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Analysis of the kelp farming industry in
Norway with regard to conceptual design
of vessels for harvesting and deployment
operations.

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Preface

This thesis provides the final 30 ECTS of a Master of Science degree in Marine Technology with a specialization in Marine Resources and Aquaculture at the University of Science and Technology (NTNU) in Trondheim. The thesis is written during the spring of 2018 and the workload has corresponded to that of one semester or, as previously mentioned, 30 ECTS. The thesis builds on a project thesis that was written in the fall of 2017, “*Design of a system for work operations in the seaweed cultivation industry*”.

The motivation for this work has been to provide valuable knowledge for anyone who would like to design solutions for the kelp farming industry but here with a main weight on design of one or more vessels. If the kelp farming industry reaches its potentials in Norway, can provide a real, valuable contribution to making the Norwegian society more sustainable. It is the authors hope that some of the work done here, can contribute to the realization of this potential.

Acknowledgments

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Abstract

Kelp farming has been identified as a possible new industry along the coasts of North-Western Europe. Cultivation of kelps could provide a sustainable source of biofuels, food, feed and other valuable components while contributing to bio-remediation of the oceans and storage of carbon dioxide. Here, the first steps of the Responsive Systems Comparison method have been used as a basis for creating an overview of the kelp farming industry and its future potentials with regard to the design of one or several vessels that can perform operations in the industry.

It was found that the kelp farming industry is, and will be, characterized by several factors in the future. Many of these factors are poorly understood at the moment and it is hard to say which ones will turn out to have the largest impact in the long run. The factors identified were the development of markets for the different end products from kelps, development of harvesting and deployment technology, development of processing methods, development of temporary storage methods, development of cost- and energy efficient conservation methods, development of on-growing facilities at sea, the environmental effects of kelp farming and the effects of seasonality and locations on the growth and chemical composition of kelps.

It was concluded that instead of trying to design systems for an industrialized, future kelp farming industry, focus should be on developing technology that can help the industry to take a step from the small-scale facilities of today, into an industry producing larger volumes.

The most pressing technological developments identified were low-cost harvesting equipment and development of short term storage methods that allow for densely stored kelps. The solutions should be designed in such a way that the functions of harvesting and storage easily can be combined with functionalities for another industry. For instance, the aquaculture industry. Alternatively, they could be designed so that they could be temporarily installed on a vessel mainly serving different purposes. By initially designing solutions that are based on kelp farming operations being a by-function, one minimizes the risks of investing in a very uncertain industry.

Norsk Samandrag

Tare dyrking er ein industri som har vorte vurdert til å ha eit stort potensial i Noreg og Nord-Vest Europa. Store havareal kan, som elles står tomme, kan nyttast til produksjon av enorme mengder biomasse. Denne biomassa produserast då utan bruk av ferskvatn, gjødsel eller verdifulle landareal. Blant sluttprodukta som kan tenkjast produsert frå tare finn vi biodrivstoff, fôr, menneskeføde, gjødsel og fleire verdifulle kjemiske komponentar. Spesielt moglegheitene for berekraftig produksjon av biodrivstoff og fôr, og då spesielt laksefôr, har ført til ei stor interesse for tare dyrking i Noreg. Til trass for dette har industrien i Noreg ikkje kome spesielt langt kva angår volum og teknologi. I dag består mesteparten av tare dyrking i Noreg av småskala matproduksjon ved hjelp av arbeidsintense metodar.

Denne oppgåva har forsøkt å kartleggje tare dyrkingsindustrien og den potensielle framtidige utviklinga til denne, med tanke på å identifisere relevant informasjon for utforming av eitt eller fleire fartøy som kan utføre arbeidsoperasjonar i tare dyrkingsindustrien. Ved hjelp av idéar frå RSC-metoden har viktige faktorar som vil spele inn på den vidare utviklinga av industrien vorte identifisert. Desse faktorane er sterkt samanbundne og vil ikkje utvikle seg uavhengig av kvarandre. Faktorane som er identifiserte er: Utviklinga av marknadane for dei ulike potensielle sluttprodukta, utvikling av hauste- og dyrkingsteknologi, utviklinga av prosesseringsteknologiar for tare, utviklinga av dyrkingsteknologien til sjøs, utvikling av system for midlertidig lagring av tare til sjøs, utvikling av kostnad- og energieffektive konserveringsmetodar, dei miljømessige effektane av tare dyrking og effektane av sesong og lokalitet på kjemisk samansetting, vekst og begroing på tara. Dei fleste av desse faktorane er framleis ikkje godt nok kartlagt til at ein på dette tidspunktet kan utføre meiningsfullt utformingsarbeid for eit industrielt fartøy. I staden burde fokus på dette tidspunktet være på å utvikle den naudsynte teknologien og dei naudsynte metodane for at tare dyrking i Noreg skal kunne ta det neste steget opp til ein produksjon i litt større skala enn det som tilfellet er i dag.

Dei faktorane som har vorte identifiserte som viktigast for ei snarleg oppskalering av industrien er effektiv hausteteknologi gode midlertidige lagringsmetodar. Hausting er den klart mest arbeidskrevjande prosessen og ei oppskalering av industrien vil være heilt avhengig av at denne operasjonen kan gjennomførast på ein meir effektiv måte. Når tara er hausta må den lagrast på eit vis fôr, og medan, den vert transportert til land. Per i dag er det ikkje etablert og testa metodar som gjer at ein kan lagre store mengder tare på ein plasseffektiv måte om bord i eit fartøy. Kjøling ved hjelp av nedkjølt sjøvatn eller ensilering er metodar som verkar lovande, men som må studerast nærmare og testast i større skala.

Det konkluderast også med at fartøy som vert utforma bør ha tare dyrking som ein bi-funksjon. For augneblinken er spesielt haustesesongen veldig kort i tare dyrkingsindustrien, så størstedelen av året vil eit fartøy mest sannsynleg ligge i opplag eller utføre andre operasjonar. For å kunne konkurrere i til dømes oppdrettsnæringa, samt minimere den økonomiske risikoen ved investeringa i fartøyet, vil det difor være hensiktsmessig at eit tidleg tare dyrkingsfartøy altså har fleire og meir solide bein å stå på.

For vidare oppskalering av industrien er det viktig at gode prosesserings metodar som utnyttar plantane på ein best mogleg måte vert utvikla, testa og implementert i stor skala. Det er også heilt avgjerande at kostnads- og energieffektive konserveringsmetodar kjem på plass. Dette er område som det allereie vert gjort mykje forskning på, men det er viktig at metodar vert testa i stor skala før dei kan verte implementerte i industrien.

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1 Introduction

Seaweed farming is an interesting possibility for contributing to meeting the increasing need for food and energy in the world. It is estimated that by 2050 the world population will have grown to 9.7 billion people (United Nations, 2015). Projections show that the increase in world population will require an increase in crop calories production towards 2050 of 69% compared to the production in 2006 (Searchinger et al., 2014). Seaweed can contribute to closing this food gap both directly as a food resource, but also indirectly as a feed source in both land- and ocean-based aquaculture. At the same time, the climate crisis the world is facing is largely due to the burning of fossil fuels. A best case scenario from the IPCC estimates that by 2050 77% of the worlds energy demand could be covered by renewable energy, with biofuels increasing its contribution from 3% in 2012 to 27% in 2050 (Olafsen et al., 2012b). In addition to this the seaweed will also have a positive effect on CO₂ -levels, since it binds CO₂ when it grows.

The report “*Value creation based on productive oceans in 2050*” (Olafsen et al., 2012b) states that climatic conditions in Norway, in combination with immense ocean areas, is ideal for producing macroalgae. It also states that Norway due to these advantages, in combination with its strong competence on marine technology, has a moral responsibility to utilize its ocean areas to contribute to the global production of food and renewable energy. The report estimates that Norway by 2050 could produce 20 million tonnes of macroalgae annually, to a value of 40 billion NOK. However, three requirements for this development are stated:

- Large volume markets must be fully developed. In this lies mainly the markets for biofuels and feed.
- Further utilization of the coastal zone is accepted in Norway, and that area efficient production technology is developed
- Efficient technology for maximum utilization of the entire plant is developed.

Another key factor for the Norwegian seaweed industry is the development of effective deployment and harvesting technology. This is pointed out in several reviews of the potential future seaweed industry. According to a market evaluation of the potential IMTA-facilities, labor costs is the largest cost for seaweed farming and increased efficiency is a necessity in all parts of the production chain (Chapman et al., 2014). The parts of the production process mentioned are hatching, deployment and harvesting. The importance of developing this technology is supported by the report “*A new Norwegian bioeconomy based on cultivation of seaweeds*” (Skjermo et al., 2014), which includes development of deployment and harvesting technology for industrial production as one of five recommendations for a profitable development of the new bioeconomy. The other four recommendations are: Development of protocols for growing of a few species in Norwegian conditions, developing processing technology for a holistic utilization of the biomass, development of new high-value products for commercialization and a mapping of the potential environmental interactions connected with seaweed production.

So far the cultivation of seaweed in Norway have been limited to kelp, although production protocols have been developed some red algae and green algae also (Broch et al., 2017).

This thesis concerns itself with cultivation of kelps in Norway, and the possibilities for the design and construction of a vessel for this industry. Currently, this industry is very small in Norway. Internationally all forms of seaweed cultivation are characterized by low-tech systems and labor intense operations. In order to be able to work with the design of systems for this industry, it is important to have an understanding and overview of the field. There is a lot of research being done all over the world on different topics relevant for seaweed cultivation, but not everything is equally interesting for Norwegian kelp farming. In the following some of the basic knowledge that is needed to understand kelp farming will be presented.

1.1 Introduction to macroalgae

Algae are photosynthetic aquatic organisms (Suganya et al., 2016). They can be divided into microalgae and macroalgae. Microalgae are not discussed in this thesis regarding cultivation. These organisms are widely different from macroalgae regarding composition and production methods and it is therefore not of interest to study these further here. Still, it is important to be aware of the distinction when studying macroalgae. Many studies, especially those looking at biofuel production, look at algae in general. One can therefore easily, and wrongly, get the impression that information that applies to microalgae also apply to macroalgae. This usually not the case. Biologically, a big difference between micro- and macroalgae is that while the first one usually is unicellular, the second one is multicellular (McHugh, 2003). Practically, the biggest difference is, as the names imply, the size.

Macroalgae, or seaweeds, include red, green and brown macroalgae (Makkar et al., 2016). Again, this thesis is limited to only one of these groups. The distinction between these groups is one that it is even more important to be aware of when studying macroalgal cultivation. A very high amount of research is made into cultivation, harvesting or applications of seaweeds or macroalgae, but often the results found only apply to the specific group, or even species studied and should not be assumed relevant for all other macroalgae species. In general, red and green algae are much smaller than brown algae and have a chemical composition with a much higher content of protein (McHugh, 2003). While red and green algae vary in size from only a few centimeters to one meter, the largest brown algae can reach up to 20 meters in length. However, 2-4 meters is more common, and some species can be as short as 30 cm. In addition to the biological difference between red-, green and brown algae, there is also the fact that red- and green algae also require different cultivation methods than what is required for kelps (Skjermo et al., 2014). This does not mean that it cannot be an interesting possibility to cultivate red- or green algae species in Norway, but that one must be aware of the differences between species when working with technology for brown algae. The difference in chemical composition has been illustrated by Tiwari (2015), who made an overview of possible products from the three different types of macroalgae. It is important to note that this does not illustrate the only products that can be produced from each component, but shows how the seaweed types contain different components, and so has different potentials.

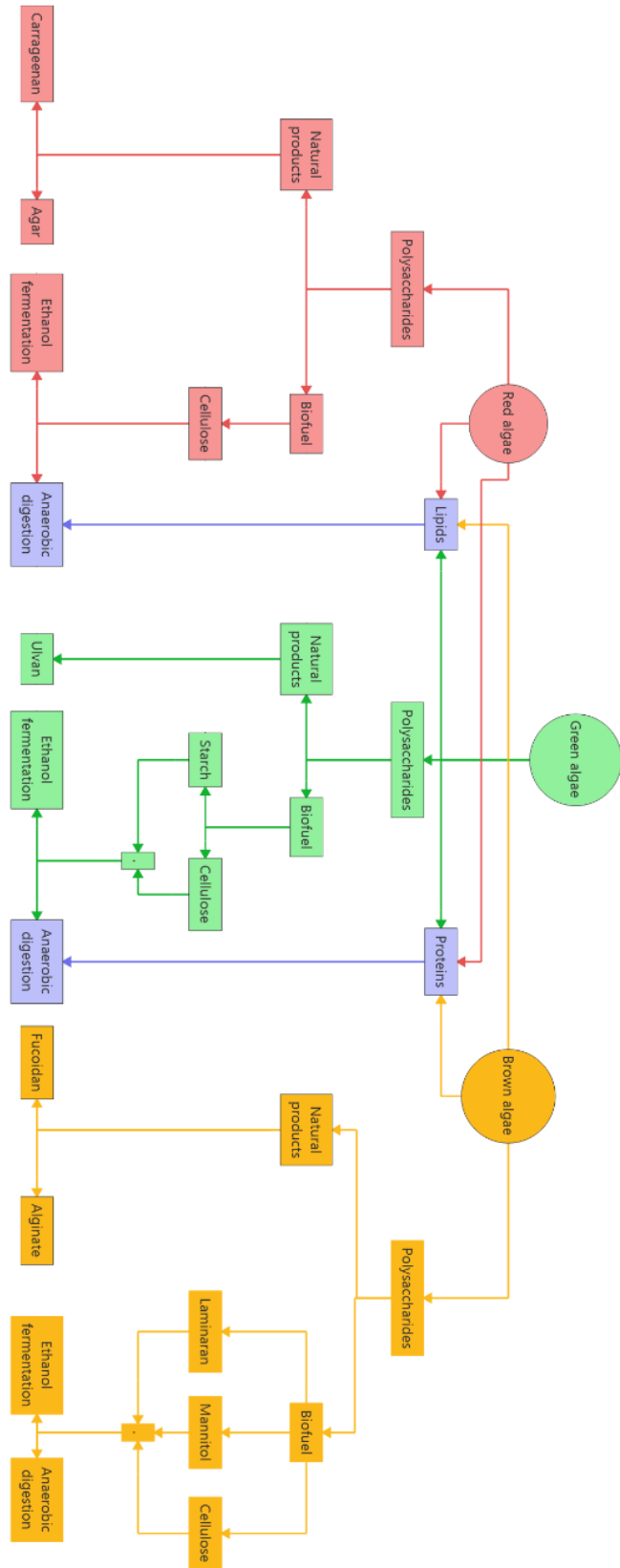


Figure 1.1: Overview of different possible products from three red-, green and brown macroalgae. It is important to note that many components in macroalgae can have several different applications. Adapted from (Tiwari, 2015).

Even brown algae are divided into sub-groups. The group that has attracted the most interest with regard to cultivation in Norway is kelps. These species are characterized by having a stipe over several years and a leaf-like part that grows out every year (Rueness, 2015). The kelps generally grow a bit deeper than the other brown seaweeds, and to bigger lengths. They are also less suited for air exposure than the other brown algae. In this thesis, only the kelps will be considered. Some kelp species have very fast growth, something which make them particularly suitable for cultivation (Øverland et al., 2014). The kelps that have been identified as most interesting for cultivation in the North-western part of Europe are *Saccharina latissima*, *Alaria esculenta* and *Laminaria digitata*. These are also sometimes referred to as sugar kelp, winged kelp (or dabberlocks) and oarweed respectively. All of these species grow relatively fast and can be cultivated on rope structures.

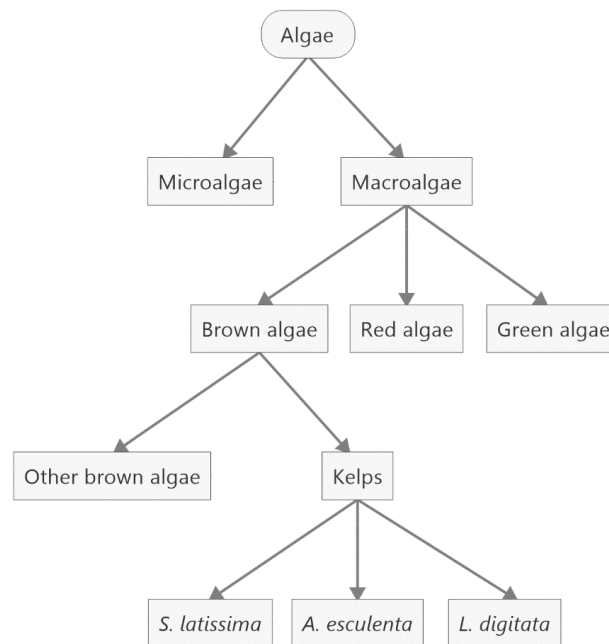


Figure 1.2: Overview of the different types of algae. It is important to be aware of the distinctions between the different types.

1.2 Seaweed cultivation

Although there are significant differences in the cultivation systems and uses of kelps compared to other seaweeds, a general presentation of how seaweeds are produced in the world today will be given here.

Harvesting of seaweed has a long history worldwide (Buschmann et al., 2017). However, only in South-East Asia has farming of seaweed turned into a large industry. In 2014 the world production of farmed aquatic plants was 27.3 million tonnes (FAO, 2016). 96 % of this production took place in the four countries China, Indonesia, the Philippines and South-Korea, with China and Indonesia as the largest producers, producing 13.3 million and 10.1 million tonnes respectively. The most common types of seaweed cultivated are red algae of the genus *Gracilaria* for agar production, the red algae *Kappaphycus Alvarezii* and *Euchema*

denticulatum for carrageenan and the kelps *Saccharina Japonica*, *Undarta pinnatifida* together with the red algae genus *Pyropia* for food use. These account for 26.6 million tonnes, or 97 % of the total production volume of cultivated aquatic plants (Buschmann et al., 2017). The long tradition for use of seaweed for food purposes in South-East Asia has laid the foundation for the growth of the seaweed industry. As different applications of seaweeds are emerging the demand for seaweed continues to increase.

The production methods in South East Asia has been described for all of the most important species and almost all of these species follow the same main production steps (Kim et al., 2017) (Pereira and Yarish, 2008) (Sahoo and Yarish, 2005). These steps include:

- Harvesting of wild spores
- Fertilization and attachment of spores on growing substrate
- Growing of sporelings in nursery/hatchery
- Deployment of sporelings in sea and on-growing.
- Harvesting

The production systems in Asia are very vulnerable to wind- and tidal driven waves. This has led to the production being limited for the most part to sheltered and shallow waters (Kim et al., 2017). In some cases, the sporelings are placed in more sheltered nursing grounds when first deployed into the sea, before being moved out to more exposed waters after a few weeks.

1.3 Status of cultivation in Norway

In Norway the seaweed farming industry is still in its infancy. Norway has a long tradition for harvesting of wild seaweeds, and is among the top three seaweed harvesters in the world, along with China and Chile (Buschmann et al., 2017). However, due to ecological concerns the harvesting of wild stocks in Norway cannot be increased in a sustainable way. This is one of the incentives for exploring the possibilities of seaweed farming in Norway. The harvested seaweed in Norway is mainly used for hydrocolloid extraction by the company FMC biopolymer, which had a revenue of NOK 1.5 billion in 2016 (regnskapstall.no, 2018). The main species used in this production is *Laminaria hyperborea* but also some *Ascophyllum nodosum* is harvested. Approximately 200 000 tonnes of seaweed are harvested annually in Norway (Fiskeridirektoratet, 2017).

Per December 31st 2017, the directorate of fisheries had given out 375 licenses for seaweed farming in Norway (Directorate of fisheries, 2017). However, the production is either not started or fully developed at most of these locations. In 2016 the same number was 274. The same year the amount of seaweed sold for food or feed purposes was 60 tonnes. This indicates that while there is a lot of initiative and exciting work going on in the seaweed industry, it still needs some maturing to become profitable.

The report “*Value creation based on productive oceans in 2050*” (Olafsen et al., 2012a) states a set of requirements for a successful seaweed industry in Norway. According to this report these are:

- Large volume markets must be fully developed. In this lies mainly the markets for biofuels and feed.
- Further utilization of the coastal zone is accepted in Norway, and that area efficient production technology is developed
- Efficient technology for maximum utilization of the entire plant is developed.

These requirements are set with a production of 20 million tonnes of macroalgae annually by 2050 in mind. In the short term, these levels of production are considered more unlikely, and the immediate technology development should be made with smaller volumes in mind. A market evaluation of potential IMTA-facilities performed by Møreforskning (Chapman et al., 2014) concludes that the largest cost in seaweed farming is labor costs connected with hatching, deployment and harvesting and that technology development for these operations is a crucial factor in the process of making seaweed farming profitable. A third report (Skjermo et al., 2014), concludes with five recommendations that should be followed in order to establish a large scale seaweed industry in Norway. These are:

- Development of deployment and harvesting technology for industrial production.
- Development of protocols for growing of a few species in Norwegian conditions.
- Development of processing technology for a holistic utilization of the biomass.
- Development of high-value products for commercialization.
- Mapping of the potential environmental interactions connected with seaweed production.

1.3.1 Production Technologies

The current development at the different locations in Norway is dominated by trial and error. At most Norwegian sites ropes are used as the growing substrate in the sea. These ropes are attached to floating rope frames, moored to the bottom or nearby land when possible. The most interesting design here, is one developed by Værlandet fiskeredskap in cooperation with the seaweed farming company Seaweed AS. This frame covers 1 ha and is suited for 4500 m of growing rope (Værlandet fiskeredskap, 2017). The construction is made so that the growing depth can be adjusted. The arc formed by the mooring ropes gives good strength, allowing smaller dimensions on the ropes and fewer mooring points. It also allows for less tension in the mooring lines. The growing ropes are attached to the frame with carabiners, making attachment and detachment of ropes easier.

At most facilities, fishing vessels or aquaculture vessels have been used to perform the deployment and harvesting. These vessels are, for most parts of the year, working with other operations, and are not ideal for these tasks. It is hard to get estimates of how quickly these vessels perform the deployment and harvesting operations, as this often depend on weather and light conditions in addition to available man power. One farmer stated that they had spent 4 days harvesting 5 tonnes (Buer, 2018), while another had spent approximately one day per

two tonnes (Raposo, 2018). However, both states that the work effort depended a lot on weather and light and therefore varied a lot from day to day. The interviewees also underlined that they are constantly trying to develop their methods for both deployment and harvesting, and therefore probably would have new numbers for the 2018-season. For instance, the first farmer was going to make big changes both to the handling method when harvesting and the logistics in harvesting.

