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Simulating the harvesting process of a sugar-kelp farm

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MASTER THESIS

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Preface

The first experience I had with the seaweed-industry was through the subject TMR4254 - Marine System Design where we, in a group of 5 students, designed a vessel for the deployment and harvest of seaweed. This project opened my eyes for the vast potential this sector have.

The project thesis is written during spring 2019, and is submitted to the Department of Marine Technology at the Norwegian University of Science and Technology. The thesis is written as the final part of my master's degree, where I specialize in Marine Resources and Aquaculture.

I would like to express gratitude to my two supervisors Pål Lader and Bjørn Egil Asbjørnslett for all the guidance and valuable feedback they have provided this final semester.

To Brage Mo and Eiving Lona at Sintef, thank you for answering all my questions and for all the useful feedback regarding both the vessels and the farm selection. I would also like to thank Ole Jacob Broch for helping me with my growth model.

Finally, I would like to thank the Norwegian Research Council, EXPOSED Aquaculture Research Centre, for providing me with the weather data used both in the models and the simulation.

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Abstract

On a global scale the need for more food production is evident, and the majority of cultivated seaweed is used for food applications. In Norway it was mainly the interest of seaweed as a component for biofuel that triggered the advancement of this industry. Norway have, with its large coastline and existing aquaculture industry, a vast potential for large-scale production.

At this moment the industry consist mainly of pilot-projects and small-scale production. The farming is done with smaller vessels using manual labour and some tools for aid. The harvested biomass is small compared to the allowed production. The existing industry is not economically feasible, and new technology and systems is fundamental for upscaling. Mainly equipment for automated efficient harvesting and seeding/deployment, along with a suitable vessel that can provide safe conditions for the crew during the process.

This thesis studies the harvesting process of a sugar-kelp farm. A suitable farm design is selected, in this case the Macroalgae Cultivation Rig designed by Ocean Rainforest, and the farm forms the basis of an estimated upscaled facility. Three vessels with different sizes and restrictions is chosen for the harvesting process.

The location was set to outside Sula in Sør-Trøndelag, where weather-data was available. To create different scenarios, the relevant weather-data was used to create a transition probability matrix. From this matrix it was then possible to use Markov chains to create several series containing the significant wave height as a function of time. The significant wave height were chosen as the variable restricting the vessels during the simulation.

A model was generated in Matlab estimating the potential production for the given location. The dimensions from the Ocean Rainforest farm were implemented, resulting in a produced amount of 77.6 tonnes wet weight per hectare. Given the initial potential of the location, in terms of nutrients, this corresponds with values estimated in other articles for the same location.

With both the weather-data and the growth potential ready, the simulation could be made in Simulink. Here it is presented how the different vessels behave given the maximal allowed significant wave height. The model tested the vessels sensitivity, and how the general harvesting cycle is affected by this. For the three vessels the results are quite different. Vessel 1 is a little sensitive, where 1 of 200 waves are above the limit. For the 40 simulations done, the vessel

operates at an average 97 percent capacity. Vessel 2 is the most limited by the weather, as 1 in 10 waves are above the allowed values. This affects the round-trip time a lot, given both waiting-time to sail to the farm, and interruption of harvesting. The last vessel, the largest one, were not affected by the waves, and the simulation was therefore performed without interruption.

Given its superiority in the simulation, it is reasonable to assume that vessel 3 is the best solution. However, there are more factors contributing. The economical aspect have not been discussed in this thesis, due to lack of data, but will be crucial for deciding a vessel in a real-life situation. A larger vessel is usually more expensive, and if the operation costs outweighs the profit, the solution is not feasible. The next step would therefore be conducting an vessel-optimization based on cost, and from this draw a more conclusive result. It was also made clear in the simulation that the selected harvest speed were not corresponding to the desired production, and therefore modeling a new harvest method should be of priority.

With the potential in available area and good growth-conditions, the industry have every opportunity at succeeding. The advances needs to be done with regards to harvesting equipment handling large amounts of biomass, along with being able to preserve them for the desired quality.

Sammendrag

På en global skala er behovet for mer matproduksjon tydelig, og mesteparten av dyrket tare brukes innenfor kategorien mat. I Norge var det hovedsakelig interessen for tare som en komponent for produksjon av biodrivstoff som startet utviklingen av denne industrien. Norge har, med sin lange kystlinje og eksisterende akvakultur-industri, et solidt potensial for storskala produksjon.

For øyeblikket består industrien hovedsakelig av pilotprosjekter med liten total produksjon. Høstingen er gjort med mindre fartøyer hvor manuell arbeidskraft og noen hjelpemidler, som kraner, brukes. Den høstede biomassen er også liten i forhold til den tillatte produksjonen. Den eksisterende industrien er ikke økonomisk gjennomførbar, og ny teknologi/systemer er grunnleggende for oppskalering. Hovedsakelig utstyr for automatisert, effektiv høsting og utsettelse av planter, sammen med en egnet fartøy som kan gi trygge forhold for mannskapet under prosessen.

Denne oppgaven studerer høsteprosessen av et sukker-tare anlegg. Et egnet design er valgt, i dette tilfellet "Macroalgae Cultivation Rig" designet av Ocean Rainforest, og anlegget danner grunnlaget for et estimert oppskalert anlegg. Tre fartøy med forskjellige størrelser og restriksjoner er valgt for høstingsprosessen.

Lokasjonen ble satt til utenfor Sula i Sør-Trøndelag, der værdata var tilgjengelig. For å opprette forskjellige vær-scenarier ble de relevante værdataene brukt til å opprette en "transition probability matrix". Fra denne matrisen var det da mulig å bruke Markov-chains for å lage flere serier som inneholder den signifikante bølgehøyden som en funksjon av tiden. Den signifikante bølgehøyden er valgt som den viktiste variabelel for begrensning av fartøyene under simuleringen.

En modell ble generert i Matlab som anslår den potensielle produksjonen for den oppgitte plasseringen. Dimensjonene fra anlegget til Ocean Rainforest ble implementert, noe som resulterte i en produsert mengde på 77,6 tonn våtvekt per hektar. Gitt det opprinnelige potensialet for stedet, i henhold til næringsstoffer, er denne verdien tilsvarende med verdier estimert i andre artikler for samme lokasjon.

Med både værdata og vekstpotensialet tilgjengelig, kan simuleringen gjøres i Simulink. Her

presenteres hvordan de forskjellige fartøyene påvirkes av maksimal tillatt signifikant bølgehøyde. Modellen testet fartøyets følsomhet, og hvordan den generelle høstesyklusen ble påvirket av dette. For de tre fartøyene er resultatene ganske forskjellige. Fartøy 1 er litt følsomt, hvor én av 200 bølger er over den tillate grensen. For de 40 simuleringene som er gjort, opererer fartøyet med gjennomsnitt på 97 prosent kapasitet. Fartøy 2 er mest begrenset av været, da 1 av 10 bølger er over de tillatte verdiene. Dette påvirker rundturstiden og bidrar til ventetid før skipet kan seile til anlegget samt avbrudd under høstingen. Det siste fartøyet, det største, var ikke påvirket av bølgene, og simuleringen ble derfor utført uten avbrudd.

Gitt sin overlegenhet i simuleringen, er det rimelig å anta at fartøy 3 er det som gir den beste løsningen. Det er imidlertid flere faktorer som bidrar. Det økonomiske aspektet har ikke blitt diskutert i denne oppgaven, på grunn av mangel på data, men vil være avgjørende for situasjonen i virkeligheten. Et større fartøy er vanligvis dyrere, og hvis driftskostnadene oppveier fortjenesten, er løsningen ikke lenger mulig. Det neste trinnet ville derfor være å gjennomføre en fartøyoptimalisering basert på kostnadene, og for dette anslå en mer avgjørende konklusjon. Det ble også klart i simuleringen at valgt innhøstingshastighet ikke var i samsvar med ønsket produksjon, og derfor bør modellering av en ny høstemetode være av prioritet.

Med potensialet i tilgjengelige områder og gode vekstforhold har industrien alle muligheter for å lykkes. Fremskrittene må gjøres med hensyn til høsteutstyr som kan håndtere store mengder biomasse, samt å kunne bevare den ønskede kvaliteten.

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Chapter 1

Introduction

1.1 Background

With the world population set on passing 9 billion by mid-twenty-first century, new sources for food will play an important part in providing resources. A natural part of the solution will be to utilize the ocean more, as high potential and large areas available makes room for an expanding industry and technological advances (FAO, 2018).

There are several advantages of producing biomass in the ocean. Firstly, it does not compete with the diminishing available space on land. Secondly, in the case of seaweeds and marine macroalgae, the need for fresh water is miniature when comparing to standard agriculture (Lehahn et al., 2016). In a world where the available freshwater is the most limited factor in food production, this have a huge potential for increasing available food in the future. It is estimated that if 10% of the ocean were used for food production, this would equal the current agriculture (Radulovich, 2011). Mariculture will therefore have an impact on the future accessibility of freshwater.

Figure 1.1 shows the amount of wet metric tonnes of biomass exploited in the year 2014. The top photo shows that the countries that cultivates the most are China, Indonesia and the Philippines. In the bottom photo the countries that have harvested the most wild stock are shown to be China, Chile and Norway. The figure illustrate clearly that the main part of seaweed farming is done in Asian countries.

