18 Selected System options concept 1

No.	Challenge	Options
1	Carrier system	Lines
2	Layout	Patches of Lines
3	Collection and storage	Hold
4	Transport system	Ship's Hold
5	Seeding mechanism	Nursery
6	Deployment	Attach a line
7	Harvesting arrangement	Could be both (specialized vessel or Harvesting with module)
8	Harvesting position	On deck
9	System position	Sail underneath

Table 19 Selected Harvest systems concept 1

No.	Function	Options
1	Approach Seaweed	Forward motion
2	Adjust removal system	Guidance system
3	Lift/Queue/Collect	Roller (Low necessity due to working on deck)
4	Remove	Not specified
5	Collect	collecting tray
6	Transport	conveyor
7	Filter	sifting Belt
8	Clean	water
9	Inspect	To be determined later (out of scope)

Variation A: Sailing underneath with a workboat

To sail efficiently underneath the seaweed farm, the vessel would need a large deck surface that is easily accessible from both the bow and the stern. The vessel should have good manoeuvrability to control the speed and stop and turn efficiently if required. The choice would be between a pontoon with a pushboat; a workboat or multicat; or an offshore supply vessel. Due to the scale of the farm and the manoeuvre capabilities it is decided to choose a multicat as work platform for the harvesting equipment.

The layout of the farm also needs to suit the use of a platform sailing underneath. Ultimately the vessel should be able to sail under the farm without facing any obstacles in the way. The use of solid floaters every 20m like the H-beam design would severely hinder the platform from sailing underneath. To avoid this there are several trains of thought:

- By using pre-tensioned lines the distance between floats could be increased. The tension ensures that the lines will stay close to the surface.
- The use of easily removable floaters. If the floaters could be temporarily removed from the ropes the lines would be freely accessible
- Liftable floats, that can easily be picked up from the surface and could be handled on board.

For the first variation it has been decided to use semi-flexible liftable floaters. The design is envisioned in figure 36.

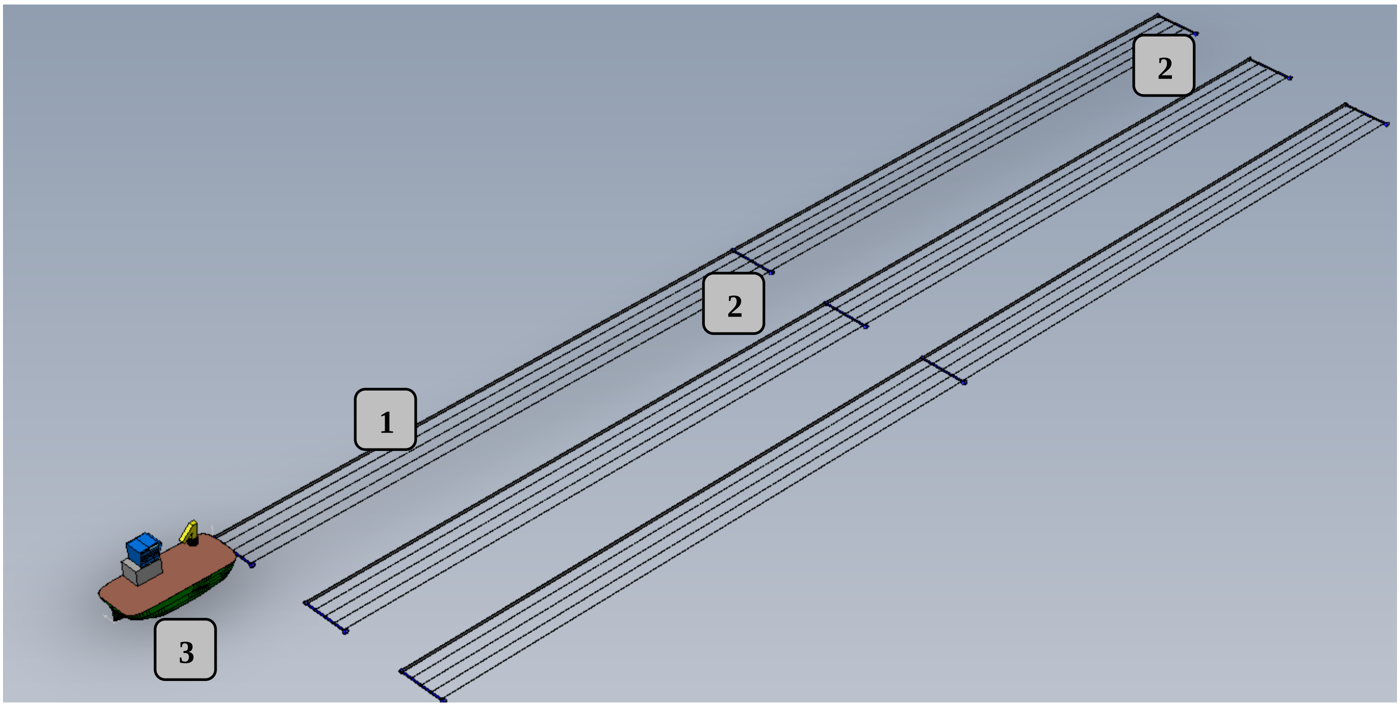


Figure 36 3D Drawing of variation A (1 Main tube, 2 separation floats, 3 workboat)

The farm patch main features:

The base of the patch consists of a flexible PE tube that is anchored on both sides. This design is inspired by the smart-unit system of the Norwegian company smart-farm, which uses a PE tube for the production of mussel spat. This system has proven to be reliable in harsh environments and severe weather (Smart Farm AS, 2014).

Attached to the main tube are semi-flexible PE floats that separate the lines through inserts in the floats. The floats can pivot around the main float to reduce rigidity of the farm. The floats are relatively thin, but on the outer end of the float is an enlarged compartment that provides additional buoyancy and ballast at the same time. This helps to avoid twist in the line and prevent the floats from tipping over.

As the vessel approaches the farm it needs to align itself with the first floater. It would than need to pull/lift the lines on deck. This could either be a complete lift or a partial lift with hinged floaters. The difference illustrated in the next pictures.

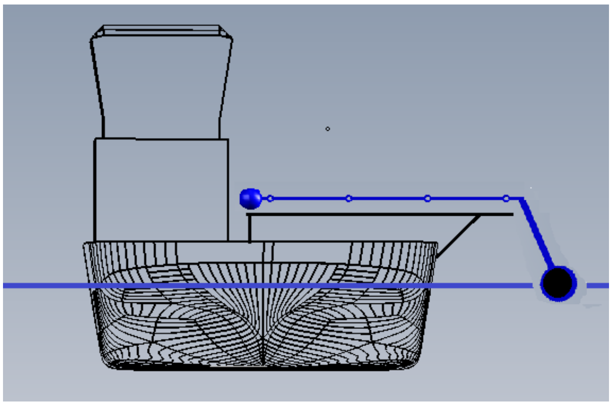


Figure 37 Example of hinged floats

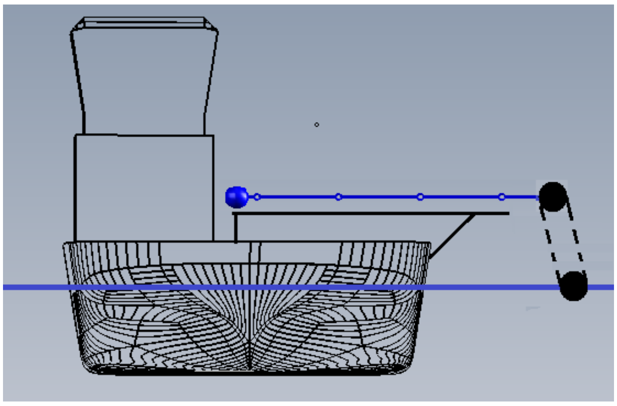


Figure 38 Example of liftable floater

Once the lines are lifted the vessel can move forwards along the main tube. If needed, the tube can also be used as guidance to keep a set distance between the workboat and the tube. Additionally it could also be used to move forward along the lines. A harvesting system on board can remove the seaweed from the lines and transport it to a layby vessel or a barge alongside the workboat.

Variation B: Reeling in the lines

Variation B is based on a different approach. It still uses a few of the proposed solutions of the beginning of variation A, yet the main difference is that the lines will be removed during harvesting, benefitting deployment.

The system will be explained through rough sketches in figure 39.

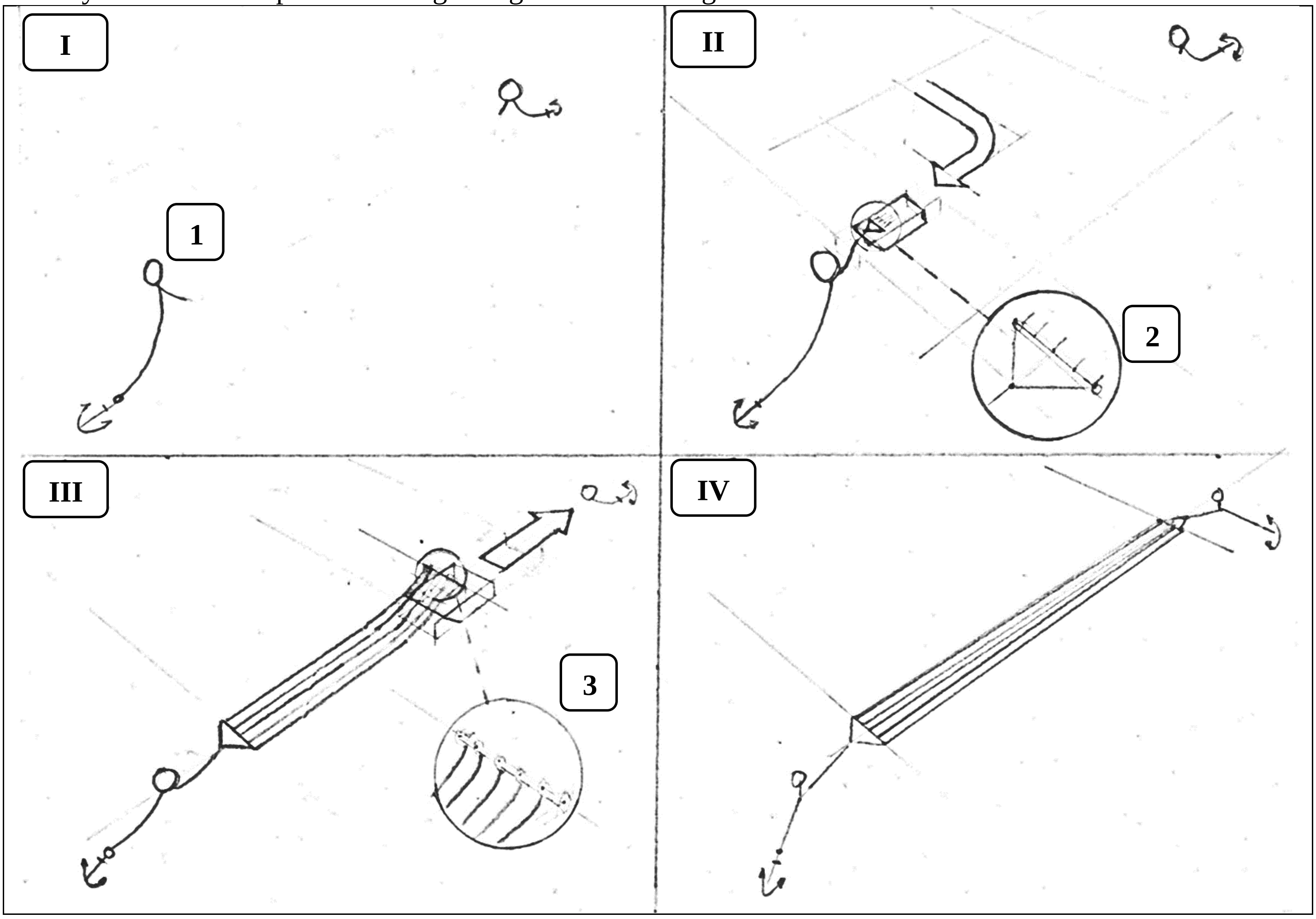


Figure 39 Sketches illustrating deployment of variation B

The initial situation (phase I) consist of anchored floats (1) moored at a set distance apart. The farm will be tensioned between the floats using the displacement of the floats. The floats could either be permanently installed, or deployed several weeks before deployment of the young sporophytes and removed after harvest.

A workboat/pontoon approaches (phase II) and attaches a spreader to the float. Attached to the spreader are substrate lines with young sporophytes, that are attached to a set of reels containing the remainder of the patch lines. Depending on the length of the patches the reels could be used for multiple patches. If required it is possible to have preinstalled spreader floats on the lines to separate the lines. This would however increase the harvesting complexity.

The vessel will sail away towards the opposite float and deploy the substrate by laying out the reels (Phase III).

Once the opposite float is reached a final spreader is released and attached to the float (Phase IV)

Conclusions

Both systems could have trouble with additional buoyancy added to the line system

Focus of the concepts is based on accessibility and line control, less on the harvesting system particulars.

6.6.2 Concept 2 and variations: using a fixed position and remote harvesting mechanism

This concept variation is based on the use of the carrier platform as an integral part of the farm. The idea is to deploy a harvesting mechanism from the ship to connect to the farm and use the floater as guidance for harvesting. This mechanism could be modular or even containerized to increase flexibility of use on a multitude of vessels/pontoons. Details are to be found in appendix O.

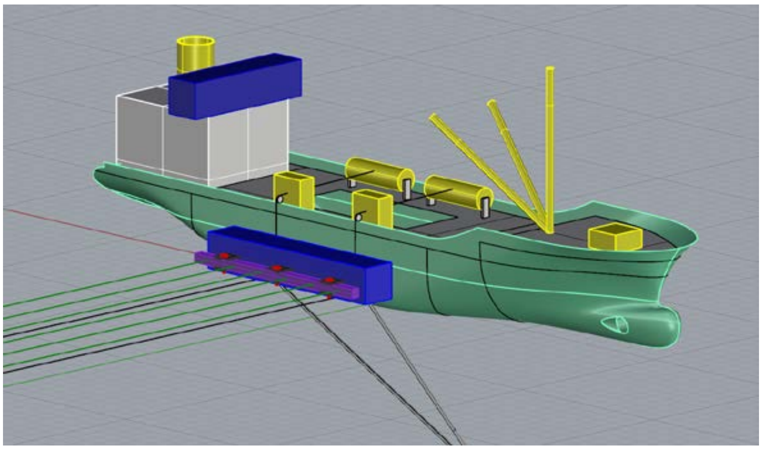


Figure 40 Impression Concept 2 Variation A

Table 20 Selected system options concept 2

No.	Challenge	Options
1	Carrier system	Lines
2	Layout	Patches of lines
3	Collection and storage	Hold
4	Transport system	Ship's Hold
5	Seeding mechanism	Nursery
6	Deployment	Attach a line
7	Harvesting arrangement	Harvesting with module
8	Harvesting position	Above water
9	System position	Remote

Table 21 Selected Harvest systems concept 2

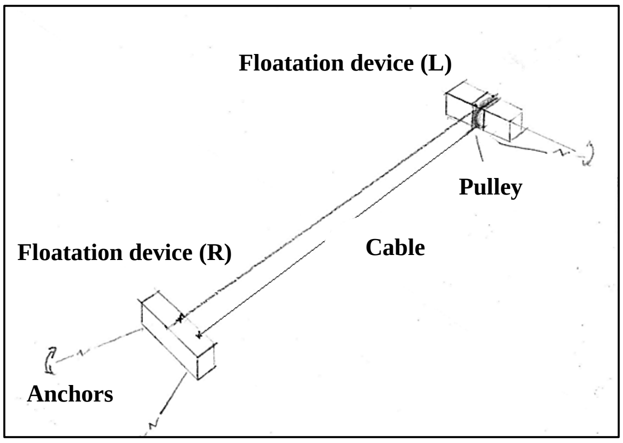
No.	Challenge	Options
1	Approach Seaweed	Winches
2	Adjust removal system	Guidance
3	Lift/Queue/Collect	Out of scope
4	Remove	Out of scope
5	Collect	Water pressure and conveyor
6	Transport	Conveyor
7	Filter	Sifting belt
8	Clean	Water
9	Inspect	To be determined later (out of scope)

Variation A.

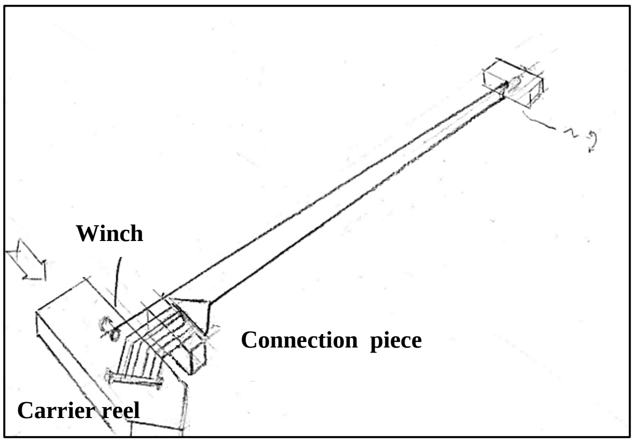
The harvest system is placed on board. It is partly based on concept 1 variation B

When the vessel approaches the farm an arm can be picked up from the floater containing the substrate line. This arm is connected to the winches and the farm is emptied

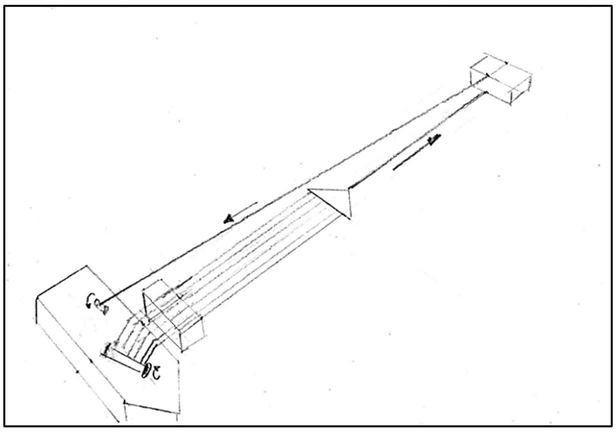
The solution is a modular work platform and a carrier construction. The platform is able to connect the substrate including the developed substrate to an anchoring structure. Working with patches increases flexibility around the salmon pens and in confined locations within a fjord. Once again the system is explained in a number of steps.

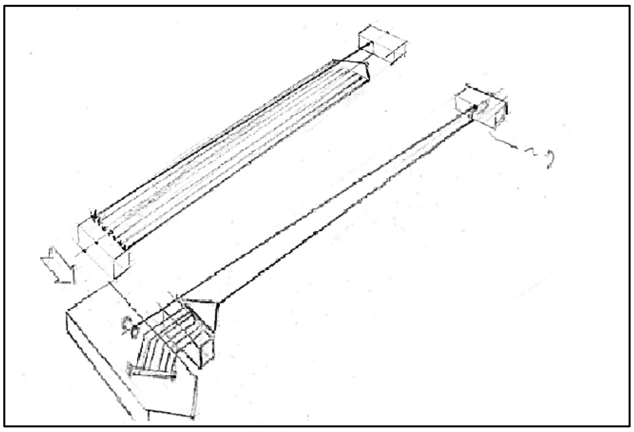


Two Anchor points are constructed and fitted with floatation devices. The floatation device on the left bares room for guidance of carrier lines and a connection point for the cable going across. The floatation device on the right side consists of a pulley system for the cable.



A work platform sails across the left side floatation device and moors itself. It deploys a connection piece fitted with the ends of several of the carrier lines, wrapped with seaweed substrate lines on a row. The carrier lines are supplied from a reel onboard the platform. The connection piece is attached to one end of the cable. The other end of the cable is attached to a winch.





The carrier lines are pulled through the water towards the right side floatation device using the winch. A tensioning system on the reel ensures a constant tension on the substrate lines.

The float reaches the right side and is locked in place via a guidance system. The carrier lines are attached to the left side floatation device and the cable is released from the whinch. The constant tension between the floatation devices ensures the level and position of the substratelines. The harvesting will be done in the opposite order with a seperation system attached to the reels.

Variation B. external module

Instead of variation A the harvester consists of a module that can be lowered on to the floater and used to harvest the farm. This will safe deck space and line tension, since the lines with seaweed do not have to be carried on board. It does increase the complexity of the operation. This system bears close resemblance with the modular oil removal systems used by Koseq (Koseq, 2015). These systems are fitted into one or multiple containers to be shipped where necessary and mounted within 12 hours. The system can be used on various vessel classes, from Platform Support Vessels, Anchor Handling Tugs, Motor Tankers and Dredgers. This amount of flexibility will reduce the investment costs and increases flexibility.

Figure 41 Illustration of the Koseq Modular Crane Pedestal System (Koseq,2015)

Similar to the yellow rigid oil boom in figure 41 a modular harvesting system could be deployed on the floatation devices. And be coupled onto the floaters. The design would contain a drum to roll-in the lines and an additional winch to extract the lines during deployment. A movable cutting installation would be used to remove the seaweed before removal.

6.6.3 Weighing the concepts

To evaluate the 4 different concepts the concepts are weighed based on a number of selection criteria. The compatibility with each requirement is a rating between 1 and 10. By adding weights to these criteria a total number of points can be determined, where the concept with the highest amount of points wins. Furthermore a number of threshold values are used that function as a minimum criteria that needs to be met. An example of these threshold values could be the maximum fabrication costs, or a minimum expected harvesting speed.

Selection criteria

The criteria are mostly based on the design objectives and requirements as far as they can be assessed in this stage. The selected criteria are appointed weights according their significance in the evaluation. To determine the weight factor, the criteria are judged in pairs. Each of the weights is based on a total sum appointed to the pairs, and on the total sum of the weights being 100. To determine the amounts between pairs the trade-offs are discussed.

The concepts are judged on ten different criteria, of which the total of the weights is displayed in brackets.

Scalable (flexible) vs Optimized design (20 pts.)