1.3.2 Production Cycles

The stages of production in Norwegian farming are in general similar to those in South-East Asia. The production is still dependent on harvesting of wild plants to produce seedlings, and the hatching takes place in labs on land, while the on-growing takes place in the sea. The collecting of spores varies a bit from species to species, and so does the fertilization and hatching process also. The species of seaweed that has been cultivated in the largest volumes in Norway is *Saccharina Latissima*, closely followed by *Alaria esculenta*. The process of seedling production is described by (Skjermo et al., 2014). For *Saccharina latissima*, the seedlings are produced by harvesting wild plants and then the release of spores is induced in the lab. The spores then settle on the growing substrate, where they grow into seedlings. Alternatively, the spores can grow free floating in cylinders and be “glued” to the growing substrate before deployment into sea. The company Lofoten Esca Verno applies both these techniques (Buer, 2018). Skjermo et al.(2013) describes that depending on the thickness of the growing rope, the rope can either be attached to a carrying rope or deployed directly into the sea. The advantage of growing the seedlings on thick ropes is that this reduces the work effort compared to growing it on thinner ropes that must be attached to thicker ropes. However, growing the seedlings on thicker ropes increases the necessary area in the lab.

When the seedlings are ready for deployment they must be transported to the farm location. Depending on what is practical this will be done by boat or by car. The deployment itself must always be done by boat. When transporting it is important that the seedlings are kept moist and that they are not exposed to harmful temperatures. Temperatures between zero and ten degrees are preferred. The optimal time for deployment will vary based on different factors such as ocean temperatures, light conditions and the size of the seedlings. Small seedlings need to be deployed earlier to achieve the same growth as larger seedlings. Here it is important to remember that the growth in December is usually very low, so if one is to deploy earlier than January, the deploying should take place in November or October. A disadvantage found with deploying earlier than October/November is that there is a much larger risk of getting other species on the growing substrate. The company Seaweed Energy Solutions deploys all of their seedlings in January/February (Raposo, 2018), while Lofoten Esca Verno in 2016 deployed in October and November for harvesting in 2017 (Buer, 2018). Lofoten Esca Verno experienced that the deployment in October got a lot more unwanted growth on the ropes than the deployment in November, but this could also be due to a difference in species. The October deployment was *Alaria esculenta*, which leaves more available area on the growing rope for other growths to settle compared to *Saccharina latissima*, which was deployed in November and tends to grow around the entire rope, leaving no available space for unwanted growths. It is not certain which factor had the biggest effect on this issue.

Harvesting usually takes place in late spring. High ocean temperatures during summer leads to bryozoan fouling on the plants with the consequence of loss of biomass, despite the good light conditions in this season. Since the fouling is decided by the temperature, harvesting can start later the further north you come. A farm in Lofoten gave that they started the harvesting in mid-May, while a farm at Frøya in Trøndelag starts their harvesting in mid-April and ends it by mid-May. It could be interesting to see if there are other algae that could be cultivated during the summer months, with less negative effects from bryozoan fouling. This could be very positive with regard to exploiting the light conditions in Norway during summer, in addition to the fact that the growth in salmon cages is at its peak in summer, making the IMTA-effects largest at this time of year.

Regarding a system for working operations it important to consider the different times of deployment and harvesting along the coast. The fact that operations are performed at different times opens for the possibility that one system could serve several locations. An important future context to consider is several production cycles within a year growing several different species. However, in the short term one needs to consider a system that has a relatively short season and needs to be able to perform other operations in its off-time, so not to be in layup for most parts of the year.

1.3.3 Processing

Most farmed seaweed is either dried or frozen. When drying the seaweeds it is important that this is done quickly after harvesting, and that it is done in a good way so as not to lose nutritional value or affect the composition of the biomass negatively (Stévant et al., 2015). Since seaweed usually contains between 70 and 90% water, the volume and biomass can be reduced greatly when dried. It has also been indicated that the seaweed can be stored for years without quality loss when dried. Stévant et al. points at several different methods for drying that in the future could become the standard way of drying seaweeds. However, once the seaweed is dried several further processing options and uses are no longer a possibility. Frozen seaweeds on the other hand can still be dried at a later occasion. When it comes to transport and storage of freshly harvested seaweeds, seawater storage has been found to be a good short-term solution. Still, experiments where seaweeds have been stored in seawater for up to 22 hours have indicated that this could have a significant impact on the nutritional composition of the plants (Stévant et al., 2017b).

The seaweed that is harvested from the wild is usually chopped and added formalin at sea for conservation. This of course makes the product unusable for feed and food purposes. The seaweed is then transported to land for further processing.

1.3.4 Markets

Currently, the market for farmed kelp in Norway is dominated by the high-end food market. The farmers that were interviewed both stated that their main focus was the food market, and here mainly as an ingredient, expressing limited faith in any new markets developing in the near future (Raposo, 2018, Buer, 2018). The reason that food, at least for now, is the main market is that kelp for this purpose has a relatively high selling price. With the volumes produced today, combined with the comprehensive work effort necessary in production, high

value products are the only options. However, the food market is limited in volume and a big shift in consumer behavior is necessary for this market to increase.

It is well documented that including macroalgae in the diet has a positive health effect (Chapman et al., 2015). Historically macroalgae have been used as a food in times of poverty and famine, but now an interest is growing for macroalgae as a local, exclusive food ingredient due to its unique taste and high nutritional value. One thing that also has led to an increased interest for seaweed as a food ingredient is its potential as a salt substitute. A lot of public health issues are tied to the high consumption of salt in the European population.

A potential issue with the use of macroalgae as food is that the algae can accumulate toxins and heavy metals that could be dangerous if consumed in high levels. These levels will depend on the surrounding water quality and the time of growth. Acceptance levels of toxins in food is regulated by the EU and so all seaweed produced for food use in Norway must be within these limits. In addition to this, production must be in compliance with the Norwegian law for food production- and safety. The country in Europe that has come furthest in development of seaweed as food is France, where they have developed a list of seaweeds that are approved as human food.

In Norway a project at Møreforskning AS, PROMAC (Promac, 2018), focusing on energy efficient processing and refining of seaweed for human food and animal feed was started in 2015. This project also contains a logical and economic analysis of the value chain and a life cycle consideration of products. This project focuses on the two brown algae *Alaria esculenta* and *Saccharina Latissima* in addition to the red algae *Palmaria Palmata*.

Two large-volume markets that have been considered with regard to the seaweed industry are the markets biofuel/bioenergy and animal feed. These markets have a huge volume potential but are limited by requirements to production costs. The value of these products is lower than for food and large-scale production, more efficient technology is necessary for this potential to be realized. Another limitation is that refining technology also must be in place, something which now is a matter of research.

A small volume, but high value market for seaweed is the market for alginate. Alginate is in Norway produced from the kelp *L. hyperborea* harvested in the wild. There are concerns over the ecological effects of this harvesting practice in Norway, and there are strict limits to how much kelp can be harvested annually. Due to its slow growth, *L. hyperborea* is not considered to be a good species for cultivation. However, the species considered for cultivation, particularly *S. latissima*, have a high content of alginate and could prove to be a good alternative source of alginate in the future.

2 Design theory

It has been established that for kelp farming to become a large-scale, cost efficient industry, the production technology needs to become more efficient. This includes the development of vessels that can reduce the need for labor force in the harvesting and deployment operations and increase the speed with which these operations are performed. This can be considered as the fundamental need that forms the basis of this thesis. All design tasks are derived from a fundamental need (Pahl et al., 2007, Blanchard, 2008, Suh, 1990). Pahl and Beitz (2007) describes that from a market analysis, requirements can be derived. This way of thinking is supported by Suh (1990), where the first step of any design process is identified to be the establishment of functional requirements from a societal need that the design shall satisfy.

A system is defined by the International Council on Systems Engineering (INCOSE) as:

“...a construct or collection of different elements that together produce results not obtainable by the elements alone. The elements, or parts, can include people, hardware, software, facilities, policies, and documents; that is, all things required to produce systems-level results. The results include system level qualities, properties, characteristics, functions, behaviour and performance. The value added by the system as a whole, beyond that contributed independently by the parts, is primarily created by the relationship among the parts; that is, how they are interconnected.” (Rechlin, 2000)

A vessel, or several vessels, is by this definition a system. According to Blanchard (2008) all systems are part of larger systems. In the case of this thesis the vessels that are considered are part of a larger system, which is the kelp farming industry. When working with the design of vessels in this industry it is important to have a good understanding of the system the vessels will be a part of. Systems are also characterized by it being possible to break them down into subsystems (Blanchard, 2008). It is important to understand the interrelations between these subsystems. Systems engineering is an approach to design where the entire life cycle of the system is taken into consideration. This includes functionality, development, production, maintenance, support and finally, retirement or disposal. Previously there was an overly strong focus on functionality, at the cost of the other factors that should be considered. The design governs the life cycle of a system (Pahl et al., 2007) and it is therefore crucial that the entirety of the systems life is considered in this early phase. It is however impossible to optimize a design for all possible future scenarios.

In design it is generally considered to be the case that changes become more and more costly the later in the process they come (Blanchard, 2008, Suh, 1990). Therefore, comprehensive research should always be done before setting the functional requirements. Functional requirements should be independent requirements in the form of functions the system must be able to perform in order to satisfy the previously identified societal need (Suh, 1990). A good designer is able to identify the functional requirements that are critical for the design and to assess which functional requirements that are of less importance. The choice of functional requirements must be based on in-depth knowledge of the domain the system is designed for.

This is again an argument for performing comprehensive research before embarking on a design task.

The design process usually consists of a few main steps. These include problem definition, a creative process and an analytical process before the solutions are evaluated against the perceived needs in the end (Suh, 1990). Pahl and Beitz (2007) similarly describe the four activities of design as conceptualizing, embodying, detailing and computing. Here less weight is put on the separation between problem definition and the creative process of developing concepts. However, it is consistent with the idea that the problem definition very often must be revised several times after concepts have been developed and new experiences have been gained, and that the two processes therefore should be considered as part of one main process. It is emphasized by most authors that the problem definition is one of the most important phases of the design process. As the problem definition is a subjective process, it is not given that all designers will land on the same problem definition (Suh, 1990). Different problem definitions can still lead to good designs. Experience will increase the probability that the problem definition is a good one, but in most cases the problem definition must be revisited several times. According to Suh, the entire design process must be redone if the functional requirements are changed after experience has been gained through later design steps. It is therefore important to try to get the FRs as precise as possible on an early stage, while still accepting the risk that one might have to go back and redo the work.

The functional requirements are defined as part of the problem definition. It is recommended to hierarchize the FRs to simplify the later design work. The FRs should, according to Suh, be governed by seven corollaries derived from two axioms of design. The two axioms defined by Suh are the independence axiom and the information axiom. These two axioms say that functional requirements should be independent and that the amount of information necessary to describe a design should be minimized. These axioms are considered to apply to all forms of design activity. The corollaries that are derived from this are as follows:

1. If a proposed design consists of coupled FRs, functional independence must be ensured through decoupling
2. Increasing numbers of FRs and constraints will increase the complexity and information content of the design. From this one can also derive that a design should not fulfill more FRs than those originally stated.
3. Several functions should be integrated into one part if possible without this leading to functional coupling.
4. Standardized parts should be used to an as large extent as possible. This will reduce the information content of the design. Interchangeable parts also allow for reduced inventory and simplification of maintenance operations.
5. All designs should strive for symmetry, as this leads to reduced information content in manufacturing.
6. When finding FRs, tolerances should also be set. High tolerances will make information content lower because it is harder to manufacture a product with tight tolerances but can lead to increased information content through reduced reliability if set too high.
7. There is always an uncoupled design requiring less information than a coupled design.

(Suh, 1990)

Design is the process of selecting design parameters to satisfy the functional requirements. Preferably, each design parameter can be adjusted to satisfy an FR without affecting any other FRs. The selection of design parameters is a nonunique process, and different designers can end up with different solutions, despite starting from the same set of FRs, without any of them having found a “wrong” solution. The design parameters are also limited by constraints. The constraints are characterized by that as long as a design parameter is within the constraints, the design is acceptable. Constraints can also be dependent on other constraints and on functional requirements. There are two types of constraints. The first type is the input constraints. These are typically constraints in the design specification, like size, weight, cost etc. The second type is system constraints. These are boundaries set by the system itself. Examples of this for a vessel can for instance be the hull shape, the machinery capacity and so on. A design parameter on a higher level in the hierarchy can function as a constraint on a lower level.

When working with systems engineering one should have a top-down approach in order to ensure the necessary overview, so that the interrelation between components is fully understood (Blanchard, 2008). It is important with domain knowledge and the ability to work in a systematic way when using a systematic approach (Pahl et al., 2007). Systematic approaches should structure the work in a purposeful way, while still facilitating intuitive and creative processes.

The work with designing vessels for the kelp farming industry, still very much finds itself in the two first steps of the design process. Some initial work has been done in the form of review articles on the potential for industrial kelp farming and more in-depth work on different aspects of the industry. Still, there is a need for more knowledge, both to understand the system which the kelp farming industry is, and to define the functional requirements for vessels operating within it. Status today is the process of moving back and forth between work on conceptualizations and work with the functional requirements. The next chapter will present some of what here is considered the most important factors that will affect the functional requirements for vessels operating in the Norwegian kelp farming industry.

2.1 The responsive systems comparison method

The first steps responsive systems comparison (RSC) method has been used as a support for the work in this thesis. The method originally consist of nine steps, divided into three groups, from information gathering through alternatives evaluation and into alternatives analysis (Schaffner et al., 2014). Here, the first three steps, which constitute the information gathering, have been used as a framework for the work with shedding a light over the most important factors in the kelp farming industry.

The goal of the RSC-process is to come up with solutions that can be evaluated in different future scenarios. Previous design methods have to a large degree been built around optimizing designs for a specific context. The RSC takes the changing contexts into consideration.

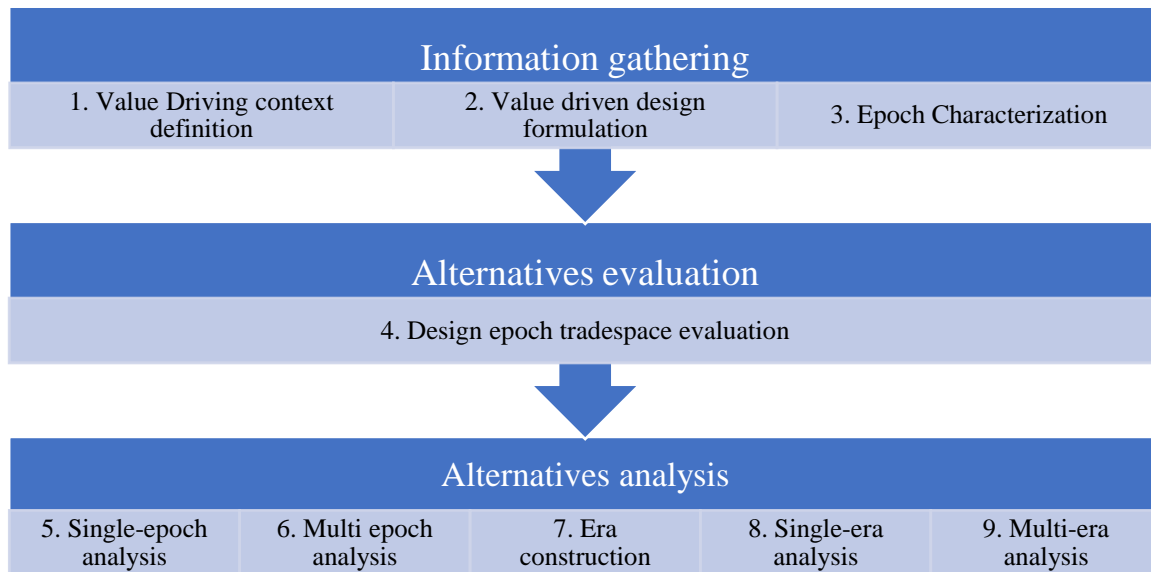


Figure 2.1: The flow of the responsive systems comparison method. Adapted from (Schaffner et al., 2014)

2.1.1 Information gathering

This first group of steps in the RSC- method consist of three steps that contribute to establish the knowledge needed for further design work and evaluation.

2.1.1.1 Step 1, Value Driving Context definition

Defining the value driving context means defining a problem statement and relevant stakeholders. Key contextual factors that could affect the problem and or solution should be identified. The past, present and possible future states of these factors should also be identified (Ross et al., 2009). This work can lead to an overall value proposition. The value proposition can serve as a link between the system design process and the business strategy of the stakeholder (Pettersen et al., 2017). This step strongly influences what will be considered a value robust design. This process defines the problem, why it is important, to whom it is important and what is required for a design to be satisfactory over its lifespan (Gaspar et al., 2013). Therefore, it is of great importance that the information gathered in this process is as accurate and complete as possible. It has been stated that interviews with decision-makers and stakeholders should be a supporting part of the information gathering steps of the RSC process (Ross et al., 2009).

2.1.1.2 Step 2, Value driven design formulation

The two main parts of this step is the quantification of performance attributes and generation of design concepts (Gaspar et al., 2013). The performance attributes are metrics reflecting how well an objective is met. The objectives expresses needs statements determined by the key decision-makers (Ross et al., 2009). It is necessary to be able to quantify the performance attributes. They should also be given minimum/maximum acceptability ranges.

The second part consists of developing concepts to meet the performance attributes. These concepts are then decomposed into design variables for the system.

2.1.1.3 Step 3, Epoch characterization

Here contextual uncertainties are characterized. The point is to set parameters that capture possible combinations of future uncertainties. These parameters are called epoch variables and they should: *“include any and all situational or operational conditions that will change over time and significantly impact the system’s delivery of value”* (Fitzgerald et al., 2011). In each epoch, all epoch variables are fixed.

3 Important factors for the future of the kelp farming industry

The kelp farming industry is in its infancy in Norway, but there are great hopes for future expansion (Olafsen et al., 2012a, Skjermo et al., 2014, Skjermo et al., 2013). However, there are many factors that will determine the success of this industry, many uncertainties and many challenges to overcome. For the industry to scale up, the production of sporophytes must be upscaled, the on-growing facilities in the ocean must be upscaled and the processing facilities must be upscaled. One will need to find the optimal time for transfer to sea and develop breeding programs in order to develop kelps that grow faster, with optimal chemical compositions. It will also be necessary to develop technologies for deployment and harvesting that are labor- and time efficient. Finally, processing technologies for a holistic exploitation of several of the kelps components must be developed and markets for these products must be created. Since these fields are developing in parallel, it is very difficult to know exactly what future one is designing for when working on one of these challenges. Some of the most important questions for the future of the kelp farming industry, especially with regard to the design of a vessel for operations in the industry, are:

- **What will be the end products and what kind of processing will be used?**
 - This will strongly influence the requirements for the handling and conservation of the kelps in addition to defining the value of the kelps.
- **What kind of storage and conservation methods are optimal for kelps?**
 - Will be strongly affected by the end products and will strongly affect the design of vessels for the industry.
- **How will the seasonality of the industry develop?**
 - Will the season still be locked to deployment in the fall and harvest in the spring?
 - It is important to know if the vessel will be able to do kelp operations all year or if it will need other possibilities the rest of the year
- **Will the industry move to more exposed locations?**
 - This will, in addition to affecting the logistics and transport requirements, possibly affect the design of the on-growing facilities at sea.
- **How will the on-growing technology develop?**
 - Big changes in the on-growing technology could lead to new requirements to the deployment- and harvesting vessels.

- **Will the kelp facilities be part of integrated multi-trophic aquaculture (IMTA) systems?**
 - Bio-remediation effects could increase the value of kelp farming, in addition to increasing growth and thereby biomass production for the kelps.
 - IMTA systems could require kelp farms in very close proximity to fish farms, this could increase the complexity in operations. It could also be an incentive for designing a multi-purpose vessel.

- **Can there be environmental or ecological issues with growing kelps?**
 - Large scale biomass production will almost certainly affect the surrounding environment, but will these effects be a problem? What are potential challenges?

In the following these questions will be discussed. It is important to bear in mind that while the design of a vessel will be affected by all these factors, a vessel design could also be a factor affecting how these different aspects develop. There is a great degree of interdependency between the factors listed.

3.1 On-growing systems

The design of the on-growing facilities at sea will be an important factor when determining the design of a vessel or group of vessels. It is important that the kelp can be easily and effectively harvested by the equipment onboard the harvesting vessel. It is also important that the deployment can be done efficiently. Finally, the on-growing systems must be able to handle the environment loads at the site and provide good conditions for the kelps to grow. The most popular systems today are different configurations of ropes and nets since these have proven to work well with regard to growth (Handå et al., 2013) and have relatively low investment, installation and maintenance costs (Fernand et al., 2017). The growing ropes are attached to moored rope frames. When using rope structures there are three different methods for seedling production. One is to grow the seedlings on smaller strings which are then twined around larger carrying ropes. This system requires a twining machine during deployment for efficient twining at sea during deployment. The second method is to grow the seedlings directly on the carrying ropes. This removes the need for the twining operation but leads to larger area requirements in the seedling production. The final method is gametophyte cultures grown free floating in water, which are attached to the ropes using a “gluing” mixture. Equipment for this operation should be installed on board a deployment vessel if this method is used. So far, this method has given mixed results in Norway.

A configuration with a continuous rope in the horizontal plane could be the solution that allows for the most efficient harvesting since the kelps then could be harvested in a continuous operation. Such a system, called “Buland” has been designed and implemented by the company “Værlandet fiskerredskap” (Værlandet fiskerredskap, 2017). The downside to such a system is that it does not utilize the cultivation area as efficiently as systems with vertically oriented ropes or nets.

An important factor for an automated harvesting system is the interaction between the harvesting equipment and lines/ropes. The ropes should be attached to the rope frame in such

a way that they can easily be detached and rolled on board. Alternatively, the kelps could be cut off the rope without detaching it. This would require some slack in the line in addition to a system that efficiently and accurately is able to get the cut off kelp into the vessel. It is possible that when designing a harvesting vessel, it could also be beneficial to try to design a compatible set-up for on-growing, instead of trying to adapt to the existing solutions.

Other on-growing systems have also been suggested but these are still only experimental and will not be discussed here.

3.1.1 Localities

The sites used for seaweed cultivation today are relatively sheltered all over the world (Kim et al., 2017). This is also the case in Norway, with relatively small farms close to shore. This could turn out to be optimal for food production, where the time window is shortest from the kelp is harvested until it needs to be stabilized. However, if the industry is going to grow and produce bioenergy or feed in the volumes described by for instance Olafsen et al. (2012a), the farms will require much larger areas. This will probably mean that the farms will be established in more exposed areas, ultimately maybe even offshore. While offshore conditions appear to be better and more stable with regard to growth of the kelps, they also represent a challenge with regard to technical demands for vessels and farms (Stévant et al., 2017c). It has also been indicated that biofouling is a problem mainly connected to sheltered locations and that moving the production to more exposed areas could reduce this issue (Bak et al., 2018). The development of the sizes and placings of kelp farms is hard to predict. When designing vessels for the industry, one will need to take into account the possibility of a fast up-scaling, a slow up-scaling or no up-scaling at all. This again will depend on the development of processing methods and market for large-scale products. When moving the production to more exposed areas, it should also be considered how this environment could affect the chemical composition of the plants.