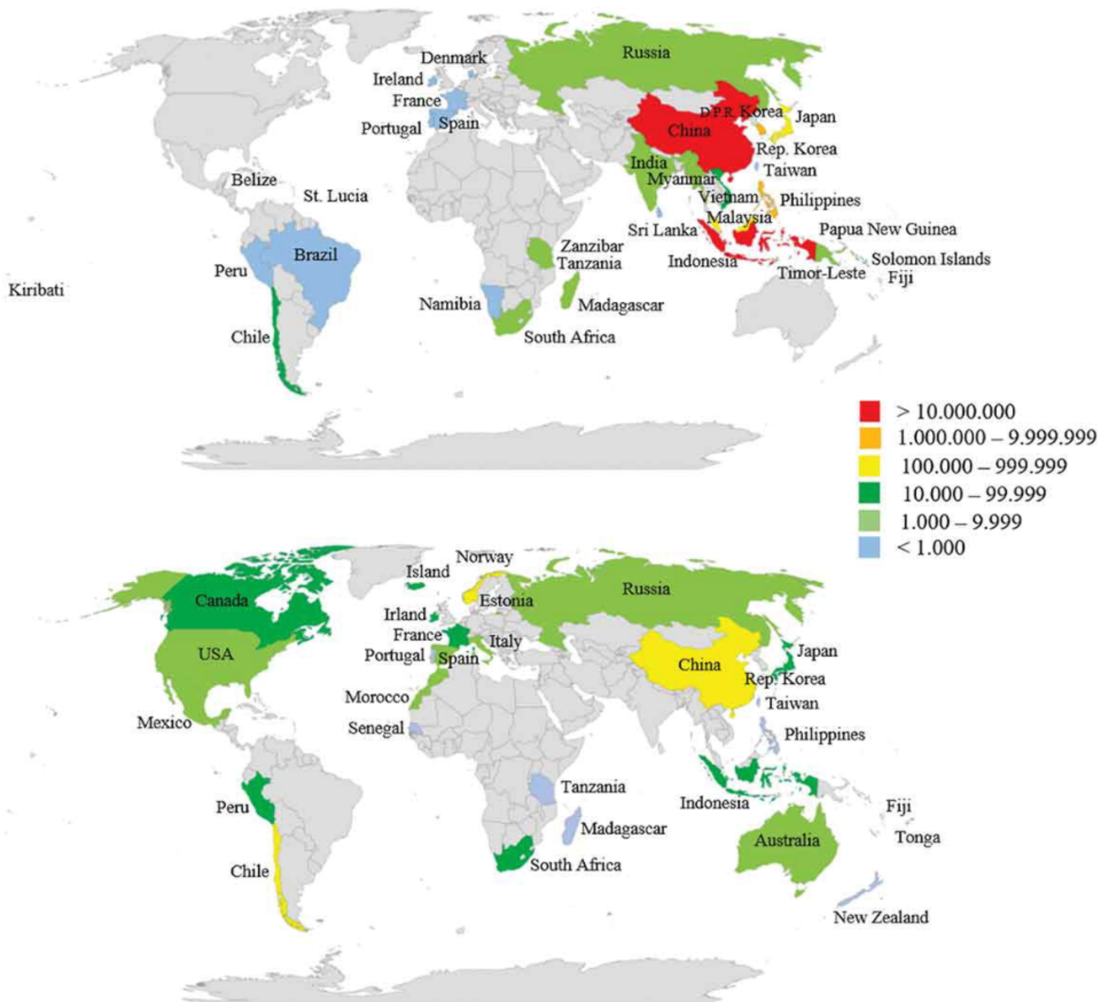


Figure 1.1: Wet metric tonnes of biomass farmed in aquaculture (top) and harvest of wild stocks (bottom). Illustration from: Buschmann et al. (2017)

The concept of farming seaweed is relatively new, starting in the mid-twentieth century, at a time where seaweed only came from wild harvest (Tiwari and Troy, 2015). While wild seaweed still are being harvested, the main focus have moved to farming, as not to deplete the resources. This was possible mainly due to the excellent conditions these countries have in regards to farming with the availability of large areas of shallow, temperate water and cheap labour (Trono Jr., 1990).

Since 2006 there have been a steady increase in the global production of seaweed, and the production have almost tripled in 2016 with a total of 30.1 million tonnes. This development is mainly a result of cultivation of tropical species of seaweed in Indonesia, and the country is nearing China in total production (FAO, 2018).

It is estimated that there are between 8000 and 10500 different species of seaweeds. These are again separated into three phyla where brown seaweeds represent 33.6%, reds 54.4% and greens 0.08%. The remaining 11.9% is either unclassified or mixed (Collins and Valentine, 2001; Tiwari and Troy, 2015).

Seaweeds uses photosynthesizes to grow, and sufficient sunlight is therefore essential. Along with the uptake of inorganic nutrients, new organic matter is created and the biomass is incorporated with CO_2. Because it only uses sunlight for energy along with the uptake of nutrients, one finds seaweed at the lowest tropical level (Skjermo et al., 2014). In terms of energy convection rates between the different tropic levels, cultivation of plants is much more effective than animal farming when it comes to energy and nutrition (Tiwari and Troy, 2015).

1.1.1 The Norwegian seaweed-industry

Norway have for many years had an industry of seaweed-trawling. The species trawled are mainly Laminarea hyperborea and Ascophyllum nodosum (Norwegian: *stortare* and *grisetare*). It is estimated that almost 200 thousand tonnes are collected every year outside the coast of Norway (Fiskeridirektoratet, 2015). This is a relatively small part of the existing stock, but there are some controversy in regards to sustainability. Trawling equipment is harsh on the seabed, and the effect on biodiversity and integrity of the ecosystems is a highly discussed issue (Stévant et al., 2017).

Norway have a clear potential for cultivation of seaweed. Over 100.000 km of coastline, along with good water quality, and a large existing aquaculture-industry. There are today, in Norway, over 400 different species (175 brown, 200 red and 100 green) of macroalgae, where many have existing harvesting methods. Even though there have been projects and studies before, it was first from 2008 and onward that the interest for seaweed cultivation blossomed (Skjermo et al., 2014).

This interest was mainly the result of companies wanting to use mass-production of seaweed as a resource for biofuel. It was therefore important to utilize a specie with a high content of carbohydrates. At the same time, the specie needed to withstand the Norwegian sea-conditions. The required qualifications were found in a wild growing seaweed, called sugar kelp. With this, some Norwegian companies invested to start small-scale production and pilot projects.

1.1.2 Sugar kelp

Sugar kelp, or Saccharina latissima, is a brown algae from the class Phaeophyceae. The kelp is found naturally along the coast of Norway (including Svalbard), as well as in other European countries like England and northern parts of Spain. It is estimated that 25-50% of the wild stock in Europe can be found along the coast of Norway, which count for 5-25% of wild stock globally (Moy and Kroglund, 2006).

Figure 1.2: 2m large sugar kelp harvested from wild population. Illustration from: Hancke et al. (2018).

The kelp grows best in temperatures under 19 degrees Celsius. It is one of the fastest growing kelp found in Europe, and has a large potential for biomass yield. It has a high level of carbohydrates that constitute between 40-70% of the weight when dried (Stévant et al., 2017; Skjermo et al., 2014).

The cultivated stock of sugar kelp have increased steadily since 2014 and in table 1.1 the quantities and value of the stock is displayed. Dulce and Nori (Norwegian: *søl* and *fjærehinne*) are included under other species, and while there are some value in the industry, the produced biomass is small. At the time there are permissions for producing several different types of seaweed, but the main trials and production is being done using sugar kelp (Stévant et al., 2017).

	2017		2016		2015	
Species	Quantity	Value	Quantity	Value	Quantity	Value
Sugar kelp	140	355	33	100	49	160
Winged kelp (Butare)	9	342	26	817	2	18
Other species	0	4	0	0	0	0
Total	149	701	60	917	51	178

Table 1.1: Quantity and value of cultivated sugar kelp. Quantity in metric tonnes and value in 1000 NOK. (Fiskeridirektoratet, 2017)

In a report made by SINTEF (Broch et al., 2017), the potential of producing sugar kelp outside the municipality of Trøndelag in Norway was discussed. The authors estimate that the possible production could be between 45-90 tonnes inside the sea boundary and between 92-164 tonnes outside. From Fiskeridirektoratet (2017) the total area approved for cultivating is 540 hectares and the total produced biomass is 60 tonnes (2016). When comparing the harvested stock to the potential there is a large difference. There are many explanations for this. Firstly, the seeding and harvesting methods used are not yet sufficiently effective. Secondly, new farm designs could increase potential in the area by doing all year production and utilize more of the water column, along with producing in more exposed areas. Lastly, the majority of the distributed licenses are not in use (Broch et al., 2017). The goal set by Olafsen et al. (2012) for productive seas in 2050 estimates a production of 20 million tonnes, which is far from the values shown in table 1.1.

Chapter 2

Problem description

This chapter of the thesis will present the problem at hand and how it will be approached, along with the set objectives.

2.1 State of art

Even though the global industry is expanding, and the biomass production is increasing, Norway does not yet have the technology for large scale production. With a desire and a potential for cultivating seaweed along the coast, Norwegian researchers and companies are now developing new farming methods. However, due to harsh environmental conditions and expensive manual work, the existing projects and farming are not yet effective enough to be economically feasible.

With the existing farms being mainly pilot- and research-projects, the amount of produced biomass is not very high compared to the potential. There have been, in the last years, done several studies with regards to upscaling the industry. This means larger farms, more exposed locations and the development of equipment suited to handle the large amount of biomass.

One of the limiting factors for the operation is the small time-window for harvesting. With the current type of operations it is also very weather sensitive, meaning that the weather limits the already narrow period for harvesting. If the industry is to reach the estimated potentials set by Olafsen et al. (2012) new solutions for harvesting needs to be discovered.

In Norway it is a goal that the process should be as automatic as possible. There are several reasons for this. Firstly, the cost of manual labour is very high in Norway compared to Asian countries. The cost of labour highly affects the total cost of production, and gives a final product with a cost too high for the market. With manual labour, it will therefore be very difficult to compete in the existing market. Secondly, with the existing pressure of efficient harvest, the small time-frame and the rougher conditions of offshore production it is an unsafe work environment for employees.