Scalability, as a property of systems, is not easy to define and in any particular case it is necessary to define the specific requirements for scalability on those dimensions that are deemed important. In the case of seaweed cultivation, it is related to the increase of capacity of the system. In other words, is it possible to use the cultivation design for a demo size farm now, and use the same design at a commercial farm later? This is combined with the question whether production for such a system can increase by using existing fabrication yards while using available equipment?

This flexibility in production and design might increase development costs for the first periods and might decrease optimal performance for a single scale operation. Another approach would be to skip this phase and build a design that is specific for one task and one scale. This saves costs but reduces flexibility. In the diagrams below the relation between the criteria and the rating are illustrated. The threshold values are illustrated in red.

Scalability (flexible design)									
1	2	3	4	5	6	7	8	9	10
Manufacturing at 1 plant in the world with highly specific equipment. Changes in dimensions not possible.				Manufactoring at specialized yards and equipment suppliers. Changes in basic dimensions possible.				Manufactoring at every yard or supplier. Bare limits in dimensional scaling.	

Optimized design									
1	2	3	4	5	6	7	8	9	10
Optimized for species from an entire class.				Optimized for species of the same order or family				Optimized for species from the same genera or species.	

Both criteria are important in this phase of research. Since budgets are low, and the design should be a proof of concept the construction needs to be simple and must be built to be able to use on preferably one genera or family of species (e.g. the family *Laminariaceae*, containing the genera Saccharina and Laminaria).

Demand for larger harvesters could increase, once feasibility has been demonstrated, but it is possible that the design changes based on lessons learned. That is why scalability has a slightly lower preference than an optimized design, therefor the weights are set as 12 points for optimized design and 8 in scalability.

Durability vs Low capital costs (25 pts.)

Due to seasonality of the seaborne operations, and the small time window it creates it is critical that the equipment is reliable. Downtime, due to repairs, malfunction or maintenance, should be as low as possible. This can be reduced in the design phase, by assessing the possible risk of failure; in engineering by applying stringent standards with regard to calculations and proposed equipment; and throughout prototype testing, using experience from durability tests. Usually this is related to higher production costs with the use of higher material grades and/or increased material usage. As with most machines and especially prototypes there is a high failure rate in the infant stage of machinery with the chance of increased maintenance costs and/or down time. On the other hand the capital costs for the equipment should be low, to reduce initial investment. As this is also a critical point in the development it is hard to judge between the two. Low maintenance is weighed 15 points and low capital costs at 10, while its threshold value is 4, meaning that expected fabrication costs cannot exceed € 2,500,000.

Low Maintenance									
1	2	3	4	5	6	7	8	9	10
Every 200 tons. (every patch)				Every 4000 tons. (every trip)				Every 20000 tons (every harvest season)	

Low Capital Costs									
1	2	3	4	5	6	7	8	9	10
Expected prize € 10.000.000				Expected prize € 1.000.000				Expected prize € 100.000	

Harvest accuracy vs harvest speed (25 pts.)

Speed is an important factor to minimize operating hours and related costs. On the other hand, the fastest approach is usually not the most accurate. This accuracy can be related to the cutting mechanism, increasing the quality of the product after harvesting, or to the ability to manoeuver into position in order to continue with a next harvesting leg, or patch. Since the prototype is built to harvest one specific species the weight of accuracy is lower compared to speed. The weights appointed are 17 for speed and 8 for accuracy.

Accuracy									
1	2	3	4	5	6	7	8	9	10
30% Spillage				5% spillage				1% spillage	

Speed									
1	2	3	4	5	6	7	8	9	10
10t/hr			Treshold: 30t/hr	75 t/hr				500t/hr	

Low time to market vs product quality (optimized parameters) (10 pts.)

Low time to market (TTM) and product quality are often assumed as opposing attributes of a development process. TTM may be shortened by skipping steps of the development process, thus compromising product quality. Fortunately there is not a system readily available right now. This means that as a product pioneer the time to market is not of such great importance. Therefore the concept which might benefit more from required optimized parameters will have a higher weight factor. TTM are weighed 3, product quality 7.

Time to market									
1	2	3	4	5	6	7	8	9	10
10 Year				3 Year				1 Year	

Product quality									
1	2	3	4	5	6	7	8	9	10
Damaged torn fronds, lot of debris				Small cuts on fronds, slight fouling				Clean and clear of debris	

Safety vs Operational costs (20 pts.)

Though all the concepts might be engineered to operate safely at all times there are certain systems that will always have an inherent safety to them. Though these systems might be inherently safe, the operational costs to run the system might be higher. Since the time to operate is limited and the available personnel is costly and sparse, all injuries should be avoidable. Therefore the most inherently safe system would be weighed much higher than operational costs. Safety is weighed at 15 and operational costs at 5. As operational costs is a critical value for a possible buyer the threshold value is set at 5.

Safety									
1	2	3	4	5	6	7	8	9	10
1 month between lost time accidents				1 year between lost time accidents				10 years between time lost accidents	

Operational costs (20 days)									
1	2	3	4	5	6	7	8	9	10
€100.000/day				€20.000/day				€ 4.000/day	

Evaluation of the concepts

The evaluation of the concepts was done was done within MTI. Using the weight system the following grades are given to the concepts:

Table 22 Evaluation of the concepts

Concept		1				2			
Objectives	Weight	a		b		a		b	
Description		Underneath		With winches		harvest on board		harvest remote	
Scalability	8	6	48	7	56	7	56	6	48
Simplicity	12	5	60	8	96	6	72	5	60
Durability	15	4	60	6	90	5	75	7	105
Capital costs	10	4	40	6	60	6	60	7	70
Accuracy	8	6	48	7	56	7	56	8	64
Speed	17	6	102	8	136	7	119	7	119
TTM	3	7	21	7	21	5	15	6	18
Product quality	7	6	42	7	49	8	56	8	56
Safety	15	5	75	7	105	8	120	9	135
Operational Costs	5	6	30	5	25	8	40	7	35
Totals	100		526		694		669		710
Grade			**5,26**		**6,94**		**6,69**		**7,10**

Based on the rating, concept 2b has a slight advantage over concept 1b and 2a. Concept 1a is clearly not in favour. Its high expected capital costs due to the complexity of the layout of the farm and the vessel, are predicted to be over the threshold value.

6.6.4 Conclusion

Even though a pre-selection has been made based on the different selection criteria (see 6.4.2), it is still possible to develop a large number of solution concepts. In addition every concept could also be engineered differently. That is why the concepts are still at a relatively descriptive level before the second evaluation is done. This is also why the details of the harvest system on board are not presented yet.

With the weighting system it is possible to find the best solution between the concepts. Even though the system works it is difficult to add weights and evaluate the different objectives. This also may have resulted in relatively small differences between the scores. The highest scoring concept will be used and in the next section the system will be explained in more detail.

6.7 Concept details

The chosen concept is further developed and engineered to a certain degree. The details of the concept are described in three parts. It starts with the description on the design of the farm patch, followed by the design of the deployment and harvesting module and its working sequence is described last. The design will still be relatively abstract; due to the work required for the exploitation model a choice was made to prioritize the exploitation model and leave engineering of the design for future matters.

6.7.1 Patch Module

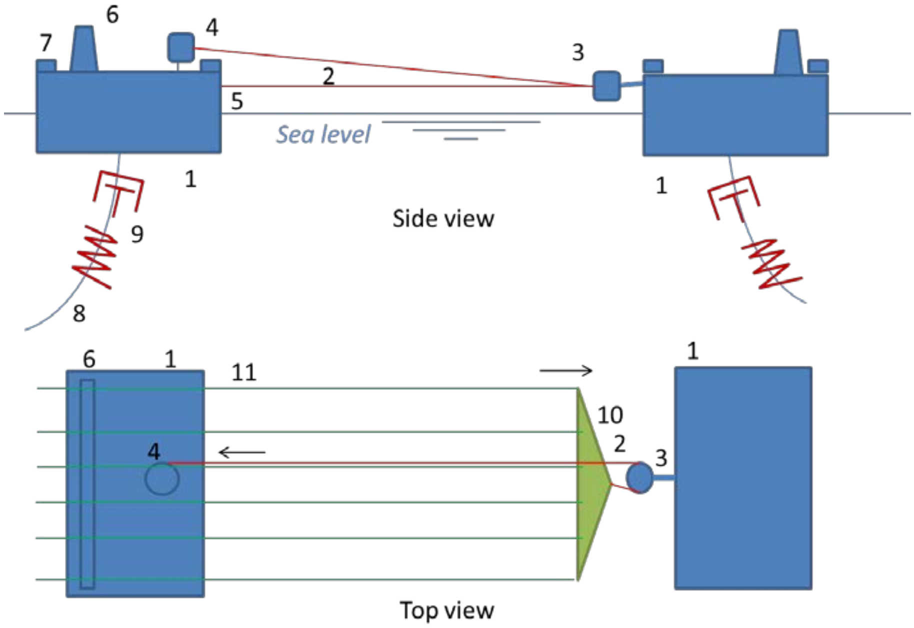


Figure 42 Schematic view of the module and floaters in a seaweed cultivation system.

All seaweed is grown just under the water line. This is done with a cultivation module consisting of two floaters (1), a floating spreader bracket (10) which the seaweed substrate (11) connects to and a movement system for moving the floating bracket between the first and second floaters for launching or harvesting the seaweed (figure 42). This movement system consists of a light weight nylon/dyneema rope (2) able to withstand the maximum expected resistance based on maximum expected current. This calculation can be found in chapter 7.4.2 and is dependent on the length of the line, number of lines and the density and size of the sporophytes (e.g. 6*100m lines Saccharina @ 2kts ≈ 7.2t /2 ≈ 3.6 t). The rope runs at one floater through a pulley (3) to be able to roll out the substrate from the same side as where it is harvested and deployed. The rope is made up of two parts, which are connected in the middle. Both ends of the ropes have been fitted with loops to attach the rope. Both ends have a small messenger line attached to the loop to be able to handle the lines. In the working situation this is explained in detail.

Each floater has an anchoring device which acts as a spring (8) and damping (9) system that compensates the wave and current forces. The floater without the pulley, here the one with the movement lines attached contains of a number of securing devised to attach two ropes to. This could be loose gear from lifting appliances or smit brackets used in salvage operations. Additionally, if required, a small drum (4) with enough capacity to store the amount of rope necessary for two lengths of farm length (12-16 mm rope) could be placed on the floater.

The floater without the pulley also contains a set of brackets (7) to attach the harvesting module to. The floater is designed to be able to carry the load of the harvesting module.

If necessary, a ballast mechanism could be installed allowing for it to be retracted further below the water surface in order to keep the structure and the seaweed plants safe under rough sea conditions. If necessary, the desired amount of modules can be assembled together into a large farm, with the required geometry for the site, into a farm site that can reach into hundreds of hectares.

6.7.2 Harvesting and deployment module

As described in 6.5.2. harvesting and deployment is done with an external module that is to be lowered at the side of a vessel (figure 43). This module consists of multiple winches, each with a cutting device and a collection system. The harvesting device is designed to be placed alongside the hull of a vessel, similar to a modular oil beam and its weight could either be carried by an on-board crane or it could be provided by the buoyancy of one of the floaters. If necessary, capacity could be increased by installing multiple modules on both sides of the vessel. Harvesting can be done very fast and with little to no manual labour, making it economically viable despite the short time span before deterioration of the seaweed.

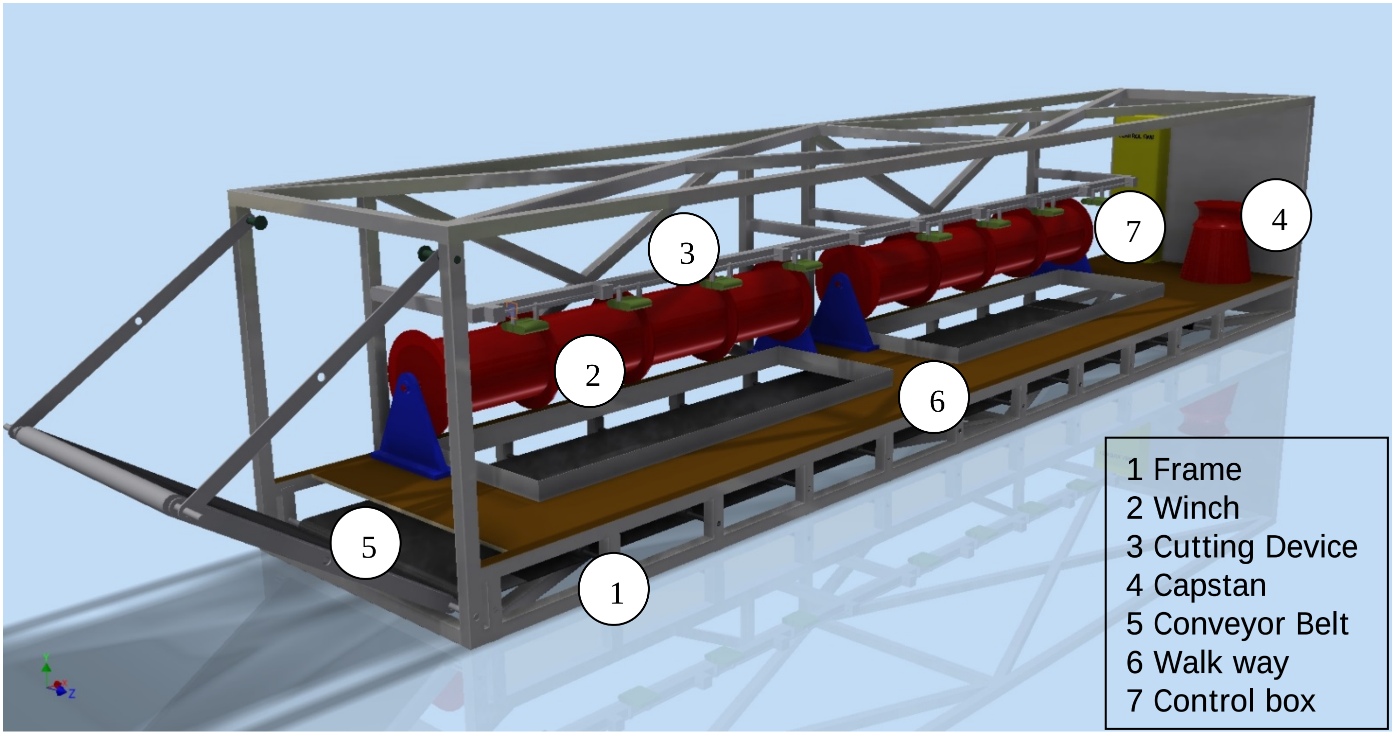


Figure 43 3D impression of the external module in Autodesk Inventor

The module is based on a regular FEU (Forty feet Equivalent Unit) that is used as a frame (1) to support the equipment. With a foot print of 40’ x 8’ or 12.19m or 2.43m there is enough space to install the required equipment. Containerization of the module increases flexibility as it can be transported either by road, rail or ship. It can be attached on the floaters by using bayonets on the bottom corners of the module and/or flipper guides similar to ones that can be found on self-actuating container lift spreaders (figure 44).

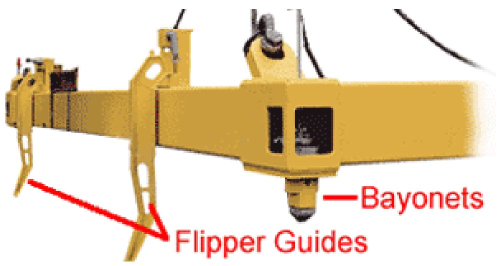


Figure 44 Example of bayonet and flipper guides (Tandemloc, 2015)

Once in place the lines of the seaweed patch can be deployed, or could be attached using locking devices on the winches (2). In the impression 2 four-drum winches can be seen. These winches have a large diameter and are wide enough to be able to reel in the 'heavy' substrate. As the speed of the winch increases, the amount of drag related to the substrate rises, increasing the load on the ropes. To ensure that the lines won't entangle or get crushed a large diameter is chosen. The drums in the 3d impression have a diameter of 60 cm and a length of 98 cm. With this size the first layer of rope on the drum could contain 151m or 116m for 12mm and 16mm rope respectively. If necessary a second layer can be used, depending on the size of the farm resulting in a rope length of 315m or 238m respectively. (Ingersoll Rand, 2015) This large Drum-Rope diameter ratio is advantageous with regard to the strength efficiency of the rope. If required, the winch surface can be grooved based on the rope diameter, allowing a more uniform winding. This will slightly decrease the length of rope on one layer (10%), but will increase the longevity of the rope and allow for larger fleet angles. With grooved systems multiple layers can be spooled on one drum. Normally with a large length / diameter radio (>6), additional bending and torsional calculations are required, since four lines are spread equally this is not deemed necessary (Vries, 1948). With this setup winch speeds of 80-120 m/min should be attainable. (M. Nijhoff, 2015, pers. comm., 02 Jul).

Above the winches are individual cutting devices (3, marked green). These will remove the seaweed from the substrate lines when these are reeled in. The devices are attached to a rail system that is used to guide the seaweed on the drums. While the substrate is reeled in, these will gradually move from one side of the drum to the other, to ensure optimal use of the winch. The cutting devices should be place in line with the expected position of the substrate lines to avoid additional loads on the rack. An example of such a system is the diamond screw level winder from LEBUS (LEBUS-Germany, 2015).

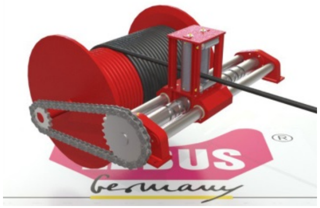


Figure 45 LEBUS level winder

The removed seaweed is collected through holes underneath the cutting devices and partly under the winches. The removed seaweed will be caught on a conveyor (5) that runs underneath. At the side of the container a conveyor can be moved outwards to increase the reach. An additional conveyor/transport system on the vessel will transport the seaweed to the vessels hold/storage area.

To provide access to the equipment and to inspect the process a walkway (6) is provided. Additional equipment on the module is a capstan (4) to use for deployment and the initial reel in of the first floating spreader. Additional pulleys or fairleads can be installed to guide the rope through the centre, these are no illustrated on the drawing. A control box or switchboard is placed to operate the equipment and provide power.

6.7.3 Deployment procedure

Deployment is mainly based on the graphical sketches in 6.5.2. Before deployment the module is rigged with substrate lines containing the young spore lings. The initial (moving) spreader bracket is already attached to the lines on the winches. When the vessel arrives the deployment rope is already attached between the floaters and held together through brackets attached on the floater. A messenger line is attached to the rope and reeled in using the capstan. This ensures that the first spreader bracket can be attached to the deployment rope in a safe way. Once connected the spreader is dropped in the water and the other and is attached to the capstan. The capstan is used to deploy the remainder of the substrate in the water. When the end of the substrate is reached a second spreader beam is attached to the substrate and connected to the floater using the bracket. At this time, the first half of the manoeuvre rope has been reeled in and, since it contains of two parts, can be decoupled from the rope. The farm is now deployed and held together by two ropes on two brackets on the float. The spreaders ensure that the ropes are held at a certain distance, and the tension on the ropes ensures that the lines stay close to the surface. Additional floatation to the substrate might be necessary, yet this will not be discussed here and now.

6.7.4 Harvesting procedure

Harvesting is the opposite of deployment, but will be discussed nevertheless. Once the module has been positioned and has been connected to the floater the last half of the movement rope is attached. While slacking this rope the bracket can be removed from the water. Once on the platform the substrate ropes are relatively slack and can be attached to the drum. The connection between the substrate and the cutting device could either be made manually, before attaching to the drum or automatically if the bar with the cutting devices attached is adjustable. The conveyor is expected to be already deployed and will be started. The first meters can be winched and the removal of the seaweed can start. While the substrate is reeled in the rope is continuously slackened to provide an even tension on the rope. Once the other spreader bracket has been reached it can be disconnected from the movement rope and both ends of the rope can be attached to the brackets on the float. The module can either unwind the rope to a larger drum or change the drums in total to be ready for the next patch. An example of the module alongside an AHTS can be seen in figure 46.

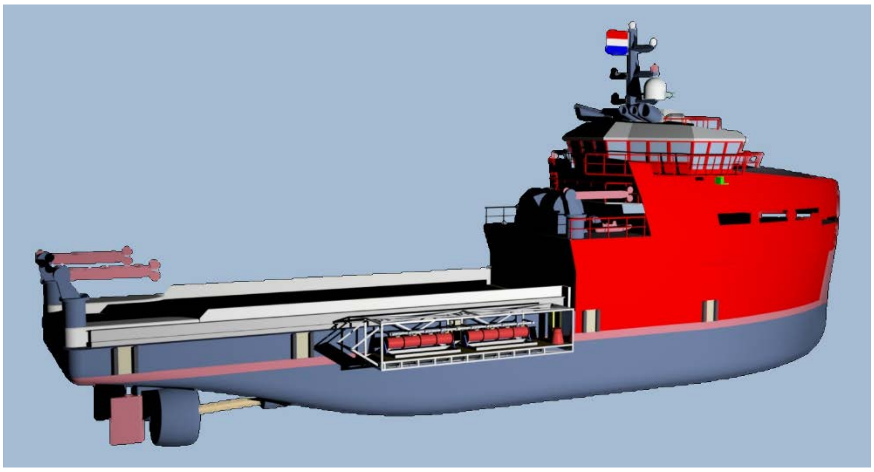


Figure 46 Illustration of the Module alongside a 48m anchor handling tug supplier (AHTS). AHTS model from GrabCAD.com (Aptilla, 2015)

6.7.5 Recommendations

It is noted that with smaller drums with higher diameters, the spooling speed can be increased further. Depending on the width between the lines this could be implemented by decreasing the width between the lines. If this is not possible, additional guiding rollers could be used to serve more lines per module.

In order to know it this increase is possible in the cultivation process, several items need additional attention.

With higher speeds the drag of the seaweed increases, and at a certain speed this increase in friction could remove the seaweed before reaching the harvesting module. A study in to maximum line speed/drag per specie could provide an answer to this question.