3.2 End products

Kelps can be used for production of bioenergy, feed, food, fertilizers and high value chemical components (Wout et al., 2013, Chapman et al., 2014, Buschmann et al., 2017, Skjermo et al., 2014). However, the value of these end products varies greatly with the general tendency that the products that has the largest market volume has the lowest prices and vice versa (Skjermo et al., 2014). All farmers interviewed for this thesis stated that the kelp they produced was sold as food or food ingredients. This because the food market has a high value. The food market for seaweeds in general is however limited in Europe and will probably not be sufficient for a large scale industrial production of kelp. The biggest seaweed product in Norway is alginate produced from *Laminaria hyperborea* harvested along the Norwegian coast. Between 130 000 and 180 000 tonnes are harvested annually (Fiskeridirektoratet, 2017) and processed by FMC Biopolymer who had a revenue of 1.5 billion in 2016 (regnskapstall.no, 2018). In addition to this, around 30 000 tonnes of *Ascophyllum Nodosum* is harvested for use in agriculture, food supplements and cosmetics (Chapman et al., 2015). Many studies argue that it is necessary to extract several components of different value from the same plant for seaweed cultivation to become profitable (van Hal et al., 2014, Øverland et

al., 2014, Fernand et al., 2017). The possibilities for this will be discussed in the end of this section.

3.2.1 Food produced from kelps

The kelp farmed in Norway today, is more or less exclusively used for human consumption. The market for kelps as food is limited in Norway but expected to increase. Kelps have many potential areas of use within the food segment. They can be used as a direct food, food ingredient or taste enhancer (Chapman et al., 2015). They can also be used to produce a healthier substitute for salt. Kelps can have many positive effects on a western diet. In addition to be a substitute for salt, more kelps in the diet could also contribute to improved intestinal health and an increased intake of fibers, vitamins and minerals. A moderate consumption of kelp can also contribute to increase the iodine intake in an iodine-deficient European diet. Iodine however, must also be considered as a limiting factor, as a too high intake of iodine can be damaging to the health. A study indicated that a daily intake of *S. latissima* would represent a threat to the health of consumers (Stévant et al., 2017a). The same study also concluded that *A. esculenta* if left untreated exceeded the limits set by the French food safety authority for cadmium. Soaking treatments in warm water for *S. latissima* and hypersaline solution for *A. esculenta* showed good results with regard to reduction of iodine and cadmium levels respectively. The soaking treatments did however also affect the nutrient content of the plants. Another potential issue with kelps as food is their ability to accumulate heavy metals from their surrounding environment (Chapman et al., 2015). Limits for acceptable levels of heavy metals in foods are regulated by the EU.

When producing kelps for human consumption it is especially important that the quality is high. This means that it is necessary to avoid biofouling and minimize the degradation of the kelp. It is documented that kelps degrade quite rapidly from they are harvested (Stévant et al., 2015). Today the kelps are harvested in facilities close to shore and stored in some form of seawater storage. This can either be tanks or in net bags floating in the sea. Storing kelp in seawater tanks has proven to be an issue as it is very hard to get the storage density high enough. One farmer gave a rough estimate of 15-20% kelp compared to water. A study on seawater storage of kelps documented a loss of valuable compounds for *S. latissima* during 22h seawater storage (Stévant et al., 2017b). These compounds could theoretically be regained through treatment of the storage water. This study concluded that logistic models to optimize harvesting and processing of kelps should focus on minimizing biomass stress and time to stabilization of the biomass. This will reduce the loss of nutritious compounds. In the report the most important cause of stress for the plants is the air exposure experienced when harvesting the kelps from the ropes. They were however not able to quantify the contribution from this stress to the release of valuable compounds during storage. For the development of the kelp farming industry it is essential that more work is done on storage and harvest methods and their effect on the quality of the kelps.

Today the kelps harvested for human consumption are either dried or frozen. The facilities used are either built by the farmers on sites close to the farm or they use nearby processing facilities with available capacity in the harvesting season. These facilities process fish or other sea foods in the rest of the year. These methods preserve the quality of the kelps very well but are also quite energy demanding. One is therefore interested in finding an alternative method

of conservation that could reduce the energy use, and thereby cost, of the production. The method that has drawn the most interest here is ensiling (Stévant et al., 2017b). Several studies have been done on the process of ensiling of both kelps and seaweed in general (Black, 1955, Herrmann et al., 2015, Wout et al., 2013), showing good promise for the method. However, large scale experiments measuring the effect on the quality with regard to food uses have yet to be done.

When it comes to the market for kelp as food especially in Norway, but also in the west in general there are projects going on to raise awareness of kelps as food and explore the opportunities. The project PROMAC (PROMAC, 2018), led by Møreforskning, focuses on energy efficient processing of macroalgae for food and feed application.

3.2.2 Feed produced from kelps

Many are interested in the potential for producing feed for fish or terrestrial animals from cultivated seaweeds. This could be an opportunity to increase the sustainability of both agriculture and aquaculture in Norway if it some of the soy-based proteins in the livestock diet could be replaced with proteins from cultivated seaweeds. Kelps generally have a low protein content around 10 % of the dry weight, though this varies somewhat from species to species and depending on season (Øverland et al., 2014). When producing proteins from kelps there are three main options. The first and simplest method is to produce a feed additive directly from the biomass. The second one is to extract the proteins from the kelp and possibly process them. The third is to use the carbohydrates in the kelp to produce protein through bio-processing.

The first method, use of kelps as a feed directly, is the cheapest one. Less processing will inevitably mean lower production costs. Another positive is the documented positive effect that consumption macroalgae have on gastric health and immune defense for livestock (Øverland et al., 2014). An issue is that the proteins in kelps have low digestibility for many species, meaning it will have a low nutritional value. Another issue with consumption of kelps is the fact that they accumulate heavy metals, arsenic and iodine from their environment (Øverland et al., 2014, Makkar et al., 2016). This strongly limits the degree to which they can be incorporated in a livestock diet.

The second method, extracting and processing the proteins, could deal with some of the issues with digestibility and toxic components. There is a potential to increase the digestibility of proteins through enzyme treatment and fermentation (Øverland et al., 2014). The processing would however increase the production cost, and the protein yields would be limited as the protein content of kelps is very limited. A method is suggested by Øverland et al. for exploitation through fractioning of the components. In this process it is considered theoretically possible to get 247 kg protein concentrate from 1000 kg of *Saccharina latissima* harvested in the spring. There are however big challenges connected with this type of fractioning and further studies will be necessary for this process to be developed for a large-scale industry.

Thirdly, there is a growing interest for production of feed for fish or livestock from the carbohydrates in kelps. The carbohydrates in kelps are undigestible for fish and mono-gastric livestock, while ruminants to some degree can utilize them as an energy source (Øverland et

al., 2014). However, methods utilizing the carbohydrates for protein production have been suggested. Øverland et al. suggests investigating the possibility of fermenting the most important types of carbohydrates in brown algae, alginate, laminarin and mannitol, into yeast. These carbohydrates are easily fermentable (Handå et al., 2009) and another advantage is that the kelps does not need to be dried before fermentation. It is however crucial that more research is done on this field to assess the potential of this process. Secondly, a processing method must be developed and assessed with regard to economic feasibility for a large-scale feed industry based on fermentation of kelp to become a reality.

Another way of utilizing the carbohydrates for protein production is suggested by Seghetta et al. (2017). This method consists of using the macroalgae as a growing substrate for heterotrophic microalgae. A method where the kelp is harvested, partially dried, chopped and hydrolyzed before being used as a growing substrate for seven days could theoretically produce around 150 kg of protein per 1000 kg dry kelp. This process will require heating during the initial drying, the hydrolysis and for drying the finished product. A study on the use of *L. digitata* hydrolysate as a growing substrate for heterotrophic microalgae confirmed that this was a very attractive approach to producing fish feed ingredients (D'Este et al., 2017). There is already an industry producing fish feed from microalgae growing on sugar from sugar plants in Brazil (kyst.no, 2017).

Both methods for protein production from the carbohydrates requires comprehensive and complex processing. It will therefore be necessary with high investments in facilities for processing. Secondly, this will probably mean that a steady supply of kelp through the year for year-round processing will be necessary for the production to be profitable. This can either be solved by finding a way of producing kelp for harvest throughout the year, or through the development of energy- and cost-efficient conservation methods allowing for kelp harvested in a short time span in the spring to be processed throughout the year.

3.2.3 Bioenergy produced from kelps

Today the use of fossil energy is contributing to climate change, acidification of the oceans and dangerous air pollution, especially in the cities. Therefore, the transition to renewable energy production is one of the most important challenges for the global community today. A contribution to this transition process is the production of gas and liquid fuels from biological material. However, much of today's production of biofuels contributes to deforestation or competes with land areas that could have been used for food production. As a consequence of this, many are now looking towards the ocean and its vast areas with the hope that biomass for bioenergy production can be produced here. The numerous advantages with cultivation of seaweeds like the fact that they do not take up valuable agricultural areas, do not need fertilizers, do not require fresh water and also can contribute to the storage of carbon dioxide has led to a lot of research being done on this topic (Jiang et al., 2016, Handå et al., 2009, Alvarado-Morales et al., 2013, Fernand et al., 2017, Seghetta et al., 2017). Because of their high sugar content and fast growth rate, kelps like *S. latissima*, *A. esculenta* and *L. digitata* are considered good sources for production of bioenergy (Seghetta et al., 2017). One report suggested that 60% of the fuel consumption in Norway could be covered by biofuel produced from kelp farmed on 1% of the total Norwegian sea areas (Fernand et al., 2017). While another estimated that an area equal to the area used for salmon production in Norway (800

km²) could sustain a production of 470 000 tonnes of ethanol (Skjermo et al., 2014). For comparison the total Norwegian consumption of gasoline and auto diesel was 4 million tonnes at the time. An issue with biofuel production from kelp is that the price of the fuel is low and several reports on the topics points to the fact that in order for the industry to be profitable additional high value components must also be extracted from the seaweeds (Fernand et al., 2017, Skjermo et al., 2014). Bioenergy is considered an almost infinite market in volume if it can be produced at an adequately low cost. One way to get the production costs down per mass is large scale production. This will again require a fast, simple and energy efficient conservation method. Drying or freezing will both require too much energy. An option that has shown great promise with regard to production of biofuels is ensiling (Herrmann et al., 2015). A life cycle analysis of the resource efficiency and environmental performance of biogas production from *Laminara digitata* and *Saccharina latissima* concluded that ensiling was superior to drying as conservation method when producing biogas (Seghetta et al., 2017). Ensiling has also been observed to increase the alginate yields from kelp (Stévant et al., 2015).

For biofuel production there are several methods to process the kelp, and it is necessary to do more research in order to find the best one. Alternatives when turning kelp into biofuels are anaerobic digestion, hydrothermal liquefaction and fermentation (Tiwari, 2015). Other methods for producing bioenergy, like direct combustion, pyrolysis and gasification are considered unfeasible due to the high moisture content of the plants (70-90%). Tiwari (2015) suggest a general processing pathway using ethanol fermentation and anaerobic digestion to produce biofuels while also extracting the high value components fucoidan and alginate to improve the economic feasibility. This method focuses on utilizing as much as possible of the total biomass. However, cost-benefit considerations must be made when developing a final processing scheme. Brown seaweeds generally have a very low protein and lipid content and the extraction and processing of these could turn out to be economically infeasible for biofuel production.

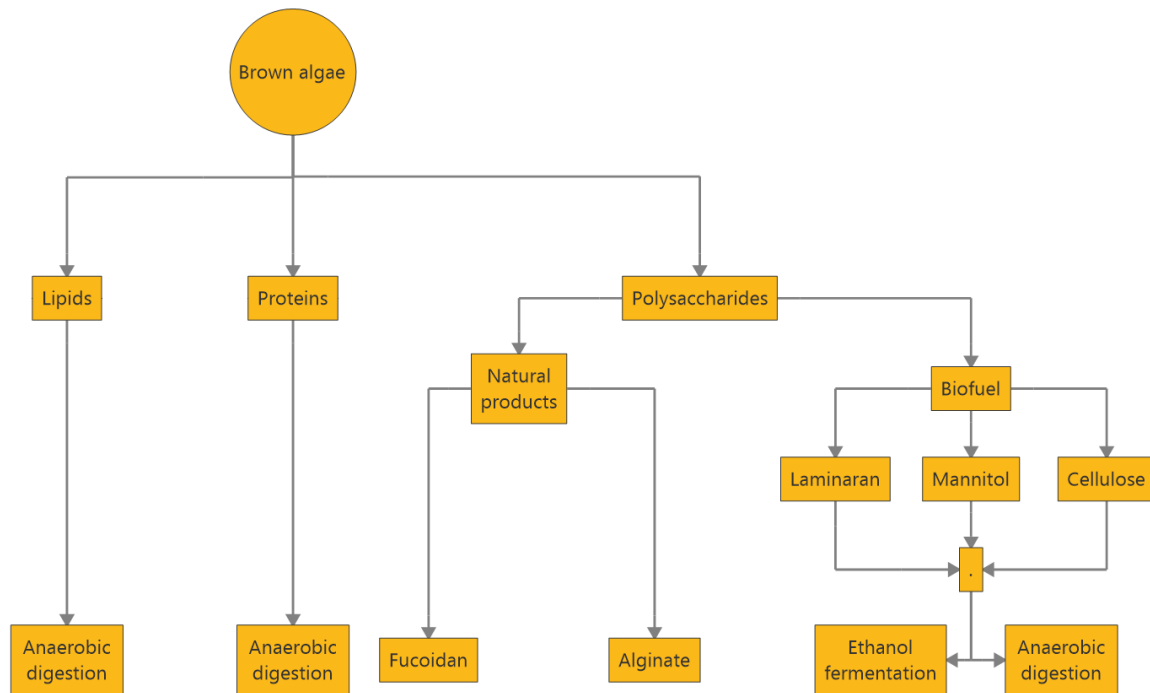


Figure 3.1: Processing scheme for brown seaweeds in general. Adapted from (Tiwari, 2015).

3.2.3.1 Anaerobic digestion

Anaerobic digestion for biogas production has a cheaper investment cost, easier operation and maintenance, and higher net energy gain when compared to fermentation for ethanol or ABE (acetone, butanol, ethanol) production and hydrothermal liquefaction for bio-oil conversion (Tiwari, 2015). This claim is supported by a study comparing life cycle analyses of biogas- and bioethanol production from the kelp *L. digitata* (Alvarado-Morales et al., 2013).

Anaerobic digestion is a complex process in four phases which is further described by Tiwari (2015). When it comes to seaweeds it was found that due to high salt and sulfate content, different carbohydrate composition and low C/N values compared to terrestrial plants led to a poor performance for biogas digesters. It is therefore necessary to utilize an appropriate microbial inoculum that can effectively hydrolyze seaweed biomass with a unique polysaccharide under high salinity conditions. Pretreatments of the seaweed should focus on minimizing microbial inhibition and maximizing methane yield. It is important to note that red-, green and brown algae vary greatly in chemical composition and that in order to develop a detailed anaerobic processing method, more specific research, focusing on one or only a few species, will be necessary.

3.2.3.2 Fermentation

The only components of the biomass used in liquid biofuel fermentation are the carbohydrates (Tiwari, 2015). The fermentation process is more thoroughly discussed in by Tiwari (2015), but can mainly be described as a process in three phases. These phases are saccharification,

fermentation and recovery. A general overview of the process for brown algae is presented in the figure below.

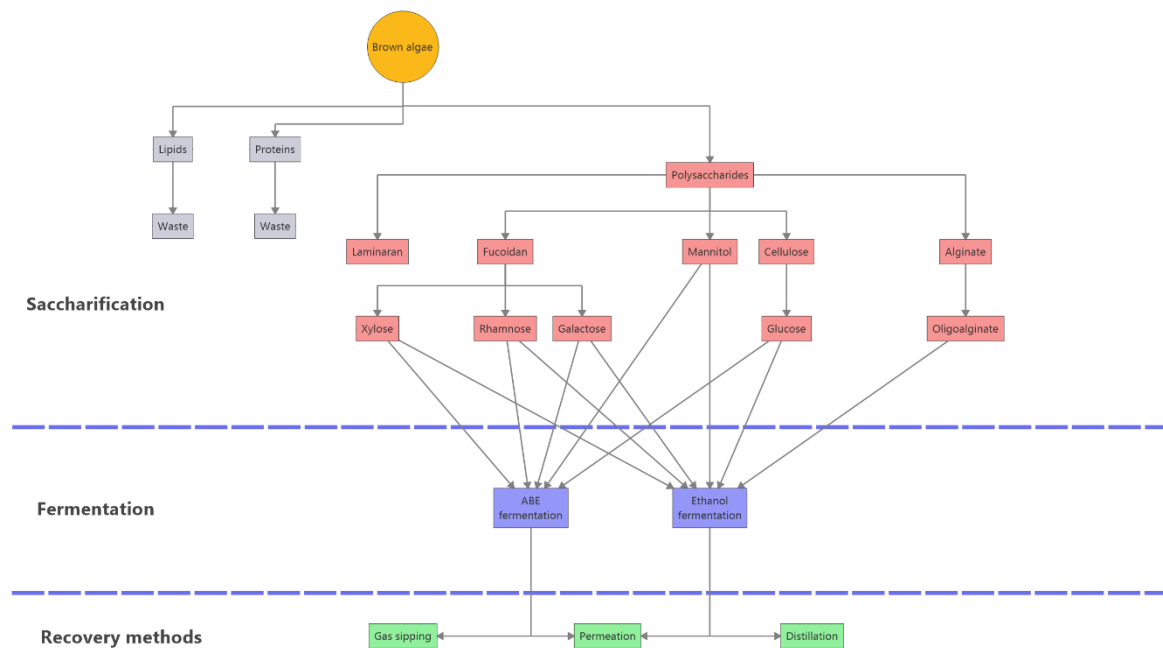


Figure 3.2: Biofuel fermentation processes for brown seaweed, showing the three main steps saccharification, fermentation and recovery. ABE refers to acetone, butanol and ethanol. Adapted from (Tiwari, 2015).

Brown, green and red algae require different saccharification conditions (Tiwari, 2015). Saccharides such as glucose, xylose, galactose, mannitol and laminaran are substrates commonly used for ABE fermentation. It is important to note that different fermentative microorganisms can only utilize specific substrates. This means that the different sugar compositions of each seaweed species will dictate what microorganism species is suitable for the fermentation process. This also means that when looking at the potential of processing of seaweeds it is important to take note of which species are being discussed. Currently the feasibility of ethanol fermentation using brown seaweeds is greatly dependent on the cost of biomass feedstock.

3.2.3.3 Hydrothermal liquefaction

Hydrothermal liquefaction (HTL) is a thermochemical process developed to convert various biomasses into bioenergy that is particularly suited for biomasses with a high moisture content like seaweeds (Tiwari, 2015). It uses a low temperature range compared to other thermochemical processes developed for the same purpose and it utilizes water in a subcritical condition as a reaction medium. While other thermochemical processes would require predrying of the biomass, this is not necessary when performing HTL. This greatly improves the energy efficiency of the process.

The main product from HTL is bio-oil. Its byproducts are solids, aqueous and gaseous. The main product can be upgraded through hydrodeoxygenation or cracking to make it more

similar petroleum oil-derived transportation fuels. The aqueous biproduct, rich in sugars, ammonia, phosphorus, potassium and sodium, can be used as fertilizer (Tiwari, 2015). A study on the energy balance of the HTL process for the four kelps *L. digitata*, *A. esculenta*, *S. latissima* and *L. hyperborea* (Anastasakis and Ross, 2015). This study found that the HTL process gave higher energy output than fermentation and similar to anaerobic digestion. It was also found that *S. latissima* and *A. esculenta* exhibited the best energy balance when processed through HTL. This study was done in the UK with kelps harvested from the coast of the UK, but these species are also very common in Norway. The results are especially interesting considering the fact that *S. latissima* and *A. esculenta* are the most commonly cultivated kelp species in Norway today (Fiskeridirektoratet, 2018).

3.2.3.4 Potential for bioenergy from kelps

As described above there is a great potential for bioenergy production from kelps due to their chemical composition, rich in carbohydrates, and their potential for fast growth in available ocean areas. In order to quantify the potential for this to become an industry however, more research must be done into the processing of specific species. More knowledge on the yields of biofuels and the costs of processing can help lay the foundation for a future large-scale industry.

It has been mentioned before that there is interest many places for the potential of producing bioenergy from kelp specifically and also seaweed in general. An optimal process for producing bioenergy is still not defined and tested, but a lot of interesting work is being done. General processes for bioenergy production are described by Tiwari (2015). A method for production of bio-crudes from four different kelp species using hydrothermal liquefaction is described by Anastasakis and Ross (2015). Alvarado-Morales et al. (2013) describes the comparison of two LCA's for production of biogas through anaerobic digestion and a combined production of bioethanol and biogas through the processes of fermentation and anaerobic digestion respectively. The kelp used in the analysis was *L. digitata*. A study by Kostas et al. (2017) showed that there was potential for production ethanol through fermentation in combination with extraction of the valuable components fucoidan and alginate and production of other extracts with bioactive attributes from *L. digitata*. In Ireland studies on especially *L. digitata* and *S. latissima* for the production of biogas and methane (Vanegas and Bartlett, 2013) and the pretreatment of these kelps with regard to biogas production (Vanegas et al., 2014, Vanegas et al., 2015).

3.2.3.5 Production of kelp for bioenergy products

A prerequisite for producing bioenergy from kelp is that large scale, cost efficient cultivation of kelp becomes a reality (Skjermo et al., 2014, Fernand et al., 2017). This means that large ocean areas must be taken to use and that efficient handling technology for harvest and deployment of the plants must be developed. The area requirements will probably also mean that the industry would have to move to more exposed locations (Stévant et al., 2017c). Combined, these two factors mean that a system harvesting kelp for bioenergy purposes, independently of what the specific end-product will be, must be able to store and transport large quantities of kelp. It is very well possible that a permanent conservation method will need to be implemented already when the kelp is harvested at sea. A large-scale industry will

probably demand dedicated processing plants that can process throughout the year. If the harvesting is done only in a limited period of the year, this means that large quantities of kelp must be stored for at least an entire year. For this to be economically feasible it is important that the conservation method is energy efficient.

In Denmark it was found that wild kelps harvested in the summer months of July and August had the highest potential for biogas production (D'Este et al., 2017). In this time of year, the highest carbohydrate concentrations were found. The reason for this is that the chemical composition of kelps varies through the year. When setting up industrial production of kelp in Norway, and evaluating its potential, this factor must be taken into account. An issue with harvesting in the summer is the risk of biomass loss due to biofouling. The biofouling starts around June depending on latitude. In Norway it will occur first in the south, where the ocean temperatures are the highest. Currently the farmers in Norway are harvesting from the beginning of April to the start of June, depending on geography.