2.2 Simulating the harvesting process of a farm

The goal of this thesis is to create a model simulation the harvesting process of a sugar kelp farm. With weather conditions being one of the main restriction for more exposed production, it is sensible to look at how the harvest cycle is affected. This is done by using vessels with different limitations, in this case a maximum allowed significant wave height. The simulation model will then analyze the consequences of this restrictions.

To be able to do that, the first thing needed is to select a location for the farm. Then for the conditions at this location it is desirable to generate realistic weather-data. In this part of the thesis different probability-models will be used to generate several series of data.

The next step will be generating a model to estimate the total production at the given cite. It is desirable that the model work for all locations that have the same type of input.

With all the input available, it should be possible to run the simulation for different vessels and weather-scenarios.

2.3 Objectives

The main objectives in this thesis are as follow:

- Select farm design and vessels for the simulation model.
- Generate realistic weather series to use for several simulations.
- Estimate a potential production at the selected cite, by generating a growth model.

- With the input from the objectives above generate a harvest simulation for the three vessels and analyze the effect the weather-restriction have on the total harvest cycle.

2.4 Structure

The thesis follows a chapter based layout in which chapter 3 will describe the system, which mainly consist of the selected farm design and the vessels used in the model. Chapter 4, 5 and 6 will present the method behind generating the weather-data and the growth model. After that the simulation model will be presented in chapter 7.

Chapter 3

System description

This chapter will describe the system around the production. There are several methods for farming sugar kelp and depending on preference and experience, different ways of seeding, harvesting and spore production is used. The total process can be separated into several steps as displayed in figure 3.1.

Figure 3.1: The different phases of production. Figure adapted from Broch et al. (2016).

The thesis will mainly focus on farming and harvesting. However, the different phases will be presented shortly as they are an important part in understanding how the process works.

Nursery/Hatchery

The hatcheries/nurseries are land-based locations, where the first part of the seaweed farming process is initialized. The result of this part is the production of sporelings that are next to be deployed. There are some main factors for a successful production in a nursery. The most important one is access to a reliable source of clean seawater. It is preferred to have a natural source, instead of artificial seawater, as the natural source have the right composition of mineral components. It is important to filter and sterilize the water before used (Redmond et al., 2014).

Seeding and Deployment

In the process of making sporelings, they need to be applied to the desired substrate before deployment. There are different types of substrates, where the most widespread method is to use ropes, but nets, flakes and more complicated materials can also be used. Due to its one dimension, the application of spores onto rope is relatively easy. The most used methods of application in Norway are twine seeding, where the strings containing the sporelings are twined onto the substrate, and direct seeding, where the sporelings are applied directly onto the substrate. The first method have more success in Norway (Alver et al., 2018).

This thesis uses ropes as substrate. When the juvenile sporelings are grown, the ropes can be placed both horizontally or vertically, or in combination, but it is important that sufficient light reaches the plants.

3.1 Farming

The cultivation cycle is different depending on the surroundings, but it was found in Forbord et al. (2012) that cultivation in Norway only is possible during autumn, winter and spring. Sugar kelp is usually deployed in September and February, and is then harvested before the summer, in May/June. This gives a growth phase in the sea at approximately 4-9 mine months. During summer the growth conditions were poor, mainly due to biofouling. If not harvested in time, the effect of biofouling can result in a loss of up to 100 % of the biomass (Skjermo et al., 2014). It is hard to estimate the level of biofouling at different locations without doing tests, as the amount depend both on temperature and location. It is possible that biofouling is less problematic for offshore farming (Broch et al., 2017).

When farming, it is ideally to place the sugar kelp in the top 15 meters of the water column. This is because, as in the nurseries, the kelp have certain requirements for an effective growth. The first one is light, as the growth comes from photosynthesis. Available nutrients for absorption is also important, but this depends mostly on the selected location. Other than this the sugar kelp does not demand much to grow, as contrary to agriculture, fertilizer and fresh water is not necessary (Hancke et al., 2018).

As mentioned in section 2.1, there exist farms for sugar kelp production in Norwegian waters, but the majority are pilot project and smaller farms. It is therefore hard to find much information regarding structures for larger production. There are several ongoing projects with an intent of both more exposed and larger farms, but the data from these studies are not available. Before a suitable farm could be selected, a cite would need to be found. The conditions on cite would present many of the constraints in regards to the design, size and layout of the farm.

3.1.1 Selecting cite

In Broch et al. (2016) and Broch et al. (2017) the authors have mapped the potential for producing sugar kelp in Møre og Romsdal and Trøndelag, two municipals in Norway. Here they have classified the potential inside the sea line, on the continental shelf and outside, and the possible quantity than can be produced. This model have been made using the numerical ocean model SINMOD. The potential production for the different areas outside Trøndelag can be seen in figure 3.2.

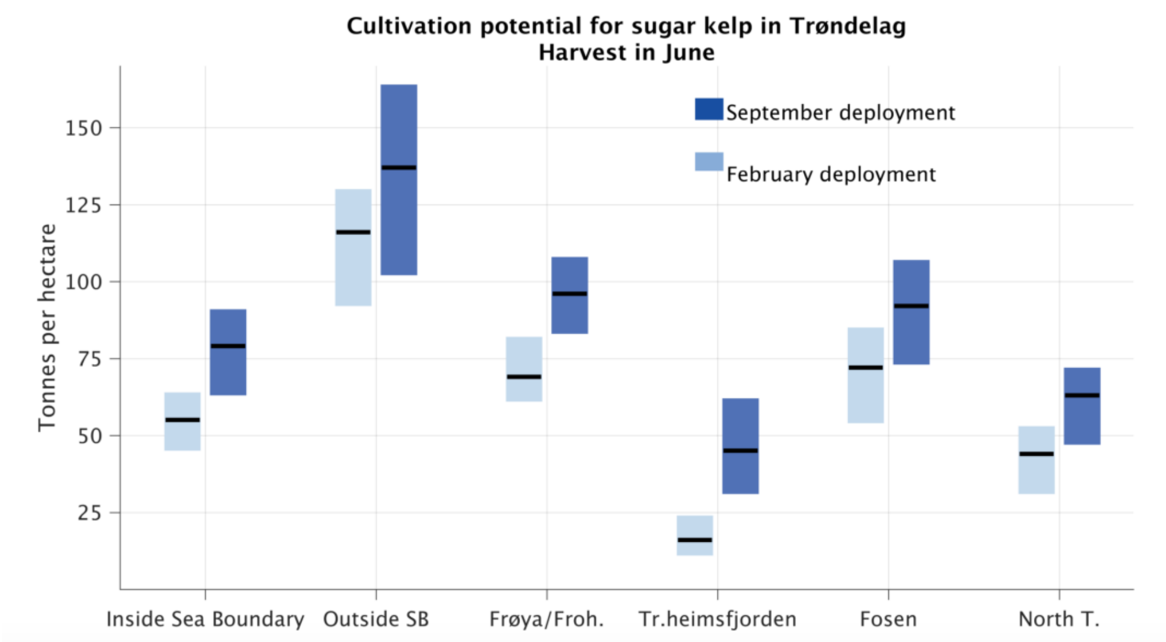


Figure 3.2: Potential production of sugar kelp outside Trøndelag. Illustration from: Broch et al. (2017)

Here the potential production depend on several factors, where the most important ones are light, temperature, nutrients, salinity and current. All these are essential when selecting location. For this thesis a location was decided both on potential and the availability of data. The location used is outside Sula in Sør-Trøndelag and can be seen in figure 3.3.

Figure 3.3: Location for farm. ©kartverket/norgeskart.no

The location have a high potential from Broch et al. (2017), and while it does not have the maximal potential, there are other advantages. There are, as mentioned earlier, available data for this location, which makes it possible to make a better model. Another advantage is the proximity to land. The island of Frøya is close, and can provide fast delivery and distribution. The area around Hitra and Frøya are scattered with many fish farms and other aquaculture, and it can therefore be assumed that the seaweed-biomass can also be delivered here. Since there are, as of now, no specific place where kelp is being collected this thesis will assume a distance from the farm to Frøya of 9 nautical miles (16.66 km). This distance is estimated using the mapping tool Sea seek.

When the location have been chosen, a suitable farm design have to be decided.

3.1.2 The farm

As mentioned earlier, the available data regarding farms is scarce. In this thesis it is desirable to use a farm of a larger size, as it mainly focuses on the harvesting. This give the options of upscaling an excising facility or look for a design that could work for the given location.

In Bak et al. (2018) the design of the Macroalgae Cultivation Rig (MACR) is described. This is a system designed and tested by Ocean Rainforest in the Faroe Islands. This rig is designed to withstand the tougher conditions found in the North Atlantic ocean. The design is based on vertical lines attached to a main line, with the possibility of multiple harvest. A schematic of this rig can be found in figure 3.4.