Another issue with increased speed, or already occurring at current predicted speed is whether the cutting device or removal system is capable to remove the seaweed at such speeds. In the concept phase this was left out of the scope, since multiple solutions are deemed sufficient for removal. At higher harvesting speed this might no longer be the case and alternative cutting methods should be studied. There are examples in the food industry where there is a defined limit in operating speeds (e.g. bread slicing machines)

6.8 Conclusion

With a limited set of requirements and a lot of knowledge gaps it is still possible to come up with a wide range of different designs. The use of existing technology is useful, yet history has learned that most of the time the harvesters are developed separately from the farms. Current developments with new types of substrates only enlarge the amount of possibilities for a harvesting mechanism. Seeing that there is no current solution or combination that could work offshore a wider search had to be made. This included both a patent search and a brainstorm session. All the ideas were organized in three different morphological overviews, based on the functional descriptions of chapter 5. One containing overall design decisions, based on the generic description of the system, one regarding the harvesting system and one regarding the carrier system.

Though the morphological overview provided a wide range of solutions, the amount of variations from these overviews is simply unattainable. That’s why an initial pragmatic selection was made, based on a number of different criteria and a decision was made to use the overview of the carrier system only as reference, without further selection. The selection reduced the number of solutions significantly.

With the selection of solutions two main concepts were made, each having a design variation. The concepts are weighed individually based on 10 selection criteria based on the design objectives and requirements. Even though the scoring system works well it is difficult to add weights and evaluate the different objectives. This also may have resulted in relatively small differences between the scores. The highest scoring concept is used and developed in more detail. This concept is heavily based on a modular container system, similar to equipment used in oil skimming equipment.

Using Autodesk Inventor the concept is further developed and details are worked out with regards to deployment and harvesting equipment and its operation. The concept does meet the set of objectives and initial requirements, yet it is still unknown whether the concept is feasible and effective. The call for more operational requirements and a way to test the feasibility of the concept is one of the main reasons to start developing an exploitation model. The preliminary design does make it easier to figure out the necessary parameters to model. Since the whole industry is still in the development phase the model should be able to evaluate various system concepts

7

Concept exploitation model

7.1 Introduction

This chapter describes a model for the calculation of the operational costs of seaweed cultivation. The model serves as a tool to evaluate various system concepts with regard to offshore seaweed cultivation. It provides an effective method to assist with design decisions, operations planning and the economic feasibility of a concept.

The aim of the model is to develop a dedicated maritime cultivation and transportation model framework that is capable of modelling the operations of a seaweed cultivator, and also supports multiple transportation planning problem types. A transportation system can be described as a set of entities and interactions between them that produce a demand for transportation (mature seaweeds) and the provisions to supply transportation services to satisfy the demand (Rajabi, 2011).

Modelling and decision support tools are often required due to the growing sophistication and dynamic nature of supply chains, and a growing integration of transportation networks. These modelling tools can be used to analyse freight transportation and to develop effective and efficient freight transportation solutions (Pendyala, et al., 2000). The principles are used in this model, and are integrated with the seaweed cultivation modelling.

In general the model must be able to include data that can describe the capacities and costs of the network facilities as well as their connections to the transportation networks. The model must also be able to include transportation network components associated with the transportation services such as travel distances, way points or hubs, and transit tariffs. In addition it should be able to integrate various system components necessary to cultivate seaweed. Lastly, a transportation supply model must be able to describe the transportation services, and their associated capacities, and costs that act on the transportation networks between the facilities.

7.2 Model definition

7.2.1 Defining the goals

As previously mentioned the general objective of the model is to provide an effective framework to assist in design decisions of a seaweed cultivation system. In addition it should assist decision-makers in their feasibility assessment of different cultivation scenarios. These multifunctional capabilities add value to the model. To clarify the implementation of the general objective, a set of goals are defined. The main goal can be divided in a number of sub goals associated with the model. To meet the goals a set of requirements are stated.

Main Goal:

To assess the economic feasibility of various operational scenarios in order to support operational and design decisions.

Sub Goals:

- Show dimension limitations of carrier structure configuration and operational equipment;
- Give insight in the various cost factors with regard to the process chain of a harvest and deployment operation;
- Illustrate the costs of the harvest and deployment with regards to the total production chain;
- Give an optimized solution to any given scenario with regards to planning of an offshore seaweed chain and determine the sensitivity of this optimization;
- Show the difference between using a modular solution on hired equipment, or a specialized purpose built harvesting vessel.

Requirements:

- Support a level of disaggregation in the data input to run various scenarios.
- Provide a method to evaluate design decisions of both the cultivator as the carrier structure.
- Describe and model the processes that will affect the cultivator in the process chain: Transport, Deployment, Harvesting, and Offloading.
- Provide a method to calculate the costs of the operations at sea, and additionally within the entire chain in order to assist in investment decisions.

7.2.2 Methodology and domain

The model is composed of three major modules: demand, supply and costs.

Demand; is the input of the model and is given in the form of a cultivation scenario. In the case of seaweed cultivation these are operational demands based on species selection, and yield, farm layout, and the distance between the farm and the port of destination and or operational limits.

Supply; is the amount of services that can fulfil demand in the form of transport routes and services, harvest and deployment services and their specific performance parameters.

Costs; determine the expected service cost, the investment costs and the overall chain cost. The combination of supply and costs will demonstrate the feasibility of the requirements of the model.

These three sections are inter-independent. The demand needs to be supplied and the services that supply the demand have certain costs. The process of assigning the supply to demand in transportation models is often referred to as transportation network equilibrium. This equilibrium is the problem of the network users (transport services), seeking to maximize or minimize an objective function (min cost, max profit, etc…) between their origin and the destination. In this case, the seaweed needs to be removed and transported from the farm to the port of destination.

To illustrate this dependency and its related topics of the three model sections a domain model scheme is presented (figure 47). The domain model scheme serves as a clear depiction of the problem domain. In this case it serves as an input to solution implementation within a software development cycle since the model elements comprising the problem domain can serve as key inputs to code construction. It describes the various entities, attributes, constraints and relationships that govern the problem domain.

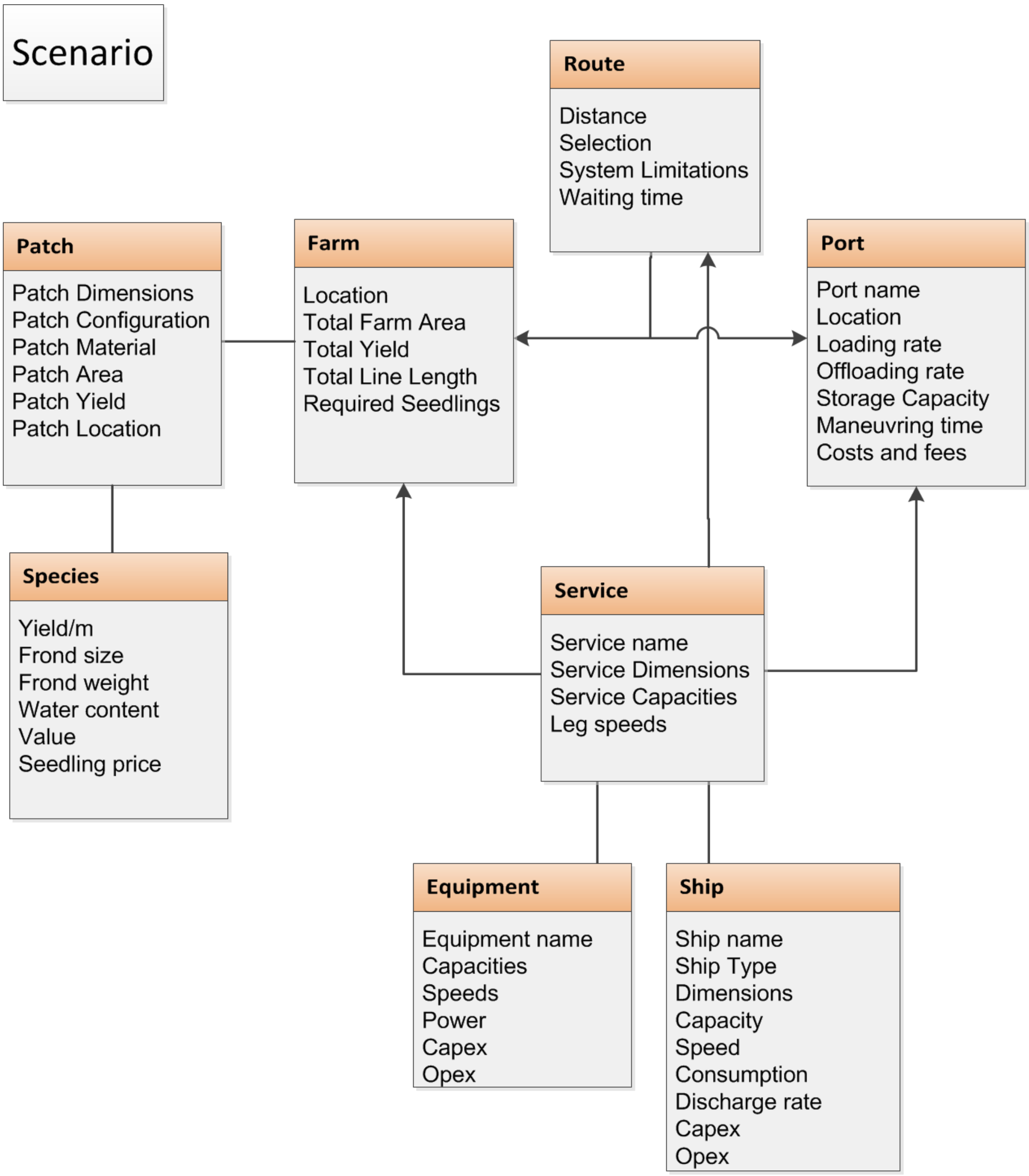


Figure 47 Domain Model Feasibility model

From left to right the following classes can be identified.

Patch. The above mentioned species will presumably grow on a multitude of different carrier structure, or in this case a patch of the farm. The patch can vary in dimensions and in configuration. It is possible to vary in different farm types (eg. Net, Line and Cloth) and their configurations. With the dimensions an area will be covered at sea, and it is possible to see whether certain configurations still match with the expected yield. In addition some patches might be at different locations to cover an entire farm, which influences the service.

Species. For most scenarios it is important to know which species will be cultivated. The advantage is that once a specie is chosen a lot of the farm parameters can be determined. Yet it is also possible to determine the effect of a change of species in an existing should one exists.

Farm. The Farm is where the seaweed species grow. It has a location and is an origin for mature seaweeds and a destination for seaweed seedlings to be deployed. Together with the specie information you can either determine the necessary area based on a fixed yield, or the necessary yield based on a fixed area.

Route. The route is the connection between the destination and the origin in the system. It concedes of a distance and provides limitations for the scenarios.

Port. The port is the origin of the seaweed species to be transported to the farm and the destination port for the mature seaweeds from the farm. Next to its location an important aspect of the port is the loading and unloading time. This has a large influence on the time available to harvest. A port also demands a certain amount of fees and a manoeuvring time.

Service. To ensure the demands are being met and the transport nodes can be served the service is required. The service is the system used in place to carry out transportation, deployment and harvesting tasks. It consists of ships and equipment to accomplish the service.

Ship. The ship serves mainly as a transport capacity between the destination and the origin and as a carrier platform for equipment necessary to harvest and deploy the seaweed.

Equipment. As mentioned earlier, the equipment is necessary to harvest and deploy the seaweeds at the farm.

A scenario is therefore a combination of the classes mentioned above. Be it in the form of demands or parameter limitations. Since the scenarios and the questions related to the scenarios can differ it is important to show the relations between them and ensure a proper input and output. In section 7.3 the shape of the model is introduced illustrating the processes and calculation that form the back bone of the model. Following with a description of the used software and the processes involved regarding the input. In section 7.4 the processes and calculations are described to determine an optimum solution.

7.3 Modelling framework and inputs

7.3.1 Modelling framework

Theory

The theory used in this model is mostly based on lecture notes from design methods classes at the Norwegian University of Science and Technology (NTNU) in Norway, which find their origin in the *theory of production* in managerial economics (Christopher & Maurice, 2010). Part of this theory is the production function. A production function is the functional relationship between inputs and outputs. Production function explains that the maximum output of goods or services that can be produced by a firm in a specific time with a given amount of inputs or factors of production.

Production Function: $Q = f(K, L)$

Q	Represents quantity of goods
K	Represents capital employed
L	Represents labour employed

Implementation

Using this approach on a shipping transport model, the ship's cargo capacity q and the number of roundtrips could be considered the two primary production factors. Multiplying the capacity of the vessel with the number of annual roundtrips result in the annual ship transport capacity:

(1.1) $$Q = q\gamma\frac{(365 - OH)}{T}$$

q	Vessel cargo capacity	t
Q	Annual ship transport capacity	t
γ	Average ship utilization rate	-
T	Roundtrip time	Days
OH	Days offhire	Days

In this equation, the roundtrip time T, is considered a constant independent of the ship size. The formula is adjusted to cultivation process of seaweed (1.2).

(1.2) $$Q = q\frac{H_T}{T}$$

q	Vessel cargo capacity	t
Q	Total farm yield	t
T	Roundtrip time	Days
H_T	Total Harvest time	Days

There are three major changes between the formulas:

1. The annual transport capacity Q, changes to the maximum expected farm yield Q.
2. Due to the seasonality of both harvesting and deployment, the available days $(365 - OH)$ change to a maximum amount of harvesting days H_T.
3. The average utilization rate γ, is eliminated due to the operational profile.

Due to the seasonality of both deployment and harvesting, both processes are limited in time. If a distinction is made between the two, the most time limited process would be harvesting. Preferably, harvesting needs to be done within a period of several weeks and the amount of volume and weight is much higher than during deployment. Therefore most formulation will be focused to harvesting, with an allowance for easy adjustment to determine deployment factors.

The utilization rate is eliminated due to the following reasons:

1. Similar to a dredging vessel operational profile, a profile with multiple trips from one source to one destination with a fixed quantity, the hold of a vessel is filled fully to minimize the numbers of trips and therefore the costs.
2. The only way the utilization rate could have an effect on the solution, is the relation between the yield of a patch and the possibility to partly harvest a patch. If the latter is possible, then it is always possible to fully fill the vessel. If this is deemed not possible, the ratio between the yield of a patch compared to the vessel size is very small. Meaning that the missed harvest, compared to the capacity of a vessel is expected to be small, therefore the utilization rate is expected to be close to 1 (0.98-1).
3. There is still uncertainty in literature to the amount of water in seaweed. This suggests that exact calculations with yields of patches are difficult are hard to make, further illustrating that the utilization rate is hard to determine. With the utilization rate already being close to 1 (reason 2), its deviation due to inaccuracy makes it a hard constant to prove (eg. It could be any number between 0.98-1).

In general the operation can be using the expected farm size Q, the expected vessel size q and a number of trips N_T; where N_T needs to be a natural number not being zero.

(1.3) $$N_T = \frac{H_T}{T},\ N_T \in \mathbb{N}1$$

N_T	Number of trips	Trips
H_T	Total Harvest time	Days
T	Roundtrip time	Days/trip

The number of trips can also be described as a combination of the total harvesting days H_T, times the frequency of trips f_T :

(1.4) $$N_T = H_T * f_T$$

N_T	Number of trips	Trips
H_T	Total Harvest time	Days
f_T	Frequency of trips	Trips/day

However, formula 1.4 has limitations since the outcome, N_T, needs to be a natural number $\mathbb{N}1$. There are two ways to resolve this, either by introducing a ceiling function, or using an integer function. The ceiling solution has the benefit to present an answer in every calculation an 8 day total harvest with a frequency of 0.2 trips per day (8*0.2 = 1.6) would still require 2 trips.
Contrary to this discrete solution without operations, a discrete solution can be used eliminating all the non-integers. The difference is illustrated in the following to graphs. It is however slightly more difficult to present the latter, as is illustrated in the figures 48 and 49.

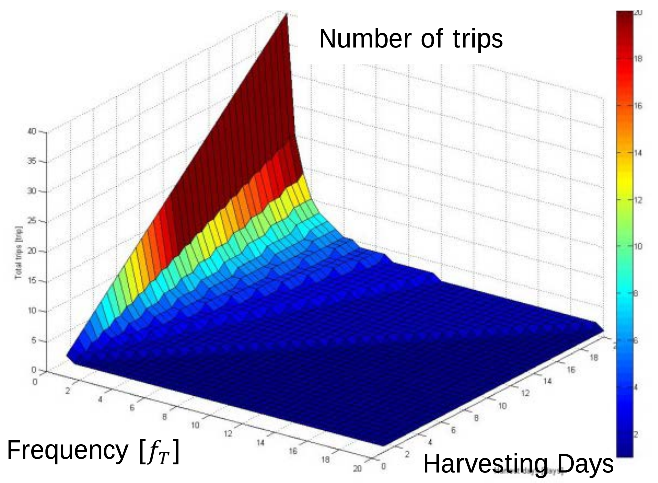


Figure 48 Surf graph using illustrating the total number of trips based on the harvesting days and frequency

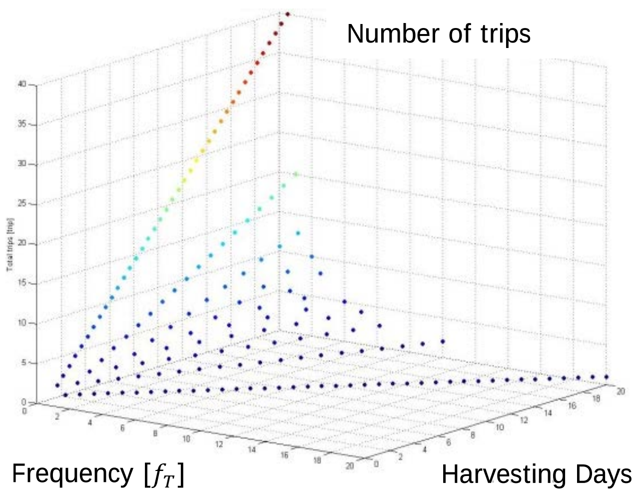


Figure 49 3D Scatter plot of the integers.

On the left a surf plot is given presenting the number of trips (z-axis) as a function of the amount of days (x-axis) and the frequency (y-axis). Plotting surfaces only work on 'continuous' functions. To ensure only the correct(applicable) calculations are used, the option is chosen to eliminate all non-integers.

This, as illustrated in Figure 49, forms the basis for the model. Using the harvesting days as a variable with a maximum limit and a variable frequency (trips/day) a number of trips can be can be generated. The frequency is used as it is easy to understand and adapt for limitations, and it is later used to determine time segments of the roundtrip. The step size of both variables can be altered to run more variants, but this will be discussed later on.

Using all the different operational profiles from figure 49, the corresponding vessel quantity can be calculated using the yield expectancy Q. As is illustrated in figure 50.

(1.5) $$q = \frac{Q}{N_T}$$

Varying the trips per day and the harvesting time, we can calculate the required vessel capacity as can be seen in figure 50. (Initial values: Q=10000, q_{max}=5000, $H_{t\ max}$=20)

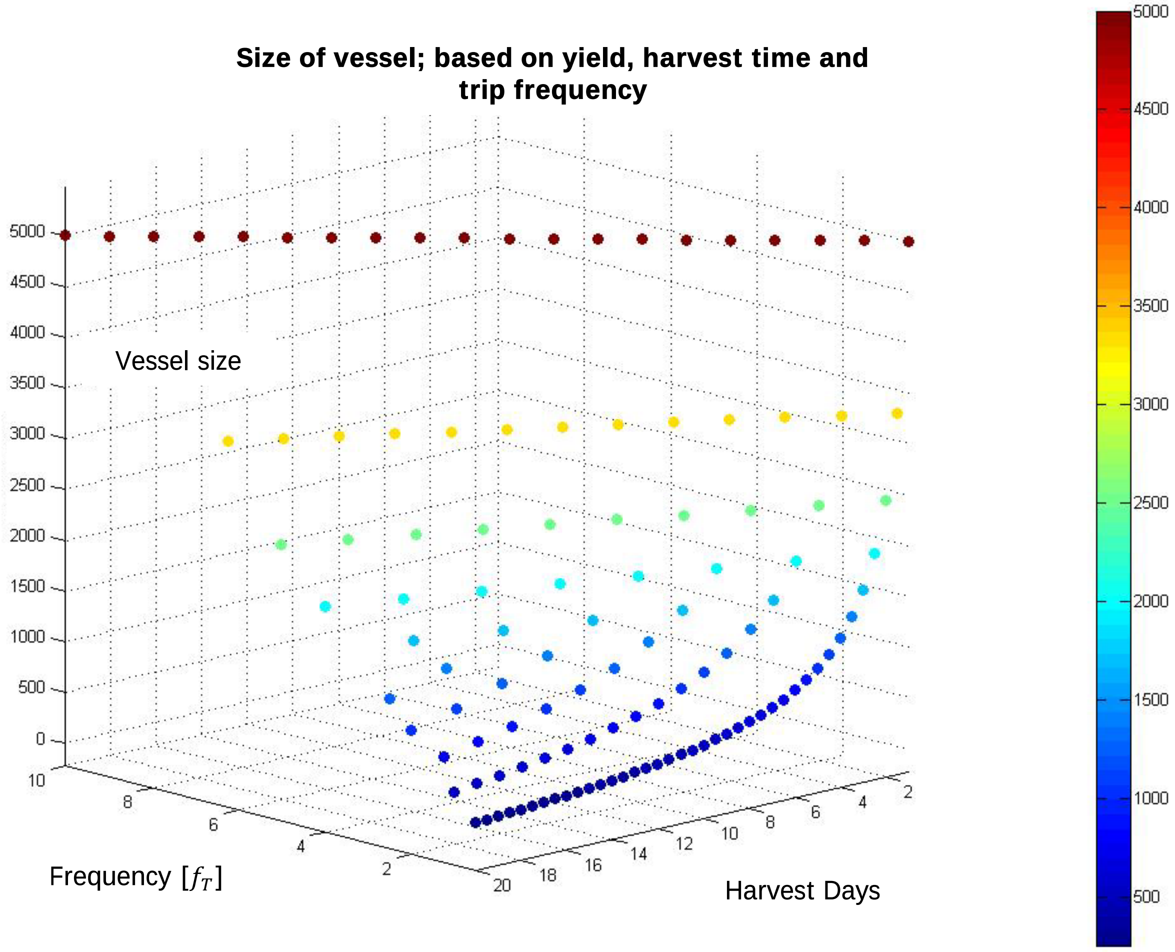


Figure 50 3D Scatter plot of different vessel sizes based on Harvest Days and Trip Frequency

Calculation of the roundtrip time segments

With the values for harvesting time, farm and vessel capacity covered it is time to focus on the operations affecting the frequency and roundtrip time.