3.2.4 Chemical components produced from kelps

Seaweeds in general contain many valuable components. In this discussion, only those that can be found in kelps will be discussed. The main focus will be on the species *Alaria esculenta*, *Saccharina latissima* and *Laminaria digitata*. These three species are the ones that are considered most promising with regard to cultivation in Norway. A comprehensive review of bioactive compounds of several different macroalgae has been made by Holdt and Kraan (2011). In this review it is emphasized that spatial variations and great seasonal variations creates difficulties when trying to say something general about the chemical composition of specific seaweed species. For instance, it was found that the laminaran levels in *Saccharina* and *Laminaria* species varied extremely, from almost nothing in February to June to maximum levels around 14 % of dry mass in September to November. This issue has been further studied by Schiener (Schiener et al., 2015) and D'este (D'Este et al., 2017). Both these studies focus on kelp species that are considered for cultivation in Norway.

Polysaccharides are carbohydrates found in seaweeds, and in kelps in particular, with a wide range of commercial applications (Holdt and Kraan, 2011). These can be used in products like thickeners, stabilizers, emulsifiers, food, feed, beverages and so on. What types of polysaccharides are found in seaweeds depend on the species of the seaweed. The kelps considered for cultivation in Norway are generally high in fucoidan, laminaran, mannitol and alginate. These polysaccharides have been showed to have an extremely wide use as bioactive components. This is further described by Holdt and Kraan (Holdt and Kraan, 2011).

L. digitata, *S. latissima* and *A. esculenta* have been found to have peaks in the laminaran content in the summer and autumn months and minimum contents in the winter months (Schiener et al., 2015). A similar pattern was found for mannitol contents, with a peak in the autumn and a low in early spring. For Alginate, the tendency was that the content in the dry mass were relatively stable through the year for all species mentioned above. Similar studies of the fucoidan levels in the kelps have not been performed. A more thorough understanding of the seasonal and spatial variations in the chemical composition of kelps in Norway specifically would be of great interest in the further process of developing a large-scale cultivation industry.

Table 3.1: Maximum and minimum levels of four types of carbohydrates in *Saccharina latissima*. Samples were harvested from the wild off the coast of Scotland at eight different times between August 2010 and September 2011. Data from (Schiener et al., 2015).

Saccharina latissima				
	Peak concentration	Time of peak	Low concentration	Time of low
Alginate	30%	September	17 %	July
Mannitol	25%	July/August	10%	February
Laminaran	14%	October	1-2%	February
Cellulose	15%	Sept./Oct.	12%	March

Table 3.2: Maximum and minimum levels of four types of carbohydrates in *Laminaria digitata*. Samples were harvested from the wild off the coast of Scotland at eight different times between August 2010 and September 2011. Data from (Schiener et al., 2015)

Laminaria digitata				
	Peak concentration	Time of peak	Low concentration	Time of low
Alginate	31%	May	23%	March
Mannitol	28%	August	9%	February
Laminaran	17%	August	~2%	February
Cellulose	15%	July	11%	May

In Norway there is already an industry producing alginate from the kelp *Laminaria hyperborea*, harvested off the coast of Norway. This industry is not limited by market, but by ecological concerns restraining how much kelp can be harvested. So far, the company FMC Biopolymer (now DuPont) has been the only producer of alginate in Norway, but now the company Nutrimar is also establishing a factory for processing of *L. hyperborea* for alginate production (Hammervik, 2018). This factory will also be supplied with kelp harvested from the wild, meaning that there will be an increased strain on the Norwegian kelp forests. The practice of harvesting wild kelps has received some media criticism due to concerns regarding effects on the ecosystem (Solbakken, 2017) and release of formaldehyde into the ocean (Egge and Trana, 2017, Nilsen and Trana, 2017, Berge, 2017). The formaldehyde is very toxic and is added to the kelp at sea for conservation purposes. This criticism could contribute to increase the interest for, and value of, cultivated kelps and the desire to develop new conservation methods. However, the harvesters state that the releases of formaldehyde, according to their own investigations, are insignificant and easily broken down in the sea (Berge, 2017, Nilsen and Trana, 2017). With regard to the ecological impacts an article published in The Journal of Applied Phycology describes the Norwegian management system for kelp harvesting as a nearly 50-year history of success that “*should be considered an example of how to properly manage a wild macroalgae harvest in a sustainable fashion*” (Vea and Ask, 2011). It is however important to note that both authors of this article both were at the time of writing, and currently are, employed in FMC Biopolymer/DuPont. The harvesting of kelp in Norway is regulated by the directorate of fisheries and the condition of the kelp forests is surveyed by the Norwegian ocean research institute. They consider the

condition of the kelp forests that are subject to harvesting as good (Havforskningsinstituttet, 2018). In the long run the alginate industry in Norway could be seen as a possible starting point for the development of industrial processing of cultivated kelps. It could also be an opportunity to replace the harvested *L. hyperborea* with cultivated *S. latissima*, *L. digitata* and/or *A. esculenta*, providing a more unquestionably sustainable feedstock to the industry.

Kelps are known to have relatively low protein levels. The study by Schiener et al. (2015) of kelps from the Scottish coast found that neither *S. latissima* or *L. digitata* exceeded 10 % protein content in the dry mass in any of the samples harvested at any time in the period. The minimum levels of protein were found to be around 5% of the dry mass. A few samples of *A. esculenta* generally showed a slightly higher protein content in this species with peaks around 12%. The harvesting of *A. esculenta* was however limited and data for the whole year was not available. Extraction of proteins from kelps as a high value product has limited potential. A potential for extraction for valuable amino acids have been mentioned as a possibility, as the *saccharina* and *laminaria* species have some of the best amino acid profiles needed in fish feed.

Table 3.3: Protein content in the dry mass of three selected kelps relevant for cultivation in Norway based on measurements of wild growing kelps in Scotland. Data for *A. esculenta* was limited to three harvest times between March and July. Data from (Schiener et al., 2015)

Species	Proteins			
	Max	Time of max	Min	Time of min
<i>S. latissima</i>	9.9%	March	5.1%	October
<i>L. digitata</i>	8.2 %	February	4.9%	August
<i>A. esculenta</i>	12.1%	March	9.4%	July

Beyond the valuable polysaccharides in the kelps, bioactive properties have been found for extracts from several Norwegian seaweed species. Extracts from *L. digitata* have been found to have effects like anti-fungicidal, anti-ulcerative activity, antioxidation, antibacterial and anti-pathogenic bacterial (Holdt and Kraan, 2011). *S. latissima* extracts have also been observed to have antibacterial effects.

3.2.5 Fertilizers produced from kelps

Many also points to the potential seaweeds can have as fertilizers for the agriculture industry, but this field has been much less explored and is not considered amongst the most important future potentials of kelp farming industry. A few studies have suggested the use of by-products from bioenergy production to produce fertilizers. For instance, did a life cycle analysis that considered biogas production from *S. latissima* and *L. digitata* production through anaerobic digestion include use of the digestate as fertilizer (Seghetta et al., 2017).

3.2.6 Extraction of several components from kelps

To exploit several components for different purposes from the same plant is a possibility that greatly could improve the feasibility of kelp farming in both Norway and the world in general.

Several studies have been performed on this topic. A method called cascading is described by van Hal et al. (2014) as a possible processing method for seaweeds. This study is part of *The Dutch seaweed Biorefinery program (van Hal, 2018)* and focuses on a biorefinery method for producing biofuels and high-value chemical components, but the approach can also be used for producing food or feed components. The cascading approach is based on fractionating all components of the seaweed. This means fractionating the carbohydrate molecules, minerals and proteins. It can also mean separating the different carbohydrate molecules before converting them into high value chemical intermediates or using them as they are. An example of processes and end products for the species *Saccharina latissima* is shown in the figure below.

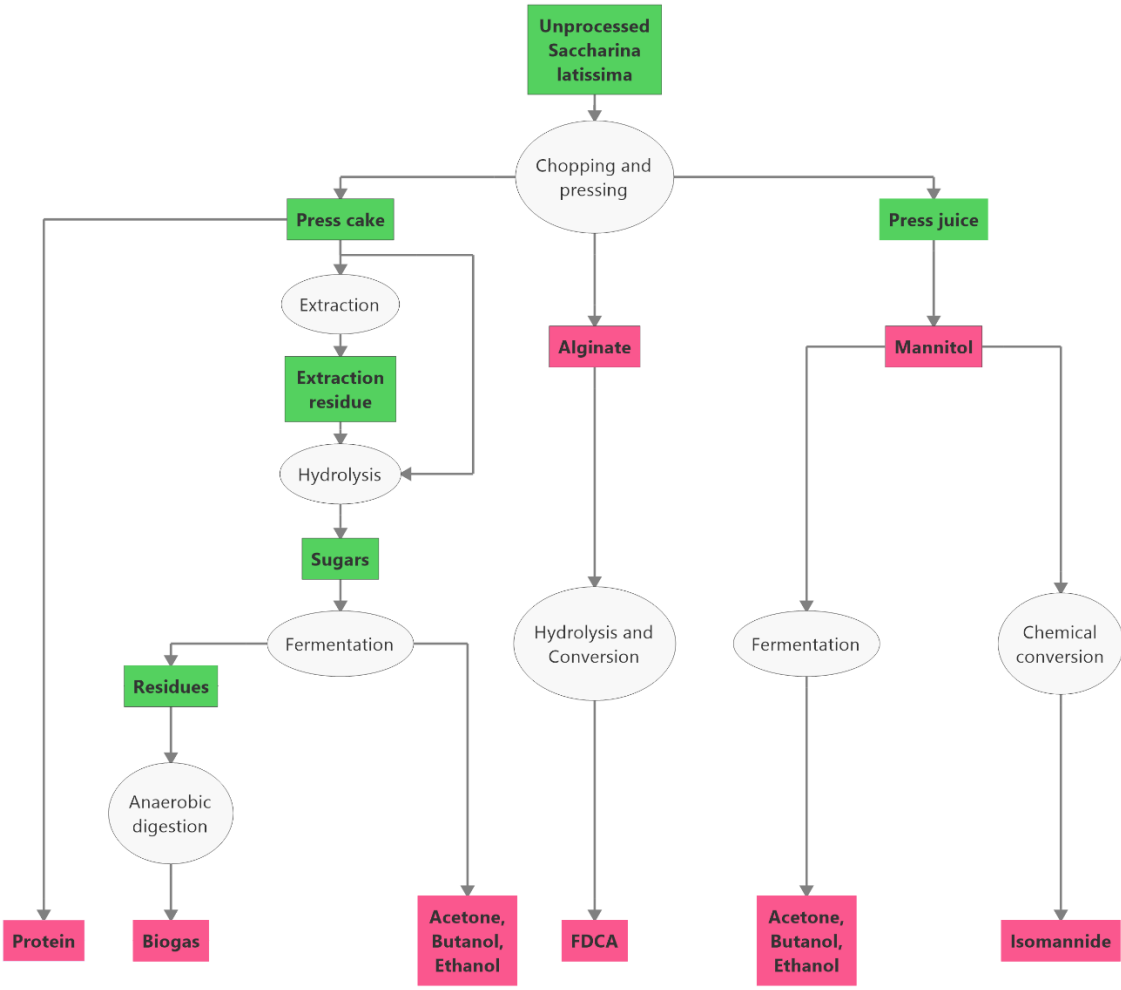


Figure 3.3: Cascading process for *Saccharina latissima*. Intermediate stages in green, processes in grey, end products in pink. FDCA refers to furan dicarboxylic acid that can be used for polyesters. Adapted from (van Hal et al., 2014).

Both mannitol and algininate can in themselves be extracted as end products instead of being processed further. Mannitol has food applications, it can be used to produce rigid

polyurethane foams, or it can be converted into intermediates for use in the production of detergents (van Hal et al., 2014). Alginate has a wide range of uses as a thickener or stabilizer.

A study from 2017 looked into the development of a refinery process for the kelp species *Laminaria digitata* (Kostas et al., 2017). Here, the end products one looked at were specialty chemicals, biofuel and bioactive compounds. A process was developed where fucoidan and alginate were extracted first. These polysaccharides have a commercially high value. The residue from remaining after extraction showed an increase in crude fiber content, making it a potential feedstock for bioethanol production. Once the bioethanol was produced it was found that a methanol extract could be prepared from the liquor waste stream which remained after the polysaccharide extraction. This methanol extract was shown to exhibit both anti-microbial and anti-oxidant activity against the human bacterial pathogen *Burkholderia cenocepacia*.

It is worth noting that the *L. digitata* was rinsed in distilled water and dried at 80 °C in a fan oven for 48 hours before being processed. The study concluded that a bio-refinery process extracting several components from *L. digitata* is a possibility, but that further optimization of the process would be a necessity for it to become commercially viable. Especially the ethanol yields were too low. A schematic overview of the main steps of the process can be seen in the figure below.

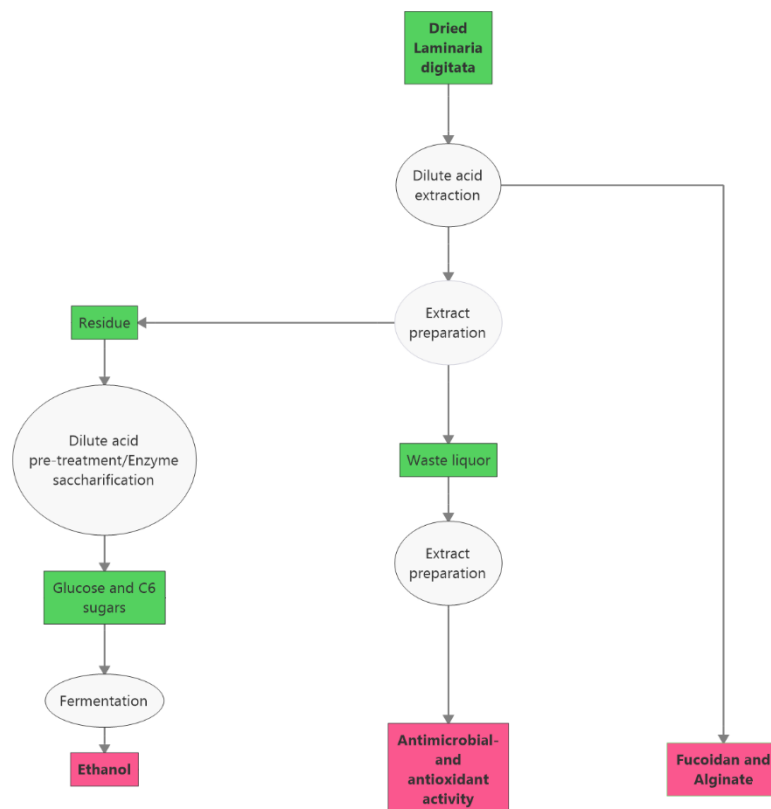


Figure 3.4: Suggested bio-refining process for *Laminaria digitata*. End products in pink, intermediate stages in green and processes in grey. Adapted from (Kostas et al., 2017).

A third study looked at the kelps *Laminaria digitata* and *Saccharina latissima* as an innovative feedstock for energy and fish feed (Seghetta et al., 2017). Here, two different pathways are assessed as part of a seaweed industry with regard to environmental performance. One method for producing energy and fertilizer and one for producing proteins. Energy, in the form of biogas and bioethanol is assumed produced from the high sugar content of the plants. Unconverted slurry material will be sold as digestate for use as fertilizer. When producing proteins, extracting them directly from the seaweeds is not considered to be adequate. The method suggested is to let heterotrophic microalgae produce proteins by utilizing the sugars from the seaweeds. The final product will be a mix of proteins and unconverted compounds. The use of heterotrophic microalgae, as opposed to autotrophic microalgae, is a relatively unexplored field. The reason that it is of interest though is that heterotrophic microalgae has the advantage of being able to grow without any lighting, thus reducing the production costs compared to autotrophic microalgae.

Five different scenarios are modelled in the study. There are scenarios of both protein production and energy production for both dried *S. latissima* and dried *L. digitata*, but also one scenario looking at energy production from ensiled *S. latissima*. The study concludes that energy production from kelps perform best with regard to environment when the kelps are ensiled due to the reduced energy consumption compared to drying. It also concludes that protein production by use of heterotrophic microalgae can compete with traditional soy-based protein production.

Generally, there are a number of interesting studies and research going on looking into the possibilities for a future seaweed industry on the coasts of the Atlantic Ocean. Many of these point to possibilities for cascading or other processing approaches utilizing the seaweeds in a more holistic way. Common for these is the interest in large volume markets like fish feed and bio-energy. A requirement for this large volume industry is efficient conservation methods or year-round production. The methods of conservation mentioned are usually drying, freezing and ensiling. Of these ensiling is the one that, at least with regard to energy consumption, looks most promising. However, ensiling is also the least tested one in national and international seaweed farming.

3.3 Transport storage and conservation of kelps

Due to their high moisture content, kelps degrade relatively quickly after being harvested (Cabrita et al., 2017). How to store the kelp and how to conserve it is considered one of the most important questions to consider when designing vessels for the industry. It is also a very open question, that has yet to be fully explored. When designing vessels for harvesting kelps it is an important question whether the kelp should be immediately conserved or just stored in a way that allows for conserving on shore. What turns out to be the optimal conservation and storage methods will be strongly influenced by the choice of end product and have great implications for the logistics chain. In this section relevant available knowledge on the issue will be presented and some possible solutions discussed.

Studies on the degradation of kelps are limited and it is hard to say something certain about what is the optimal way to store and conserve it. A study of the effect of cooling on quality loss in the red algae *Palmaria palmata* and the green algae *Ulva rigida* found that these seaweeds could be stored at 4°C for up to 14 days and still have acceptable quality (Liot et al.,

1993). It would be very interesting to see how kelps would perform in a similar experiment. The same study also found that while washing with seawater had a positive effect on the quality of the seaweeds, washing with freshwater seemed to accelerate the degradation process. Another temporary storage method, which is very popular in the Norwegian industry, is seawater storage. Either in the form of a net bag filled with kelps, floating in the sea, or in the form of tanks on the decks of harvesting vessels filled with circulating seawater. A study on the effects of this kind of storage found that although some loss of dry mass was indicated, the quality of the kelps was preserved after 22 hours of storage (Stévant et al., 2017b). In this study the quality was considered with regard to using the kelp for human food purposes.

In the Norwegian industry the most popular methods of conservation today are freezing and drying. Due to short distances from the farms to the processing facilities and an adequate capacity at the facilities this system has worked quite well. The facilities used for drying and freezing are facilities that are usually used in the fishing industry but has available capacity in the harvesting season. Examples of this are a fish factory where the kelp is frozen and packed in boxes, a drying facility usually used for drying of fish heads and a facility for receiving crab. If the industry is going to grow into a truly large scale, larger facilities with year-round production of kelp products must be established. This means that it is necessary with a conservation method that does not limit the potential end products of the kelp and preserves the quality for a whole year.

3.3.1 Conservation methods

Kelp farming is subject to a strict seasonal regime and the harvesting will probably be limited to specific periods of the year for a foreseeable future. If dedicated facilities for the processing of kelps are going to be built, a conservation method that allows for kelp processing to be distributed throughout the year will be a necessity. Drying, freezing and ensiling are considered as the main options when it comes to long term conservation of seaweeds. Of these, particular interest has been shown for ensiling, due to the energy efficiency of the method. It is also worth mentioning formaldehyde here. This chemical is currently in use to conserve wild harvested *L. hyperborea* for alginate production along the Norwegian coast. Since formaldehyde is highly toxic, it is not considered suitable for conservation of kelps that are produced for food or feed purposes. In the following, status and opportunities for kelp conservation methods will be discussed.

3.3.1.1 Drying

Stévant et al. (2015) did a study on drying of kelp with regard to establishing an industrial drying facility for kelp in the Norwegian county of Møre og Romsdal. Some observations from this work are that if the kelps are to be used for food purposes they should be dried at low temperatures to achieve the highest possible quality, while high temperatures could increase the efficiency when drying kelps for large volume purposes with lower quality demands. When producing food, sensoric properties, together with components like pigments and proteins, are very important. These are best maintained when dried at low temperatures. A large volume production where high temperature drying has proven suitable is alginate production. It was concluded that while drying can serve as part of a preprocessing step for

later processing and use, it also changes the chemical composition of the plant, thereby limiting the opportunities in the downstream process.

Stévant et al. (2015) suggested two important measures to reduce the costs of the drying process. Firstly, they suggested utilization of excess heat from other industries, specifically from a gas facility and an incineration plant in the region. By utilizing this heat, processing costs could be greatly reduced. While the gas facility had a year-round surplus of heat production, the incineration plant mainly had a surplus during the summer, while heat was distributed to the surrounding area during the colder months of the year. Secondly, they suggested that energy efficient drying technology should be used. Several methods were described in the study, like Multi-belt drying, tunnel drying, barrel drying, fluid bed drying, milling drying, freeze drying and infrared drying. Further work will be necessary to find out what would be the optimal method. It was also emphasized that more work should be done on studying the effect of ensiling and milling of the plants prior to drying. Ensiling would allow for a distribution of the drying out over a larger time span. Milling or cutting of the biomass into smaller pieces will lead to faster drying but could have negative effects on the composition and nutritional value of the biomass.

The importance of the drying technology will depend greatly on the development of the kelp industry. While some processing alternatives depend on the kelp being dried first, others depend on it not being dried first. It is at the moment not known what the main products for the kelp industry in the future as this will be. This will depend on the market prices, development of processing technology and the development of cost efficient production systems. However, many of the processing methods suggested at this point are based on dried kelps. The processing method developed by Kostas et al. (2017), producing specialty chemical, biofuel and bioactive compounds, is based on *L. digitata* which is dried at 80°C for 48 hours. This is also the case for the anaerobic digestion process for producing biogas from amongst others *L. digitata* and *S. latissima* described by Vanegas and Bartlett (2013). Dried kelps are also used as a basis for a method for integrated production of bioethanol and proteins through hydrolysis and fermentation (Hou et al., 2015). Finally, some comparative life cycle analyses of biogas production and protein production from *S. latissima* and *L. digitata* were based on both dried and ensiled raw material (Seghetta et al., 2017). In this study it is worth noting that the ensiled kelp specifically performed better with regard to environment and energy balance due to the reduced need for drying.

When performing drying a common preprocessing step is to wash the kelps with either freshwater or seawater even though this might lead to a loss of water soluble components (Stévant et al., 2015). Since freshwater tends to accelerate the degradation of kelps, seawater is recommended for this purpose.

3.3.1.2 Freezing

There is little literature and studies made on the effect of freezing on kelps. One thing that is clear is that it is energy demanding, due to the kelps high moisture content. Freezing is generally considered to be a method that does not alter the properties or composition of kelps significantly.