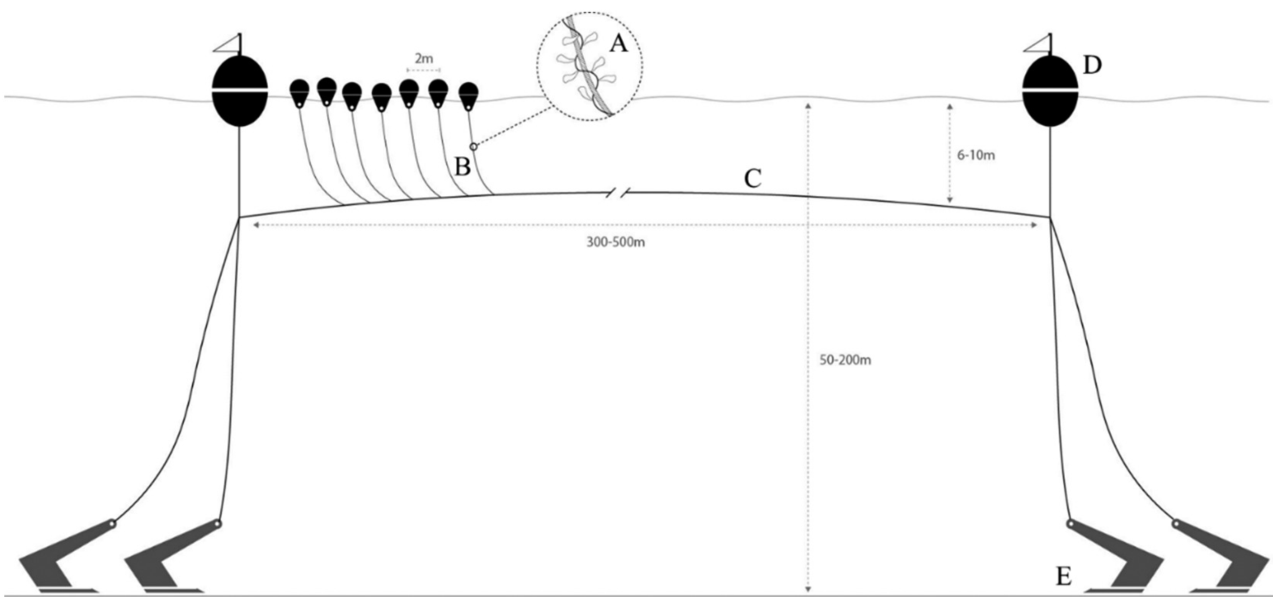


Figure 3.4: Figure showing the Macroalgae Cultivation Rig from Ocean Rainforest. Illustration from Bak et al. (2018)

The figure display how the vertical lines are all attached to a submerged main line 6-10 meters from the surface. The advantage of using this model was firstly that it has been tested in similar weather conditions, and also that the article Bak et al. (2018) provided accurate values in terms of space-requirements, number of growth lines and the potential production from these types off farms.

The schematic show the 500 m long main-line, where 250 growth lines are fastened with a spacing of 2 meters. With each growth line being 10 m long, the total length of growth lines are 2500 m. The article uses seeding material from Hortimare BV, estimating a minimum of 200 sporophytes per meter of rope. This means that each rig contains approximately 500 thousand individual sporophytes, and these values will be used for modeling the potential growth. Each rig needed an average space of 1 ha, or 0.01 km^2, based on the 500 meter main-line and 10 meter space on each side. The estimated potential per hectare inside the baseline is between 45 and 90 tonnes per hectare (Broch et al., 2017). In this thesis it is desirable to look at a farm of significant size. This is here done by using several of the MACR. 10 rigs have been estimated, and the total farm will therefore occupy an area of 0.1 km^2.

There are advantages and disadvantages of this design, and the farm selection will be further discussed in section 9.1.2.

3.2 Harvesting

With a large-scale production comes high demands for equipment handling deployment and harvesting. Especially harvesting, as the attached biomass makes for a more difficult challenge then when the substrate is deployed into the ocean. In the large producing countries, like China and Indonesia, nearly all the harvesting is done manually.

For the existing projects in Norway, this process of harvesting is usually done in a combination of assisting equipment, for example cranes, and manual labour. In figure 3.5 the harvesting process used by Seaweed Energy Solution AS is shown. Cranes are used to lift the lines out of the water, and then manual labour is used to remove the biomass. In the season of 2014-2015 this gave a harvest capacity of 5 tonnes/day, and was described as very tiresome work (Alver et al., 2018).

Figure 3.5: Harvest of sugar kelp in Frøya, Norway (2013). Illustration from: Hancke et al. (2018).

If Norway is to compete with foreign industry, the process of harvesting, need to be automated. This is because the cost of manpower with the time-consuming harvesting makes the final product very expensive. The solutions regarding the vessels will set the standard for how efficient the industry can become. As of now there are no harvesting-solutions that works for an automatic process. For the Macroalgae Cultivation Rig it is estimated that the harvest of each line takes approximately 8 ± 1 min, meaning the rig is harvested in 3.5 days, using 9.5 hour work days (Bak et al., 2018). This was done using a crane to lift up the lines and place them on modified frames on-board to let gravity do the harvesting. How this method compares to a theoretically automated solution is hard to say. This thesis will therefore assume this harvest speed in the simulations.

3.2.1 Vessels

If upscaling the industry, the vessels selected needs to have room for new harvesting and deployment equipment, space for conserving and storing the biomass, and the ability to handle the weather and forces on site. It is also an advantage to have equipment for cleaning and storing the substrate, in this case ropes, after harvesting.

Such a vessel would make the process less weather-dependent, as harvesting and deployment could be performed in worse conditions then today. The system for maneuvering would therefore need to be reliable as the movements could lead to damaging the farm. The system for connecting and releasing the substrate from the farm should also be automatic, or semi-automatic, as to minimize the risk of injury.

Designing a specific vessel for the operation might not be the optimal solution as the harvesting and deployment periods are short, and the vessel would not be needed for the majority of the year. With this period being 6-8 weeks, the cost of maintaining the boat during the rest of the year would make it impossible to have profits. This means that the vessels need to have different work in the off-season.

There are several solutions for how this could be done. A solution could be a vessel with modules, that outside the seaweed-season could be applied to either the fishing or aquaculture industry. It is both a solution to own these vessels, and then hire them out, as well as only hiring the vessels during high season.

The main parameters for these vessels would then be capacity, harvesting speed and the ability of handling different weather conditions. Capacity in this case means how much biomass can be stores per trip. The method of storage would also depend on both the capacity and the size of the vessel in terms of length, width and depth. Depending on how one wish to conserve the biomass, the space needed for storage would be different, meaning two ships of equal size can store different amounts.

For this thesis three ships have been considered. These ships are, with some alterations, based on estimates from the project *Taredyrkningsfartøy 2020* by Sintef, a Norwegian research institute. The main values used in this thesis can be seen in table 3.1.

Vessel	Length	Width	Depth	Capacity	Wave-restriction	Hull-type
1	15 m	10 m	2 m	40 tonnes	1.5 m	Catamaran
2	15 m	8 m	2.4 m	100 tonnes	1 m	Conventional
3	24 m	12 m	3 m	200 tonnes	2.5 m	Conventional

Table 3.1: Main values for vessels

Vessel 1 is inspired by the vessels used for service in the aquaculture industry, and consists mostly of deck-space and equipment for lifting and performing other services. It does therefore not have much storage capacity, and it is assumed that the kelp is stored in containers on deck. Vessel 2 have similar dimensions as Vessel 1, but consists of a conventional hull, and have therefore normally more storage-space bellow deck. As an alternative usage, this vessel could be applied for seaweed-trawling in the off-season. The third vessel is nearly 10 meters longer than the first two, and have twice the storage. The dimensions are based on larger service-vessels in aquaculture, and does therefore normally have sufficient equipment, mainly adequate crane handling.

One of the most important factors here was deciding the wave-restriction parameter. This is the maximum significant wave height the vessels can perform harvesting-operation in. These numbers were decided based on several factors. The fist one was information from the company Seaweed Energy Solution AS, that the maximum height for their setup was 0.5 m. This is for a 12 meter vessel and manual harvesting. From *Tarefartøy 2020* it is preliminary estimated that a larger ship of around 30 meters can operate in wave-heights of 4 meters. Based on this the three values are estimated. It is however, hard to know exactly what the correct values should be, as this depends on the harvesting equipment and the layout of the farm.

From section 3.2 the harvesting-time for each line is described, and the first two vessels use this value. The third, and larger vessel, does also follow the same speed, but have the possibility of harvesting two lines at the same time due to its size.

It was difficult to find service-speed for vessels of the size used in this thesis. From a technical report by Propel, in collaboration with Vista Analyse, a prognosis was done for different ship-sizes, engines- and fuel-technology for coastal traffic (Jensen et al., 2015). In this report, a graph describing engine-effect vs speed for offshore-supply ships displays that for an engine-effect between 500 and 100 kW the speed should be between 9-10 knots. While similar vessels to the ones used in this thesis did not display the service-speed, they did display engine-size, and with an average of just under 1000 kW, it is estimated that all three vessels sails at a speed of 9 knots or 16.66 km/h.

Conservation

A small harvesting period is not the only time-sensitive part of the operation. One of the characteristics of seaweed is that it starts rapidly decomposing once harvested. It is therefore essential to invest in methods of maintaining quality of the harvested biomass. The intended use of seaweed will determine these methods, as the quality of the biomass have different restrictions for the different markets.

The most important factor will therefore be the technology available on the vessel. This could be equipment for freezing/thawing, drying, RSW-tanks or other possible solutions. The possible equipment therefore depends on the size of the vessel in combination with the desired end-product. This means that the accessibility for different solutions are more likely for the larger vessel used in this thesis. The different solutions will not be discussed further here, as it is not the main focus of this thesis.

Distribution/market

For distributing the product, the close proximity to land gives the selected location an advantage, but the value of the final product depend on the quality and the method of conservation. An estimated use and price of different products are displayed in table 3.2 bellow. Here it is shown that the kelp can go from anything from bellow 10 NOK/kg to over 100 NOK/kg. As mentioned in the section before, the price is highly dependent on the quality of the product.