The harvesting roundtrip time T is divided in four segments:

T	Total Roundtrip Time	Days
T_P	Time in port per roundtrip	Days
T_H	Time for harvesting per roundtrip	Days
T_W	Time avg. delay per roundtrip	Days
T_S	Time at sea per roundtrip	Days

(1.6) $$T = T_P + T_H + T_W + T_S$$

Instead of using the segments as constant values, they vary based on the parameters in the scenario. There is one more variable needed to calculate the different times and that is the velocity V. This directly varies the sailing time, which is a variable of speed and distance between the origin and destination. This distance has to be covered twice, since the total roundtrip time is calculated.

(1.6) $$T_S = \frac{d}{V * 24}$$

d	Sailing distance	Nm
V	Vessel Speed	kn

The time in port is determined by the vessel size and a certain working load related to the discharge or loading rate.

(1.7) $$T_P = \frac{q}{w_{LL}}$$

w_{LL}	Loading/unloading rate	t/hour

The waiting time is also hard to predict. It is a combination of delays, break times and crew exchange. Every shift, independent of their work hours is expected to take 45 min of break time. The average delay due to maintenance and heavy weather is expected to be one hour per day.

(1.8) $$T_W = \frac{\left(0.75/24\right) * \frac{shift}{day} + 1/24}{f_T}$$

The remaining time left for harvesting, T_H, can now be calculated by subtracting the above times from the time it takes to complete one trip. To ensure that the function doesn't give rogue values it is limited by minimization of $T_H > 0$. This is important when other factors influenceT_H.

(1.9) $$T_H = \frac{1}{f_T} - T_S + T_W + T_P \ \ , where\ T_H > 0$$

Calculation of the required harvesting speed

Knowing the harvest time each trip, allows the possibility to determine the required average harvesting speed in hours. This value is useful, to determine the required equipment specifications later.

(1.10) $$w_{Har} = \frac{q}{(Th * 24)}$$

w_{Har}	Harvesting rate	t/hour

This value is an influential limiting factor and therefore it should be possible to set limits to this value.
One way to determine the limit is to calculate this with the known patch configuration.

The harvesting time T_H [days] therefore needs to be divided in: the time necessary to manoeuvre towards a seaweed patch t_m [s], and the time to harvest the patch t_p [s] multiplied by the number of patches available before the vessel has filled.

(1.11) $$T_H = \frac{\left(\frac{q}{q_p}\right) * (t_p + t_m)}{(3600 * 24)} \quad or \quad t_p + t_m = \frac{q_p}{w_{Har}}$$

q_p	Yield per patch	t
w_{Har}	Harvesting rate	t/hour
t_p	Patch harvesting time	s
t_m	Patch manoeuvre time	s

The time to manoeuvre is based on the time necessary to sail from patch to patch and additional time for docking. The sailing time is based on the average distance between the patches d_p [nm] times the manoeuvring speed V_m [kn]. The docking time is a given constant for the setup time to harvest a patch dock t_s [s]. Depending on the patch configuration it might be necessary to setup the harvest equipment multiple times.

(1.12) $$t_m = \frac{d_p}{V_m * 3600} + t_d \qquad t_p = \frac{q_p}{w_{Har}} - t_m$$

In addition it is possible to determine a certain winch speed if the farm patch would consist of several lines. The total quantity of the patch is the length of the patch l_{pa} [m] times the number of lines n_l times the yield per line γ_l [t/m].

The time needed to harvest a patch is the length of the patch l_{pa} [m] times the number of lines n_l divided by the speed of the winch v_{wi} [m/s] times the number of winches installed n_{wi}.

$$q_p = l_{pa} * n_l * \gamma_l$$

(1.13) $$t_p = \frac{l_{pa} * n_l}{v_{wi} * n_{wi}}$$

$$t_s = \frac{n_l}{n_{wi}} * (t_{att} + t_{det})$$

q_p	Yield per patch	t
l_{pa}	Length of patch	m
n_l	Number of lines	
γ_l	Yield per meter line	t/m
v_{wi}	Speed of winch	m/s
n_{wi}	Number of winches	
t_d	Time to setup	sec
t_{att}	Time to attach to the substrate	sec
t_{det}	Time to detach from the substrate	sec

7.3.2 Software and Input flow

Now that the frame work calculations and processes of the model are presented, it is necessary to determine how the data is introduced to the model, what modelling software is being used, the flow of the data and the possibility to optimize a scenario.

As we mentioned in section 5.2 there are numerous classes in a scenario that provide information in a scenario. To ease the use of input, Microsoft Excel is used to serve as a clear input user interface. This serves as a starting point in the model.

The model and calculations are done in Mathworks Matlab. Matlab can calculate the data and present it in ways that Microsoft Excel cannot. Examples are 3d scatter and surf plots to present the data and multidimensional matrices. A benefit of using Excel for input is that all the data is presented to the user in a neat way and the user doesn’t need to change the constants used in the code of the Matlab model.

The output of the calculations is presented in Matlab, and some requested data is send to an Excel file for further examination.

Excel Input flow

The flowchart in figure 51 illustrates the flow of the input.

When excel is opened the program is ready to receive input of the scenario parameters. Before the model is run the model resolution and parameter limits have to be checked if they are within respected limits. The next block is a possible decision on whether the farm layout should be a part of the calculation. When checked the layout should be inserted and the dimensions and effective yields are calculated. If the layout matches the expectations it is possible to use this data to calculate and expected maximum harvest speed. The data should be saved before starting the Matlab model. Detailed information of the input possibilities is given in following sections.

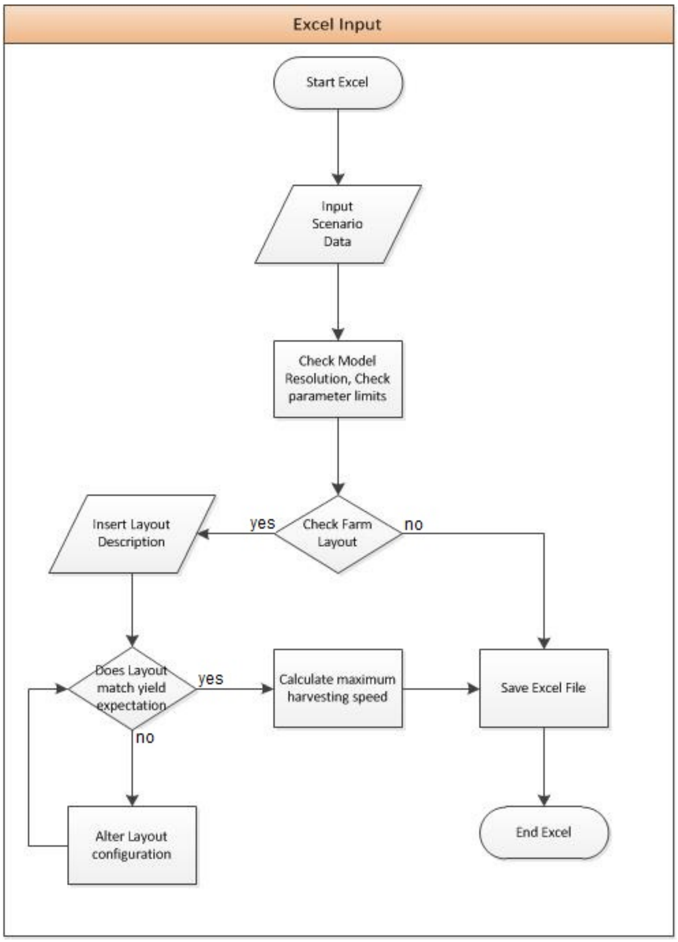


Figure 51 Input flow chart

Excel input work sheets.

To present an overview of the various classes and their relationship, the following section will describe the input fields on the Excel work sheet. Though a lot of information translates directly to Matlab, certain fields don not and could either serve as additional information field or a selection or decision calculation outside of the Matlab model, or information necessary to calculate certain outputs in the model. In each field the RED coloured field serves as a user input and the GREEN as a calculation based on the user input.

Specie Data

This is one of the most important scenario selections. It directly affects yield expectations and transport necessity in the form of water content. The seedling price and value directly affect the processing chain costs.

In the specie data fields a selection can be made on the specie to be farmed. The selection of species is linked to a database worksheet, and will automatically fill in the additional data given on the picture. The data base could be expanded or updated if required. For now support is given to calculate with 5 different species.

SPECIE DATA		
Species	1-Sacc	
Yield/m	11,7	kg/m
Avarage frond size	1,45	m
Av. Frond weight	0,11	kg
Av. No of Frond/m	106,4	Fronds
Water percentage	90%	
Value	€ 1,20	€/kg DM
Seedling price	0,0005	€/seedling

Figure 52 Specie data input field

Farm Data

The Farm data consists of three main data fields. In the top there is a selection for various farm types. Currently there are three options in the model: lines, nets, and cloth. Currently the line model is best supported for extensive calculations, but this will be discussed further on in the harvesting equipment section. Based on the selection of the farm type, certain input fields will change to represent the correct data.

The next section of data fields cover the general data of the farm. A surface area in combination with the specie selection will determine the average and total yields and give a rough estimate with regards to seedling and substrate information.

FARM DATA			
General		1-Line	
Total Farm Area		50	ha.
Avarage Yield DM		20	ton/ha
Avarage Yield WM		200,00	ton/ha
Total Yield DM		1000	ton
Total Yield WM		10000,00	ton
Total length line		854,70	km
Req Seedlings		90909091	seedlings
Max.Harvest days		20	Days
Per Patch			
Length of Lines		150	m
Number of lines		12	
Width between lines		0,5	m
Total Line length		1800	m
Dimension area		900	m2
	or	0,09	ha
Expected yield WM [Surface]		18,00	ton
Expected yield WM [Line length]		21,06	ton
Av exp yield WM		234	ton/ha
Safety zone [extra]		5	m
Surface with Safety zone [extra]		2560	m2
Expected yield WM		82,27	ton/ha

Figure 53 Farm data input field

When a net or cloth system is used the total length of line field transforms to a predefined yield correction with regards to a line system. This factor can be changed in the data base file and is currently based on estimations. When research leads to more specific data, the database allows for easy adjustments outside of the actual input sheet. An example is the unknown effects of the obstruction of sunlight on the seaweed due to increasing densities in various configurations.

The final section covers information concerning the patch. Again these data fields change depending on the farm type chosen. In the example above a line system is selected, so the main parameters are the number of lines and the width between those lines. Below the input are the yield expectations. This is a useful tool to determine whether your selected patch dimensions match with the expected yield. This is especially useful if the surface area is limited (eg. Norwegian fjords and wind mill parks). An example of the use of the use of this module is now presented.

The patch in the scenario in figure 53 consist of lines with a total combined length of 1800m and covers a calculated surface area of 0,09 ha. Based on the surface expectations the yield of this patch is 18 t WM (0.09ha * 200 t/ha). Looking at the line length separately, the 1800 meters of line of the patch should contain 21,06 t WM (1800m*11.7 kg/m). In this example the expected yield from the lines is higher than expected surface yield, which determines that the design is suitable according the expectations. If the width between the lines example would be twice as large (1m instead of 0.5m), the calculated surface yield would double, where the expected line yield would stay the same. In this case the farm design would not meet the expectations.

Additionally it is possible to implement a safety zone in the design of the patch layout. As you can see in the example above, a small safety zone of 5 m around the patch results in a decrease of the expected yield of 65%.

Transport and logistics

The transport and logistics section contains data fields with regards to the route, the destination harbour and the expected waiting times.

In addition to the distance from the harbour to the farm, the internal distance between the patches can be changed. One other important factor is the offloading rate. Up till now the focus was on the capacities with regards to transport and harvesting equipment, yet one very important factor is the offload rate. Since this factor directly influences the time in port.

TRANSPORT AND LOGISTICS DATA			
Distance Harbor-Farm		20	nm
Offload rate		400	Ton/hr
Harbour fees	€	0,50	(€/t DWT)/Docking
Fuel Price	€	800,00	€/ton
Distance Patch-Patch [extra]		0,02	nm
Expected delay harbour/transport/weathe		1	hr/day
Expected delay crew shifts and breaks		2,25	hr/day

Figure 54 Transport and logistics data input field

Vessel data

This section is devoted to the information with regards to the ship class.

In the first field the number of vessels can be selected. The way this is currently implemented is very basic. The total harvested amount of seaweed to be harvested is divided by the given number of vessels and the individual trip times are calculated. This method could be valid, up until the scenario introduces limitations to the number of vessels that can partake in one activity simultaneously. An example would be if 5 vessels are planned for the harvest, and the port is only able to handle one vessel at a time. This is still possible, until the time expected time alongside the berth, T_p, exceeds $1/5^{th}$ of the trip time. For the expected scenario calculations this will suffice. And if deemed necessary could be changed in the future, adding complexity to the model.

In the crew fields it is possible to alter the number of crew and the no. of hours per shift. The number of crew is the number of crew required to operate the vessel and the equipment. The costs are based on a crew salary diagram presented in the ITF (The International Transport Workers' Federation) offshore collective agreement. This agreement sets out the minimum standard terms and conditions applicable to all Seafarers serving in any offshore vessel or Mobile Offshore Unit (MOU). The calculations are described in section 5.4.2. With the number the crew composition alters and a day rate is produced.

VESSEL DATA		
Number of vessels	1	
Crew	3	persons
Shifts	8	hour/day
Single crew	€ 600,00	per day
Total crew costs	€ 1.800,00	per day
SFC	210	g/kWh
Maintenance	0,50%	/purchase value/yr
Min Sailing speed	3	kn
Max Sailing speed	8	kn
Min Capacity	50	t
Max Capacity	10000	t
Min Power	50	kW
Max Power	5000	kW
Aux Power	100	kW
Adm. Constant	0,00481	
Exp block coeff	0,86	
L/B	7	
B/D	2,5	
Dwt/Depl	1,48	

Figure 55 Vessel Data input field

An important factor with regards to fuel consumption is the specific fuel consumption of the engines. This is based on the engine data from the cargo ships used to determine the Admiralty's constant in the previous section. The maintenance factor is used to determine the price of the maintenance of a newly build vessel. More about newly build vessels in the cost section.
The next section limits the speed and the capacity of a vessel. This could be used to incorporate a range of regionally available vessels and/or regional limitations with regards to speed and capacity.

The bottom section is a set of ratios used to determine the expected size of a new build vessel, which can be used to compare a specialized new build vessel with hired equipment.

Resolution and fixed inputs.

To increase the resolution of the answers it is possible to change the step size of the variables. It will take longer to run the model but the accuracy will increase. The default step sizes are displayed in the illustration to the left. It is also possible to limit certain factors if the circumstances require this. This function is useful to predict the operational profile when the capacity is known. Due to the nature of the model it is not possible to use the capacity number exactly. This has to do with the resolution and the way the quantities are generated (the capacities are always the total yield of a farm divided by an integer). In a list next to the fixed input display a selection can be made. If there is only one type of vessel available the fixed capacity of the vessel with the closest capacity below the used quantity should be used.

RESOLUTION		
	Steps	
Speed steps	0,1	kn
Total harvesting days	0,5	days
Days per trip	0,5	days

Figure 56 Resolution input field

FIX INPUTS			
Fixed Harvest Days	**OFF**	7	days
Fixed Vessel Capacity	**OFF**	1714	ton

Figure 57 Fixed Input Field

Input fields discussed in the next chapter

There are a number of additional input fields for the model. These are for cost based optimizations, financial appraisal and equipment limitations. These subjects are discussed in the next chapters.

7.4 Cost calculation, model flow and optimization

In order to find an optimum solution for a scenario, a value has to be added to the various activities. Since the quantity of seaweed to be harvested is fixed, it is not necessary to maximize the output, as is done in a conventional production model. Instead, the scenario will optimize based on currency. This could be done by either minimizing costs, or maximizing profit. Despite the fact that the market value from imported seaweed is known, the price expectations for harvested seaweed in the Northern European region fluctuate. Therefor the choice is made to optimize based on the expected costs.

7.4.1 Model flow in Matlab

To understand the flow of information in the model a flow chart is made. The flow chart is divided in four sections that relate to the direction of code in the model. A short description of the various chapters follows:

1. **Introduce Trips and capacities**

In the first section the model imports the data from the excel sheet and converts it to code. In matlab this is done using the `xlsread` function. This function reads data from a selectable worksheet in the Microsoft Excel spreadsheet file and returns the numeric data. With this input two loops are created: The variation in harvesting days, and the trip frequency (see 7.3.1). With each combination of harvest days and frequency the no. of trips are calculated.

Together with the expected yield the desired capacity is calculated.

2. **Determine the various time frames**

In this section the speed is varied and with the speed and trip frequency it is possible to calculate the four different time activities. With the harvesting time and the yield per trip a general harvesting speed can be calculated and verified with the information from the excel sheet.

3. **Calculate the expected operational costs**

In this section the expected related operational costs are calculated. This is based on expected energy calculations and related fuel costs, and the expected operational costs of the equipment and personnel in the form of hiring costs.

4. **Determine optimum solution**

With the costs of each and every calculation known, it is possible to determine the optimum by searching for the minimal costs. The minimum costs happen at a certain amount of harvesting days, a specific frequency and sailing speed. The values of this minimisation are exported to excel using the `xlswrite` function. Using the visualisation tools in Matlab the values are presented in graphs.

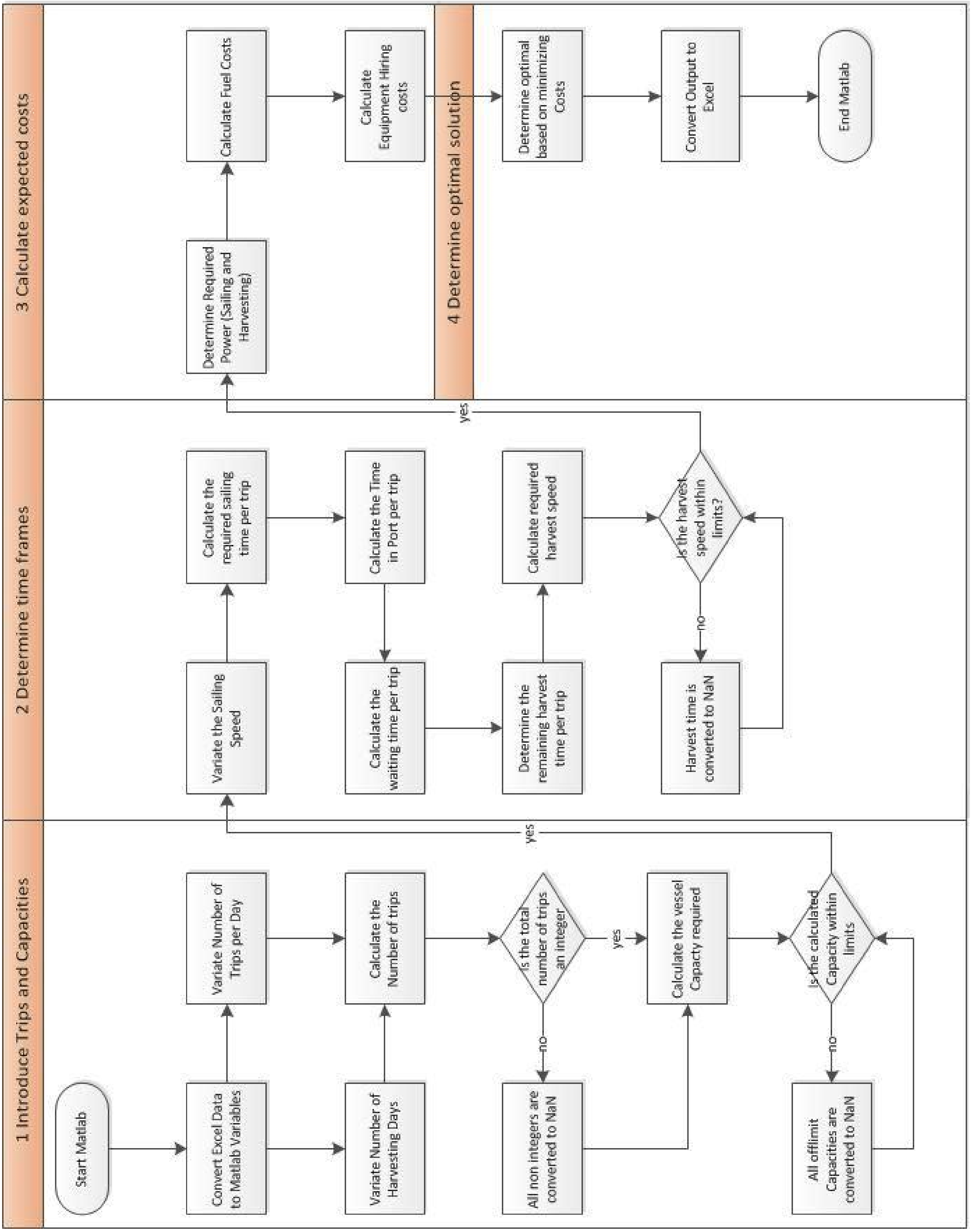


Figure 58 Flow chart Introducing Trips and Capacities

7.4.2 Costs calculations

As described in section tree of the flow chart the costs are based on various factors:

- Expected required power calculations for harvesting equipment, transport and auxiliaries
- Expected equipment operational costs
- Personnel costs
- Transport and port costs

Power calculations and related costs

Trip costs

The ship's size and speed will influence the ship's operating costs. The dominant factor here is the influence of speed on the fuel costs. The required power at a certain speed and with a certain capacity can be calculated with:

(2.1) $$KW = k * q^{\alpha} V^{\beta}$$

This bears close resemblance with the 'admiraliteitsconstante', with a value α of 2/3 and β of 3. The difference is the use of the displacement instead of the ships carrying capacity.