3.3.1.3 Ensiling

Ensiling consists of storing a crop in an anaerobic environment and reducing the pH in the material in order to reduce the activity of plant enzymes and unwanted microbial activities (Wout et al., 2013). The purpose of this is to preserve the nutritional value of the ensiled material as well as possible. In agriculture it is a well-established practice of ensiling for instance grass for use later in the year. Bales or silos are used to achieve an anaerobic environment and lactic acid bacteria can ferment the biomass into lactic acid, which reduces the pH in the crop. It is also possible to add lactic acid bacteria or spray the biomass with acid right after harvest, to accelerate the pH reduction process. It is important that this acid does not represent a health risk for the consumer of the biomass if the biomass is intended for food or feed purposes.

The possibility of ensiling kelp is considered a very exciting opportunity for the kelp industry. With the kelps degrading so quickly after harvest and conservation methods like drying and freezing being so energy intense and formaldehyde being as toxic as it is, ensiling is coming up as an energy efficient, non-toxic alternative with great potential. Especially a large-scale industry, producing feed or bioenergy, will depend on an all-year supply of raw material. The most promising way of achieving this is to find a way to ensile large quantities of kelp. However, ensiling could also serve as a beneficial temporary storage method before drying or during transport for other purposes than the extremely large volume products.

Until the last decade or two, there has been a large interest for industrial cultivation of kelps, and thereby also conservation of kelps, in the western part of the world. Until some more recent works, a review study by Black (1955) was one of the most important publications on the topic of kelp ensilage. This study is still frequently quoted in articles on seaweed cultivation and conservation. The report by Black is mainly a review of the work on seaweed ensiling up until that point. Some interesting observations were that the smaller pieces the algae were chopped into, the faster they degraded. It was also found for the kelp *Laminaria cloustoni*, that while ensiling led to changes in the chemical composition, most of the quality was preserved.

In the last years, several studies on ensilage of kelp have been done (Cabrita et al., 2017, Herrmann et al., 2015, Wout et al., 2013, Redden et al., 2017, Gallagher et al., 2017). These are mainly written in a context of bioenergy production, but there is also some interest for other end products. Generally, the studies have confirmed Blacks' finding, that the chemical compositions did alter, but that most of the quality was preserved after ensiling.

Herrmann (2015) studied the effect of ensiling on the potential for methane production from five different seaweed species. These were *Ulva lactuca*, *Ascophyllum nodosum*, *Saccharina latissima*, *Laminaria digitata* and *Saccorhiza polyschides*. Of these the two first ones are not kelps, and their results are of limited interest for this thesis. The three last ones are kelps and therefore very interesting. In this study the kelps were harvested from the wild, washed in freshwater, chopped into small pieces and put into 1-liter jars. The kelps were manually compressed to remove air. It is worth noticing that no drying was performed before ensiling, and no acid was added. Silage effluent was collected in beakers under liquid paraffin to ensure anaerobic conditions also for the effluents and prevent air from infiltrating into the silos. The longest storage period measured was 90 days. It was found that ensiling was a promising method, that could potentially increase methane yields under the precondition that silage

effluents were collected and utilized. For *L. digitata* and *S. latissima*, a higher theoretical specific methane yield was obtained after ensiling compared to fresh biomass. It was generally found that the kelps in the study showed higher biomethane yields than *A. nodosum* and *U. lactuca*.

Redden et al. (2017) studied the changes in ash content, higher heating value and dry matter of the kelp *L. digitata* and the red algae *Palmaria palmata*. Here we will focus on the results for *L. digitata*. In this study it was found that after a year of ensilage the ash content remained constant and the higher heating value increased due to a continuous wet matter loss. However, the energy available from each kilogram of kelp ensiled declined to 78% after one year. Similar results were observed for *P. palmata*. The effect of spraying the kelp with the lactic acid bacteria *Lactobacillus plantarum* compared to natural ensiling was also studied. It was found that pH was lower for the treated samples compared to untreated samples during the entire storage period. A lower pH results in a biomass with potentially greater overall stability. It was however not documented that the lactic acid bacteria treatment had any effect on the dry matter content, higher heating value or ash content in any of the investigated seaweeds.

Cabrita et al. (2017) studied the effect of ensiling on three different seaweeds, one of which was the kelp *S. latissima*. The study was done in the context of the feasibility of ensiling seaweeds from an IMTA system for later use as animal feed. The effect of adding lactic acid bacteria prior to ensiling was also investigated but this only showed minor effects on fermentation. In this study, cultivated kelp from Portugal was harvested, washed in freshwater, wilted at room temperature for 24 hours, then cut to particles of 10-20 mm before the lactic acid bacteria additive was sprayed on to half of the samples and biomass was put into 1-liter, air tight, glass jars. The biomass was manually compressed to remove air from between kelp particles. The biomass was then stored for up to nine weeks. In general, this study also found that chemical composition was preserved during ensilage.

Wout et al. (2013) describes in their patent application methods for ensiling macroalgae and uses of ensiled macroalgae. Like the methods that are described above, this patent also describes the ensiling of macroalgae both naturally and pretreated with an additive of an inoculant comprising lactic acid bacteria.

Some of the ensiling methods described above does not involve any form of dewatering, while others involve some wilting or drying before ensiling. Though good results have been achieved for the ensilage of kelps, it could ultimately turn out that dewatering treatments before ensiling could be preferable. Dewatering methods are also interesting as they lead to a reduced energy consumption in later drying if this is required (Gallagher et al., 2017).

Gallagher et al. (2017) have in general considered three types of pretreatments for ensiling: Treatments that in themselves reduce water content, treatments which make the macroalgae amenable to screw-pressing and treatments that otherwise favor good ensiling by acting as silage additives. Screw pressing have shown good results as a preprocessing method before ensiling for grasses, but for now it has not proven effective for untreated macroalgae. When screw-pressing grasses one has achieved a biomass with less moisture and a press juice which is rich in organic and inorganic compounds, that can be channeled into other applications for the production of high-value-added products. With macroalgae, the only thing one has

achieved so far is producing a sticky mass and no press-juice. This study is based on samples of *L. digitata* harvested off the Welsh coast at several different times of year.

In total, Gallagher et al. (2017) tested 14 different treatments. Some observations made were that treatment with hydrochloric acid successfully conditioned the kelp for screw pressing, air drying increased dry mass content with a minimal loss of dry matter and that immersion methods led to the highest juice production. In general, the majority of the weight loss after treatments was due to loss of moisture. Still, some dry mass was also lost as dissolved solutes. It is also found that washing of macroalgal material reduces water-soluble carbohydrate content. However, saline conditions can be an issue for later processing steps, and washing could therefore be a necessary pretreatment despite the loss in dry mass. Finally, it was observed that the effect of the different treatments varied with the season of harvest, indicating that the optimal treatment could depend on the season.

Six of the pretreatments studied were immersion methods. Kelps were immersed in seawater, saline solution, ultrapure water, formic acid solution, hydrochloric acid solution and phosphoric acid solution. Of these hydrochloric acid solution and phosphoric acid solution were the only treatments that proved effective as a preprocessing method for screw-pressing. Ultrapure water was the treatment that gave the worst general results, as osmotic uptake of water actually led to an increased weight and water content after treatment. Seawater proved to be a good control treatment, with little change in weight. It was also found in the study that season of harvest may influence the usefulness of different approaches.

Of the fourteen pretreatments, five were spraying treatments. In these treatments reagents were evenly sprayed over the algal surface. Reagents tested were concentrated formic acid, concentrated propionic acid, concentrated Crimpstore silage additive, concentrated hydrochloric acid and concentrated phosphoric acid. Again, the highest press juice yields achieved by the phosphoric and hydrochloric acid, although not nearly as high as for the immersion treatments. Together with air drying, treatments with concentrated mineral acids (hydrochloric and phosphoric) gave the highest dry mass contents after treatment.

The other three treatments that were tested were air drying and salt or dry ammonium formate crystals shaken evenly over the algae. Air drying was the method that showed the highest loss of fresh weight. It is however also the most energy demanding method.

3.3.2 On board storage and transport of kelps

The optimal storage and transport solution for harvested kelps will depend on what is chosen as the further processing steps. If the kelp is going to be used solely for alginate production, formaldehyde is an adequate solution, despite being criticized for its potential harm to the environment. If the kelp is going to be used for production of feed or food products, formaldehyde is completely out of the question. Especially kelp for direct human consumption has very high-quality requirements. In addition to this, the storage methods must be considered with regard to the energy demands at sea, and volume requirements. How densely the kelp can be stored will depend on what method is chosen for preservation of quality on board the transport and/or storage vessel. In general, it is considered an issue if the kelp is stored too densely, because of heat generation in the center of the biomass (Stévant et al., 2017b). Another issue is that direct sunlight and even just contact with air will accelerate

the degradation process (Stévant et al., 2017a, Flavin et al., 2013). For optimal kelp quality harvest ideally takes place on a cloudy day with a temperature between 0°C and 10°C (Flavin et al., 2013).

Currently seawater storage is, as mentioned previously in this thesis, the most popular method for storing the kelp after harvest. This is either done in tanks on the deck of the harvesting vessel or in net bags pulled after the vessel. An experiment was also done with storing it in net bags inside the well of a well-boat from the aquaculture industry, but this was not very successful. The method of seawater storage has so far worked okay as long as the volumes handled has been low and the transport distances have been short. Seawater storage in tanks have so far proved to be volume intense, with a density of 150-200 kg of kelp stored per 1000 L. If the kelps are stored more densely than that one has seen issues with the circulation. Floating net bags have been described as a transport solution in New England by Flavin et al. (2013). A possible downside to this system is the loss of valuable compounds documented by Stevant et al. (2017b). For small scale, high quality products, this method could still prove to be a feasible solution. For the large scale, large volume production different storage methods must be considered. In these productions, freezing or drying at sea can be ruled out early, as they are considered too energy consuming to be feasible. It is however important to underline that drying still is an opportunity as a downstream processing step on land. The main three options for storage at sea are considered to be ensiling, refrigerated seawater cooling or some form of preprocessing for ensiling. Storage in net bags or something similar in the ocean is also a possibility that could be discussed further.

3.3.2.1 Ensiling as an on-board storage method

If ensiling is going to be used as a storage method at sea and during transport from farms to facilities on shore, there is first of all need for a lot more knowledge about the process. A protocol for large scale ensilage of kelps must be developed, and necessary equipment for at sea ensiling must be defined and developed. It is also necessary to identify for which end products ensiling is an acceptable pretreatment. A currently unanswered question is whether or not the kelp should be pretreated before ensiling. A few studies of the effect of ensiling on the quality of kelp has found that ensiling can be successful without any pretreatment or only a minimum of pretreatment. In Herrmann's study (2015) the kelps were simply washed with fresh water and cut into pieces with no drying, pressing or other dewatering treatments. It is worth noticing that this study also emphasized the importance of utilizing the effluent, which was significant, from the ensiled material to improve the feasibility of the production of biofuels. Also Black (1955) describe ensiling experiments where the ensiled material is not dried or dewatered first, only washed and minced before ensiling. This could indicate that if ensiling is going to be done at sea, a machine for mincing or chopping of kelps will be necessary. Beyond this machine a compactor for bales or some other ensiling system must be installed. Large scale testing of ensiling has yet to be performed, and little to no experiences with ensiling of kelp in silage bales is available. Development on this topic should be followed closely. If it turns out that seaweed can be ensiled in bales at sea with little to no pretreatment, this will have very big implications for the further storage and transport system. The kelp will now have almost no requirements for storage beyond space. If the kelp were to be ensiled in tanks or in some sort of storage room on board a vessel this will set stricter requirements for the design of the vessel. Finally, it is also possible that one finds that it

would be preferable to spray the kelps with a lactic acid bacteria additive before ensilage. If this is the case, equipment for this must also be installed on the harvesting vessel.

3.3.2.2 Pretreatment for ensiling at sea or during transport

It is a possibility that one finds that the optimal solution is to ensile on shore and perform pretreatment for this during transport and storage at sea. It is not known what is the optimum dry mass for ensiling kelp but any loss of water content will be beneficial (Gallagher et al., 2017). Gallagher et al. (2017) tested 14 different pretreatments for ensilage of *L. digitata* and found that there were several methods that had positive effects. These methods however have limitations. While hydrochloric acid proved to have positive effects on making screw-pressing a possible dewatering method, there is concern that the use of this acid could pose a risk for damage to vessel or crew and therefore is not a preferable treatment at sea. Drying, which was found to be the most stable and efficient dewatering treatment also represents an increased energy consumption and thereby a reduction in economic feasibility. Especially if one is producing a high volume, low cost product like feed or biofuel.

3.3.2.3 Refrigerated seawater cooling

A final possibility for storage at sea is in tanks with refrigerated seawater cooling. In this system the function of the water will only be a cooling effect. The seawater could even go in pipes and the kelp could be stored completely dry. An advantage with this would be that one avoids losing valuable soluble components from the kelp, as documented by Stévant et al. (Stévant et al., 2017a). It is however limited how long the kelps can be stored with only cooling to preserve quality. More knowledge on how long kelps can be stored cold without significant quality loss will be crucial for the development of refrigerated seawater cooling as a storage method for kelps at sea. Liot et al. (1993) did a study on the green algae *U. rigida* and the red algae *P. palmata* and the effect of cold storage on the quality of these seaweeds. While it was stated that manufacturers gave that the seaweeds could be stored for two to three days without significant quality loss, the study found that the seaweeds could be stored for up to 14 days at 4 °C and still have acceptable quality. A similar study should be done for the most promising kelp species for cultivation in Norway, *S. latissima*, *A. esculenta* and *L. digitata*.

3.4 Seasonality of kelp farming and chemical composition of kelps

The current kelp farming industry is strongly affected by the seasonality of kelps. Biofouling during summer makes it a necessity to harvest during spring time. The abundance of competing microorganisms makes it impossible to get any growth on ropes deployed in the ocean before the fall. The light conditions during winter gives so little growth that kelps cannot be harvested again before spring. In addition to this, the chemical composition of the kelps varies through the year (Schiener et al., 2015, Holdt and Kraan, 2011, Gallagher et al., 2017, D'Este et al., 2017), with the optimal chemical composition not necessarily coinciding with the optimal time of harvest. Finally it has also been observed that the chemical

composition of kelps can vary between the locations where they grow (Schiener et al., 2015). This could be influenced by light conditions, wave and current and nutrient availability.

3.4.1 Seasonal variation in chemical composition

The species that are currently being cultivated in Norway, *Saccharina latissima* and *Alaria esculenta*, both have very high water content (80-92%) (Skjermo et al., 2014) with a maximum dry content towards summer and minimum towards winter (Schiener et al., 2015). The seasonal variation in the chemical composition of kelps through the year is due to the kelps having adapted to varying light conditions and nutrient concentrations in the sea.

Generally, the kelps *A. esculenta*, *S. latissima* and *L. digitata* have similar chemical composition. They all have relatively high levels of carbohydrates and low levels of proteins. However, the levels of some components in the dry mass varies greatly through the year, while other levels remain relatively stable. Some studies on this has been made and will be presented in the following but there is still a lot more work to be done to get a full overview of how this works.

Schiener et al. (2015) did a study over a 14 month period on the seasonal variations in the kelps *L. digitata*, *S. latissima*, *A. esculenta* and *L. hyperborea*. The species were chosen for their high potential for cultivation but in this thesis *L. hyperborea* is not considered as equally interesting compared to the three others. Here only the results for *L. digitata*, *A. esculenta* and *S. latissima* will be presented and discussed. The study of *A. esculenta* was somewhat limited due to a lack of available samples. While the other species were harvested eight times over a period of 14 months, *A. esculenta* was only harvested three times over a period of four months. This makes it hard to say much about the seasonal variations through an entire year. The components that were considered to be of interest in this study were the carbohydrates cellulose, laminaran, mannitol and alginate together with proteins, ash, metals and polyphenolics. The study also looked at the seasonal variation in dry content in the plants. The kelps in this study was harvested from a shallow and narrow sound, with a swift current running through off the Scottish west coast.

Schiener et al. found that the moisture content in all species investigated peaked between 85% and 90% during the winter months before it decreased towards summer. The lowest moisture content appeared to occur around July/August. Generally, the lowest moisture levels were found between 80% and 85%, but in *L. digitata* moisture levels down to 76% were observed in July 2010. Analysis of micronutrients showed a significant accumulation of metals, especially during the winter months. The total metal content generally varied between lows around 6000 mg per kg to highs of 12 000 – 14 000 mg/kg. These variations were mainly driven by the variation in potassium (K) content, helped by the variation in Sodium (Na). These metals were the metals that varied the most through the year and also the metals that were found to be the most abundant in all of the kelps. Data for the whole year were not available for *A. esculenta* but the available data seemed to coincide with the observations for the other species. Significant levels of Magnesium and Calcium were also observed in the plants but the levels of these were much lower than for Sodium and Potassium and the content remained relatively stable through the year. The ash content seemed to strongly correlate with the content of metals, with coinciding peaks in the winter for all species. The ash content also

seemed to vary greatly, from lows around 20% in the summer and highs around 40-45% in the winter.

The level of carbohydrates is important when considering bioenergy production, feed production where the carbohydrates are used as a substrate for protein production, or extraction of the valuable carbohydrates alginate, mannitol, laminaran or fucoidan. It was found that the content of carbohydrates generally drops towards the winter months and starts increasing in the spring towards summer. This was observed for all of the species that were investigated for 14 months. It is interesting to note that while the high value components laminaran, mannitol and alginate showed relatively large variations through the year, cellulose seemed to be much more stable through the year. Especially laminaran and mannitol showed extreme variations as can be seen in the table below.

Table 3.4: Carbohydrates in *Saccharina latissima*. Peak and low in content of dry mass. Data from (Schiener et al., 2015)

Saccharina latissima				
	Peak concentration	Time of peak	Low concentration	Time of low
Alginate	30%	September	17 %	July
Mannitol	25%	July/August	10%	February
Laminaran	14%	October	1-2%	February
Cellulose	15%	Sept./Oct.	12%	March

Table 3.5: Carbohydrate content in *Laminaria digitata*. Peaks and lows in content of dry mass. Data from (Schiener et al., 2015)

Laminaria digitata				
	Peak concentration	Time of peak	Low concentration	Time of low
Alginate	31%	May	23%	March
Mannitol	28%	August	9%	February
Laminaran	17%	August	~2%	February
Cellulose	15%	July	11%	May

Proteins are interesting with regard to using the kelps for feed or food purposes. In all four kelps studied by Schiener et al., the protein levels were highest in the first quarter of the year, and lowest in the third quarter. Generally, the contents varied between 5 and 10 % of the dry mass. The protein levels were also found to closely follow the nitrogen profiles, which also peaked in the first quarter of the year with lows in the third.

Polyphenols were also investigated due to their wide range of antioxidative, antimicrobial and anti-inflammatory properties. It was found that the polyphenol levels were highest in *A. esculenta* and *S. latissima*. In these species it was observed highs of 1.5% and 0.7 %

respectively. In *L. hyperborea* and *L. digitata* the polyphenol content varied between 0.1% and 0.2 %. The highest levels of polyphenols were found to be between May and July. The lows were found in March for *A. esculenta* and *S. latissima* and in October for the two other species.

The report by Schiener et al. concludes that there is still more work to be done in order to fully understand the seasonal variations in the chemical composition of kelps and the factors that determine for this. This knowledge will be important for the further development of the kelp farming industry. The seasonal and spatial variation in chemical composition will affect where and when optimal harvest will take place. For instance, it is pointed out in the article that if ethanol fermentation is the goal of the production, it is possible to optimize the level of carbohydrates by harvesting in the summer and autumn. A positive by-effect of this is also that at this time of year the levels of polyphenol, ash, protein and moisture were observed to be low, which could be positive for the ethanol fermentation process.

An important work on the chemical composition of kelp is a study by Holdt and Kraan (2011). It is also referred to this study in the sections about biofuel and the section about valuable components in this thesis. In this study of bioactive components in kelps, and several other seaweeds, they find that there are also significant seasonal variations in the composition of kelps. Much of the data on kelps is based on Norwegian studies done in the fifties (Haug and Jensen, 1954, Jensen and Haug, 1956). They for instance found, as was reported by Schiener, that the ash content of *S. latissima*, *A. esculenta* and *L. digitata* was lowest in September, October and November and highest between February and June. For the same species it was found that dry content was highest between July and September and lowest between January and March. For the polysaccharides the variation was observed to vary depending on the type of polysaccharide. Laminaran showed extreme variations, with almost no laminaran in *Saccharina sp.* and *Laminaria sp.* from February to June and maximum levels from September to November. Alginic acid levels peaked from March to June with lows between September and October. However, peaks had also been observed during winter in other studies in the same areas. They also found the highest levels of proteins in the period from February to May.

A study of seasonal variations in kelps has also been performed using Danish kelps but here with a specific focus on the potential for biogas production and the levels of polyphenols (D'Este et al., 2017). In this study the species *S. latissima* and *L. digitata* were studied. It was, as in the previously mentioned studies, that there are significant changes in the chemical composition of kelps through the year. In the study the chemical composition was not directly investigated, instead the biomethane production from the kelp samples was measured. It was found that there was a much stronger impact of harvesting season on the methane production for *L. digitata* than from *S. latissima*. However, the highest yields were observed in August for both species. This is consistent with the findings by Holt and Kraan and Schiener et al. in the previous discussion, where it was found that the maximum levels of carbohydrates occur in the fall. It is however also stated that the production of biogas through anaerobic digestion is not only regulated by the amount of carbohydrates in the plant but also by the C:N ratio and the levels of Sodium and Potassium. According to D'Este et al. the kelps had a C:N ratio within the optimal range of 20:1 – 30:1 from June to September but the methane yields were still lower in June due to high levels of potassium in the biomass. This shows that when one

wants to cultivate kelps for a specific end-product understanding of the chemical composition and its variation through the year is important in order to optimize the production cycle.

3.4.2 Spatial variation in chemical composition

It is not only the season that can affect the chemical composition of kelps. Nutrient availability, ocean temperature, light conditions, salinity, waves and currents will also be different at different farm sites. Which factors are important and how they affect the kelps are still poorly understood. Some observations that have been made on this topic is that salinity seemed to have a negative correlation with the sugar content in the grown kelps (D'Este et al., 2017). In Denmark significant variations in biogas potential was observed between kelps harvested at different locations but it was not possible to determine which factors were determining for the potential. Polyphenol production has been shown to be reduced if the salinity of the water is high, but it could not be proven for the Danish kelps in the study by D'Este et al. (2017). A reason for this could be that the polyphenol content is also influenced by other factors like nutrient availability and light. The production of polyphenol is a defense mechanism against the strong irradiation from sunlight and therefore increases in the spring and summer when the kelps are exposed to more sunlight. It has also been indicated that kelps grown on larger depths produce less polyphenols due to a lower irradiation exposure.

It has also been found that kelps grown in more turbulent water generally have a higher alginate content than kelps grown in calmer water (Schiener et al., 2015).