Component	Product	Potential price
Whole plant	Food	Low-medium
Extracts	Cosmetics	Medium
	Prebiotics	Medium
Polysaccharides	Pharmaceutical products	High
	Substrate for fermentation (biofuel)	Low
Protein/amino acids	Fish and animal feed	Low-medium
	Bio-active peptides	High
Polyohenols	Antioxidants (food, feed, cosmetics)	High
	Antimicrobial products (preservatives, anti-fouling etc.)	Medium-high
Ash	Fertilizer	Low-medium
	Valuable minerals	Medium-high

Table 3.2: Possible uses for seaweed and prices. Table adapted from: Skjermo et al. (2014)
Low < 10 NOK/kg; Medium 10-100 NOK/kg; High > 100 NOK/kg

Chapter 4

Method

In this thesis the different methods are presented in different chapters. Chapter 4 will describe the theory behind discreet-time Markov chains along with the software used in the thesis. In chapter 5 this theory and models will be used to create Markov chains for the desired weather conditions, and from there generate new data series. From there the potential growth at the selected cite is estimated in chapter 6. The last chapter, chapter 7, combines the results from the previous chapters with the simulation tool, creating the down-stream process of harvesting the sugar-kelp farm.

4.1 Discrete-time Markov chains

Markov chains are defined as a stochastic process where random variables are used in a discreet time (Sigman, 2009). This means that each step is independent of earlier values and is defined by different states. The values only depend on the current state. From Sigman (2009) "stochastic processes are meant to model the evolution over time of real phenomena for which randomness is inherent". It is normal to define the stare as X_n, where n is the time and S is used to define the state space. The Marcov chain can therefore be defined as,

$$P(X_{n+1} = j | X_n = i, X_{n-1} = i_{n-1}, ..., X_0 = i_0) = P_{ij} \tag{4.1}$$

where X_n is a stochastic process for all n $\geqslant$ 0, and where all states are defined in the state space S, for states i_0, ..., i , j ∈ S (Ross, 2010).

A Markov chain contain a number of N states. P_{ij} represent in equation 4.1 the probability of transition from state i to state j, when in state i. The probabilities from the different states form a N x N matrix, which is known as the transition probability matrix. The matrix can be seen in equation 4.2.

$$P = \begin{pmatrix} P_{00} & P_{01} & P_{02} & \dots \\ P_{10} & P_{11} & P_{12} & \dots \\ \dots & \dots & \dots & \\ P_{i0} & P_{i1} & P_{i2} & \dots \\ \vdots & \vdots & \vdots & \end{pmatrix} \tag{4.2}$$

To explain further how the matrix and states are defined, an example of a transition matrix is shown in figure 4.1. The example shows the transition matrix for three different sea-states, calm, moderate and rough, and the probability of changing.

$$P = \begin{array}{c c} & \begin{array}{ccc} Calm & Moderate & Rough \end{array} \\ \begin{array}{c} Calm \\ Moderate \\ Rough \end{array} & \begin{pmatrix} 0.60 & 0.30 & 0.10 \\ 0.20 & 0.65 & 0.15 \\ 0.25 & 0.55 & 0.20 \end{pmatrix} \end{array}$$

Figure 4.1: Example of a transition probability matrix for three sea-states

To illustrate further how the matrix works, the matrix from figure 4.1 have been visualized in figure 4.2. Here it is clear how the different states, in this case calm, moderate and rough, interact with each other in the Markov transition matrix.

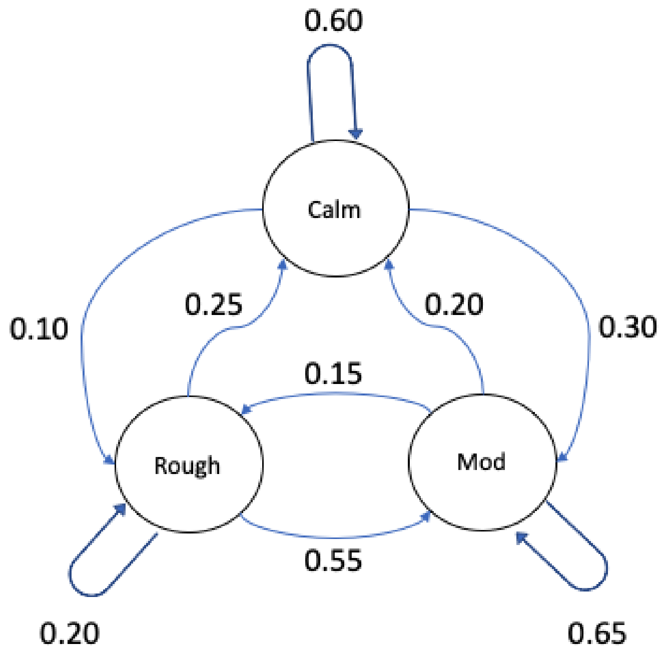


Figure 4.2: Visualization of matrix displayed in figure 4.1

4.2 Software used in the thesis

The software used in this thesis is mainly MATLAB, and within MATLAB the simulation tool, Simulink. MATLAB was used to generate the scripts for both the growth, weather-data and as code-blocks in the simulation.

Simulink is used for model-based design where the simulation takes form in a block-diagram environment (MathWorks). With this system it is possible to present a virtual model of a real-world system, within the limitation and simplifications done by the user and the program. In this thesis the simulation is used to make a roundtrip model for seaweed-harvesting, given certain limitations and restrictions.

Chapter 5

Operability

5.1 Weather data

For the model simulated in Simulink it was desirable to base the weather-data on real data, as to get a more real-life model. This also makes is easier to use the model for other locations as the weather-data input will be similar. This thesis have received data from the Norwegian Research Council, EXPOSED Aquaculture Research Centre, grant number 237790. The data consists of current, wave and wind data along with other measurements like salinity and temperature etc.

The data is collected from a Marine Harvest facility outside Sula, an island in Sør-Trøndelag, Norway. The coordinates for the location is at 63.82 °latitude and 8.38 °longitude, and the location is currently used for fish farming. The data from the buoy will not be presented explicitly, due to it being confidential. To use the data, time series will be made using Markov chains.

5.2 Wave generation using Markov chain simulations

By using the data from SFI Exposed, in this case the significant wave height (m), a time series of waves have been generated. This have been done using a Markov chain simulation in Matlab. The main part of this code is from Ciucu et al. (2015), which is available online, and this code generates the probability matrix. A random number is selected, and the string of wave heights is then defined. The states are shown in table 5.1. Here the first state represent wave heights from 0 to 0.1866 meters, the second from 0.1866 to 0.3732 meters and so on for all nine states. This range have been found by taking the maximum height from the data and then dividing it by the number of states one wish to use.

State	0	1	2	3	4	5	6	7	8
Wave height [m]	0.1866	0.3732	0.5598	0.7464	0.933	1.1196	1.3062	1.4928	1.6794

Table 5.1: The wave heights values for the 9 states used in the Markov chain

The matrix is made using data from 20.04.2016 to 10.06.2016 , and consists of hourly measurements resulting in a total number of 1185. It needs to be taken into consideration that the data collected here only represent the harvest-period for one specific year, and is therefore hard to say if the conditions this particular year is worse or better than average. This means that the Markov chain and the generated waves used in this thesis is only one possible representation of the conditions in this area.

Table 5.2 bellow displays the probability matrix used. The matrix shows that for the first three states the probability of staying in that respective state is over 70 percent. In the later states, mainly the two last ones, the probability of staying in those states is less than 50 percent. This indicates that it is more likely to stay within the lower states.

State	0	1	2	3	4	5	6	7	8
0	0.8131	0.1776	0	0.0093	0	0	0	0	0
1	0.0466	0.8485	0.0886	0.0093	0.0023	0.0047	0	0	0
2	0	0.1575	0.7047	0.1142	0.0079	0.0157	0	0	0
3	0	0.0392	0.2026	0.5490	0.1830	0.0196	0.0065	0	0
4	0	0	0.0094	0.2830	0.5189	0.1698	0.0094	0	0.0094
5	0	0.0141	0.0563	0.0563	0.2535	0.5070	0.0704	0.0423	0
6	0	0	0	0.0270	0.0270	0.1892	0.5135	0.2162	0.0270
7	0	0	0	0	0	0.0500	0.4000	0.4000	0.1500
8	0	0	0.1429	0	0	0	0.4286	0.1429	0.2857

Table 5.2: Probability matrix representing the probability of changing states

The Markov matrix is then used to simulate 40 different weather scenarios. These are then saved. This is firstly to eliminate the need to create new scenarios for every run, and secondly so that the different vessels can experience the same data. The three boats have different criteria for weather conditions, in this case maximum significant wave heights. To make a more accurate comparison it is therefore desirable to use the same weather simulation for each vessel. Figure 5.1 bellow shows the mean probability from the 40 weather scenarios. Here, each box represent the probability of being in that state, and the figure shows clearly how the probability is distributed.