(2.2) $$k = \frac{\Delta^{2/3} * V^3}{KW}$$

Using data of General Cargo vessels, with a dead weights between 500 and 5000, the constants can be determined (see appendix Q). The constant k calculated is 4,481 $*10^{-3}$ with a standard deviation of 7,56$*10^{-4}$. These are based on flat water cruising speeds in calm weather. However, an additional factor is necessary to correct for currents and low speed power calculations. To do this an additional speed factor, V_+ is introduced.

(2.3) $$V_+ = 1 + 2^{\left(\frac{1}{1+V}\right)}, \qquad \mathrm{KW} = k * q^{2/3} * (V + V_+)^3$$

The fuel cost per round trip can then be calculated as the product of the fuel price, specific fuel consumption, the required propulsion power and the number of days at sea for the vessel (here we assume no fuel consumption in port). The cost per trip can be calculated with:

(2.4) $$C_{Ft} = p_F * spc * KW * T_s * 24$$

C_{Ft}	Cost of fuel per trip	€/trip
p_F	Price of fuel	€/g
spc	Specific fuel consumption	g/kWh
KW	Required power per trip	kW
T_s	Time of sailing trip	days

Harvesting equipment and auxiliary energy costs

In the same way additional fuel costs for harvesting and auxiliaries are calculated. Auxiliaries are fuel costs related to the expected amount of auxiliary equipment on board. This could be anything from accommodation services and appliances to auxiliary equipment in the engine room.
The required power for the harvesting is a factor times the amount the amount to be harvested per hour. The first estimations are based on a suction system using a pump

Expecting the harvesting to behave like a pump the following assumption is made. A linear increase of required power based on the following equation.

$$(2.5) \qquad P = \frac{Q_p * H * \rho * g}{3600 * \eta_p}; \qquad P = kp * w_{Har} \; [kW]$$

P	Required power pump	kW
η_p	Pump efficiency	
Q_p	Pump capacity	m^3 / h
H	Head	m
ρ	Specific density	Kg /m^3
g	Gravity constant	m/s^2
kp	Power constant	
C_{Fe}	Costs with regards to equipment power	€/trip
C_{Fa}	Costs with regards to auxiliaries	€/trip
PA	Auxiliary power	kW

The constant used in the model is based on the required power per ton of grain which is estimated at 2.1 l/t or 10 kW/ton/h (Špokas & Steponavičius, 2009). With the calculated power it is possible to determine the fuel costs.

$$(2.6) \qquad C_{Fe} = p_F * spc * P * T_h * 24$$

The auxiliaries costs are based on a constant amount of power, PA, that is required to provide for auxiliary equipment in and around the accommodation spaces engine room and deck equipment.

$$(2.7) \qquad C_{Fa} = p_F * spc * PA * T_h * 24$$

Personnel costs

As mentioned in 5.3.2 the personnel costs are based on the crew salary crew salary diagram presented in the ITF. Since our operations are in North European waters the *ITF Minimum Wage Scale for Crews on MOU's (NORTH EUROPEAN WATER RATES)* are used. The monthly costs are converted to day rates with a ratio of 12/200, based on a 200 days per year contract. The consolidated salary as referred to in the scale covers all work performed seven days per week, 12 hours per day inclusive of meal and rest breaks. Again this can all be changed in the database files. With the total number of crew increasing the crew composition changes as well. Depending on the crew composition the following table is made:

Table 23 Crew Composition and Costs

Crew no	Captain	Ch Eng	Mate	Eng	Maroff	AB	Cook	ITF Day rates
1	1							€ 353
2	1					1		€ 550
3	1				1	1		€ 783
4	1				1	2		€ 981
5	1	1	1			1	1	€ 1.343
6	1	1	1			2	1	€ 1.540
7	1	1	1	1		2	1	€ 1.768
8	1	1	1	1		3	1	€ 1.966
9	1	1	2	1		3	1	€ 2.243
10	1	1	2	1		4	1	€ 2.440
11	1	1	2	2		4	1	€ 2.668
12	1	1	2	2	1	4	1	€ 2.901

In the excel input sheet this is later combined to a single crew daily costs, based on the number of shifts per day and a total amount of daily crew costs. The calculation of personnel costs per trip is done with the following formula.

$$(2.8) \qquad C_{Ct} = C_{Cd} * f_T$$

C_{Ct}	Crew costs per trip	€/trip
C_{Cd}	Crew costs per day	€/day
f_T	Frequency of trips	Trips/day

Transport operational costs

Tugs and barges

The capacity of the vessel and the required power also has influence on the costs. To assist in the assessment of the cost factors, information is gathered from Ciria's *a guide to cost standards for dredging equipment* (Bray, 2005). CIRIA is the construction industry research and information association and their publication Offers a standard method to establish the capital and related costs of various types of dredging plant and equipment commonly in use. The costs related to the capacities are calculated through the use of the Inland Hopper Barges calculations. These day rates are linear with the lightweight data, which in turn are closely linear with the capacities. For the calculations of the power requirements information from the SCOPIC clause is being used (Lloyds.com, 2014). SCOPIC stands for "Special Compensation P and I Club" which is an optional addendum to a Lloyds' open form salvage contract. It specifies compensation costs for equipment and material used in salvage operations.

Additional power is introduced to calculate the price. Tugs prices are based on their maximum amount of horse powers, and not necessarily the required horse power during a tow or push operation. For now we assume that both the ship and the barge are being hired. The additional costs aside from fuel will be:

(2.9) $$C_{Bt} = \left(C_{Bq} * \ q \ + \frac{C_{BI}}{H_T}\right) * \ f_T$$

C_{Bt}	Cost of hiring capacity	€/trip
C_{Bq}	Quantity based hiring fee	€/day
C_{BI}	Initial hiring fee barge	€/day

(2.10) $$C_{Tt} = \left(C_{TkW} * (KW + 100) + \frac{C_{BT}}{H_T}\right) * \ f_T$$

C_{Tt}	Cost of hiring capacity	€/trip
C_{TkW}	Power based hiring fee	€/day
C_{BT}	Initial hiring fee Tug	€/day

Mobilisation and harbour fees

For mobilisation, C_{MTB} an additional two day hiring fee is being implemented.

(2.11) $$C_{MTB} = 2 * \ (C_{Tt} + C_{Bt}) \ / \ f_T$$

The harbour costs are equivalent with the ship size and the number of trips and based on the 2014 port charges of the port of Bergen (Havnevesen, 2014). These are normally based on the gross tonnage of a vessel and consist mainly of harbour dues, wharfing fees, goods charges and Crane fees. The harbour dues are paid once and wharfing fees are based on a commenced 24 hour period, while the crane fees are due per hour.

(2.12) $$C_{HFt} = Ccrane * T_P + Chf * q$$

$Ccrane$	Cost of crane rental	€/hr.
Chf	Fees based on capacity	€/t
C_{HFt}	Harbour fees per trip	€/trip

Harvesting Calculations

The costs for harvesting equipment can be calculated in two ways. The first is a rough estimation based on the harvesting speed and vessel capacity. However since not much is known about the expected costs of the equipment it is not easy to predict a cost factor. As will be shown in the following an assumption is made, based on the required equipment on the prototype.

Rough estimation

Initially the factor to determine the equipment costs for the harvesting mechanism, would be a factor times the harvesting speed plus a base cost (see below).

(2.13) $$C_{Eq} = (w_{Har} * \ C_{RE} \ + \frac{C_{BE}}{H_T}) * \ f_T$$

C_{RE}	Cost of equipment rental	€/t/hr.
C_{BE}	Base costs for eq. rental	€/t
C_{Eq}	Eq. rental per trip	€/trip

Because the harvesting equipment is a vital part of the entire design process, it is worthwhile to do more work in estimating the related costs. Functional the harvesting can be divided multiple sub functions, now simplified in three:

- Collection of seaweed
- Removal of the seaweed
- Collection and transport of seaweed to the cargo compartment

Based on calculations with different harvesting systems in scenario B (ch 8.3) it is decided to update 2.13 with additional costs and instead of a linear increase a polynomial increase is used.

(2.13a) $$C_{Eq} = \left(C_{RE}\left(w_{Har} + \sqrt{w_{Har}}\,\right) + C_{ct} * w_{Har} + \frac{C_{BE}}{H_T}\right) * \ f_T$$

C_{RE}	Cost of equipment rental	€/t/hr.
C_{BE}	Base costs for eq. rental	€/t
C_{ct}	Rent collection and transport equipment	€/(t/hr.)/day
C_{Eq}	Harbour fees per trip	€/trip

To increase accuracy and help engineering it is decided that the three sub functions are calculated individually, as described in the following sections.

Collection of the seaweed

The prototype of a seaweed cultivation machine was based on the principle that the seaweed is collected and brought to the cutting section through the use of winches. To determine the required type and strength of the winch, the drag of the wire is approximated. In using the average specie size, patch length and the amount of sporophytes per m, it is possible to estimate the amount of drag.

In their report on the response of offshore cultivated Laminaria, Buck and Buchholz (2005) derive a relation between the frond length and average width, resulting in an approximation of the blade area. They also determine that there is a close relation between the blade area, the current velocity and the drag force. When multiple seaweed blades are used in a close array to imitate a natural seaweed canopy (or a harvest line for that matter), drag on the array of Laminaria blades was smaller than the total drag. The ratio of the drag from a clump of blades to the sum of the individual was between 0.35 and 0.38.

With this information it is now possible to determine the required drag force of a seaweed line.

The required harvesting speed in m/s:

(2.14) $$v_{wi} = \frac{\left(\frac{w_{Har} * 1000}{\rho_l} * \frac{3600}{3600 - t_m}\right)}{n_{wi}}$$

Calculation to determine the resistance and the related costs:

v_{wi}	Speed of winch	m/s
F_{wi}	Force per winch	N
F_{blade}	Force per blade	N
γ_{Canopy}	Canopy ratio	-
C_{Fwi}	Rental costs of winches	€/N
C_{Twi}	Total costs collecting	€/trip

(2.15) $$F_{wi} = F_{blade} * \gamma_{Canopy} * \frac{spores}{m} * l_{pa} * \ {v_{wi}}^2$$

(2.16) $C_{Twi} = (F_{wi} * n_{wi} * C_{Fwi}) * f_T$

The cost for renting a winch are derived from on A-Plant, one of the world's leading equipment rental companies (APlant.com, 2014). Costs for renting a winch are estimated at = € 225 /T/Day. If instead a winch module needs to be bought prices can be expected between € 10000-12000/T, based on prices from Emcé winches. (G. Sijl 2014, pers. comm., 11 Nov). Most winches work between 10-40 m/min depending if they are fit with a planetary drive or a worm wheel drive, reducing harvesting speeds significantly. This can be adjusted in the input file.

Removal of the seaweed.

The removal of the seaweed is based on the use of a cutting device. This could either be done with a rotating or a reciprocal blades. Similar to the collecting of seaweed through the use of winches, the expected costs for removal of seaweed are expected to be related with the speed of the winches. The potential costs for this equipment can be taken from rental sites that rent plant head cutters, or general hedge trimmers. Dependent on the number of lines that can be operated the calculation is as follows:

(2.17) $C_{Rwi} = (n_{wi} * C_{rem} * v_{wi}) * f_T$

C_{Rwi}	Trip Cost of removal eq. rental	€/trip
C_{rem}	Rent Removal equipment	€/(m/s)/day

Collection and transport

Collection and transport is expected to be done via transport bands. Though these costs are expected to be less than the other harvesting equipment these costs could also be calculated based on the harvesting rate. Like the cutting equipment prices can be used from industrial transport bands.

(2.18) $C_{Cwi} = (n_{wi} * C_{ct} * w_{Har}) * f_T$

C_{Cwi}	Trip Cost of transport and collection eq. rental	€/trip
C_{ct}	Rent collection and transport equipment	€/(t/hr.)/day

Optimizing operational costs

The costs are all added together with the following formula

(2.19) $$C = \sum C_{trip\ related} * N_T + C_{MTB}$$

After which the minimum function is used to find the smallest elements in array

(2.20) $$[A, I] = min(C(:))$$

With this minimum function the matching values of H_T, f_T and V are found

(2.21) $$[Opt.H_T, Opt.f_T, Opt.V] = ind2sub(size(C), I);$$

These optimum factors and their related speeds, costs, and power consumption are used in the output section to allocate the output into useful data.

In figure 59 the optimization is visualized. The chart displayed illustrate the different possible number of vessel configurations based on a total farm capacity of 12000t. The six different lines illustrate different vessel sizes based on the frequency and the amount of trips. Depending on the step size and the harvest days limitation numerous of these charts are being made. In this specific scenario a step size of 3 hours was chosen with a maximum of 20 days meaning that there are 159 other charts that may have 1 or multiple vessel configurations. In this case the harvesting speed and transport speed were limited eliminating most non applicable configurations.

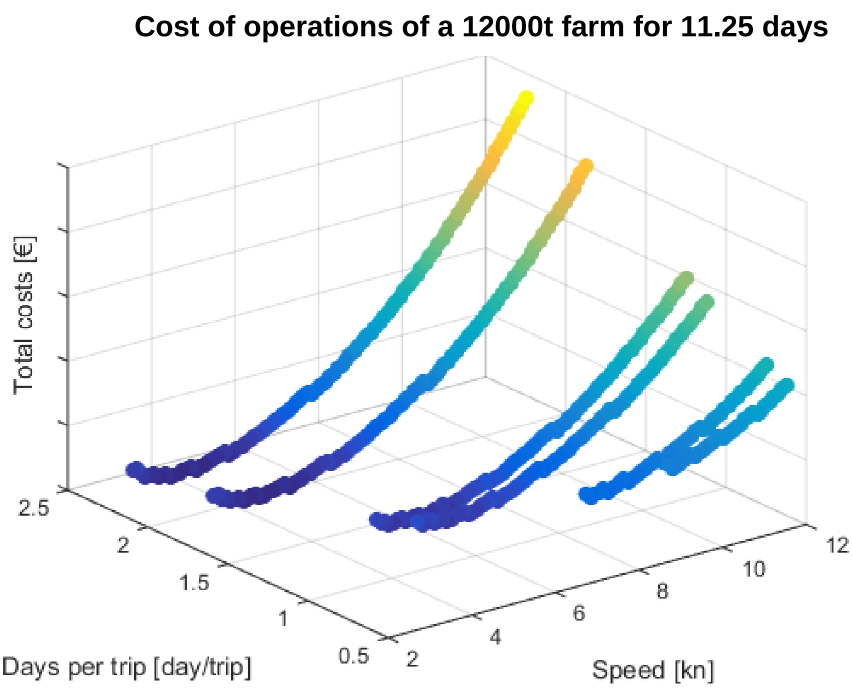


Figure 59 Visualization of optimization of costs (Scenario A ch 8.2)

7.5 Output

7.5.1 Output flow

Vice versa to the input flow, a conversion follows from the Matlab parameters to Excel cell values. This conversion is done to easily be able to copy the values in the correct format for the thesis, illustrate the data through additional graphs and charts, and do further calculations. This process can be captured in the following flow diagram.

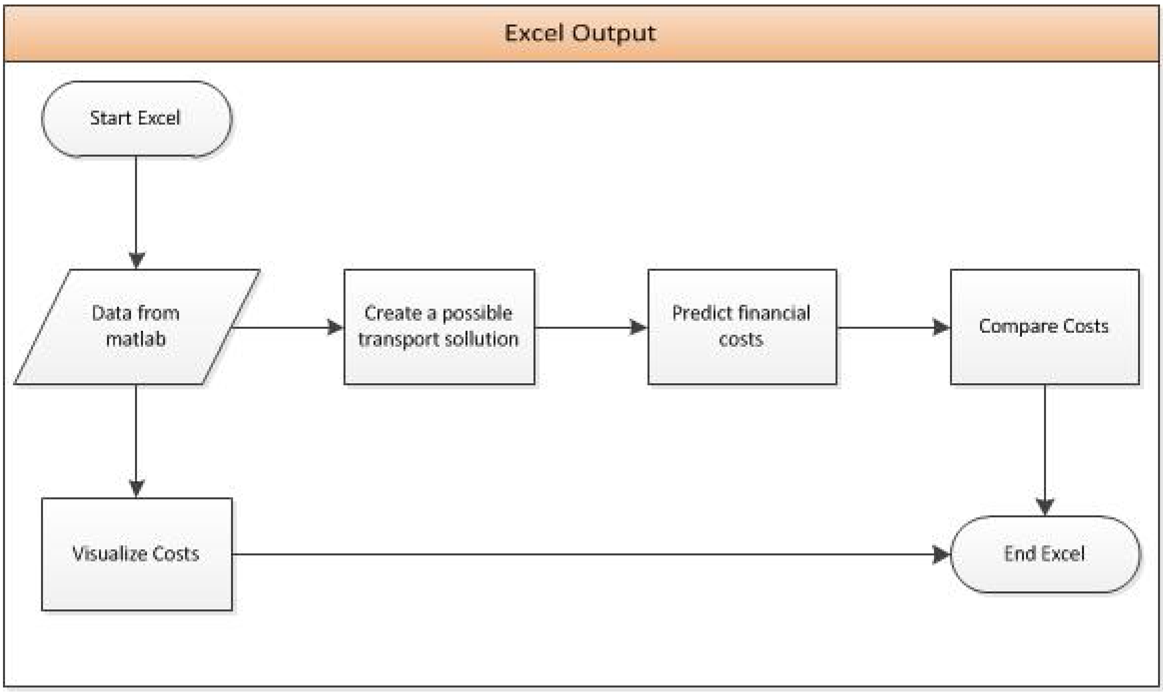


Figure 60 Output flow

7.5.2 Key parameters

This section illustrates the values that will be used to evaluate the calculations. In order to meet the requirements of the model the output should be sufficient to describe and model the processes that will affect the cultivator in the process chain: Transport, Deployment, Harvesting, and Offloading. In order to do this the following sequence of data is exported:

- Main variables

  The values of H_T, f_T and V at the optimum (lowest cost). With these values it is possible to calculate everything. Other important related factors are the vessel capacity q and the total number of trips N_T.

- Time intervals per trip

  The times necessary for each operation per trip: port time, T_p, harvesting time, T_H, the sailing time, T_S, and waiting time T_w.

- Power and harvest parameters

  To determine additional requirements for equipment and transport arrangement the different power consumptions are calculated. If the system consists of a line substrate additional harvesting information needs to be presented to help with engineering of the concept.

- Fixed and variable costs, totals and specific costs

  All the costs need to be presented to show how the total harvesting costs are calculated. With the yield it is possible to determine the specific costs per ton, which makes it easier to compare different systems

7.5.3 Data visualization

Data visualization is done in order to effectively evaluate the results of the model. This section describes the different methods that are used and briefly explains what is necessary for an effective output. This covers the sub goal to illustrate the costs of the harvest and deployment with regards to the total production chain. To achieve this, Pie charts, 3D scatter plots, 2D scatterplots and surf plots are used in both Matlab and Excel.

Matlab matrix visualisations

Matlab is mainly used to produce 3D plots to explain the functionality of the model and visualize the optimization. Examples of 3D scatter plots and surf plots are covered in figure 48 and 49 in chapter 7.3.1. A conversion is necessary to build up to convert surf plots into scatter plots, but will not be discussed here.

Chain costs

The chain costs are divided in the following 6 main processes: Nursery, Installation, Deployment, Harvest, Drying and Packaging. In order to compare different cultivation techniques and related different process chains pie charts are used. This will make it easy to see which process dominates the chain, and were improvements could have the most results.

Operational cost build up

The build-up of operational costs is used similarly as the chain cost, to see to which degree the different parameters influence the different costs. Five main expenses can be derived being: Rent (Transport capacity), Total Fuel, Personnel, Equipment and Harbour fees. This is however not a static build up since it is dependent on the three variables of the model (Days, Trips and Speed). Usually these are speed dependent graphs, where an optimum is expected to be found between the sailing speed and related fuel cost, and capital and operational costs of the vessel (in this case related to the harvesting speed. To see the dependency between costs and speed the harvesting days and the number of trips should be fixed. Based on the output calculations this results in a fixed amount of harbour fees and personnel cost. The personnel costs could be related to the harvesting speed but this is currently left out of the scope.

7.6 Specialized vessel comparison analysis

This section illustrates the added data to the model to be able to make a comparison between rental equipment and investments in a specialized vessel. Using ship design literature an attempt is done to estimate rough dimensions and a relating new building price. With investment data it is possible to determine an average day rate in order to compare the price per harvested ton.

7.6.1 Generating a specialized vessel

To start the comparison between the rental price calculated from the optimization model in Matlab and a specialized newly build vessel, more details are required to compare the costs. The goal of this section is to describe the method to determine the day rate for a vessel. To determine the capital cost and help to conceptualize this vessel it is important to determine the dimensions. This often starts with determining the length of the vessel. According to Schneekluth & Bertram (1998), there are three ways to determine the length of the vessel based on its predicted capacity and speed:

1. *Formulae derived from economic efficiency calculations (Schneekluth's formula).*
2. *Formulae and diagrams based on the statistics of built ships.*
3. *Control procedures which limit, rather than determine, the length.*

Due to the characteristics of the vessel (especially low speeds) the formulas in (Schneekluth & Bertram, 1998) vary largely.

Table 24 Determining vessel length (Schneekluth & Bertram, 1998)

Used Formula	Length ($Dwt = 2400t,\ \Delta = 3552t,\ V = 6kn$)
Schneekluth	58.3 m
Ayre	68 m
Posdunine	62.2 m
Völker	54 m

Another way to determine the dimensions is using a set of predefined ratios. These could be taken from reference ships, similar to the ones used to determine the admiralty coefficient in formula 2.2. To determine the principal dimensions in the model the following ratios and formulas are used:

Expected Block Coefficient	cb	0.86
Length/Breadth Ratio	$\tau_L = l/b$	6.5
Breadth/Depth Ratio	$\tau_B = b/d$	2.5
Depl/Dwt Ratio	$\tau_\Delta = \Delta/Dwt$	1.48

With the required cargo capacity known (DWT) it is possible to determine the LBT

(3.1) $$LBT = Dwt * \tau_\Delta * cb$$

The LBT could also be found by using

(3.2) $$LBT = l * \frac{l}{\tau_L} * \frac{l}{\tau_B * \tau_L}$$

Using the goal seek function in Excel it is possible to calculate the required length matching the calculated LBT using the deadweight.