3.4.3 Variation in biofouling and growth

It is not only the seasonal variation in chemical composition that must be taken into consideration when determining time of deployment and harvesting for cultivated kelps. It is also important to consider the effects that biofouling can have on the quality of the kelps and loss of biomass and the effects that factors like light, ocean temperature, salinity and nutrient availability can have on the growth plants growth. It has been thoroughly documented that as the ocean temperatures increase, the risk of biofouling increase and with it quality loss, and ultimately biomass loss will occur (Handå et al., 2013). The timing of this phenomenon is believed to depend on temperature, and has been observed to occur at different times in different countries (Rolin et al., 2017). In Spain severe biofouling can start already in April, while it in Ireland and Norway has been observed to start in June or July. Cultivated kelps have been found to grow well in late autumn and spring, with little growth in winter and even biomass loss in summer (Handå et al., 2013). This has led to the conclusion that cultivated kelps must be harvested in late spring or early summer, depending on quality requirements, in order to avoid biomass and quality losses. However, it has been observed that kelps cultivated in more exposed waters or very far north have been able to grow through summer without significant quality- or biomass losses (Bak et al., 2018). This allows a production where the blade is only partially cut when harvesting making several harvests before re-seeding of the lines possible. In the Faroe Islands four harvests of *S. latissima* and three harvests of *A. esculenta* over a 16 month period without re-seeding was successful (Bak et al., 2018). This contributed to greatly reduce the production costs. A study from Shetland also indicated that there was potential for several harvests without re-seeding (Rolin et al., 2017). Here, results also indicated that *S. latissima* was more suited for several harvest due to higher re-growth

rate and less biofouling observed during summer. Generally the kelps will accumulate the storage carbohydrates laminaran and mannitol during autumn and utilize it for tissue growth during winter (Schiener et al., 2015). During winter it has been suggested that nitrogen reserves are built up to sustain rapid growth during spring and into the summer months.

It is also worth noting that a study performed in Norway found that samples of *S.latissima* grown in locations with similar water quality had much higher growth if they were grown in areas with higher current than with low current (Skjermo et al., 2013). This indicates that not only could production costs go down when producing kelps offshore due to larger farms, but it could also mean higher biomass yields per area cultivated.

3.5 Environmental considerations and potential issues

Kelp farming is widely regarded as a great potential contribution to a more environment friendly society. However, some potential challenges must also be concerned when developing the industry. In the following, the potential upsides and downsides to kelp farming will be briefly discussed.

3.5.1 Genetic interactions

Previously, cases of accidental introductions of non-native seaweed species have led to population explosions and significant ecosystem alterations several places in the world (Stévant et al., 2017c). In order to avoid this kind of issues as a consequence of kelp farming in Norway, it has been decided that when harvesting kelps for seedling production, they must be harvested from the area in which they shall be grown. In this way one will avoid introducing new species in addition to not compromising the local variations in the kelp populations along the coast. However, there is a growing interest for breeding of both kelps and seaweed in general. Breeding efforts have so far proven effective in improving crop yields for several seaweed species in Asia (Stévant et al., 2017c). Breeding programs could provide positive properties for the kelps such as higher growth, better chemical composition or higher resistance to biofouling. However, it is not possible to prevent the kelps from releasing their spores into the ocean, thus mixing their gene-material with the wild populations. Breeding of sterile plants has been suggested, but has so far not proven successful (Stévant et al., 2017c). There is also a worry that massive cultivation can provide a source for appearance of new mutants with properties that make them better fit for the environment than the local population (Fernand et al., 2017).

3.5.2 Impact on ecosystems

Kelps can assimilate dissolved inorganic nitrogen and phosphorus, contributing to a mitigation of eutrophication of coastal environments (Stévant et al., 2017c). This is particularly interesting with regard to the issues in the Norwegian fish farming industry with eutrophication, especially in shallow fjords. However, it will require very large areas to consume all the dissolved nutrients from a standard Norwegian fish farm (Fernand et al., 2017). A modeling study have shown that a one-hectare kelp farm could take up less than 0.5% of the dissolved inorganic nitrogen from a fish farm producing 5000 tonnes of salmon.

A second important impact of kelp farming is its potential to store CO₂. A truly large-scale kelp industry could provide a contribution to actually reducing the CO₂ levels in the atmosphere. Kelp farms could also provide a habitat for invertebrates and fishes. Overall positive effects on local biodiversity have been indicated for seaweed farms, but further research is needed to provide evidence of this. It could also become an issue that harvesting of cultivated kelp will represent the removal of a habitat for the organisms living there (Fernand et al., 2017). Another potential downside in local ecosystems is the fact that the kelp farms could provide shading over pelagic the pelagic zone or even the benthic zone in shallow waters, thereby reducing the natural primary production in these areas (Stévant et al., 2017c, Fernand et al., 2017).

3.5.3 Epiphytes and diseases

High-density cultivation of biomass can pose an increased risk of problems with pathogens and epiphytes. Especially biofouling, which is discussed more in detail in a previous section, represent an issue for cultivated kelps (Handå et al., 2013). With regard to IMTA-systems, it is not known if kelp farms could have positive effect as a barrier for pathogens or a negative effect as a reservoir for disease agents (Stévant et al., 2017c). This is a matter that should be studied further.

3.5.4 Area utilization

A large-scale kelp industry will require large areas, something that potentially could conflict with other interests like fishing, shipping and other activities at sea (Stévant et al., 2017c). It is important that the kelp farms are set up and placed in way that allows for other activities in the area not to suffer too much. An area utilized for kelp farming will for instance limit the opportunities for fishing and kelp harvesting. Additionally, ships with draughts of 2 meters or more will probably not be able to pass over. It has also been suggested to integrate the farms into other ocean constructions such as wind farms.

3.6 Alternative operations

Efficient deployment and harvesting is considered one of the most important bottlenecks for further expansion of the industry in northern Europe. At the moment the harvesting season in Norway is extremely short and the revenue in the industry is low. It is very probable that a vessel that is built for the kelp farming industry will require an alternative use to improve the economic performance of the vessel. It is even a possibility that the first vessel designed for the very young industry of today should have a main function different from kelp harvesting and deployment. Secondly, it is not necessarily so that the same vessel should be used for both harvest and deployment. It is therefore interesting to look at the possibilities of combining functionalities for the fish farming industry with kelp farming operations. Which operations one aims to combine with the kelp farming operations could have a defining effect on the design of the vessel, creating requirements for the development of on-board equipment. Other uses like fishing or kelp harvesting could also be considered as alternative operations, but these will not be considered here.

The most important factor when choosing an alternative use is to identify which parts of the year the vessel definitely will be in use in the kelp farming industry. Secondly, it is necessary to find out which kind of operations are in demand at this time of year in the fish farming industry and which operations are in demand the rest of the year. Here, one must also consider which operations it could be suitable to combine with kelp farming operations and how this could be done.

There is a wide range of system and vessel concepts that could potentially have a use in the kelp farming industry. It is not given whether the system should consist of one single vessel or if it should consist of several vessels. For instance, in the case of kelp harvesting, it is thinkable that one vessel would perform the harvesting operation, while another vessel stored and transported the harvested kelps. In this case the harvesting vessel would be the most complex one, but relatively small, while the storage vessel would be less complex and much larger. Automated equipment for deployment, harvesting, processing and storage is still not developed for the kelp farming industry. This means that while it is difficult to know the requirements for the vessel. At the same time this means that one has a bigger freedom in designing the vessel, as the equipment can be part of the designing process and be adapted to the optimal design. This however, makes it very difficult to evaluate what types of aquaculture vessels would be combined with kelp farming activities.

3.6.1 Service vessels in the fish farming industry

A comprehensive study of the service vessels in the aquaculture industry was performed in a masters thesis at the Department of Marine Technology at NTNU Trondheim (Nekstad, 2017). Based on Nekstads work, a brief overview will here be given over the vessels in the industry and the operations they perform. At the end of this section there will also be given a short overview of some considerations regarding exposed aquaculture. This is particularly interesting with regard to the kelp farming industry, which probably will need to utilize more exposed areas if it is going to grow as much as it is hoped.

The vessels in the aquaculture industry can, by length, broadly be divided into three groupings. Vessels with a length overall (LOA) below 15 meters, vessels between 15 and 24 meters, and vessels longer than 24 meters. This division is a consequence of the regulative system for aquaculture vessels. The Norwegian Maritime Authority has different sets of rules for the different vessel lengths, with more and stricter regulations with increasing size. Additional rules also apply if the vessels gross tonnage exceeds 500 tonnes, but almost no vessels of this size are built today. Another factor that can affect the vessel is the effect of the propulsion machinery. If it exceeds 750 kW the vessel must have a certified chief engineer on board at all times, and a manned machinery room when maneuvering in and out of ports. In general, it is desirable to design a vessel so that as few rules and regulations as possible applies. This will reduce both building costs and operational costs.

Aquaculture vessels can either be specialized or multi-purpose. While specialized vessels usually have the advantage of having a more optimized mission performance, they do not have the same opportunity that multi-purpose vessels have to adapt to changing needs and demands in the industry. Another advantage with specialized vessels is that by performing just one specialized operation, the crew will also become more specialized, thus performing this operation better than a less specialized crew. Most companies in Norway have both

purely specialized vessels and vessels with capability to perform several operations. There are however big differences between companies in what is their main focus. Some companies have almost exclusively specialized vessels, while others have chosen to lean more on multi-purpose vessels. One way of implementing multifunctionality on a vessel is to install twist-lock systems that allow for the installment of different containers with different equipment, depending on the operation that shall be performed.

3.6.1.1 System breakdown

A basic understanding of how aquaculture vessels are composed is necessary to establish some basic concepts that could also work in the kelp farming industry. Nekstad divides the systems of aquaculture vessels into *ship systems* and *mission related systems*. Here, *ship systems* refer to the basic functions necessary for the vessel to function, while the *mission related systems* refer to the systems that are necessary to perform specific tasks or missions. A coarse breakdown of *ship systems* divides them into *ship structure, propulsion and maneuvering* and *accommodation*.

3.6.1.1.1 Ship structure

The most important part of the ship structure is the hull, and this will be the focus of this discussion. Most aquaculture vessels have either a monohull or a catamaran design. The advantages with catamaran hulls are that they usually give a large deck area, high stability and low draught. When performing heavy operations stability is a great advantage and especially the smaller vessels usually have a catamaran design. However, the high stability could be an issue when performing exposed operations, as it could lead to very high accelerations. Another factor to consider is that monohull vessels usually have more available cargo space. What is the optimal, choice depend on the missions the vessel shall perform.

3.6.1.1.2 Maneuvering and propulsion

When it comes to machinery, one will always try to avoid crossing the 750 kW limit, so that one must not have a certified chief engineer on board. Beyond this, the main two options when it comes to propulsion is diesel-mechanical or diesel-electric. Gas turbines or a fully electric system with a battery package could also be considered, but this is not common in the industry at the moment. A diesel-electric system has the advantage that it allows for more flexibility with regard to the placing of the main engine, as the engine no longer needs to be directly connected with the propeller. For a catamaran this has the additional advantage that two propellers, in different hulls, can be powered by the same engine. When a diesel-electric system is installed one can, if several generators are installed, choose which one to use depending on what is optimal with regard to fuel consumption in the performed operations. Finally, a diesel-electric machinery with several generators will also provide redundancy considering engine breakdowns. Still, the most common system is a traditional diesel-mechanical system with auxiliary engines and/or shaft generators connected to the main engine for production of power for equipment and thrusters. Monohull vessels have, due to their increased space below deck, more flexibility when it comes to choice of machinery arrangement.

For maneuverability most service vessels have both a stern and an aft thruster in each hull. This increases the ability to maneuver in tight spaces and close to farm cages. It is very important to avoid accidents when performing operations close to fish cages due to the risk of fish escapes. Fish escapes is both a big economic loss in addition to be a big issue for the reputation for the entire fish farming industry.

3.6.1.1.3 Accommodation

Accommodation includes crew facilities, technical spaces and service spaces. The required technical spaces will be mission specific, and for multi-purpose vessels, vary depending on what mission is performed. The crew facilities are the crews living areas like cabins, common spaces and sanitary facilities. The service spaces include galley, laundry, provision store and such. It is important that the service vessel has accommodation that is up to the standards of the industry making the vessel an attractive work place.

3.6.1.1.4 Mission related systems

The mission related systems are coarsely divided into three main areas; *work deck*, *cargo space and tanks*, and *equipment and systems*. What missions can be performed will depend on these systems and the requirements to the systems depend on the missions that are to be performed.

3.6.1.1.5 Work deck

All operations are launched from the work deck and it is defining for what types of missions the vessel can perform. Generally, a large work deck area is desirable. Large work decks allow for more efficient and safer operations for the crew. A large deck also allows for more equipment installed and a larger area for storing of cargo. However, it is important to have a work deck that has few obstacles in order to keep operations as safe as possible. It is also preferable that it is easy to clean and disinfect to prevent spreading of diseases. If container twist locks are integrated in the work deck containers can easily be installed and removed depending on the operations that are to be performed.

3.6.1.1.6 Cargo space and tanks

Cargo space below deck can be an advantage as this frees up the deck area for equipment or can contribute to keeping a clean, and thereby safer, deck. Cargo spaces below deck also increases the general cargo capacity of a vessel. This in turn can improve the efficiency of the vessel when performing operations that require transportation of a lot of equipment, like the launching of a new farm. As a cargo hold can be used for housing systems and equipment that doesn't need to be installed on deck, it can contribute to the vessel being able to perform a wider range of operations and missions, thus increasing the vessels flexibility.

If containers are to be used for storage below deck, a container skidding system could be required for handling, moving and securing of storage containers. In this case the containers could be handled by cranes installed on the vessel and it would be necessary to have a cargo hatch on the main deck to provide access.

A vessel can also have tanks installed permanently, containerized or both. This can allow transport of feed, fuel, oil, septic water or other bulk or liquid cargos. Containerized tanks can also be stored on deck, but will require a container twist lock system, as previously mentioned. For transport of live fish, it is also necessary to have systems for oxygen production, sea-water pumping and ozone production. The ozone production system could be required in any case for tank cleaning.

3.6.1.1.7 Systems and equipment

The systems and equipment utilized during the missions the vessel is designed to perform can be placed on the main deck or below. Cranes, winches, diving containers and such are examples of systems and equipment. The systems and equipment can be subject to various rules and regulations in addition to the requirements of clients. They can be permanently installed or modularized in order to ensure flexibility for the vessel. Equipment can also be temporarily installed by for instance welding them to the deck, and then removed later.

3.6.1.2 On Exposed aquaculture

It is a broad political goal in Norway to expand the aquaculture industry into more exposed areas. This will increase the production potential of the industry in addition to potentially solving or reducing some of the issues in the industry today such as the sea-lice problem and the issue with over fertilization of the areas around the fish-farms. When talking about a large-scale seaweed farming industry, one will have to consider more exposed sites than what is currently in use. Seaweed farming is an area intense industry and there is great potential in utilizing the vast, but exposed, areas along the Norwegian coast. Therefore, it considerations towards moving the farms to more exposed areas should be made when designing a harvesting vessel. What needs to be considered is the increased requirements that will apply to a vessel and its equipment when performing exposed operations. This concerns stability, station keeping, heave compensation and general safety and reliability measures. Moving the facilities to more exposed areas will possibly also lead to changes in operations or entirely new operations due to an increased size of structures or new structure designs. This applies to both fish- and seaweed farming. Finally, more remote locations will strongly affect the logistics of the operations through longer sailing time to and from facilities.

Some factors that are listed by Nekstad that could be affected by the moving of aquaculture to exposed locations are:

- Hull shapes

The advantageous stability of catamarans could become an issue in exposed waters with harsher environmental loads. Vessels with a high stability in roll will get shorter rolling periods and consequently experience large accelerations. Large accelerations can in turn lead to discomfort for the crew and damage to vessel, equipment and cargo.

- Machinery and propulsion
Harsher conditions could require more of the propulsion system, both in terms of power and maneuverability. Vessels performing ROV operations offshore are required to have dynamic position (DP) class 2 or 3, and this will probably be required for exposed aquaculture vessels also. DP is also an advantage when performing operations close to aquaculture facilities, as it reduces the risk of damaging impacts between cage and vessel or interference with the mooring system.
- Storage space
With larger distances and larger facilities, the requirements for transport capacity will probably increase. This includes feed, fuel, consumables, equipment, waste water and so on.
- General vessel size
Generally, the vessels will probably tend to be larger for exposed operations, as the requirement for equipment and working platforms will increase. It will for instance probably be necessary with a decompression chamber for vessels performing diving operations in exposed locations.
- Generally increased requirements to equipment
In harsher conditions cranes can be required to have heave compensation and ROV vessels could be required to have a launch and recovery system (LARS) and a tether management system (TMS). This will increase the amount of time it is possible to perform such operations. Nekstad however, assumes that heave compensation will not be required in the cranes for exposed operations. Another possible requirement for cranes that are to perform offshore operations is a constant tensioning and an automatic- and manual overload protection system. In harsh conditions this can improve the safety on board when performing crane operations. For vessels transferring people to the facilities a gangway with motion compensation could be required
- Equipment for new missions
A series of equipment types for new missions that could be relevant in exposed aquaculture is also listed. These include equipment for catching of escaped fish, emergency response for rescue and fire-fighting and anchor handling but will not be further considered for the vessels in this thesis.

3.6.2 Missions for service vessels in the aquaculture industry

Service vessels perform a wide range of missions in the aquaculture industry. According to Nekstad (2017) it is important to understand which missions a vessel could be required to perform and how these missions can be performed, in order to design a vessel that meets the

needs of stakeholders and is able to compete in the market. Nekstad divides the missions into 11 main groups, which are:

- Net installation
- De-licing and disease handling using tarpaulin
- Mechanical de-licing
- Cleaning and disinfection of farm structures and systems
- Inspection, maintenance and repair (IMR)
- Light construction work
- Anchor handling and mooring
- Towing
- Support, Fish farm
- Supply and transport

These mission groups come with different requirements to equipment and design for the different vessels. While the demand for some operations remain relatively stable through the year, some missions experience significant peaks and lows through the year.

3.6.2.1 Net installation

This mission consists of installation of new nets, changing of existing nets or removal of old nets. Installation of new nets is usually done when a new farm is launched, or an old farm has been out of use for a while. Old nets are removed when farms are shut down or if it is going to be out of use for a while. Often, when the fish is butchered in the spring, the nets will be removed before the following season, with new nets installed after the following season, before the new fish enters the facility. This can also contribute to reduce spreading of disease from the old population to the new one. Changing of nets is usually done if there has been some form of irreparable damage to the existing net. There are generally not very large variations in demand for this type of operation.

Net installation and removal requires cranes and winches for lifting and lowering of the bottom rings. It is also required to have ROV or diving capabilities for inspection of the net after installation.

3.6.2.2 De-licing and disease handling using tarpaulin

There are several ways of treating the salmon for sea lice. Sea lice is a tremendous problem for the salmon industry in Norway today and numerous efforts are being made to deal with it. Here de-licing treatment using tarpaulin is described. This method is also used for treatment of other diseases in the salmon industry. The method consists of enclosing the net cage with tarpaulin and then pumping chemicals into the closed volume. In order to cover the entire net, the bottom ring must be lifted so that the volume is reduced. Stretching and positioning of the tarpaulin is an operation that will require a secondary vessel in addition to the main treatment vessel. The main vessel should, in addition to transport, store and mix the chemicals, provide fresh seawater and oxygen to the contained fish. It could also be required that either the main vessel or the secondary support vessel have ROV capabilities for inspection and control of the positioning of the tarpaulin.

Generally, the levels of sea lice increase in the fall. This has led to the general demand for de-licing treatments to increase in this period as well. While bath treatments were a very popular method a few years ago, it is now possible to see a dramatic decrease in popularity for this treatment method. This could be due to increased resistance to the chemicals for the sea lice or because of concerns over fish welfare. Still it is possible to an increase in demand in the late summer, with a peak typically occurring between week 34 and 40 (Late August to early October). Previous years there have also been short peaks in the demand early in the year, but this has not been observed the last two years.

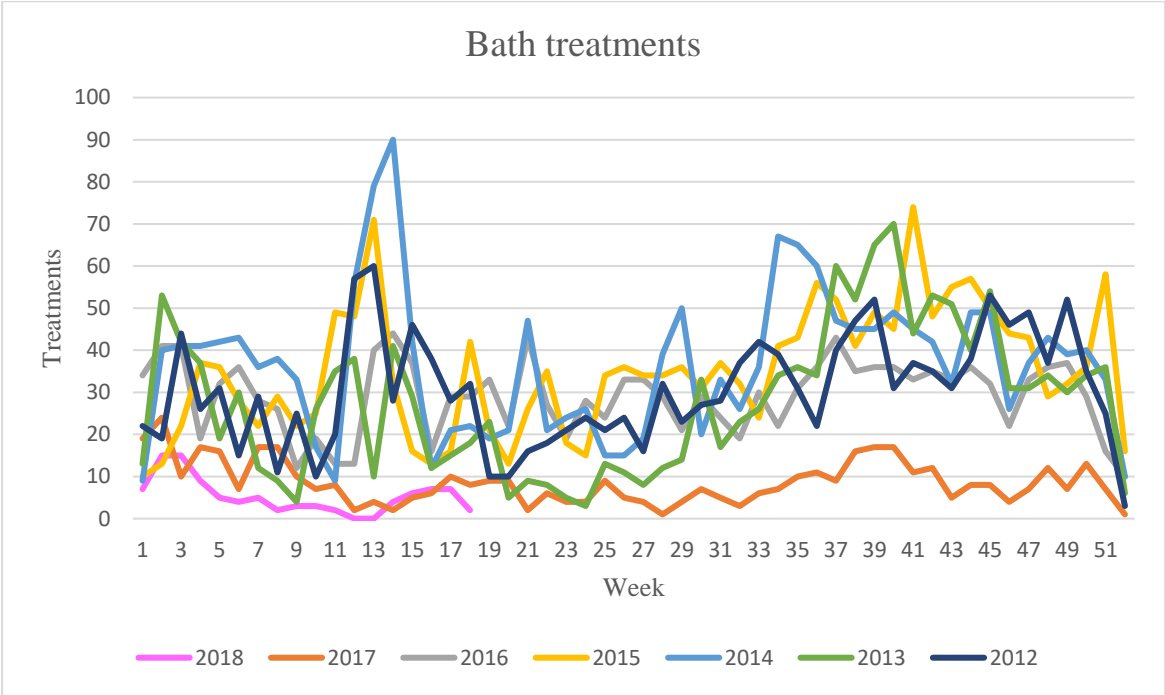


Figure 3.5: Number of bath treatment performed in the Norwegian aquaculture industry since 2012. Only bath treatments with regard to de-licing is included, but both bath treatments using tarpaulin and well boat is included. Data delivered by (BarentsWatch, 2018)

3.6.2.3 Mechanical de-licing

Mechanical de-licing is performed on board the service vessel. So, in order to treat the fish, it must first be pumped into the vessel. This requires that a fish pump is installed, in addition to the mechanical de-licing equipment. It is also preferable to have equipment for installation of displacement nets and lifting of the bottom ring, so that the fish can be comprised and easier to pump. This can also be done with support from a secondary vessel.