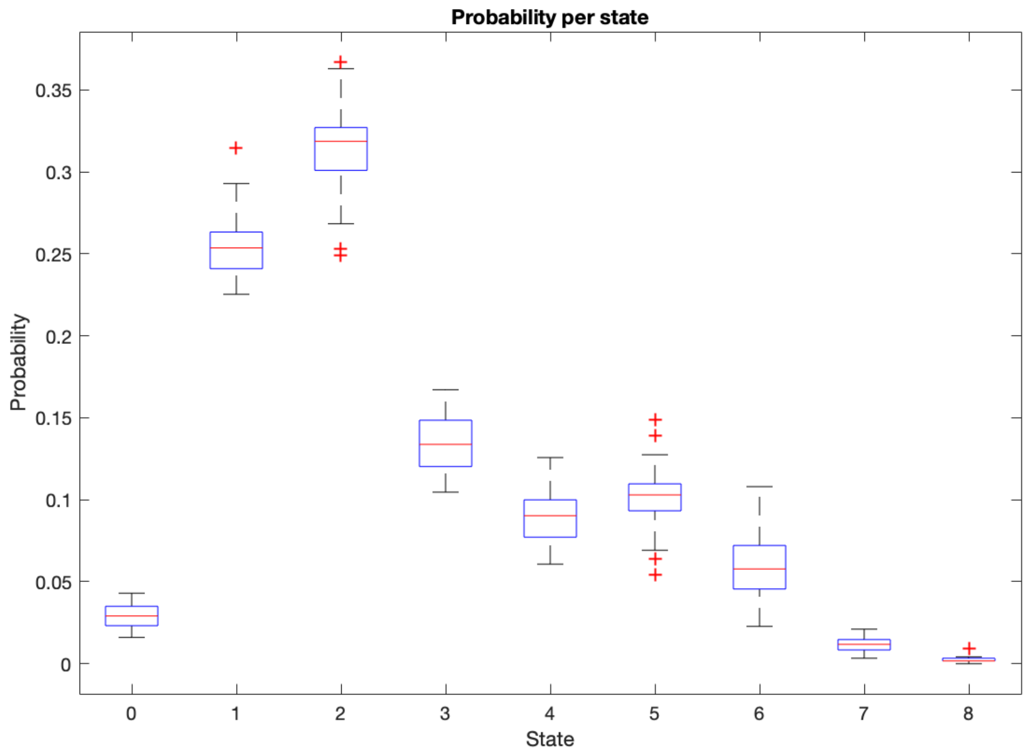


Figure 5.1: Mean probability of each state for the 40 simulations

The figure shows that the probability of being in state one or two is over 50 percent, corresponding to a significant wave height at a maximum of 0.5598 meter for state two. An example of the weather scenario for one of the generated series can be found in figure 5.2. The mean significant wave height are on average around 0.58 meter, with some peaks reaching to nearly 1.7 meters.

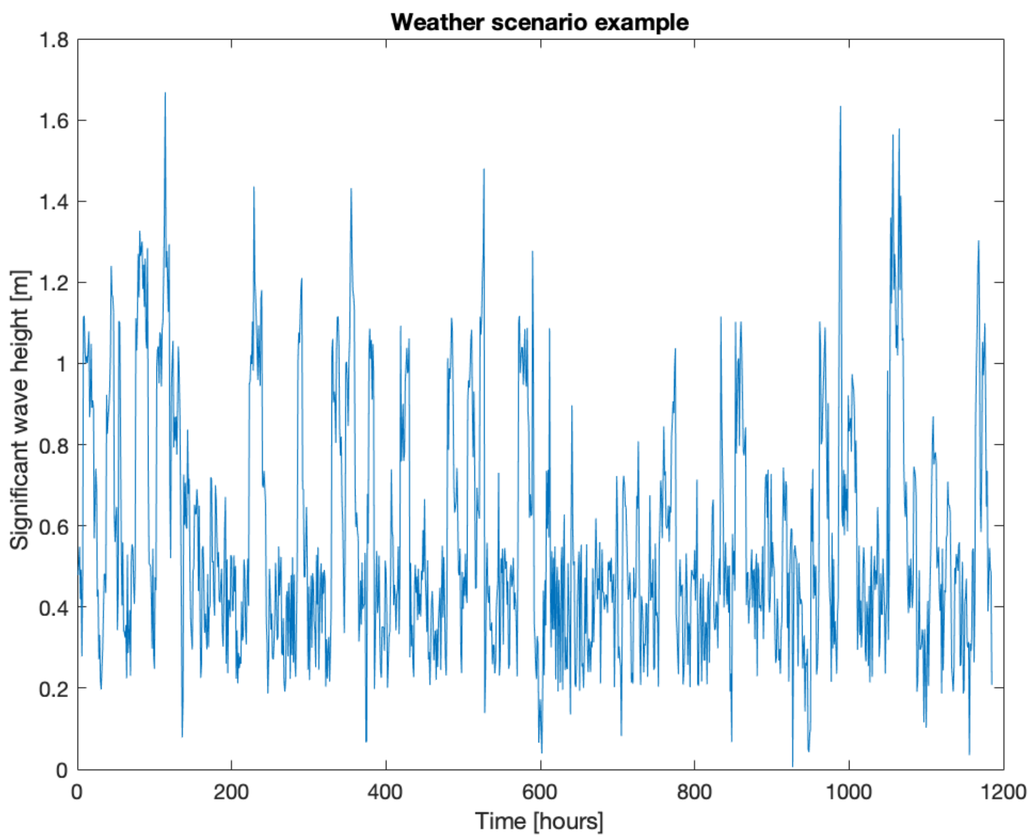


Figure 5.2: Weather scenario example for significant wave height

Chapter 6

Growth potential

A model to estimate the growth potential for the selected location is made in this thesis. This is done to get a more realistic potential production for the specific location. The growth model is made in a way so that using another location and different values do not change the basic of the model, only the input. This means that the model is suitable for all locations given available input.

There are recent studies where the cultivation potential have been discussed and estimated. This can be read about this in: Broch et al. (2019, 2017, 2016); Broch and Slagstad (2012). These articles agrees on the most important factors and variables for growth; light, nutrients, temperate and currents. In table 6.1 some of the optimal values are presented.

Species	Temperature	Salinity	Nutrients	Currency
Sugar kelp (Saccharina latissima)	10-15 ° C	>25 g/kg	>4 mmol/m^3	0-0.25 m/s

Table 6.1: Values for optimal growth, sugar kelp. Table modified from Broch et al. (2017).

As mentioned in section 3.1.1 the potential for Trøndelag was mapped using the numerical ocean model SINMOD. The study revealed that inside the sea boundary there is an estimated average production of 60 to 110 tonnes per hectare in the area around Frøya. This also depends on the type of farms, but it can be used as an estimate to verify if the growth-model is accurate. It also depends on the time of deployment, and the September deployment, as in this thesis, have an estimated higher potential than deploying in February. There have been done several studies trying to map and describe the potential for kelp production. As there are currently no large facilities producing kelp in Norway, some of the studies are based on upscaling. It is therefore important to critically evaluate the estimates done, as they do not necessary reflect the true potential. On the other hand, the potential could also be vaster than expected (Broch et al., 2019).

In late winter and early spring, nutrients are stored in sugar kelp. These nutrients then contributes to growth in late spring and early summer. In summer growth is reduced, due to storing of carbohydrates, and is not that relevant in this thesis due to the dates of harvesting. This is more to get a general view of the growth pattern of saccharina latissima. The growth-rate continues to be lower during autumn, and increases as described first in late autumn. This cycle corresponds well with the dates chosen for the simulation. The harvesting also happens before biofouling happens in summer. This cycle is important in understanding the growth-patterns of the sugar kelp, and this way it is possible to simulate the growth in a more realistic manner.

6.1 Generating a model to model growth

To simulate the growth of sugar kelp, a model found in Broch and Slagstad (2012) have been used to find the composition and seasonal growth. If not stated otherwise, the equations in this chapter are from this article. The same goes for the constants, and the explication for each constant can be found in the article, and will not be discussed in this thesis.

Weather data from the EXPOSED Aquaculture Research Centre have also been used in this chapter. The values used are: temperature, currents and salinity, and the use of these provides a more accurate output. The data is confidential, and will not be presented explicit in this thesis. Modeling the potential growth is not an easy feat, as there are little quantifiable data in terms of nutrient-content, but values have been selected or estimated for the other variables, and will be described later in this section. The time-window for growth in this thesis is set from 01.09.2016 to 31.05.2017. As for the weather-data in chapter 5 the values used are only a representation of that specific year, and will mainly serve as input for the model.

To generate a model it is important to know the different input and output that contributes to the changes in values. A schematic have been made of the model, and can be found in figure 6.1. In this overview the main elements are the carbon and nitrogen reserves, that are the most important factors for the growth of the structural mass. The different parts of the schematics will be presented in separate sections bellow.

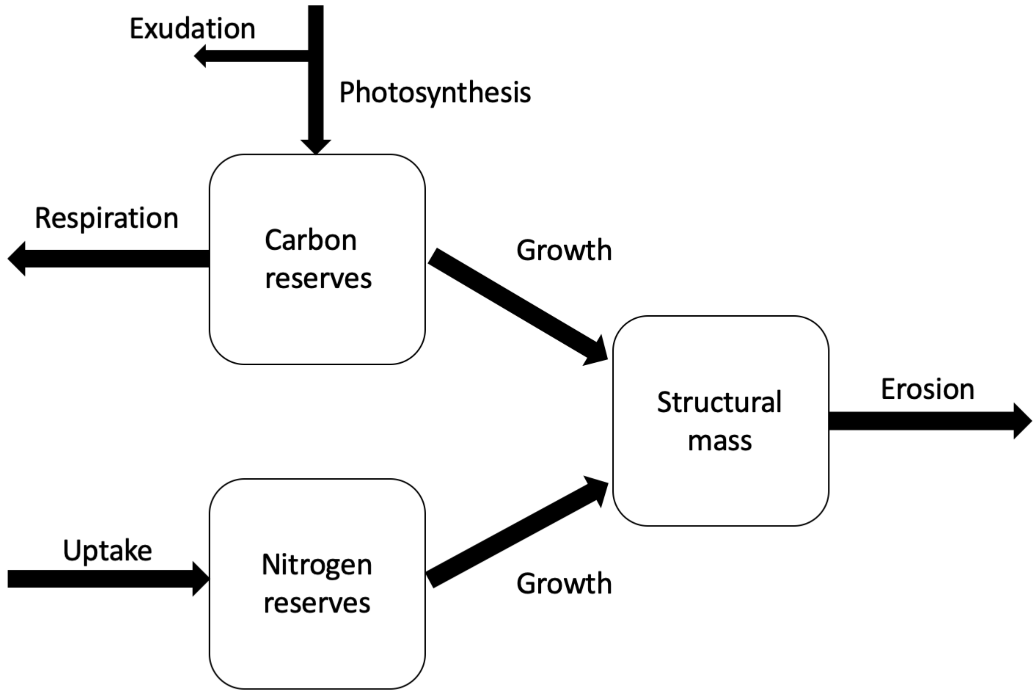


Figure 6.1: Overview of the growth-model. Adapted from: Broch and Slagstad (2012)

With this model there are different types of variables, from environmental variables to auxiliary variables. These are presented in table 6.2, and will also be presented in the sections they are a part of. A full list of variables and constants can also be found listed in the beginning of appendix A.