Additionally a check can be done on the interference of bow and stern wave systems according to the Froude number. Unfavourable Froude numbers with mutual reinforcement between bow and stern wave systems should be avoided. The following formula should be as close to an integer as possible:

(3.3) $$\frac{L'}{\Lambda} = \frac{g * L'}{V^2 * 2\pi}$$

Again, due to the low predicted speeds it is not a dominant factor. If a scenario requires higher speeds, this might change.

7.6.2 Determine related costs

New build price

There are multiple ways to determine the new build price of a vessel based on its dimensions. Aside from the construction costs the new build price is also dependant on market conditions. In this model the new build prize is determined on the following factors with their dependencies in brackets: Casco (dimensions), Machinery (Power), Accommodation (Crew), Towing/Equipment (Winch Power).

(3.4) $$C_{NB} = LBT * C_{LBT} + (P + PA + KW) * C_{ER} + Crew * C_{AC} + F_{wi} * C_{WI}$$

With the new build price it is now possible to divide the capital costs in time based intervals. Dependent on the financing arrangement, part of the ship has to be paid from equity, where other parts will have to be loaned. The following section briefly illustrates the factors.

Equity

Equity is the amount the company is investing from its own balances. Part of this would have to come from the company, a private equity firm, a venture capital firm or an angel investor. Part of this could also come from subsidies. A percentage is usually applied based on the new built price.

Loan and interest

In order to pay for the remainder of the harvester a company would have to take a long term loan with a bank. The loan necessary for the purchase of the ship will be for the remaining part of the new build price. It is possible to argue whether there is more money required upfront to pay the operating costs for the first couple of months. However it is assumed that this will even out in the first year and is therefore not applied in the model. The interest rate for the loan can be set in the input model, as well as the repayment period.

Depreciation

Depreciation is the loss of value of the harvester. In the model this is presented through a remaining price at the end of a certain period. To determine the annual depreciation the difference between the new build price and the remaining value is divided by the total numbers of years.

Operational Costs

These are all the costs directly associated with sailing the vessel on a certain route. The operational costs are based on a total number of operating days per year. A description of each expense can be found in table 25.

Table 25 Operational Costs

Expense	Description
Fuel Costs	The yearly fuel costs can be determined using the total number of operating days and the average daily fuel consumption.
Port Fees, Canal dues	The harbour fees is similar to the one calculated in formula 2.12
Cargo Handling	Cargo handling is added in the port fee.
Operational expenses	The costs of running the vessels. The operational costs of a vessel comprise of costs that are independent of the voyage, but dependent on a vessel being active or not.
Crewing costs	The crew of the harvesting vessel can be determined on the number of shifts. Depending on the contracts with the crew, and the length of both the harvesting and the deployment season, the company would need more crew to permanently man the vessel. This will however not be taken into consideration for these calculations.
Maintenance and repair	The yearly expected maintenance costs are based on a percentage of the new building price.
Insurance and Administration	The insurance and administration fees are left out of the model. These are relatively small and are not part of the rental model, which benefits comparison between the two.

7.6.3 Determining the day rate

With all the previously described expenses it is possible to determine annual running costs. To attract possible investors careful thought has to be taken to determine a day rate with a reasonable return on investment (ROI). Because the risks of investment are still quite high investors are also interested in discounted ROI and discounted cash flow. Though determining the correct utilization rate is very complex, taking in account the market and future trends, it is simplified by determining the net income as a percentage (X) of the total average costs.

$$(4.1)\ \ Total\ annual\ costs = \frac{Total\ financing\ costs}{financing\ period} + Crew + Maintenance + Fuel + Harbour\ fees$$

$$(4.2)\ \ Dayrate = \frac{x * total\ annual\ costs + av.interest + depreciation + OPEX}{operational\ days}$$

It is now possible to calculate the cash flow over the entire operating period of the cultivator. With this cash flow the following investment ratios can be calculated, to see whether the day rate is profitable.

$$(4.3)\ \ ROI = \frac{Gain\ from\ investment - Cost\ of\ investment}{Cost\ of\ investment}$$

Result on investment is a performance measure used to evaluate the efficiency of an investment or to compare the efficiency of a number of different investments. To calculate ROI, the benefit (return) of an investment is divided by the cost of the investment; the result is expressed as a percentage or a ratio.

To calculate the year-over-year growth rate of an investment over a specified period of time the compound annual growth rate (CAGR) is calculated. The compound annual growth rate is calculated by taking the nth root of the total percentage growth rate, where n is the number of years in the period being considered.

$$(4.4)\ CAGR = \left(\frac{Ending\ value}{Beginning\ value}\right)^{\left(\frac{1}{t}\right)} - 1$$

To account for differences in valuation economist often use the term present value. It is the value of an expected income stream determined as of the date of valuation. Taking into account a specific discount rate the profitability of an investment can be analysed. The sum of the present values is often described as Net present value (NPV).

$$(4.5)\ NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0$$

where:

C_t = net cash inflow during the period
C_0 = initial investment
r = discount rate, and
t = number of time periods

With the net present value it is now possible to calculate a discounted ROI and CAGR. These values are used to determine whether the chosen cost percentage (x) suffices for the investment to be sufficient. Another aspect that will be taken into account is that the cash flow should be positive at all times in order to prevent the use of additional loans.

With these tools implemented it is possible to include the comparison between rented equipment and a specialized vessel. In scenario C of chapter 8 the implementation will be discussed.

7.7 Conclusion

The model developed in this chapter has achieved all the required goals listed in chapter 7.2. Separating the model into different modules (supply, demand and costs) as a basis for the domain model helped structuring and the development significantly. Using the domain model and various production models, an exploitation model has been developed that is capable to carry out the prescribed tasks and can form the basis of more complex models. Functions and parameters can be added to increase modelling accuracy in the different aspects of the model.

The separation of the trips in four operational aspects meant that specific parameters could be developed in order to aid the designer or discover technological or operational limits that affect the costs. More on these limits will be discussed in the different scenarios in chapter 8. The decision to base the optimization on the costs instead of the profit was made since the calculations will be made with finite amounts of seaweed. Through the use of a flow chart different stages were introduced to simplify the modelling decisions and increase understanding of the working principles for future use. To increase accuracy in determining the build-up of costs, the various expenses were separated and made time and configuration dependent. This separation allows future users to add operational solutions and compare the effects.

Because the model is used to determine multiple scenarios and concepts, additional visualisations were introduced and key parameters were separated. To develop comparisons between modular equipment and the use of specialized vessels, investment parameters where introduced to produce a fair day rate and related price per ton. In the next chapter the functionalities of the model framework will be demonstrated through the use of 3 different scenarios.

The model has seen various iterations based on earlier calculations. Though a model is never finished, it has been decided that the current model suffices the general needs. The main goal, to assess the economic feasibility of various operational scenarios in order to support operational and design decisions, has been met. Possible alterations or additional functionalities are discussed in the recommendations, after evaluation through the scenarios.

8

Cultivation scenarios

With the developed exploitation model the validity of the model can be determined and its capabilities can be demonstrated. To do this a number of scenarios have been created. There are three different scenarios, varying in scale and cultivation techniques. Each scenario starts with a brief introduction, in which the situation is explained and the main problem is put forward. This is followed by a number of goals established to divide the problem in specific, measurable and realistic goals.

The introduction is followed by a number of key data inputs relevant to separate the main requirements from the scenario from other requirements and limits. The data is put in excel according the input flowchart, and the matlab script is being run, editing the output file with the results. The results are discussed and visualised in the next section. Occasionally iterations are described to come towards a valid calculation. In the conclusion the scenario is summarized.

Aside from the validity of the model it is also of interest to see whether the design decisions and assumptions that led to the model are also valid in different scenarios. This could determine if there are specific areas by which the concept, or something in the rest of the process chain needs additional attention in future development. Based on experience from the calculations, a list of recommendations is made to aid in future alterations of the model.

8.1 Scenario A: Demonstration in the Norwegian Fjords

8.1.1 Introduction

Based on the business case given by Hortimare and discussed in chapter 5.3.2, the first scenario will involve the cultivation of seaweed near a fish farm in the Norwegian fjords. The main objective of this scenario is to find the optimum harvester and related operational profile in combination with design equipment specifications. Since this business case has been calculated by Hortimare, it will be interesting to see whether the estimated harvesting costs will match.

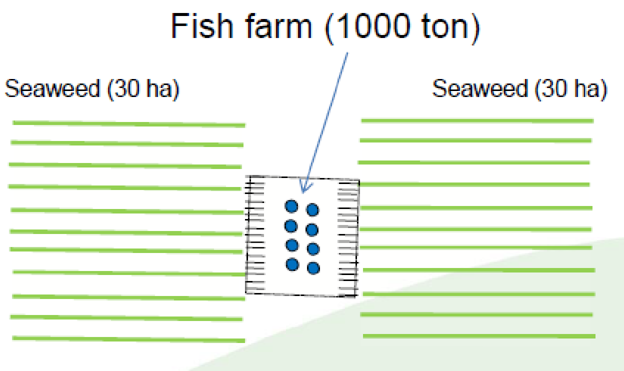


Figure 61 Illustration of scenario A

8.1.2 Goals

The main goal of this scenario is to determine the validity of the model to calculate an optimum harvester configuration and related operational profile with the given design restrictions. Based on initial calculations with the model, it is safe to say that an optimum can already be generated, as will be demonstrated early in this scenario. To see whether the answer is relevant the number of sub goals will thereby be based on the accuracy of the model and the effects that input alterations have on the outcome in order to say something about the sensitivity of the output.

Sub goals.

- Illustrate the effect of different sailing speeds on the total costs.
- Illustrate the effect of adding a single day on the total costs and operational profile.
- Determine the effects of doubling the harvest speed.
- Determine and illustrate the harvesting costs in relation with an expected production chain.
- Illustrate the effects of using different resolutions on the calculation time and the accuracy of the outcome. Determine based on these effects a respectable model resolution.

The results are used to explain the basis calculations used to determine the optimum solution and evaluate whether the results are acceptable and explicable.

8.1.3 Input

To briefly summarize the scenario, a single ship/harvester will harvest the required 60 ha. farm, within the permissible window of 21 harvesting days. The farm is constructed of patches with lines, estimations indicate a maximum length of 150m, breadth to be determined. The operation will run 24 hours per day with two different crews each doing a 12 hour shift each day. The equipment is limited to an average harvest speed of 100 t/hr. Average harvesting speeds includes manoeuvring, attaching and detaching times. To simulate limited availability of transport capacity, the vessels capacity is limited to 3000t and a maximum speed of 12 kn. Since the entire supply chain is under development harbour facilities are limited to a discharge rate of 200 t/hr equivalent to 10 fully loaded 20' containers per hour.

The key inputs of the scenario are covered in the table 26. The complete input file is covered in Appendix S.

Table 26 Key input data scenario A

Key data input	
Species	Saccharina latisima
Farm Area	60 ha.
Patch Size	0.1 – 10 ha.
Max no. harvest days	21
Work days (8/12/24):	24 hr/day
Shifts:	2
Offload Capacity Harbour	200 t/hr
Distance Farm - Harbour	20 nm
Limitations:	
Max. Capacity vessel	3000 t
Max. no. of vessels	1
Max. speed:	12 kn
Max. average harvest speed:	100 t/hr

8.1.4 Calculations and outputs

To cover all the sub goals the calculations are done in two phases. The first phase determines the optimal solution, and requires two calculations in order to determine the optimal resolution and calculation speed. The scenarios are calculated on the same pc (I5 @ 4.5 Ghz, 8gb ram, 64-bit) to see the effects of the resolution. The second phase involves using the capacity and the number of harvesting days from the previously determined optimum and use these as fixed inputs in an additional calculations. With this it is possible to use a 2D scatter plot in order to illustrate the build-up of the costs.

Cost optimization (low resolution)

The first run is done at a low resolution with a step size of 0.5 harvesting days and 0.5 days per trip. The calculation took 43 seconds (using Matlab's built-in profiler) where it could be noted that the reading (57 times / 23 s) and loading (18 times / 7 s) of excel values significantly increases calculation time. Since this accounts for more than half of the total calculation time, it is worth mentioning that optimizations with regard to the excel conversion time are worthwhile; more on this in the conclusion.

As discussed in chapter 7.5.2 the key operational parameters are summarized as displayed in table 27.

Table 27 Scenario low resolution operational profile parameters

Item	Value	Unit	Duration [hr]	Percentage
Harvesting days required	**12**	days		
No. of trips per day	**0,5**	Tr/day		
Total trips	**6**			
Vessel capacity	**2000**	ton		
Min. Sailing Speed required	**3,6**	kn		
Time sailing	**0,463**	days	11:06:40	23%
Time in port	**0,417**	days	10:00:00	21%
Time waiting	**0,085**	days	02:02:24	4%
Time harvesting	**1,022**	days	24:50:56	52%

The parameters are within the set limits. It can be observed that the determined sailing speed is close to the minimum limit. The second phase of the calculation is related to the cost build up and various sailing speeds, and will illustrate why this is the case.

Since the first scenario involves harvesting with line based substrate it possible to calculate additional design parameters, as displayed in the table below.

Key data output [Wet Mass]	
Average harvesting speed	80.5 t/hr
Added time per patch	276 sec
Actual required harvest speed	113.84 t/hr
Required individual winch speed	0.45 m/sec
Required individual pulling power	1.2 t
Expected cost	
Rent	€ 26.669,29
Fuel	€ 26.634,88
Personnel	€ 18.796,67
Equipment	€ 26.342,82
Harbour costs	€ 25.800,00
Total costs	€ 124.243,65
Costs per ton	**€ 10,35**

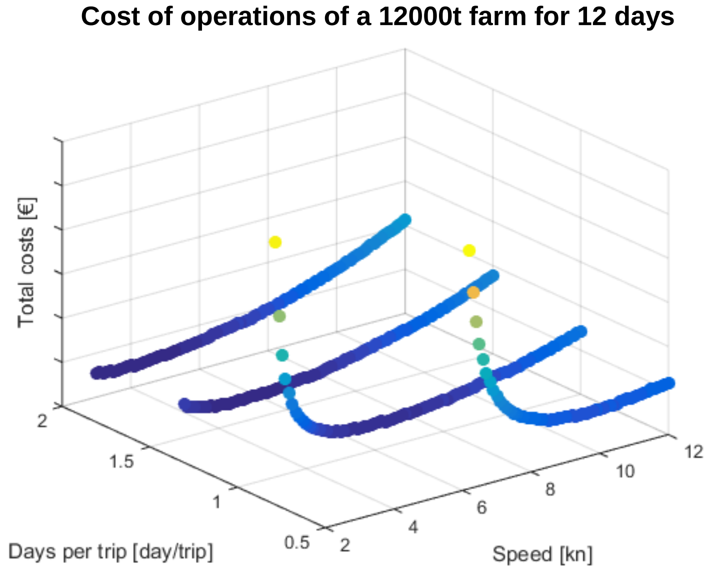


Figure 62 3D Scatter plot of low resolution total harvesting costs at fixed harvest days and capacity

The first three parameters are based on the configuration of the patch. The average speed is based on the available harvest time. The patch contains 12 substrate lines and the equipment is based on a 6 drum configuration. Using manoeuvring time of 36 seconds (based on the distance between the patch) and attachment an detachment times of 60 seconds respectively, this results in an additional time of 276 seconds and an actual required harvest speed of 113.84 t/hr. For a 6 drum system this means a required line haul speed of 0.45 m/sec and a winch power of 1.2t per line. The other data relate to the expected operational costs. The optimum and rough resolution is illustrated in the figure 62.

Cost optimization (high resolution)

The second run is done at a resolution with a step size of 0.125 harvesting days (3 hours) and 0.125 days per trip (trip intervals of 3 hours). Theoretically this requires 16 times more calculation time, which can also be seen in a calculation time of 220 second, significantly (5 times) longer than the rough resolution. Aside from the calculation time, the key output parameters do not differ much (see table 28). Instead of 12 days it now takes 11.25 days and the capacity remained the same. The impact on the operational costs will be discussed on the next page.

Table 28 Key operational parameters scenario A (high resolution)

Item	Value	Unit	Duration [hr]	Percentage
Harvesting days required	**11,25**	days		
No. of trips per day	**0,533**	tr/day	**45:00:00**	
Total trips	**6**	days		
Vessel capacity	**2000**	ton		
Min. Sailing Speed required	**4,2**	kn		
Time sailing	**0,397**	days	**09:31:26**	**21%**
Time in port	**0,417**	days	**10:00:00**	**22%**
Time waiting	**0,080**	days	**01:54:45**	**4%**
Time harvesting	**0,982**	days	**23:33:49**	**52%**

Key data output [Wet Mass]	
Average harvesting speed	84.9 t/hr
Added time per patch	276 sec
Actual required harvest speed	122.84 t/hr
Required individual winch speed	0.486 m/sec
Required individual pulling power	1.3 t
Expected cost	
Rent	€ 27.783,59
Fuel	€ 26.634,88
Personnel	€ 17.621,87
Equipment	€ 26.566,26
Max. speed:	€ 25.800,00
Total costs	€ 124.186,86
Costs per ton	**€ 10,35**

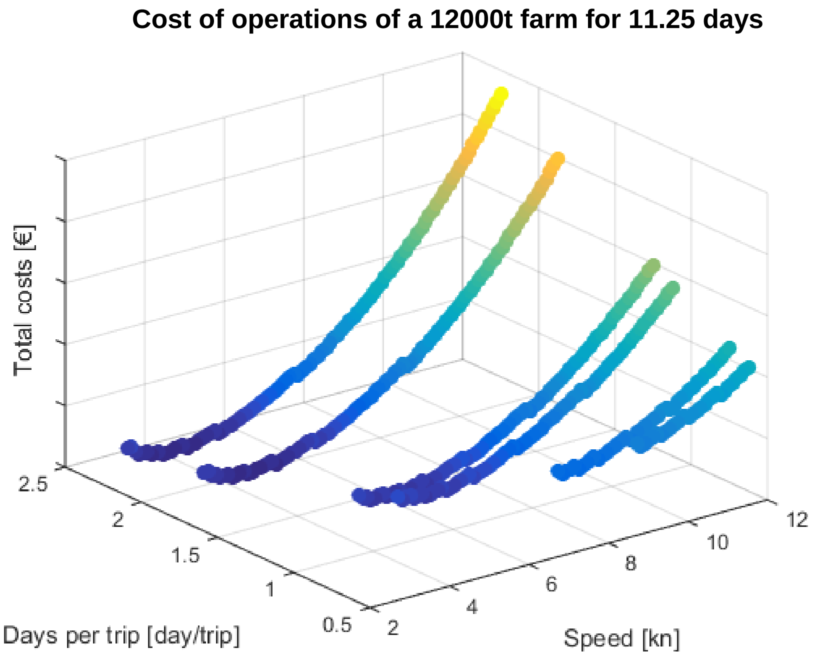


Figure 63 3D Scatter plot of high resolution total harvesting costs at fixed harvest days and capacity

The little difference in operational parameters also reflects in the difference in costs and equipment requirements. The total operational costs differ only € 56,79 (€ 124.243,65 - € 124.186,86). The required harvesting speed is 4.4 t/hr higher (5.5% increase). More on these results in the conclusion of scenario A.

Second calculation with harvest days and capacity fixed

To illustrate how the total operational costs are build up the scenario is run with a fixed capacity of 2000t and a fixed number of days of 12 (figure 64).

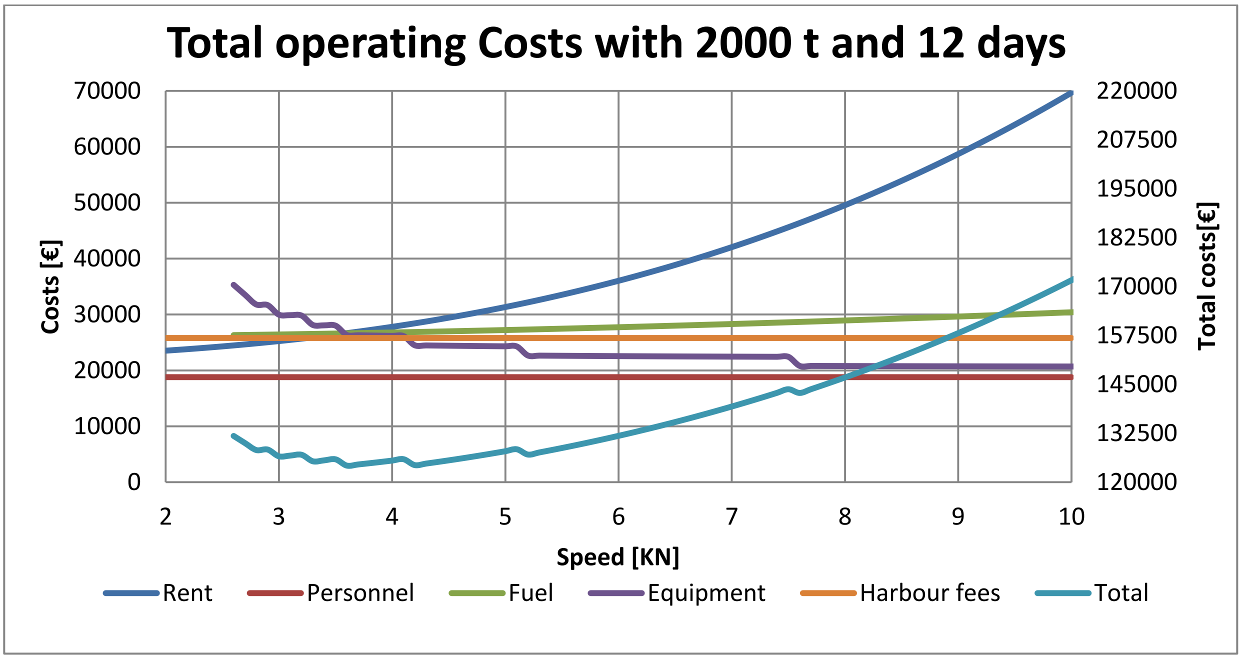


Figure 64 Scenario A cost build up

As can be seen in figure 64 there are a number of fixed costs. Since the capacity is fixed, the time in port is a fixed value and the fixed amount of harvesting days relate to a fixed amount of personnel costs. The equipment costs lowers with the increased speed as the harvesting rates rapidly decline; the hiccups are a result of the ceiling function in the required winch power in order to calculate with tenths of tons accuracy. The costs that affect the raising costs at higher speeds are related to the required power for the rental equipment. With the current input this heavily affects sailing speed in respect to harvesting speeds

Calculating chain costs.