While the popularity of bath treatments has decreased drastically the last two-to-three years, the case has been the direct opposite with mechanical treatments. While the demand seems to be a bit more stable, it is still possible to see clearly that it is higher in the second half of the year than in the first half.

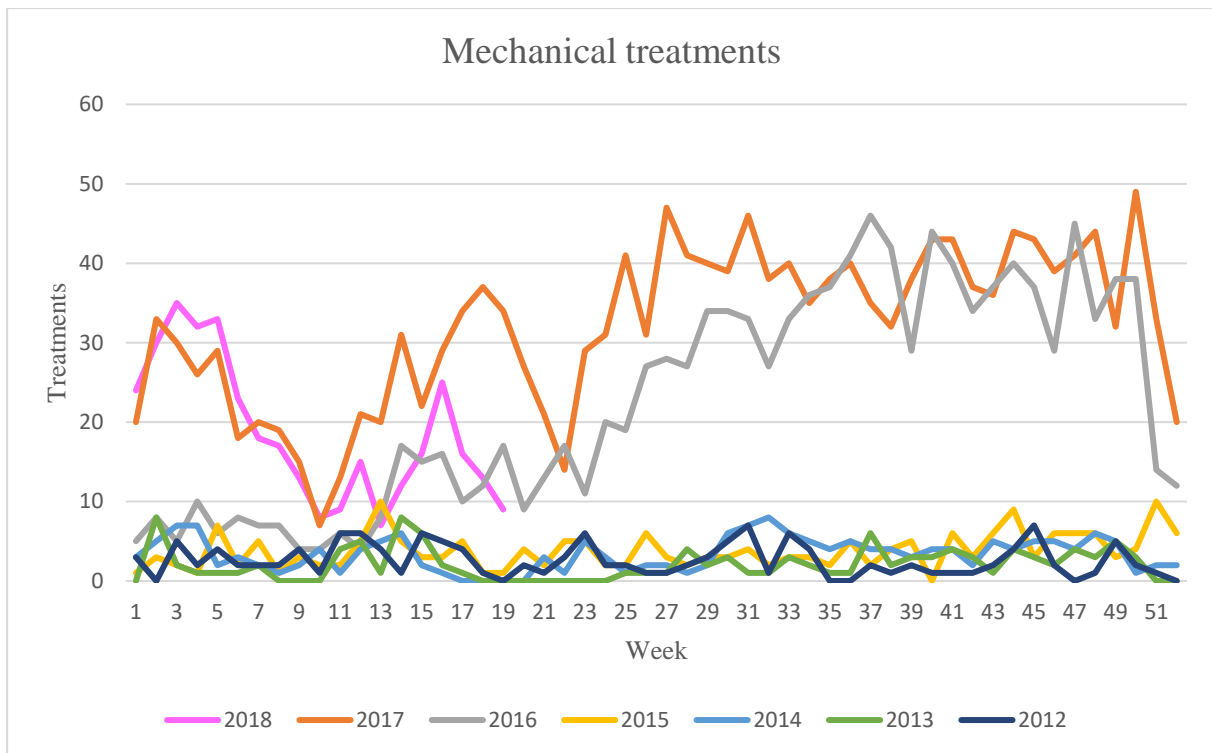


Figure 3.6: Mechanical de-licing treatments in the Norwegian aquaculture industry since 2012. Data delivered by BarentsWatch (BarentsWatch, 2018).

3.6.2.4 Cleaning and disinfection of farm structures and systems

This mission consists of cleaning and disinfection of different farm components using either tarpaulin, divers or ROVs. The parts of the farms that are cleaned and disinfected are divided into collar and bottom ring, feed-barge and simply other systems and structures. The cleaning and disinfection of farms is usually done in the following period (late summer and fall), after farms have been emptied. It is an important part of reducing the risk for spreading of diseases. Collar and bottom ring is cleaned and disinfected aboard the vessel after being lifted by a crane. Cleaning can be done using handheld high-pressure washers or a washing rig. While the feed barge can be cleaned by using a tarpaulin to enclose it before disinfectants are pumped into the enclosed volume, other structures and systems must be cleaned by divers or ROVs. These can also clean the feed barge, as an option to the tarpaulin treatment. It is assumed that as the salmon industry moves to more exposed areas, the use of ROVs will increase in favor of divers.

3.6.2.5 Inspection maintenance and repairs

Inspection, maintenance and repairs can often be performed by either divers or ROVs. However, there are also maintenance and repair work that needs to be done above the water line and there can also be maintenance and repair operations that cannot be performed by neither divers nor ROVs. Inspections are performed on a regular basis, to ensure that there are no damages and to assess the wear and tear on the cage systems. Maintenance and repairs are planned very much based on these inspections. It is also necessary to inspect after installation and after maintenance and repair work is performed. A typical repair operation that can be

performed by divers or ROVs is repair of holes in the net. When parts of the system or structure cannot be repaired by ROVs or divers it is common that the parts in question are lifted onto the work deck of the vessel for safe and efficient operation. Generally, it is also considered that the use of ROVs will be preferred over divers in more exposed facilities.

Net cleaning is also included in the IMR-grouping. This cleaning operation must be performed much more frequently than the cleaning and disinfection operations described in the previous section. The main purpose of cleaning the net is to remove the fouling, which increases the weight of the net and the drag forces on it in addition to reduce the flow through the net. Nekstad consider this a maintenance operation due to the frequency with which it must be performed. Fouling generally increases towards the end of summer and into the fall. Leading to an increased pressure on the washing fleet in this period of the year. Many service boat companies have dedicated vessels for net cleaning.

3.6.2.6 Light construction work

Light construction describes installation of farm systems and parts of a farm's infrastructure. This could be installation of the cages themselves or support systems.

3.6.2.7 Anchor handling and mooring

This grouping considers all missions required to launch and retrieve the anchor and mooring system of a fish farm. This include deployment and retrieving of anchors, anchor lines, anchor bolts, buoys, coupling plates and mooring lines. It also includes tensioning of mooring lines and anchor lines in addition to some maintenance and repair operations on the anchor and mooring systems. For anchor bolts, divers or ROVs must be used. These vessels are generally in a quite stable demand and are not considered to be a good match for combination with kelp farming. They will however probably be needed in the kelp farming industry, as the mooring and anchoring of kelp farms has a similar set up as the ones used in fish farming.

3.6.2.8 Towing

This mission grouping only consist of towing of new or existing farm structures, feed-barges or barges for de-licing and disease treatment. These vessels are in a relatively stable demand and are not considered suitable for combination with kelp farming operations.

3.6.2.9 Support, fish farm

Many operations require the support of a secondary vessel. The support needed can be general support, ROV support or diver support during either well-boat operations or de-licing/disease handling operations. There is also sometimes need for vessels used as hotels during operations at fish farms. When supporting well-boats or de-licing/disease operations support vessels usually aid in the lifting of the bottom ring, deployment of displacement net or deployment of tarpaulin. They can also be required to provide ROV or diver support for inspection of the net after the operations have been performed.

3.6.2.10 Supply and transport

Five different transport missions are described by Nekstad. These are transport of cleanser fish or smolt, transport of cargo and supplies, transport of chemicals, transport of personnel and transport of waste. The last one is of course only transported *from* the farms. Transport of cleanser fish and smolt have quite similar requirements. A difference between the two is that while smolt is set out at several times of year, cleanser fish have an extremely clear peak period for set out into fish farms. This trend has been even clearer the last years, as the popularity of cleansing fish as a de-licing measure has increased together with an increased production and capture of the different species of cleanser fish. The extreme peak in demand starts around week 29 (midsummer) and lasts until around week 40 (early October).

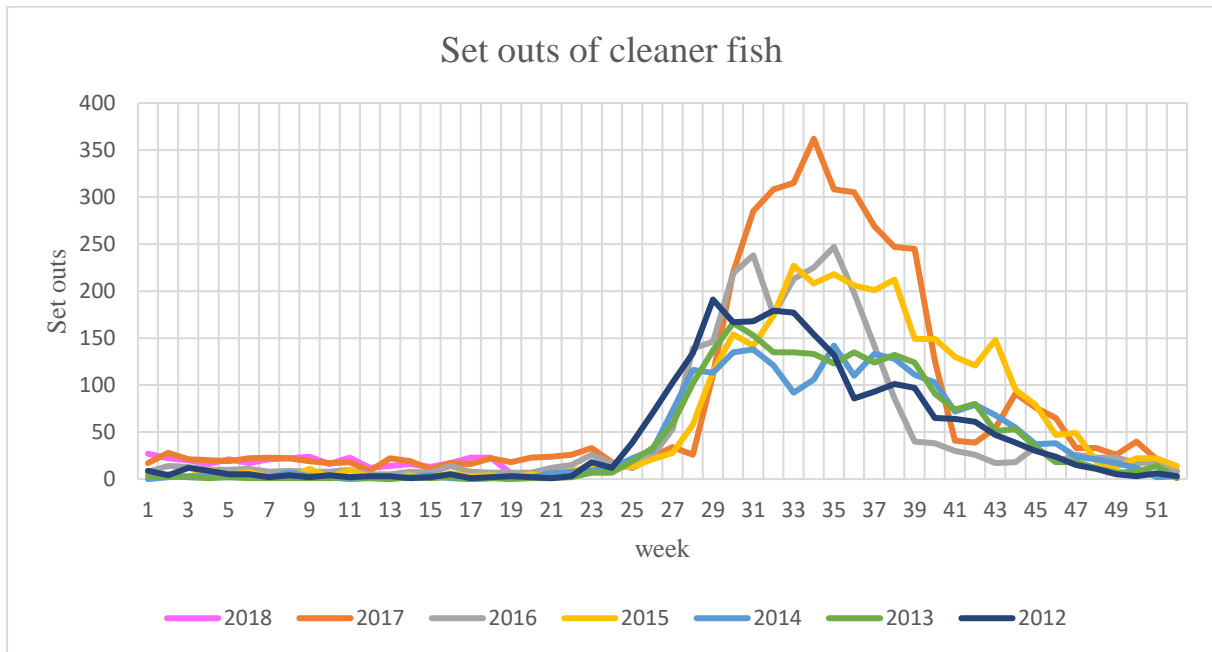


Figure 3.7: Total number of set outs of cleanser fish since 2012. Data delivered by BarentsWatch (BarentsWatch, 2018)

Personnel transport is usually done by smaller vessels available at the farm. Transport of supplies and cargo is an activity that is required all year, with little variations in demand.

4 Design contexts

It has been established that a good design depends on a good problem definition (Suh, 1990). This includes an understanding of the context in which the design is intended to operate. This is much of the basis for the responsive system comparison method that was the initial basis for the work with this thesis (Schaffner et al., 2014, Ross et al., 2009). The work with this thesis has revealed that there is a great need for a structured and comprehensive description of the current situation and the future possibilities for the kelp farming industry with regard to development of vessels for the industry. The industry can develop in several different directions and through different paths. In the following an overview of the available knowledge considered most relevant for a vessel and its operating contexts will be presented along with a description of possible future contexts. The work is meant to provide a basis for further work with the design of kelp farming vessels and the equipment and systems required to perform these operations.

4.1 Development of the industry

The development of the industry will depend on many different factors. These factors are described in more detail in the previous chapter. One of the factors that also will affect the industry is the development of vessels that can provide fast and efficient harvesting and deployment operations. Thus, this work is indirectly affecting the industry it is describing.

What is interesting when trying to understand the future development of the kelp farming industry is that there is a very clear idea of what kind of industry one hopes to have in the future. However, how far into the future one will have to go to get there is not known. It is also very possible that the future industry ends up looking quite different from what is imagined at this point. We also know what the industry looks like now. Operations and technology are quite similar along the Norwegian coast and the end products are mostly variations of food products. What this thesis attempts to shed a light over is the possible paths through the “black box” between the situation now and the idealized future industry.

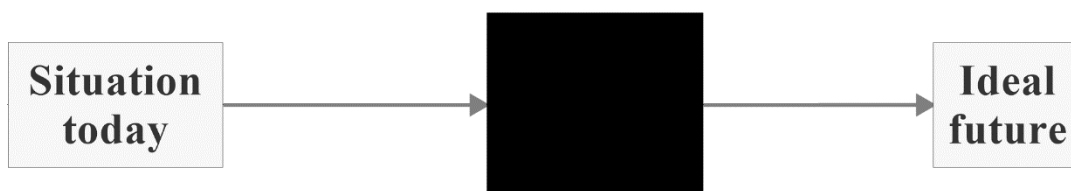


Figure 4.1: Simple illustration of the issue with not knowing how the future will develop. The situation today is of course known and there also exist a relatively clear vision of the ideal future industry, but the path to get there is unclear and filled with uncertainties. This is illustrated by the black box between now and then.

Some characteristics of the kelp farming industry in Norway today is that it is small-scale, producing mainly food products, strongly dependent on the natural season of kelps and relatively low-tech and labor intense. The future industry on the other hand, is visualized to be large-scale, producing several end products through complex bioprocessing with year-round production and produced using automated operations on efficient vessels, reducing the need for manual labor. More characteristics of the two situations can be seen in the figure below.

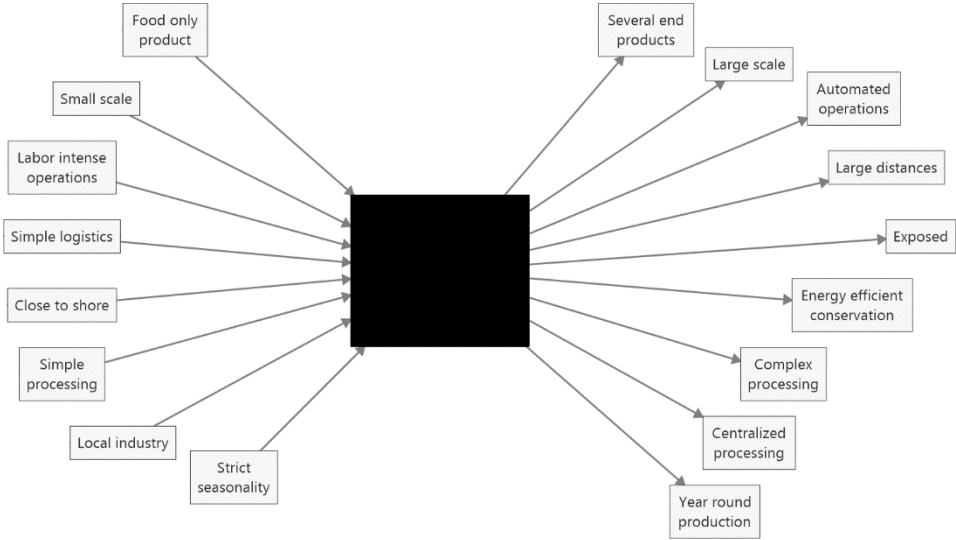


Figure 4.2: Characteristics of the kelp farming industry now and in the idealized future. It is not known how the different characteristics will develop and at what pace. To the left of the black box one can see the characteristics of the industry today while on the right side the characteristics of an idealized future industry are listed. It is not necessarily so that all of these characteristics must be in place for a large-scale industry to be successful.

4.1.1 A stepwise scenario description of context development

The characteristics of the industry today are drastically different from the characteristics of the future industry. The development of the characteristics can, and will, to some degree happen in parallel, but there will also be some strong interactions between different characteristics. Here a stepwise development scenario will be described. It is not necessarily so that innovations and development will happen in the order described here, but it is meant to demonstrate how operational contexts can develop on the way to a large-scale kelp farming industry. The figure shows an overview of the process.



Figure 4.3: Stepwise development of the kelp farming industry.

In the following a description how ten characteristics of the kelp farming industry could develop from today and into the future is presented. The ten characteristics are listed below.

- Production volumes
- Cultivation technology
- Ocean transport systems
- End products
- Harvest- and deployment operations
- Transport storage methods
- Conservation methods
- Processing facilities
- Processing methods
- Seasonality of the deployment, growth and harvest

Many of these characteristics are strongly linked with each other, and their developments will be strongly linked. Still, it has been considered appropriate to split them into separate characteristics. This way of presenting a list of characteristics is inspired by the exogenous uncertainties described in the responsive systems comparison method (Schaffner et al., 2014). Exogenous uncertainties are part of the value driving context definition and are later used for epoch characterization. The different steps described below can be seen as equivalent to different epochs in the RSC-method, but where the RSC-method generates many different eras, here only one course of development is described.

4.1.1.1 Situation today

The situation today has already been described several times in this thesis and will not be discussed further here, beyond the table showing the status of the characteristics.

Table 4.1: Overview of the characteristics of the kelp farming industry in Norway today. Based on the discussion in the previous chapter.

Characteristic	Status
Production volumes	Small
Cultivation technology	Rope cultures
Ocean transport	Short distances. Transported in small vessels also used for harvesting.
End products	Food and food ingredients
Harvest and deployment operations	Labor intense, inefficient. No specialized vessels. Some prototypes on twinning machines and harvesting equipment.
Transport storage methods	Seawater storage. Either in net bags in the sea or tanks on deck. Low density of kelp per m ³ .
Conservation methods	Freezing or drying.
Processing facilities	Freezing and drying is either done in local facilities used for fish- or crab processing in the rest of the year or in small facilities built or rebuilt by the farmers.
Processing methods	Processed immediately. Freezing and drying also serves as the main processing.
Seasonality	Strict. Harvesting is limited by the biofouling in summer. Deployment is limited by the natural life cycle.

4.1.1.2 Development into step 1

In this scenario it is imagined that the first development is a simple harvesting vessel for the industry. The vessel is built either as a multi-purpose vessel or a modular vessel that can perform other operations outside the strict harvesting season. Here, the vessel is assumed to use refrigerated seawater (RSW) tanks to store the kelps after harvesting. It is also imaginable that the harvesting and the storage and transport is done by two different vessels. It could be preferable to have a harvesting vessel that is very small and a slightly larger vessel for storage and transport. Interaction between these vessels will however complicate the operations at sea. Prerequisites for this development is that it is verified that the RSW system adequately preserves the quality of the kelps during ocean storage and transport. Secondly, harvesting equipment that either does not limit the other functionalities of the vessel or can easily be removed and installed must be developed. Another factor here is that the on-growing rope cultures might be adapted to this harvesting system. With this vessel in place, the production costs could be reduced, and the production volumes could be somewhat increased as a consequence of more efficient operations. It is also assumed that the market for kelp as a food product has increased a little bit. Some farmers will need to increase the capacity of the facilities that receive the kelp and process it. Today this is not an issue, since the kelp is harvested over several weeks, but if farms are to harvest everything in days, using a harvesting vessel, appropriate facilities for receiving the kelp must be built. This could represent a bottleneck for this step, as the costs of establishing these facilities could stand in the way of farmers being able to increase their harvesting efficiency.

Table 4.2: Characteristics of context step 1.

Characteristic	Status
Production volumes	Small to moderate
Cultivation technology	Rope cultures
Ocean transport	Short distances. Transported in small vessels also used for harvesting.
End products	Food and food ingredients
Harvest and deployment operations	Much more efficient harvesting. Reduces costs significantly.
Transport storage methods	RSW tanks in the vessel or a support vessel.
Conservation methods	Freezing or drying.
Processing facilities	Freezing and drying is done in local facilities built or rebuilt for conserving and storing the kelps. They have the capacity to process large amounts of biomass in a short time.
Processing methods	Freezing and drying also serves as the main processing. Used in food applications.
Seasonality	Strict. Harvesting is limited by the biofouling in summer. Deployment is limited by the natural life cycle of kelps and competing organisms in summer. The seasonality also decides the chemical composition of the harvested kelps.

4.1.1.3 Development into step 2

The second step of development could be development and verification of large-scale ensiling methods for kelp. This will allow for processing facilities to be centralized and the processing to be spread out over a whole year. Challenges with ensiling kelps for food applications is the effect ensiling could have on qualities like taste, texture, color and smell. If methods for ensiling at sea are also developed this could allow large upscaling of the production and moving of production to more exposed facilities, since the time spent in ocean storage and transport is no longer an issue. The increase in production volumes will also lead to a need for vessels with a much larger storage capacity. However, with the ensiling technology in place, the transport vessels will not need to be very complex. A natural solution to consider in this context is a smaller vessel that harvests and ensile the kelp and one vessel that stores it. Alternatively, the large vessel might need to receive untreated kelp and perform some form of pretreatment for dewatering before ensiling is performed. It is also thinkable that it is found not to be feasible to ensile the kelp at sea. In this case the kelps will need to be stored in RSW tanks on board and ensiled on shore. Drying and freezing of such large volumes is considered to energy demanding. Moving some of the production to more exposed areas could also contribute to an expansion of the harvesting season if biofouling should turn out to be reduced in more exposed waters. With the expansion of the industry that is imagined in this step, it is also necessary to produce more products than food. The alginate market is currently underfed and the processing technology for alginate production from *L. hyperborea* is already well established. This makes it natural to assume that alginate production for *S. latissima* as well could be a good place to start. *S. latissima* has shown good results in exposed conditions and have a relatively high content of alginate. In this step it is also assumed that a technology for efficient deployment is also in place. This leads to a context as described in the characteristics table for step 2 on the next page.

Table 4.3: Characteristics of Step 2

Characteristic	Status
Production volumes	Moderate
Cultivation technology	Rope cultures
Ocean transport	Both shorter and longer distances. Transport on large vessels when appropriate.
End products	Food, food ingredients and alginate
Harvest and deployment operations	Efficient and automatic harvest and deployment.
Transport storage methods	Ensiled or in RSW tanks
Conservation methods	Ensiling of large volumes. Still some freezing and drying at small farms producing exclusively food.
Processing facilities	Centralized factories for alginate production. Large transport distances. Small on shore facilities for small farms producing food.
Processing methods	Alginate produced at specially built factories. Factories for processing of <i>L. hyperborea</i> already in place, these could maybe also adapt their systems for <i>S. latissima</i>
Seasonality	Harvesting season expanded into the summer months in more exposed locations and far north.

4.1.1.4 Development into Step 3

For the industry to reach a new level, large volume products will be a requirement. These products can either be biofuels or animal feed, including fish feed. This will require development and verification of efficient processing methods, possibly exploiting several components of the kelps for different applications. Both biofuel production and feed production can be based on processing of the carbohydrates in the kelps, but feed can also be produced based on the proteins in the kelps. However, with protein levels being very low in late spring and early summer and the proteins in kelps having low digestibility, this is considered less feasible. The production of biofuels will require long term storage or year-round production, dedicated facilities built for the processing and very large production volumes produced at low costs. This will of course mean that the production systems and the vessels involved in the production need to be up-scaled. The upscaling will require further use of exposed areas, as large-scale kelp farms in sheltered waters quickly will come in conflict with other activities. This further movement to exposed areas could lead to the possibility of multiple partial harvests on the most exposed farms. This could lead to longer periods of work for vessels in the industry, maybe even year-round activity. It is assumed that if the development happens as imagined, the alginate production described in the previous step will continue into this step also. This leaves the following characteristics table.