Symbol	[]	
A	dm^2	Frond area
C	$gC(gsw)^{-1}$	Carbon reserves
N	$gN(gsw)^{-1}$	Nitrogen reserves
μ	day^{-1}	Specific growth rate
W_w	g	Total wet weight
W_d	g	Total dry weight
W_s	g	Dry weight of structural mass
β	$g\ O_2\ gm^2\ h^{-1}$ (μ mol photons $m^{-2}\ s^{-1})^{-1}$	Photoinhibition parameter
P_s	$g\ O_2\ gm^2\ h^{-1}$	Photosynthesis parameter
I	μ mol photons $m^{-2}\ s^{-1}$	Irradiance (PAR)
T	$°C$	Water temperature
U	m/s	Current speed
X	mmol L^{-1}	Substrate nutrient consentration

Table 6.2: Variables used in model. Adapted from: Broch and Slagstad (2012)

The model have some restrictions and assumptions, where the main ones are listed bellow, but all are described further in the article.

- The volume is proportional to the frond area which again is proportional to the structural mass.
- General turbulence in the water is not considered.
- The chemical compositions in the structural mass and in the reserves are fixed.

6.1.1 The generated script

The model was generated using Matlab. Given that the majority of the variables was time-dependent, the script forms a loop of the given growth time. This loop generates new values each step in the model. To be able to start the model, it was necessary to generate initial values for many of the variables. The full script can be found in appendix A. The Matlab-script also contains a full list of every constant used in the model.

6.2 Structural mass

The structural mass is the main output from this model. To calculate the frond area there are several variables that needs to be decided. As seen in figure 6.1 the structural mass increases based on the carbon and nitrogen reserves, and decreases with the loss of biomass, erosion. The structural mass also depends directly on the frond area, the area of each leaf.

6.2.1 Frond area

Equation 6.1 describes the rate at which the frond area change. This equation depend mainly on the specific growth rate μ and the frond erosion v. The frond area changes over time and the step of change is set to one hour in this thesis. By selecting a start value A, it is possible to calculate the change in frond area.

$$\frac{dA}{dt} = (\mu - v)A \tag{6.1}$$

6.2.2 Specific growth rate

The specific growth rate depends on the frond area, the nitrogen and carbon reserves and the water temperature. μ is calculated in equation 6.2. Here the N_{min} and C_{min} are constants found in the article.

$$\mu = f_{area} f_{temp} f_{photo} f_{salinity} * min\left(1 - \frac{N_{min}}{N}, 1 - \frac{C_{min}}{C}\right) \tag{6.2}$$

f_{area} changes with the frond area. This part of the equation lowers the growth rate when the frond area is high, and is based on the fact that the plant will grow relatively faster when it is small.

f_{temp} gives the effect of water temperature. In the beginning of the simulation this value is constant at one, but as the temperature drops bellow 10 degrees Celsius, the value changes with $f_{temp} = 0.08T + 0.2$.

f_{photo} accounts for the change in day length, and the amount of light available. The values used in this part is found in Broch et al. (2019), where the change in day length is plottet over the year for several different location.

$f_{salinity}$ is not included in Broch and Slagstad (2012), but a new addition in Broch et al. (2019) gives the values as shown bellow in equation 6.3. However for the data presented in this thesis, the factor have no effect as the salinity is larger then 25 at all times, thus equalling 1. The unit for S is PSU, practical salinity unit.

$$f_{salinity} = \begin{cases} 1, & \text{for } S \geq 25 \\ 1 + \frac{S-25}{18}, & \text{for } 16 \leq S < 25 \\ \frac{S}{32}, & \text{for } 0 \leq S < 16 \end{cases} \tag{6.3}$$

6.2.3 Frond erosion

Frond erosion is the continuous loss of biomass, and is mainly dependent on the tissue-age and the motions from the water. In the article the frond erosion is defined based on the frond area, as seen in equation 6.4. This simplification is because tracking the age of the kelp would be complicated, and it is therefore easier just to model it based on the size of the kelp. Since the model does not take water turbulence into account, it is not possible to track the loss from this aspect.

$$\upsilon = \left(\frac{10^{-6} exp(\epsilon A)}{(1 + 10^{-6} exp(\epsilon A) - 1)} \right) \tag{6.4}$$

This way of modelling frond erosion is quite simplified, and the actual loss could be quite different than what the model describes. Since the model does not take other environmental processes into account, it could be assumed that the frond erosion is higher than estimated.

6.3 Nutrients

The sugar kelp absorbs both nitrogen and phosphor. However, along the coast of Norway, it is normal the nitrogen that is the limiting factor. This means that to have an increase in production, there needs to be an increase in available nitrogen (Broch et al., 2017). In van der Molen et al. (2018) the model is expanded to include phosphor. However, in this thesis, there are no data available for the uptake of phosphate and it will therefore only include carbon and nitrogen. In the rapport done by Broch et al. (2019) it has been assumed that the limiting nutrient that affects growth are nitrogen. The concentrations of CO_2 have not been taken in to consideration, along with micro-nutrients.

For the carbon and nitrogen levels there were little available data. From Broch and Slagstad (2012) minimum values for nitrogen and carbon were presented the model along with the maximum for nitrogen. These values can be seen in table 6.3. The level nitrogen and carbon are an important part in simulating realistic values for the growth.

	Minimum value	Maximum value	Selected start value
Nitrogen	0.01	0.022	0.022
Carbom	0.01	-	0.6

Table 6.3: Minimum and maximum values for carbon and nitrogen. Adapted from Broch and Slagstad (2012)

6.3.1 Nitrogen

The amount of nitrogen found in the plant is a sum of the nitrogen fixed in the structure, and the nitrogen found in the reserves, respectively N_{struct} and N. To calculate the nitrogen level, equation 6.5 was used. The equation calculate the rate at which the nitrogen level change.

$$\frac{dN}{dt} = \frac{1}{k_A} J - \mu(N + N_{struct}) \tag{6.5}$$

While k_A and N_{struct} are constant values, the equation also depends on the growth rate, μ, and the nutrient uptake, J. The nutrient uptake is calculated by using eqution 6.6.

$$J = J_{max}\left[1 - exp\left(\frac{-U}{U_{0.065}}\right)\right]\left(\frac{N_{max} - N}{N_{max} - N_{min}}\right)\frac{X}{K_X + X} \tag{6.6}$$

The variable X from table 6.2 represent the external nutrient concentration and varies with the environment. Due to lack in data this value was set based on values from Fossberg et al. (2018). In the article the concentrations are measured in regards to a nearby fish farm, and how the release of waste, feces and inorganic nutrients affect the values. In this thesis, nearby fish farms are not taken into account. The value used in the model is 0.3 mmol/L, and is set constant for the simulation. Setting the value constant affect the nutrient uptake rate, J, and may give lower nitrogen reserves than what the location could provide.

The current, U, in this equation were given by the data from EXPOSED, where the values were collected at 7 meters depth.

6.3.2 Carbon

As for the nitrogen, the structural carbon and the carbon from the reserve equals the total amount of carbon. The rate at which the carbon level change is also given by a differential equation, as seen in equation 6.7. The main elements of this equation is the gross photosynthesis, P, the respiration rate, R, and the exudation rate, E.

$$\frac{dC}{dt} = \frac{1}{k_A}\Big[P(I,T)(1-E(C)) - R(T)\Big] - \mu(C + C_{struct}) \tag{6.7}$$

The gross photosynthesis were calculated in equation 6.8. The equation used temperature and irradiance as input.

$$P(I,T) = P_S(T) * \Big[1 - exp\Big(\frac{\alpha * I}{P_S(T)}\Big)\Big] * exp\Big(\frac{\beta * I}{P_S(T)}\Big) \tag{6.8}$$

The temperature of the water have an effect on the growth, and as with the current, data was available from the EXPOSED location. The variable dependent on the temperature is P_S, which can be calculated as shown in equation 6.9. Here α and I_{sat} are constants, while β is calculated using the maximal photosynthetic rate and iteration. This process can be seen in the script in appendix A.

$$P_S = \frac{\alpha I_{sat}}{ln(1 + \frac{\alpha}{\beta})} \tag{6.9}$$

There were no available data for irradiance in the data provided by EXPOSED, as lights intensity is not normally recorded. In Broch and Slagstad (2012) there are some estimated environmental data from another source, but this source is no longer available. In the article they have made a figure estimating the daily total irradiance at 5 meters dept. This changes from being nearly zero in October-January, to almost 40 in May-July with the unit [mol photons m^{-2}

day^{-1}]. This data was compared to data found in Foldal (2018), where the only data available was from March to May. The values are similar when comparing the data form the overlapping months, with around 3-15 mol photons m^{-2} day^{-1}. In Foldal (2018) the collected data is from Frøya, which is in close proximity to the location in this thesis. By estimation values from the two publications, light data have been assumed for the location, and can be found in table 6.4 and visualized in figure 6.2. The values selected for irradiance is then used to calculate the photosynthesis.