With the known harvesting costs it is now possible to determine the chain costs. The results can be seen in the table and pie chart below.

CHAIN DATA			
	Wet	Dry	
Nursery	€ 45.45	€ 454.55	/ton
Installation		€ 150.00	/ton
Deployment	€ 8.28	€ 82.83	/ton
Harvest	€ 10.35	€ 103.54	/ton
Drying		€ 80.00	/ton
Packaging		€ 60.00	/ton
Total		**€ 930.91**	**/ton**
Water percentage		90%	

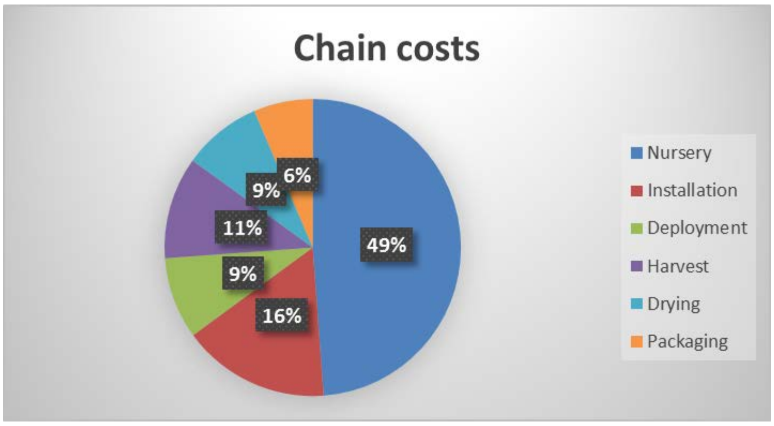


Figure 65 Pie Chart of the production chain costs

As clearly illustrated the offshore cultivation of seaweed roughly takes up 36% of the production costs (20% operational and 16% installation costs). Compared to the expected production costs predicted in chapter 4.1 this coincides with the highest scenario (€ 950/ton). Even though the seedling costs are slightly higher than the scenario, they are within the expected range. As mentioned before, the costs at the nursery have a large effect on the total price (49%). Decreasing nursery time through novel deployment methods could significantly lower production costs.

It needs to be told that drying and packaging has not been taken into account in that prediction. The water percentage also plays a big role in the expected production costs. Lowering to 85% results is a reduction in costs to € 884.36 /ton.

The installation costs have been taken from the lower prize estimate, based on the fact that shallower and calmer water is selected for this pilot.

8.1.5 Conclusions

The overall conclusion is that the model predicts the expected costs rather well. It is remarkable to see how close the estimated costs relate to the estimated costs in the Wageningen Report. The optimized costs of €10.35 per ton DM are very close to the predictions of €104. - per ton DM that is noted in the report. The model also allows for flexibility in its use and application. This is further demonstrated by answering the sub goals below:

1. Resolution

As can be seen from the calculations the effects that come from altering the resolution are not large. While it took 5 times longer to calculate, the optimal solution with a higher resolution was only €56,70 cheaper than the one with the lower resolution. With a yield of 12.000 ton and costs well above €120.000,- these effects are little. Yet it depends on what is requested. If it possible to limit a number of design parameters, or when more parameters are fixed and/or known, working with a higher resolution could boast an advantage. Since all the costs are based on approximates it is not advised to work with a higher resolution than used in the first calculation.

2. Shorten the harvesting days.

The effect of changing the amount of harvesting days with a small amount are limited, as can be seen from the calculations with different resolutions. If indeed necessary, due to conditions or weather expectations, the effects could still be calculated by limiting the harvesting days in the input.

3. Doubling the harvesting speed.

This question has relevance to the construction of the harvesting device and the necessity to increase the speed. The optimal average harvesting speed is between 80.5 and 85 tons. If this is now limited in the input file to a minimum of 160 tons the results change significantly. The effects on a higher equipment speed could already be seen in the graph attached to the second iteration. Doubling the harvesting speed lowers the optimum to 7.5 harvesting days increases the vessel capacity to 2400 t and increased the total cost to €175,976.76; an increase of €50,000. -. Since the manoeuvre and attachment speed is similar, the required actual harvesting increased significantly, further increasing the required winch power from 1.2t to 6.2t.

4. Effects of sailing speeds

Varying the speed will only affect the harvesting time and sailing time. A small increase or decrease doesn't influence the price much.

5. Chain costs

As can be seen from the pie graph the harvest cost are still a small part of the expected chain costs (11%). Even doubling the harvesting speed would only increase the cost within the entire chain with 4%.

Remarks

The calculation time could be decreased by optimizing the read and write process in excel. This could be optimized by reading matrixes instead of single values and converting these in excel to single digits. This will avoid unnecessary computation. The algorithm could be changed to avoid costly functions, and recomputation is to be avoided by storing results for future use.

8.2 Scenario B: Experimentation on the North Sea.

8.2.1 Introduction

The first scenario has calculated an optimum solution and the framework proved to deliver the necessary data, within acceptable boundaries. However, the scenario was limited in a number of ways; it did find an optimum for the specific operation, what it didn't do is find an optimum in system design choices. Though information is limited towards specie data and substrate development it is interesting to see whether the framework can deal with this information and see whether it can help in future design decisions. It must be stated that there is no additional code to find an optimum between species, substrates and cultivation methods. Though this can be implemented in a later stage, the current optimizations are based on varying the input data and running the model a multitude of times.

Figure 66 Illustration of stichting Noordzee Boerderij

The idea to mix species and substrates is not new. The goal of Stichting Noordzeeboerderij, an organisation instituted to combine forces in the development of seaweed cultivation in the North Sea, is interwoven in this scenario. One of their concepts is also described in chapter 6.2.1. Much like the agricultural sector a century ago the organization wants to develop a farm with a multitude of substrates and species to research optimal cultivation conditions. Having permission from the local government to start experimenting on the North Sea, the Stichting is looking towards investors to develop small demonstration farms.

8.2.2 Goals

The main goal of the North Sea scenario is:

To demonstrate the possibility to compare multiple scenarios by diversifying main operational input parameters such as: substrates, species and cultivation techniques.

In order to demonstrate this, and add relevance to the goals, a number of sub goals and research questions are discussed below.

The following Questions arise with regards to comparison of different cultivation techniques:

- What is required to create variations in cultivation methods?
- Is it possible to distinct an advantageous method through comparison?

Related interesting topics could be the simultaneous cultivation of different seaweed species. With relate questions such as:

- Which species and cultivation methods could be combined?
- And related to that: What if the individual value per specie is lower, yet combining species increases the number of harvest days and lowers the costs due to an increased usability/occupation.

8.2.3 Input selection

In order to achieve the main goal a large variation in inputs is required. Chapter 7.3 illustrates how this is interwoven in the input file. In order to understand which inputs are used for this scenario the inputs are divided in three different categories: constants, limits and variable data. To make a fair comparison between the species and techniques a number of key inputs are fixed.

Constant data

The following constant parameters are similar in all calculations and are based on the following description:

At a remote location 10 nm offshore a seaweed demonstration farm with an effective farm surface of 100 ha or 1 km^2 is available to test different seaweed cultivation configurations. The farm consists of 100 patches of 1 ha in different configurations. The harbour capacity is estimated at an offloading rate of 400t/hr, based on mobile / small scale bulk offloading technology (Siwertell, 2015). There is a preference from the stichting Noordzeeboerderij to work one shift a day of maximum 12 hours. To illustrate the effects one comparative calculation will be made with a 24 hr, 2 shift day.

Limits

The following limits are used:

- Limit in vessel capacity of 5000 ton due to manoeuvring and harbour restrictions.
- Minimum and maximum speed of 3 and 12 knots respectively.
- Average harvest speed is limited to 200 t/hr.

Variable data

As per introduction the model needs to run a number of different calculations to make an indirect comparison. Table 29 illustrates the variable cultivation inputs for the scenario.

Table 29 Cultivation parameters scenario B

Substrates	Species	Cultivation method
Line	Sachharina latissima	Annual
Net	Laminaria digitata	Perennial
Cloth	Ulva lactusa	Vegetative cultivation

As can be seen, in the table there would be 27 variations in the calculations, resulting in 27 different input files, even without regarding combinations of systems on one farm. To limit calculation and evaluation time the following presumptions are made:

- With regard to the different substrates.

It could be argued that the cloth substrate is similar to a net, only with decreased grid sized and lowered yield correction. Since the use of cloth has only been used on a handful of pilots it is hard to predict the yield. According to W. Brandenburg (2014, pers. comm., 26 Oct.), the increased density reduces solar input and decreases the yield significantly. This also means increased nursery costs, since more seedlings need to be used in order to increase the yield. The same happens with a net. There for the cloth size is not used, yet it is already integrated in the input file. The yield is reduced with a correction factor that can be adjusted in the data sheet in the input file.

The complete number of changes in the input can be seen in table 30. This table describes which cells in excel change and what needs to be filled in.

Table 30 Variation in input cells for substrate parameters scenario B

Substrate	Line	Net	Cloth
Input Cell (Excel)			
D17	Total amount of line	Yield correction	Yield correction
D23	Length of Lines	Length	Length
D24	Number of lines	Breadth	Breadth
D25	Width between lines	Grid size	
D26	Total Line length	Total Line length	

To make a fair comparison the line yields are used in the calculations; the yield is based on kg/m instead of an average t/ha. Using the net as a substrate, the total yield is automatically adjusted to the line yield from the data multiplied by the total line length and the yield correction.

- With regard to different species.

The variations in substrate and annual or perennial cultivation are done with one species (Saccharina). This will suffice to demonstrate the ability to handle the specific differences. To equalize the patch sizes, the difference in surface area has to be adapted in the harvest parameters of the input sheet.

- With regard to general cultivation techniques.

Vegetative cultivation has up until now only been officially done with Ulva, though natural harvest is based on this principle. To simulate these effects the brown weeds have a harvesting season of 20 days where Ulva's season is spread out over one entire summer season (100 days).

This will also have an effect on the chain costs for Ulva. With vegetative growth, there is little feed coming from the nursery. It is expected that the initial yield comes from the nursery, and 10% thereafter to make up for lost yield. The variable input data and sub scenarios are summarized in table 31.

Table 31 key input data Scenario B

Key data input	Saccharina	Saccharina	Saccharina	Laminaria	Ulva	Saccharina
Substrate type	Line	Line	Net	Line	Line	Line
Cultivation	Annual	Annual	Annual	Annual	Vegatative 5 harv./yr	Perrenial
Farm Area	100 ha.					
Patch Size	1 ha.					
Max no. harvest days	20	20	20	20	**5*7**	20
Expected total harvest WM	23400 t	23400 t	28185.3 t	16000 t	**5*12000t**	**1.5*23400t**
Work days:	**12 hours**	24 hours				
Offload Capacity Harbour	400 t/hr					
Distance Farm - Harbour	10 nm					

8.2.4 Calculations and results

Optimizations

The first batch of calculations revealed that a few adjustments in the model where necessary to increase the accuracy and feasibility of the model:

1. The equipment costs related to harvesting a line system were much higher in comparison with a net system of similar proportions, which resulted in an unfair comparison. This is rectified by altering the calculation of the equipment costs when using a net system and the related input values as can be seen in chapter 7.4.2 where formula 2.13 is changed to 2.13a.

2. The increased patch sizes lead to increasing attachment and detachment times (see formula 1.13), resulting in negative winch speeds in formula 2.14. Therefor a limit was introduced to this value ($v_{winch} > 0$ m/s).

With the necessary changes to the model, the results of the sub scenarios can now be calculated and the results can be seen in table 32.

Table 32 Key parameters of the different cultivation scenarios

Key data output	Saccharina 24 hr	Saccharina 12 hr	Saccharina	Laminaria	Ulva	Saccharina 24 hr
Substrate type	Line	Line	Net	Line	Line	Line
Cultivation	Annual	Annual	Annual	Annual	Vegatative 5 harvests/yr	Perrenial
Harv. days	19.5	20	20	20	20	20
Capacity vessel	1800 t	4680 t	2822 t	4000 t	2400 t	3510 t
Trips	13	5	10	4	5	10
Speed required	3.7	9.8	11.1	6.3	4.6	4.4
Av. Harvest speed [t/hr]	73.276	145.255	199.817	90.344	67.393	107.538
Time sailing	05:24:19	02:02:27	01:48:06	03:10:29	04:20:52	04:32:44
Time in port	04:30:00	11:42:00	07:03:18	10:00:00	06:00:00	08:46:30
Time waiting	01:31:48	02:02:24	01:01:12	02:33:00	02:02:24	02:02:24
Time harvesting	24:33:53	32:13:09	14:07:23	44:16:31	25:36:44	32:38:22
Cost per ton WM	7.62	22.7	16.97	15.30	9.39	8.75

The most noteworthy observations are stated below:

When the capacity of the cultivation module is increased with double the amount of winches, the overall time lost on manoeuvring, attaching and detaching significantly lowers. Therefor the required actual harvesting speed lowers as well. With current drag calculations, this resulted in needing only a third of the required winch power, drastically lowering equipment cost. Overall this reduced the total harvest cost by 50%.

With 12 hour working days the equipment costs rise enormously, mostly due to the required harvesting speeds. The average harvest speed only tells part of the story, the actual harvesting speed rises more due to the manoeuvring, attachment and detachment times staying similar. Looking at the configuration of the concept and limitations in winch speeds it is not even possible to use 12 hour days, unless more harvesting systems are being used.

The drag factor has a big influence on the outcome of the equipment costs. Since the relationship between the surface area and the force is based on the research from Buck and Buchholz (2005), the only available tool was a graph from their research (Depicting the relation between drag force, surface area and current speed). Though the relation could be derived in several exponential formulas it has been decided, based on the frequency of usage, to manually transform this data and fill in the force. Neglecting adjustments in frond size, results in large differences in equipment cost and overall costs. An example is the difference between Saccharina and Ulva. Ulva has double the amount of fronds per meter increasing the drag, however the surface area is roughly 10 times smaller resulting in a friction force of 0.2N instead of 2.67N for Saccharina, for one frond of seaweed at a current speed of 1m/s.

If more data was available with regard to the expected drag force of larger canopies, accuracy of expected winch power can be enhanced, resulting in more adequate equipment costs. The used reduction factor of 0.38 is only based on a small size canopy. When the size increases the overall drag is expected to be lower.

Chain costs

To determine the effects of the various cultivation techniques the chain costs are calculated. The following chain costs are expected from three different cultivation techniques: annual, vegetative and perennial (table 33).
Seedlings for a 100 ha farm are estimated at € 1.000.000 to provide. Taking into account possible losses during vegetative cultivation this is increased to € 1.400.000. Installation costs are based on a fixed amount per year (€ 350.000) with a ten percent increase due to the fact that it is used more for vegetative cultivation.

Table 33 Expected chain costs cultivation techniques scenario B

Chain costs per year		Saccharina 24 hr	Ulva	Saccharina Perennial
Yield per year	t DM	2340	6000	1755
Nursery	€/t DM	€ 427,35	€ 233,30	€ 284,90
Installation	€/t DM	€ 149,50	€ 64,16	€ 199,43
Harvest costs	€/t DM	€ 76,20	€ 93,90	€ 87,50
Deployment	€/t DM	€ 50,00	€ 30,00	€ 33,30
Drying	€/t DM	€ 80,00	€ 80,00	€ 80,00
Packaging	€/t DM	€ 60,00	€ 60,00	€ 60,00
Total / ton / yr		€ 843,05	€ 561,36	€ 745,13

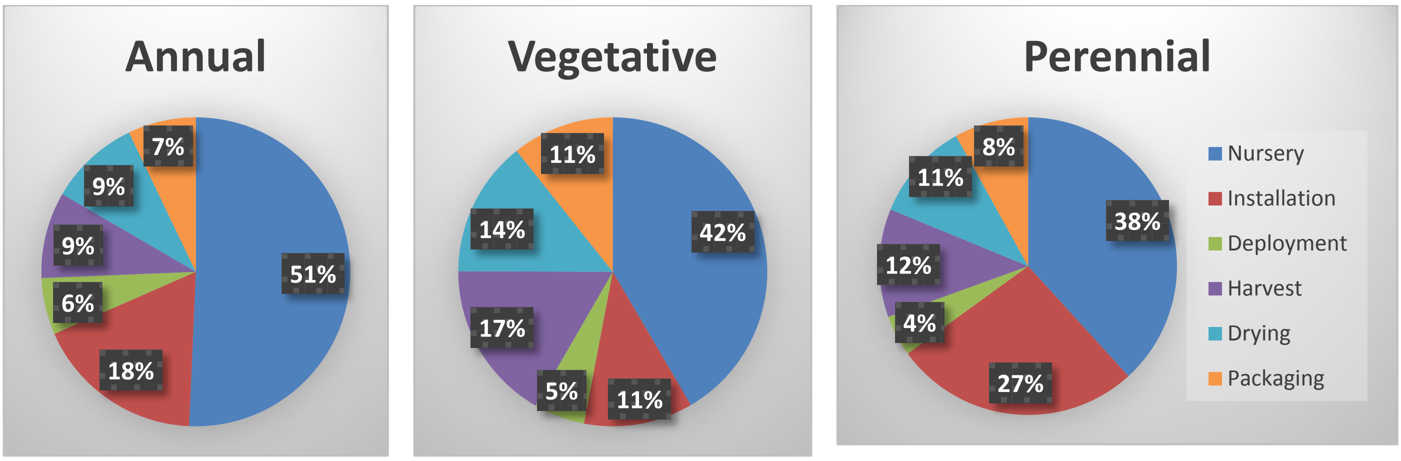


Figure 67 Pie charts of chain costs scenario B

Looking at the pie charts it can be seen that there is not a big difference between annual and perennial harvest. There is a bigger difference if compared to vegetative cultivation. With increased harvesting and lower total costs the harvesting percentage increases. The Nursery remains to be dominating the overall costs.

8.2.5 Conclusion

The model is proven able to compare multiple scenarios by diversifying cultivation parameters, meeting the main goal. Based on the results from the various sub-scenarios a clear distinction in the operational profile and running costs can be seen between the various substrates, cultivation techniques and species used. These results also demonstrate meeting the requirement in the level of disaggregation in the data input to run various scenarios.

As the scale increases the limit in harvesting days becomes an issue. The need for continuous operation is very clear based on the difference in costs between a 12 and a 24 hour operation. This is mainly due to the fact that there is no difference in the harbour operations due to the fixed offloading speed. The harvest speed required nearly doubles (98% increase) and the sailing speed almost triples (165% increase). Based on the input and the model it is easy to advice against 12 hour daily operations or shorter, unless it is deemed necessary. The calculation for a 12 hour day is based on limiting the total time to operate. If a more detailed comparison is needed, sailing back and forth between a rest port or calculating the costs for a crew tender should be added. The first could be done by using the model to optimize for a daily trip taking into account a minimal yield to be harvested per day in order to suffice the limited seasonal requirements.

The use of vegetative cultivation has clear advantages from a cost point of view. Though it might be harder to contain in rough weather increasing technological difficulties, from an operational standpoint this clearly is the most beneficial cultivation technique. The yield could be increased if combined with the cultivation of brown seaweeds earlier in the year. Based on the comparison between Laminaria and Saccharina, the latter boasts a bigger advantage due to the higher expected yield per meter and reduced operational costs.

There are certain cultivation techniques that boast obvious advantages over others, e.g. the amount of operating hours per day and vegetative cultivation. Based on the difference in input data between Laminaria and Saccharina the advantage currently is with Saccharina. This is however, based on very immature data, making it harder to draw a hard conclusion between the two. The same applies with the comparison between the different substrates. There is simply not enough information on yields per area or line. The model has shown that it is possible to make the comparison and as more information from research becomes available can easily be updated.

8.3 Scenario C: Large scale industrial farms using specialized production vessels

8.3.1 Introduction

With the possibility to add variety in the cultivation methods proven in Scenario B, the next step is to predict larger scale farms. According the predictions in chapter 4.1.4 it is possible that farms can increase in sizes of up to 25km^2. Although there are a lot of design and engineering challenges, it is interesting to see whether the tool could provide the operational parameters required for future engineering. A lot of questions remain with regard to operational and investment decisions at this scale. There are several main questions when it comes to these investments:

- At which point is it more interesting to have multiple vessels working instead of one?
- At what point (which amount of operating days) is it interesting to invest in a specialized vessel?
- What are other boundaries that affect the scale increase of the farm?

To determine an optimum with regard to most of these questions the farm size has to be variable. The model doesn't vary farm sizes as of yet, making finding this optimum an iterative process. It is therefore decided that the farm size will remain constant, varying the running costs of operating multiple vessels, to compare these with predicted day rates from a specialized vessel. The questions have been reformulated as follows.

- What effect does scale have on the price? (comparison with other scenarios);
- At which point is it interesting to double or quadruple the capacity / amount of cultivators?
- Does the financial tool provide an adequate way to compare between rental equipment and a specialized vessel?

Figure 68 Expected North Sea Seaweed cultivation in 2022 (Hortimare, 2014)

8.3.2 Goals

The main goal for the large scale scenario is:

To prove the ability of the model to predict parameter differences when operational scale increases, and to be able to accurately compare rental equipment and a specialized vessel.