Table 4.4: Characteristics of the kelp industry in Step 3

Characteristic	Status
Production volumes	Large
Cultivation technology	Rope cultures scaled up. Possibly improved based on experiences from the industry so far.
Ocean transport	Mainly long distances. The industry dominated by large, exposed farms.
End products	Mainly biofuels and/or feed. Valuable by-products important. Possibly also production of less valuable by-products. Alginate production continues as in Step 2.
Harvest and deployment operations	Efficient and automatic harvest and deployment. Larger and improved vessels.
Transport storage methods	Ensiled or in RSW tanks
Conservation methods	Ensiling of large volumes dominates.
Processing facilities	Centralized factories for alginate production. Large transport distances. Small on shore facilities for small farms producing food.
Processing methods	Alginate produced at specially built factories. Factories for processing of <i>L. hyperborea</i> already in place, these could maybe also adapt their systems for <i>S.latissima</i>
Seasonality	Multiple partial harvesting from the most exposed locations. Generally harvesting from early spring (south) and into summer (north and somewhat exposed).

4.1.1.5 Development into Step 4

This step could also be characterized as an idealized future context, as it is very close to most visualized scenarios. Here, all parts of the value chain have been improved to improve the cost efficiency of the industry and the production scale has increased again. The kelp industry is making a valuable contribution to reducing the use of fossil fuels in Norway and contributing to improve the sustainability of the salmon industry. This gives us the following table of characteristics:

Table 4.5: Characteristics of the kelp farming industry in Step 4.

Characteristic	Status
Production volumes	Very large
Cultivation technology	Rope cultures scaled up. Possibly improved based on experiences from the industry so far.
Ocean transport	Industry dominated by large volumes transported far.
End products	Biofuels and feed are the dominating end products.
Harvest and deployment operations	Efficient and automatic harvest and deployment. Larger and improved vessels.
Transport storage methods	Ensiled or in RSW tanks
Conservation methods	Ensiling
Processing facilities	Large centralized factories.
Processing methods	Efficient methods producing feed and fuel, but also exploiting by-products.
Seasonality	Multiple partial harvesting from the most exposed locations. Generally harvesting from early spring (south) and into summer (north and somewhat exposed).

4.1.1.6 Idealized future context

This situation is included as an image of a future where everything works out perfectly. Images like this situation is often used when describing the immense potential of the industry, but it is important to be aware of all the pieces that must come into place to get here and understand how far the industry have to go to achieve a situation like this.

In this step it is imagined that the production is moved fully offshore. In production systems that no longer necessarily are based on ropes or look like the systems used today. It is not even given that they are moored to the bottom. These offshore production systems could be completely free from biofouling allowing multiple partial harvests of kelps, which allow low production costs per mass. Specialized vessels work for the industry all year, designed for kelp farming only. Pretreatment and processing can even be done offshore on vessels or in floating offshore constructions. This leaves us with the following table:

Table 4.6: Characteristics of the kelp farming industry in an idealized future.

Characteristic	Status
Production volumes	Extremely large
Cultivation technology	Offshore systems. Possibly based on ropes.
Ocean transport	Long transport distances to shore.
End products	Biofuels, feed and by-products
Harvest and deployment operations	Specialized vessels. Automatic and efficient.
Transport storage methods	Ensiled or processed offshore.
Conservation methods	Ensiling
Processing facilities	Large centralized factories or processing offshore.
Processing methods	Efficient methods producing feed and fuel, but also exploiting by-products.
Seasonality	Multiple partial harvesting allows for year-round production

5 Concepts

Based on the presentation of the different contexts in the previous chapter, some concepts will here be briefly described. This is in part done to illustrate how the information gathered can be applied to the design of vessels and in part to provide a fundament for further design work. Three different development steps from chapter 4 will be used as a basis here. For each scenario, a feasible concept that could be designed and built at that point in time will be presented. The chosen steps are the situation today, Step 2 and Step 4. The situation today is of course very interesting to look at, because it says something about what is the opportunities right now. Step 2 describes a moderate increase in production and expansion of the product range. This could become the situation in the industry for a long time, if the truly large-scale end products should not turn out to be feasible. In Step four, the industry has grown into a large-scale industry producing biofuels and feed as a main product. Different variants of this future is what is often described in feasibility reviews and is used as a fundament when talking about the great potential of seaweed- or kelp farming in North-West Europe.

While the contexts described in Chapter 4 is described as consecutive contexts. The development could also take entirely different turns. While the development in the previous chapter could be described as constant increase in each step, it is imaginable that we also could have decrease or no change over time. For instance, should the vessels designed for the first context consider the possibility of both slow and rapid increase through something looking like the steps described. In addition to this, it should also consider no change in the industry throughout the systems lifetime or even a decrease in the production, which in the case of kelp farming, would mean an end to the industry.

5.1 Concept 1, situation today

For the situation of today in the kelp farming industry, there is a very limited potential for vessels. Vessels that could perform more efficient operations could contribute to the development of the industry into what is defined as Step 2, with larger production volumes, but the industry is characterized by low revenues and costs must be kept at a minimum. If vessels are designed with for the intention of immediate realization, it is also important to consider the possibility that the expansion is not successful or that the industry in its entirety could fail. It is therefore natural to have as a prerequisite for the vessels that they should be built with potential perform operations in the aquaculture industry or some other coastal industry like fishing or kelp harvesting. The seasonality that dominates the industry of today is also an argument for the vessels to have the potential to perform more operations than only those relevant for kelp farming. In this situation harvesting is performed from April to the start of June. Deployment is performed in the fall or early winter, but as experience is gained in the industry the optimal times of deployment will be identified along the coast and deployments will probably be performed in a much narrower window of time.

Harvest and deployment have very different requirements. When harvesting, a solution for storing and transporting large biomasses must be in place and the equipment for getting kelp

aboard a vessel will greatly differ from the equipment needed to twine and deploy seeded ropes. This leads to very different requirements both in size, shape and equipment for the vessels performing the two operations. It is an intuitive assumption that when designing a kelp farming vessel, the vessel should be designed for the two operations harvesting and deployment. But due to the difference in requirements, and the fact that the operations are performed at completely different times of year, it is here concluded that the possibility of two different vessels performing one operation each should also be considered. Here, it is very important to underline that both vessels will need to have the ability to perform alternative operations when not working in the kelp farming industry independently of how the industry might develop. Development of deployment technology is considered less urgent and is not included in this step. Some basic functional requirements for a vessel designed for this context is listed below. These functional requirements are relatively wide and will all include subfunctions.

Table 5.1: basic functional requirements for context 1.

Functional requirements context 1
Harvesting of kelp
Ability to maneuver over kelp farms
Storage capacity
System for preservation of kelps
Transport capacity
Handling and offloading of kelps
Capabilities for performing other operations

A constraint for the design is that the costs of installing kelp capabilities must be kept at a minimum. This also goes for the operational costs for the kelp farming operations.

5.1.1 Concept description

As it is described by Suh earlier, design is the choice of design parameters to satisfy the functional requirements. Here, a fundamental concept description will be given, in the form of how the different functional requirements can be met. Many of these solutions are not tested, so the concepts must be seen mainly as suggestions that could be studied with regard to further realization of a design.

Since the period performing operations in the industry is so limited and the future is so uncertain, it is here considered to be best to design vessels with a main function outside the kelp farming industry, but with kelp farming operations as by-functions. This again means that it is interesting to look at vessels that already exist in, for instance, the aquaculture industry, and see how they can be adapted for kelp farming operations. The main weight is put on the design of a vessel or vessels for the harvesting operation, which is considered the most critical operation for increasing the feasibility of the industry.

In section 3.6.2 some missions performed by service vessels in the aquaculture industry were presented. Of these, particularly net washing and de-licing operations were found to have a marked increase in demand in late summer and in the fall. This means that there is an

overcapacity for these missions in the aquaculture fleet in the rest of the year. Especially transport of cleaner fish showed extreme variations in demand through the year, in addition to an apparent increase in popularity as a de-licing method over the last years. With several companies now looking at the possibilities of designing specialized vessels for transportation of cleaner fish (iLaks.no, 2018a, iLaks.no, 2018b, Soltveit, 2018), it should be investigated if these vessels could be adapted to perform harvesting- and/or storage of kelps. An important question when deciding on a concept in this step is the choice between one or two vessels. If one has two vessels one can perform the function of harvesting and offloading, while the other one can perform the function of storage, preserving and transport. They will both need capabilities for performing alternative operations. If the vessel performing the harvesting does not perform the storage of the kelps, the vessel could be quite small and have a double hull. Vessels with double hulls usually have smaller draughts and large work decks, but low storage capacity beyond the storage capacity on deck (Nekstad, 2017). A small draught can be an advantage when maneuvering over the rope systems. If the harvesting equipment and the equipment for kelp handling is easily removed the vessel could easily be used as a support vessel for the aquaculture industry in the rest of the year. The second vessel performing storage, preserving and transport will need large cargo space and should therefore be a mono-hull vessel or a barge. If a barge is chosen, the harvesting vessel should have capacity for tugging of the barge. A barge could be fitted with a container with a preservation system, which could be replaced with for instance a container with net washing equipment or other types of equipment, depending on demand, in the rest of the year. An advantage with a barge and container system is that it is cheap to produce and operate, and the concept can easily be scaled up. Preservation of the kelps could potentially be ensured by an RSW cooling system. It needs to be verified that this solution does in fact preserve the quality of the kelps but results so far look promising. If the storage is done aboard a mono-hull vessel, the most promising vessel type to use is cleaner fish transport vessels. These vessels have a very specific season when they are in high demand in the late summer and fall. This is long after the harvesting is finished in the late spring/early summer. However, to ready a vessel like this for kelp storage and preservation will require additional systems for RSW-cooling. Alternatively, a modular solution, where a container-based storage system could be installed when storing kelps and another container-based system specially built for cleaner fish transport could be installed for this operation. A weakness with designing a vessel for storage is that this design not easily can be scaled up if the industry grows. If the industry should collapse the vessel can go over to exclusively performing cleansing fish transport, possibly supported by transport of smolt. However, if the industry grows an entirely new design must be developed to handle the larger quantities. This design will probably be over dimensioned for cleanser fish transport. A table describing the FRs and corresponding DPs selected in this discussion is shown on the next page.

Table 5.2: Functional requirements and design parameters

Functional requirements context 1	Design parameters small harvesting vessel	Design parameters storage vessel
Harvesting of kelp	Harvesting equipment	-
Ability to maneuver over kelp farms	Propulsion and maneuvering systems	-
Storage capacity	-	Container
System for preservation of kelps	-	RSW-cooling
Transport capacity	-	Propulsion system on vessel. Tug for barge.
Handling and offloading of kelps	Crane and tanks on deck	-
Capabilities for performing other operations	Support vessel in aquaculture	Cleaner fish transport or net washing barge

Some critical aspects for this concept solution is that RSW is, as previously mentioned, verified as a feasible storage method for kelps. An alternative method, that could prove suitable is ensiling and an eye should be kept on the development of ensilage technology for kelps. Secondly, it must be established at what densities kelp can be stored. This will strongly depend on the results from the study of preservation methods.

5.2 Concept 2, Moderate increase

In this step the industry has grown into producing larger amounts of kelps and utilizing more exposed locations for production. In the description of the development up to this point, it was assumed that vessels were designed and developed on an earlier stage for an industry in a smaller scale. The characteristics defined for this step in section 4.1.1.3, can be seen in the table below.

Table 5.3: Characteristics of Step 2, as defined in section 4.1.1.3

Characteristic	Status
Production volumes	Moderate
Cultivation technology	Rope cultures
Ocean transport	Both shorter and longer distances. Transport on large dedicated storage and transport vessels when appropriate.
End products	Food, food ingredients and alginate
Harvest and deployment operations	Efficient and automatic harvest and deployment.

Transport storage methods	Ensiled or in RSW tanks
Conservation methods	Ensiling of large volumes. Still some freezing and drying at small farms producing exclusively food.
Processing facilities	Centralized factories for alginate production. Large transport distances. Small on shore facilities for small farms producing food.
Processing methods	Alginate produced at specially built factories. Factories for processing of <i>L. hyperborea</i> already in place, these could maybe also adapt their systems for <i>S.latissima</i>
Seasonality	Harvesting season expanded into the summer months in more exposed locations and far north.

In this context the harvesting season is expanded into the summer months, making washing and de-licing operations less attractive as an alternative operation. It has also been developed a processing method for producing alginate from cultivated kelps. This has in turn opened a new market for the kelps allowing for a large increase in production volumes, which has led the production further out in the sea, into more exposed farming locations. For it to be possible to distribute the processing of kelps over longer time periods, ensilage methods have been developed for long term conservation. Here, ensiling is assumed to be performed on shore, but it is possible that ensiling could be performed at sea also. All large up-scaling of the kelp farming industry depend on the development of some sort of energy efficient long-term conservation scheme. The kelps that are produced for alginate production will need to be transported over long distances from the farms or the landing facilities to centralized factories. At the moment there are only two alginate factories in Norway, one in Rogaland and one in Trøndelag. In this context focus will be on the large volumes of kelps produced for the alginate industry. It is imaginable that already existing vessels can serve the smaller food producing industry.

An industry producing much larger volumes will depend on fast and efficient deploying and harvesting of kelps. It is currently not known when the optimal season for deployment will be, but the longer the kelps are in the sea, the longer they will grow. It is therefore natural to assume that the deploying will take place in late summer and early fall. It is not given that the same vessel should perform both the harvesting and the deployment operations. The functional requirements are very different for harvesting and deployment and a vessel performing both operations will probably need to have a modular set-up where equipment for the different operations is installed depending on need. An advantage with using the same vessel is that one will get a crew that is specialized in kelp farming operations, feeling ownership to the tasks. The capability and dedication of the crew should not be underestimated as a factor in the performance operations. Since there are uncertainties regarding the seasonality of demand for vessels in this context, alternative operations are more difficult to assess. The most important functional requirements for vessels in this context are summarized in the table on the next page.

Table 5.4: Functional requirements in Step 2

Functional requirements context 2
Harvesting of kelp
Deployment of kelp
Ability to maneuver over kelp farms
Large storage capacity
Preservation of kelps
Transporting kelps
Handling and offloading of kelps

Generally, revenue is higher in the alginate industry, but the concepts still have costs as an important constraint.

5.2.1 Concept description

With the increased production volumes there is no longer any doubt that the functionalities of storage and harvesting should be separated. A large vessel will be needed for storage, but beyond the large storage capacity there will be little requirements to it. If ensiling methods that can be performed at sea is developed, either the large storage vessel can have capabilities for performing ensiling, or the smaller harvesting vessel could ensile the kelps before the kelp is transferred to the storage vessel. An advantage with the first solution is that ensiling equipment will take valuable work space on the deck of the harvesting vessel. An advantage with the second solution is that just about any vessel with large storage capacity could be used as storage vessel if the kelps are already ensiled. An important challenge for these concepts is the handling of the kelps, ensiled or not, and the efficient and safe transfer of the kelps between the vessels. A concept that also could be considered if ensiling is performed on the harvesting vessel, is storage of the kelps in a temporary depot before a transport vessel could come by and pick it up at convenience. This could be a very cost-efficient logistics solution as the storage vessel would not need to wait while the harvesting vessel harvested. It must be underlined however, that this concept will depend on an ensiling method being developed, that allows for ensiling to be performed at sea without requiring too much deck space.

A conservation method that is used today, although not being very popular, is the use of formaldehyde. This is used to conserve harvested *L. hyperborea*. It should be noted that this also could be an option for storage of kelp for alginate production. It would however be damaging to the image of the industry and limit the potential end uses of the cultivated kelps.

If one is to design a concept in this context, the requirements and conceptual design can be based on the knowledge gained in the process leading up to this situation. It is however difficult to create a meaningful, detailed concept based on the ifs and maybes that we have today.

5.3 Concept 3, Large-scale kelp production

When discussing the potential of kelp farming this context is often what is visualized. Large areas are used to produce large volumes of kelps for use as a sustainable fuel or feed source.

This is why a lot of effort has gone into development of bioprocessing schemes for biofuel production and development of technology for a large-scale cultivation industry. It is however still a long way to go to get to this point, and what the industry exactly will look like, if it is successful in getting there, is not known. What is certain is that it will be very different from the industry we have today. If one wants to develop a vessel concept for a large-scale kelp industry in Norway it is important to be aware of all the characteristics listed in the table below and be aware that the status described here is not a prediction of how things *will* be, but a suggestion as to how it *could* be.

Table 5.5: Characteristics of Step 4, a large-scale kelp farming industry.

Characteristic	Status
Production volumes	Very large
Cultivation technology	Rope cultures scaled up. Possibly improved based on experiences from the industry so far.
Ocean transport	Industry dominated by large volumes transported far.
End products	Biofuels and feed are the dominating end products.
Harvest and deployment operations	Efficient and automatic harvest and deployment. Larger and improved vessels.
Transport storage methods	Ensiled or in RSW tanks
Conservation methods	Ensiling
Processing facilities	Large centralized factories.
Processing methods	Efficient methods producing feed and fuel, but also exploiting by-products.
Seasonality	Multiple partial harvesting from the most exposed locations. Generally harvesting from early spring (south) and into summer (north and somewhat exposed).

In this context the industry is considered to have year-round, large-scale production mainly for the large-volume end-products feed and biofuel. It is assumed that more efficient equipment for harvesting and deployment is developed based on experiences from previous stages. Ensiling is used as the dominating conservation method and the cultivation systems are still based on rope systems. However, the shapes sizes, capacities of equipment and the exact methods used is incredibly hard to predict. However, some functional requirements can be identified for the system performing the harvesting and deployment operations. If valuable byproducts are to be produced it is important that the conservation method used does not reduce the potential for extracting these.

Table 5.6: Functional requirements in Step 4, a large-scale kelp farming industry

Functional requirements context 2
Harvesting of kelp
Deployment of kelp
Ability to maneuver in and around
Storing large amounts of kelps
Conservation of kelps
Transporting kelps
Handling and offloading of kelps

The requirements are very similar to those in the previous section. However, a constraint here is that everything needs to be much more cost efficient, since the products now are low-value products instead of the high-value product alginate. The scale of the system must also be much larger and able to handle much larger volumes of kelp than in the previous section.

5.3.1 Concept description

What a system concept can look like in this context is almost impossible to say. Not knowing much about the equipment or methods used to handle, store and process kelps makes it very difficult to say anything meaningful about one or more vessels performing operations in this context. It is clear that a large vessel must be involved, and that an energy efficient conservation method for the kelp must be installed. However, a design must be based on more knowledge, that has yet to be gained.

6 Conclusions and further work

The kelp farming industry in Norway has been found to be small, with a low revenue but with a large potential. The largest potential lies in the production of enormous volumes of biofuel and animal feed. But there are also potentials in the form of extraction of valuable chemical components and possibly food, if the market develops in a positive way. At the moment focus in a lot of the research that is being done is on the potential for a large-scale industry, but it could appear that development of technology for a closer future, where kelp is produced in a more moderate scale also should be in focus. There is a long way to go to get to a large-scale biofuel production of kelps, and more meaningful results could be achieved if one instead focused on developing solutions that could take the current industry a few steps further. The knowledge gained in these steps could probably provide valuable experience for further expansion.

The first three steps of the responsive comparison method have proven to be a useful framework for gathering information about design contexts even for an innovative and uncertain industry like the kelp farming industry. Factors that will strongly affect the industry, particularly with regard to development of vessels performing operations in the industry, have been identified. The most important ones are listed below.

- Which end products one chooses to produce will affect many aspects of the cultivation process and how the kelps must be treated and process. It is possible that several end products are produced, even from the same plant.
- The processing methods for many potential end products are not finally established. Which processing methods are chosen or turn out to be the most feasible will affect the optimal end product and how the kelp must be handled after harvest.
- The development of on-growing systems will strongly affect the equipment required for a vessel performing operations at kelp farms. At the moment these are based on ropes, and there is little indication that this will change in near future. The orientation of the ropes however is subject to variations.
- If moving of kelp facilities to exposed or even offshore locations is proven successful, this will have large implications for the requirements to on-growing systems and vessels performing operations.
- Temporary storage methods and possible storage densities will affect the shape of vessels performing harvesting operations. Little work has been done in mapping the effects of different storage methods on harvested kelps.
- Conservation, or long-term storage, of kelps is a factor that will be deciding when one wishes to scale up the industry. If year-round production does not become a reality, it is a requirement that cheap and energy efficient conservation methods are in place for large-volume production to become feasible.
- The seasonality of growth, chemical composition and biofouling for kelps sets strict seasonal frames for the industry today. How different factors like breeding and choice of on-growing locations can affect these seasonal factors will affect the operational profile for vessels working for the industry and the yields of the end products.
- The potential environmental effects of kelp farming could also affect the industry. Potential negative effect could damage the opportunities for establishing an industry, while positive effects could strengthen the value of the industry. At the moment it looks like kelp farming

will have mainly positive effects on the environment, but the effects of truly large-scale farms are yet to be seen.

What has been found to be of utmost importance for the design of vessels for this industry is an understanding of the interrelationships between the different factors affecting the design. It is also important to have an understanding of the fact that the industry that can be observed in Norway today is completely different from the industry that is described in the most optimistic descriptions of the future potentials of the industries. It is therefore important to keep in mind when designing if one is designing for the situation as it is today or some future context, and what assumptions one has made for this future context. Often it can be tempting to describe a future context in part and then fill the holes in ones' knowledge with knowledge of the situation today, but this knowledge may not be relevant depending on the characteristics set for the future context.

6.1 Further work

In this work it was early observed that energy efficient storage methods is one of the most important problems that must be solved. It is important to establish and verify the effect of a method for storing kelp immediately after harvest until the biomass is stabilized. Methods based on refrigerated seawater cooling (RSW) and ensiling should be further studied. Together with storage methods, development of equipment for efficient, automatic and safe harvesting of kelps from rope structures, make out the two most important factors for an immediate growth in the production volumes in Norway. The design of the interface between on-growing systems and on board harvesting equipment should probably be included in the development of harvesting equipment. It is also a limiting factor that the current market, the food market, is saturated, and a new market must be found. Finally, vessels designed for the industry today should have kelp farming as a by-function, to limit the risk if the industry were to collapse, and to have other work outside of the very short harvesting season we have today.

In the long run, it is important that energy efficient conservation methods are developed. Here, ensiling has shown the greatest promise and should be further studied and tested in a large scale on relevant kelp species. Further, the studies of bioprocessing methods for kelps should be followed closely, and work should be done to establish methods that can exploit several components of the plant in a cost-efficient way. It is also important that the effects of seasonality and on-growing location on chemical composition, growth and biofouling is better understood. Especially with regard to the potential of moving the production to more exposed locations.

7 References

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