8.3.3 Input

The following key data inputs can be identified:

Table 34 Key input parameters and limits scenario C

Key data input	
Species	Saccharina latisima
Farm Area	2500 ha.
Patch Size	10 ha.
Max no. harvest days	30
Work days:	24hr
Crew:	2*6
Offload Capacity Harbour	1500 t/hr
Distance Farm - Harbour	40 nm
Limitations:	
Max. Capacity vessel	15000 t
Max. no. of vessels	4
Max. speed:	16 kn
Max. number of winches:	20
Max. calculated av. harvest speed:	290 t/hr

The choice to use 30 harvest days is based on expected improved cultivation techniques and monitoring. A crew of 6 persons is minimal to be expected, harvesting such quantities and operating larger sized equipment. The offload rate is also chosen to have increased significantly due to specialized offload quays in order to minimize time in harbour. To be able to have such a massive farm, outside of commercial and leisure shipping lanes the distance between the farm and the offload harbour has increased to 40 nm. The maximum transport vessel capacity has been set to 15000t. The harvest and transport vessel is still calculated to be the same, only multiple vessel configurations will now be calculated. The increased vessel size allows for multiple modules to be placed alongside, increasing the capacity to 20 winches and a maximum harvest speed of 290 t/hr.

In order to compare the calculated operational cost with a specialized vessel the following financial data is used to determine the annual costs and a positive day rate (table 35).

Table 35 Financial Data used to determine the dayrate

Financial Data		
Annual maintenance	5%	Of NB cost/year
Equity	30%	Of NB cost
Interest rate	5%	/year
Repayment period	10	years
Operational period	15	years
Rest value perc.	20%	Of NB cost

Important for the financial comparison is the amount of working days. Since this has effect on the day rate multiple calculations will be done with different day rates (30,60,90,120).

8.3.4 Calculations and results

The following calculations are based on the use of rental equipment to carry the harvest module alongside and transport the seaweed to shore.

Table 36 Key operational output parameters calculating multiple vessel use for scenario C

Vessels Used	1	2	3	4	5
Key data output	No Outcome Due to limitations in harvesting days and harvesting speed no valid calculation could be made.			Possible	Possible
Harvest days				30	27.5
Capacity vessel				12500 t	9090 t
Trips				10	11
Speed required				4.8 kn	4.6 kn
Av. Harvest speed				284.5	267.395
Time sailing				0.694	0.725
Time in port				0.347	0.253
Time waiting				0.128	0.106
Time harvesting				1.831	1.417
Cost per ton WM				7.80	7.81
Limits				Harvesting speed	

Using the rental model, there was no valid outcome of the model using 1, 2 or 3 vessels due to the capacity and harvest speed restrictions. This can be seen as the first possible solution (using 4 vessels) is close to the maximum harvest speed limit and capacity. Due to the high harbour capacity the time in port is limited allowing for additional vessels (accounts for 11.5% and 10.4% of the total time respectively). Since the price per ton is roughly the same between a 12500t and a 9090t harvester, the first will be used as a comparison with a specialized vessel.

Calculating a specialized alternative

To calculate the alternative, a vessel size of 12500t is used. This results in the following dimensional parameters:

Figure 69 Calculated vessel data and related new build prize

Vessel Data		
L/B	6,50	
B/D	2,50	
DWT	12500,00	T
Depl	18500,75	T
LBT	21512,50	m3
L	131,47	m
B	20,23	m
D	8,09	m

Build price	
Harv. Equipment	€ 1.591.572,72
Casco	€ 19.360.800,00
Accommodation	€ 450.000,00
Engines	€ 1.190.411,98
Total Costs	**€ 22.592.784,70**

The calculated cost price is roughly equal to a 7000t displacement Trailing suction hopper dredger (Bray, 2005). A 19000t TSHD is expected to have a value of € 50.5 million. The difference is to be found mainly in the required equipment costs.

With this information the day rate could now be calculated, based on the amount of working days. This calculation uses formulas from chapter 7.9. The input for the cash flow calculations is given in Appendix T. To determine the margin on the costs, an iterative approach was used by changing the value with integer percentages, until the cash flow in the first year was positive.

Table 37 Determining the day rate and related cost/ton scenario C

Amount of days	30	60	90	120	Break Even (209)
Annual costs (1st 10 years)	€ 3.669.458,08	€ 4.192.870,89	€ 4.716.283,69	€ 5.239.696,50	€ 6.792.487,83
Margin on costs	20%	18%	16%	14%	11%
Day rate	€ 134.226,78	€ 76.184,02	€ 56.603,81	€ 46.639,23	€ 34.273.28
Cash flow 1st year	€ 1.509	€ 22.334	€ 22.223	€ 1.175	€ 14.791
ROI (15 yr)	230%	234%	234%	229%	233%
CAGR (15 yr)	8,3%	8.4%	8.4%	8.3%	8.3%
dROI (15 yr)	77%	80%	80%	77%	79%
dCAGR (15 yr)	3,9%	4.0%	4.0%	3.9%	4.0%
Cost per ton WM	€ 29,36	€ 16.77	€ 12,58	€ 10.48	€ 7.80

It takes roughly 7 months of operation per year in order to meet a break-even point running a specialized vessel compared to 4 smaller rented vessels. Using a specialized harvester for a single harvest is therefore not economically viable, if compared with rental calculations. Compared to the expected costs of € 10,4 predicted in chapter 4 the price is nearly three times higher. If annual usage of harvesting equipment increases due to e.g. the harvest of several species or global seasonality, this option should be re-evaluated using more accurate data available at that time.

8.3.5 Conclusion

The main goal of using the model to determine larger scale seaweed operational costs has been met. It is clear that at a larger scale the seasonality of seaweed, and the resulting harvesting period is an even greater restriction. This could either be resolved by increasing the number of harvesters or increasing the scale of the harvesting module. Due to the nature and fragility of harvesting seaweed from a flexible substrate it is likely that the first option might prove to be the first step in scale increase.

Based upon the earlier scenarios the price of €7,80 per ton is not much lower than the €10,35 calculated in Scenario A, where the scale has increased by 42 fold. This has to do with similar input costs for the equipment and the transport based cost calculations and the fact that the first possible solution already uses 4 ships, when limited to a capacity of 15000t.

The financial comparison is a useful addition to the model to predict and compare the daily costs. It shows that for the early projects operating on only one type of seaweed and non-vegetative cultivation, a specialized vessel is not economically viable. Using a specialized vessel might prove viable, when used for vegetative cultivation, especially when used in different geographical harvesting seasons, prolonging the daily operational costs.

Questions that still remain when calculating scenarios at larger scale, further away from shore side facilities are:

- What effect does long distance carriage have on the quality of seaweed? And should the sailing time per trip than be limited?
- Would it be interesting at that point to invest in drying, freezing or packaging equipment on board?

8.4 Conclusion and recommendations for model development

Based on the three main scenarios ran in this chapter, the framework is able to deliver a multitude of options to assess the economic feasibility of various operational scenarios in order to support operational and design decisions.

Due to the complexity of all the calculations and the model itself, it has been decided that not all variations have been calculated. Though this could be done, it would go beyond the scope of this thesis. The three scenarios have been created to demonstrate the core possibilities of the model. In further iterations of the model and/or scenario setups, modes could be found to automate the calculation of multiple scenarios at once, to increase the variability of the optimization.

There have already been a vast number of alterations to the model and once deemed complete enough to demonstrate the numerous scenarios the choice has been made to fine tune the model, without making large alterations.

With regard to scenario A, it is clear to see that the model has clear advantages when working with smaller scale farms. The predicted harvesting costs of € 10.35/t wm are very close to the predicted € 104/t dm for the harvesting operation predicted in chapter 4. This further emphasizes the relatively small impact of harvesting in comparison with other costs in the chain.

In scenario B the model demonstrated its use when handling more complex questions with regard to optimal specie usability and cultivation techniques. Even though information is really sparse, with a few assumptions it is possible to show noticeable differences. It can be concluded that with a limited harvesting time the costs of running a 12 hour day operation far exceed the costs for a 24 hour day operation.

Scenario C demonstrates the ability to handle larger scale scenarios. The operational limits at larger scale determine the need for multiple vessel setups. It is possible to use financial assessment tools to compare a rental based scenario with a build vessel (voyage charter) scenario. Based on the assessment presented the specialized vessel becomes competitive with more than 100 days of use (approaching €12/t WM) and equals the lowest rental price at 209 days. This comparison is still based on the limits in the rental scenario, making it difficult to draw definitive conclusions. The use of a cooperative vessel could increase the economic viability, only when multiple species are used and/or vegetative cultivation in combination with farms on both sides of the equator to have two harvesting seasons per year.

The scenarios illustrated that the expected harvesting cost vary between € 75 and € 230 per ton DM. In running the scenarios, the seasonality and resulting restriction in harvest days proved to be a limiting driver due to the required increase in mostly the harvesting speed. Every scenario was written with the transport and the harvest vessel being the same. Harvesting accounted between 52% and 68% of the operational time, depending on sailing distance and offload speed. Since this is the most controllable component in the operation it is important that operational limits are clear. Limitations for the cultivation module will be in the form of winch, and removal speed. The related drag effects on the winches, the float and the attached seaweed, together with limitations in removal methods are the next step in engineering the design for optimal use. Especially since these also affect scalability.

The costs of seedlings have the largest effect on the production costs when modelling the production chain. Dependant on the cultivation technique and specie the percentage varied between 38% and 51%. Decreasing nursery time through novel deployment methods could significantly lower production costs. The chain costs for dry mass seaweed have been calculated with a water percentage of 90%. If this could be reduced through domestication, for example by artificial selection and genetic breeding, this could lower the production costs significantly.

The results of the three scenarios already provide a great insight in the operational aspects of the offshore cultivation of seaweed. Based on the limited availability of information, it is still possible to compare and demonstrate multiple possibilities of the model.

Recommendations for model development

Since the harvesting time forms a limiting factor in most scenarios, it might be interesting to start investigating in a profit based model. Extending the harvest time might lower the overall value, due to the inconsistent quality of the harvested seaweed, but if the costs are much lower the profit might increase. But more information on cultivation techniques is needed to determine this. With a profit based model it is also interesting to include the investment in harbour offloading equipment to increase offload rates, to decrease harvesting speed and lower equipment costs. Other possible features are briefly discussed on the next page.

Added features

- Enhanced data base with more species and detailed information;
- Enhanced output file to increase data visibility;
- Be able to optimize taking account multiple species;
- Enhanced patch predictions taking in account the maximum density;
- Increased calculation time optimizations;
- Include post processing of seaweed in the model (dry times etc.).
- Increase / Include patch parameters to optimize patch dimensions in combination with manoeuvrability.
- Being able to determine an optimal point (distance) where it is more useful separating harvest and transport components. In other words include the possibility to separate the harvesting and transport component to work with different configurations. E.g. one harvester with three barges (1 loading, 1 in transit and 1 offloading), or multiple small harvesters with one large storage facility and multiple barges running from there.
- The personnel costs could be related to the harvesting speed, where by higher harvesting speed increase the amount of human interaction, resulting in a demand for a higher crew count.

Some of these options might be easier to implement than others, but it is certain that all this is possible to add to the current model. With a global increase in farms it might be better to return to the more conventional transport models based on localized demand.

9

Conclusions and recommendations

9.1 Conclusions

Despite the broad and novel subject of the assignment, there are several conclusions that can be drawn from the research. Using the Integrative and Rational method as proposed by Cross (2008) has proven a solid basis for the structure of the report and will therefore be used in the conclusion as well.

A novel seaweed cultivation module has been designed based on extensive market research, function analysis, state-of-art and various design decision tools. The module is able to harvest line based substrates with different species of seaweed attached to a set of floaters. The module can be used on a number of different carrier vessels and is containerized to be able to be transported and deployed worldwide. The design is able to harvest farm sizes of up to 100 ha, depending on patch configuration and vessel manoeuvrability. It is scalable since it uses basic design principles and parts that can be produced in most marine production environments. To aid in further design development and feasibility assessment of different cultivation scenarios a model framework has been developed. Through a multitude of scenarios the model proved a viable tool that can be used to determine optimal solutions for a wide range of different input questions.

9.1.1 Market Analysis

Seaweed can be cultivated for a wide array of products. Its complex lifecycle makes it difficult to cultivate and requires advanced techniques, especially when cultivation areas move further offshore. The seaweed market is rapidly growing, with a 7.4% annual volume increase in the past decade it is predicted to grow in the foreseeable future. This is further increased by a growing demand for more sustainable food sources.

The food market, with its relatively high value and growing demand, is the most logical market to produce for. There are little additional production costs and the supply chains are already mostly established with other marine products or imported seaweeds. Initial value estimations of €2.50/kg DM compared with predicted production costs between €0.60 and €1.50/kg DM show that seaweed cultivation for human consumption is economically viable. Based on expected development paths, increased yield and bioremediation around existing aquaculture sites, IMTA seems like the most probable development direction in the foreseeable future. The added fact of calmer waters, added nutrients and increased interest and knowledge from this sector makes development in this direction even more attractive.

Further investigation revealed that earlier attempts at offshore cultivation have not always been successful. There are severe knowledge gaps in different aspects of offshore cultivation. It is very hard to predict expected costs of young sporophytes, and specie selection is difficult. Cultivation techniques are still under development and offshore pilots are undertaken to learn the effect of adverse offshore conditions on the construction and yield predicaments. There is little information on the effects of mechanization of cultivation processes on possible market shifts; also caused by an unknown product market in Western

Countries. It is clear that this influences the scale of offshore seaweed farms in the near future, where a lot of time and effort has to be made increasing knowledge in these areas.
It is also clear that the production for biomass feedstock alone is a futile effort at this moment in time, both from an economic and technological viewpoint. Literature has already shown this, even though often based on outdated information. Based on own calculations with recent commodity values and conversion techniques there is still a gap of at least six to one between the possible feedstock value and the production costs, even without conversion costs. The price for regular energy has to rise significantly, and even then there are a lot of other sustainable energy sources. It is remarkable that there is still a lot of research done in this area.

9.1.2 Development of the concept

With information from different stakeholders and literature a probable process chain for offshore seaweed cultivation has been developed, separating the development of sporophytes, the operations at sea and processing ashore. Often the production of the seaweed and the installation and/or maintenance of the substrate are separated in these chains. It is noteworthy that the installation and maintenance are often left out of the abilities of a cultivation vessel; something that might become more important once farms start to move further offshore. Function modelling has been used to further define the mission profile and cultivation related tasks. The main functions selected to be part of the design are: the deployment, harvest and transport between the farm and the offload destination. These encompass all production processes at sea with the exception of monitoring growth, which even on a large scale farm can be done with smaller vessels and or remote sensing. Based on the selected business case in relation with other aquaculture activities a set of operational parameters have been established, resulting in a set of primary requirements. The lack of extended knowledge of cultivation techniques required additional information to generate a set of suitable design requirements.

In order to increase overall understanding in cultivation technologies and possibilities a state of art research was done in the history and development of currently used mechanical harvesters and cultivation substrates. A patent search revealed that there have been small scale attempts to mechanize the current industry, often coming from countries high in the global production list such as China and Korea. The use of existing technology is useful, yet research has learned that most of the time the harvesters are developed separately from the farms. This is critical due to the non-rigidity of the substrate and the fragile nature of the seaweed attached. Current developments with new types of substrates only enlarge the amount of possibilities for different harvesting techniques. To come up with novel solutions a brainstorm session was held, and ideas where filtered and organized in three different morphological overviews. An initial pragmatic selection was made, based on a number of different criteria and a decision was made to use the overview of the carrier system only as reference, without further selection. Future developments could alter the selection criteria or outcome, but based on the criteria set for the business case in Norway the solutions in the overviews where often eliminated to one or two options per functions.

With this rough outline for design, four different concepts were created. The concepts are weighed individually based on 10 selection criteria based on the design objectives and requirements. Even though the scoring system worked well it is difficult to add weights and evaluate the different objectives. In future development of the design, this will probably be made clearer by the buying party. This also may have resulted in relatively small differences between the scores. The highest scoring concept has been further developed and resulted in the final design. The concept does meet the set of objectives and initial requirements, yet it is still unknown whether the concept is feasible and effective. The call for more operational requirements and a way to test the feasibility of the concept is one of the main reasons to start developing an exploitation model. The preliminary design does make it easier to figure out the necessary parameters to model.

9.1.3 Exploitation model and results

The exploitation model was made, based on the theory of production in managerial economics and verification of the model through different scenarios, where comparison with literature helped validation of operational costs.

The scenarios illustrated that the expected harvesting cost vary between € 75 and € 230 per ton DM. In running the scenarios, the seasonality and resulting restriction in harvest days proved to be a limiting driver due to the required increase in mostly the harvesting speed. Every scenario was written with the transport and the harvest vessel being the same. Harvesting accounted between 52% and 68% of the operational time, depending on sailing distance and offload speed. Since this is the most controllable component in the operation it is important that operational limits are clear. Limitations for the cultivation module will be in the form of winch, and removal speed. The related drag effects on the winches, the float and the attached seaweed, together with limitations in removal methods are the next step in engineering the design for optimal use. Especially since these also affect scalability.

The costs of seedlings have the largest effect on the production costs when modelling the production chain. Dependant on the cultivation technique and specie the percentage varied between 38% and 51%. Decreasing nursery time through novel deployment methods could significantly lower production costs. The chain costs for dry mass seaweed have been calculated with a water percentage of 90%. If this could be reduced through domestication, for example by artificial selection and genetic breeding, this could lower the production costs significantly.

Though a lot of improvements can still be made, the model can already help determining essential cultivation decisions and configurations. The calculated production costs prove the economic feasibility of the design and the concept as a whole. More knowledge in seaweed cultivation could only enhance the accuracy of the data, further improving estimations and model development.

9.2 Recommendations

Market

To increase development a proper market research is highly recommended. If investors could be informed with accurate data and clearly identified risks it might become easier to get the necessary research budget. An open information stream between the different actors throughout the production chain is necessary to eradicate the knowledge gaps as quickly as possible.

This Thesis has mainly been constructed with industry pushers in mind. Although most of them have been in contact with possible buyers, more information about the required end product and its form and scale could benefit further development of the design.

Research

Keep open loop in research. Even though many pioneers would like to keep their resources to their own, due to the expensive costs of prototypes and the extended time of pilot projects a lot of effort is undertaken to gain knowledge on novel techniques. As a starting researcher it is hard to gain in depth information relevant to the task at hand. It was over the course of several months that the stakeholders could be identified, approached and results could be shared.

Aside from research in harvester design, it is even harder to find information on offshore substrates and dynamic loads. In order to develop and assess farm designs more research is required in the field of hydromechanics and dynamics in relation with farm designs. This information is necessary to assess failure modes of the farm as well as possible environmental effects

Investigation is necessary in removal methods. With increasing harvesting volumes it is very important to know whether certain methods provide limits as scale increases.

Abbreviations

Symbol	Description	Unit
	Framework: implementation	
q	Vessel cargo capacity	t
Q	Total farm yield	t
γ	Average ship utilization rate	-
T	Roundtrip time	Days/trip
OH	Days offhire	Days
H_T	Total Harvest time	Days
N_T	Number of trips	Trips
f_T	Frequency of trips	Trips/day
	Framework: Calculating time segments	
T_P	Time in port per roundtrip	Days
T_H	Time for harvesting per roundtrip	Days
T_W	Time avg. delay per roundtrip	Days
T_S	Time at sea per roundtrip	Days
w_{LL}	Loading/unloading rate	t/hour
w_{Har}	Harvesting rate	t/hour
d	Sailing distance	Nm
V	Vessel Speed	knots
	Framework: calculating harvesting speed	
q_p	Yield per patch	t
t_p	Patch harvesting time	s
t_m	Patch manoeuvre time	s
l_{pa}	Length of patch	m
n_l	Number of lines	
γ_l	Yield per meter line	t/m
v_{wi}	Speed of winch	m/s
n_{wi}	Number of winches	
t_d	Time to setup	sec
t_{att}	Time to attach to the substrate	sec
t_{det}	Time to detach from the substrate	sec
	Cost Calculation Power requirement	
C_{Ft}	Cost of fuel per trip	€/trip
p_F	Price of fuel	€/g
spc	Specific fuel consumption	g/kWh
KW	Required power per trip	kW
P	Required power pump	kW
η_p	Pump efficiency	
Q_p	Pump capacity	m^3 / h
H	Head	m
ρ	Specific density	Kg /m^3
g	Gravity constant	m/s^2
kp	Power constant	
C_{Fe}	Costs with regards to equipment power	€/trip
C_{Fa}	Costs with regards to auxiliaries	€/trip
PA	Auxiliary power	kW

Symbol	Description	Unit
	Cost Calculation crew and transport.	
C_{Ct}	Crew costs per trip	€/trip
C_{Cd}	Crew costs per day	€/day
f_T	Frequency of trips	Trips/day
C_{Bt}	Cost of hiring capacity	€/trip
C_{Bq}	Quantity based hiring fee	€/day
C_{BI}	Initial hiring fee barge	€/day
C_{Tt}	Cost of hiring capacity	€/trip
C_{TkW}	Power based hiring fee	€/day
C_{BT}	Initial hiring fee Tug	€/day
$Ccrane$	Cost of crane rental	€/hr.
Chf	Fees based on capacity	€/t
C_{HFt}	Harbour fees per trip	€/trip
	Harvesting Calculations	
C_{RE}	Cost of equipment rental	€/t/hr.
C_{BE}	Base costs for eq. rental	€/t
C_{Eq}	Eq. rental per trip	€/trip
C_{RE}	Cost of equipment rental	€/t/hr.
C_{BE}	Base costs for eq. rental	€/t
C_{ct}	Rent collection and transport equipment	€/(t/hr.)/day
C_{Eq}	Harbour fees per trip	€/trip
v_{wi}	Speed of winch	m/s
F_{wi}	Force per winch	N
F_{blade}	Force per blade	N
γ_{Canopy}	Canopy ratio	-
C_{Fwi}	Rental costs of winches	€/N
C_{Twi}	Total costs collecting	€/trip
C_{Rwi}	Trip Cost of removal eq. rental	€/trip
C_{rem}	Rent Removal equipment	€/(m/s)/day
C_{Cwi}	Trip Cost of transport and collection eq. rental	€/trip
C_{ct}	Rent collection and transport equipment	€/(t/hr.)/day

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Appendix

The appendix is covered in a separate document.

Contents