Month	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
μ mol photons m^{-2} s^{-1}	57.9	23.1	9.2	8.1	11.5	34.7	69.4	81	127.3

Table 6.4: Table containing values for irradiance

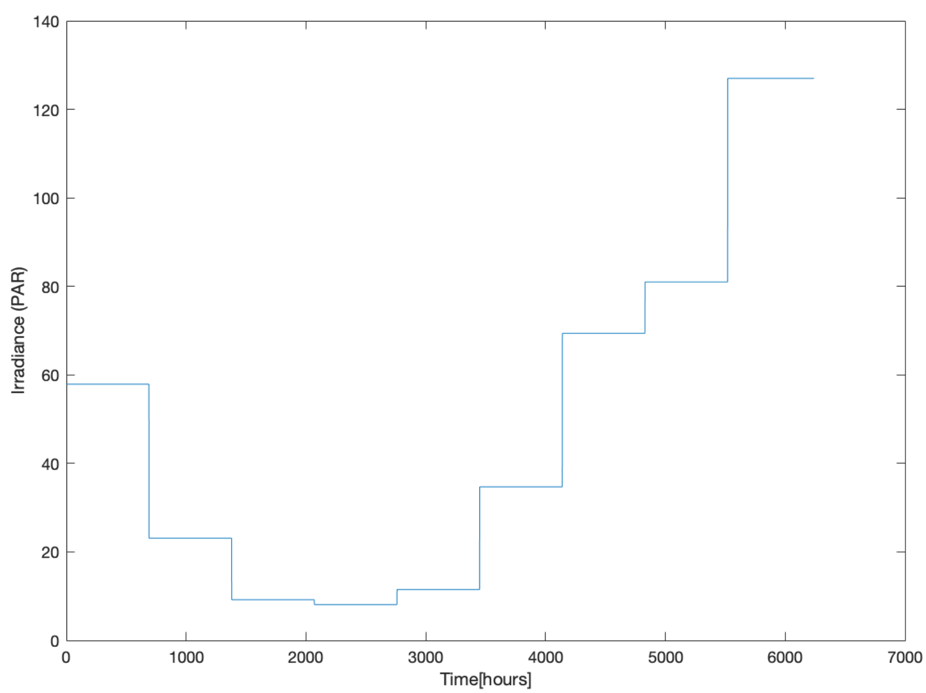


Figure 6.2: Irradiance

The respiration rate and the exudation rate depend respectively on T and C, and the equations found in Broch and Slagstad (2012) are used directly.

6.4 Dry and wet weight

The equations for calculating the wet and dry weight is found, here seen in 6.10 and 6.11

$$W_d = k_A\Big[1 + k_N\Big(N - N_{min}\Big) + N_{min} + k_C\Big(C - C_{min}\Big) + C_{min}\Big]A \tag{6.10}$$

$$W_w = k_A\Big[1/k_{dw} + k_N\Big(N - N_{min}\Big) + N_{min} + k_C\Big(C - C_{min}\Big) + C_{min}\Big]A \tag{6.11}$$

These equations uses the value of N, C and A in a given moment to calculate the weight of the sugar kelp. For the final hour in the growth potential simulation the values are shown in table 6.5. The frond area plotted over time can be found in figure 6.3

A [dm^2]	N [g]	C [g]	W_d [g]	W_w [g]
17.71	0.0102	0.8809	30.47	155.23

Table 6.5: Final values for growth model

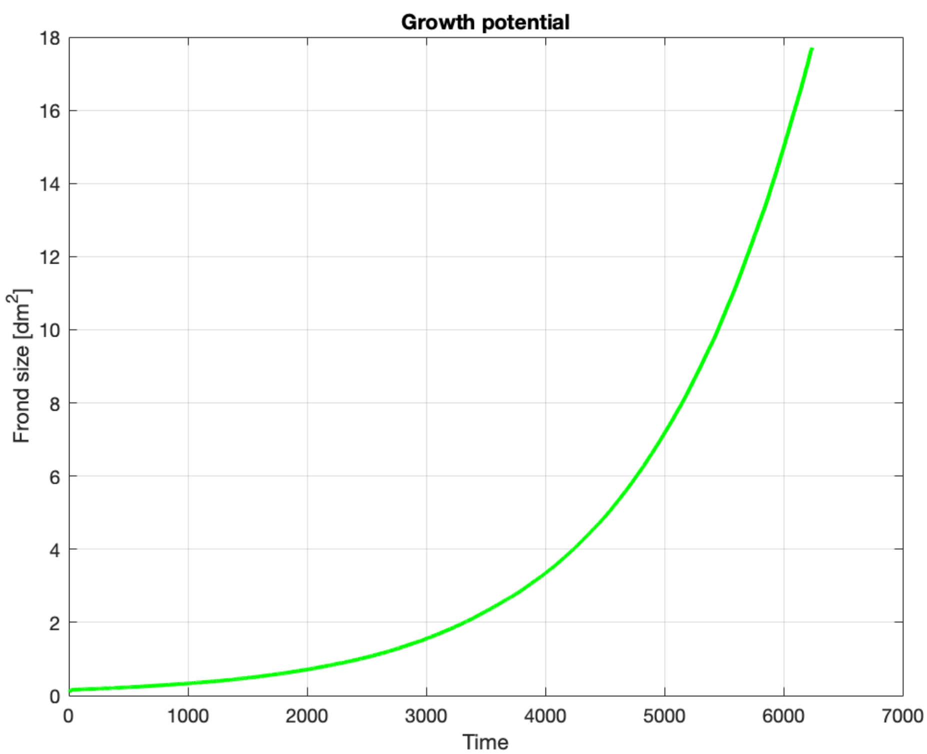


Figure 6.3: Irradiance

From Fossberg et al. (2018) the relationship between the frond area and the length/width of each leaf can be seen in equation 6.12.

$$A = 0.75 * L * B \tag{6.12}$$

In section 3.1.2 the Macroalgae Cultivation Rig from Ocean Rainforest is described, and it is estimated that there are half a million plants/sporophytes per system. With a wet weight of 155.23 grams, this gives a total production of 77600 kg or 77.6 tonnes wet weight. These values are then used in the simulation described in chapter 7.

Chapter 7

Simulation

After the weather-series and the growth model have been made, the data is used as input in the simulation model. This is done by generating a script in Matlab that access this data before running the simulation. This script can be found in appendix B. Here the growth model and the weather series have been referenced, before the desired vessel are selected. The last part of the script runs the simulation in Simulink. A simplified model of the simulation can be found in figure 7.1.

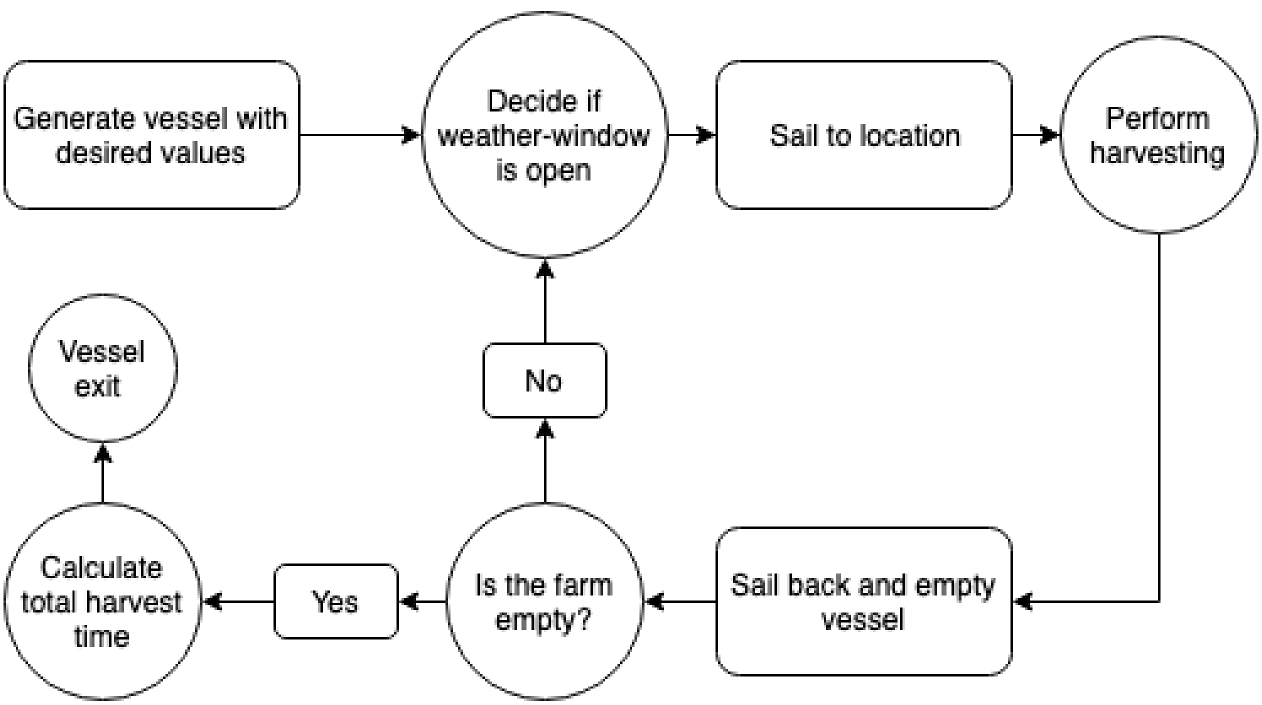


Figure 7.1: Flow chart for one harvest cycle in the simulation model

7.1 The simulation model in Simulink

The model from Simulink can be seen in figure 7.2, and a larger version of the model can be found in appendix C.

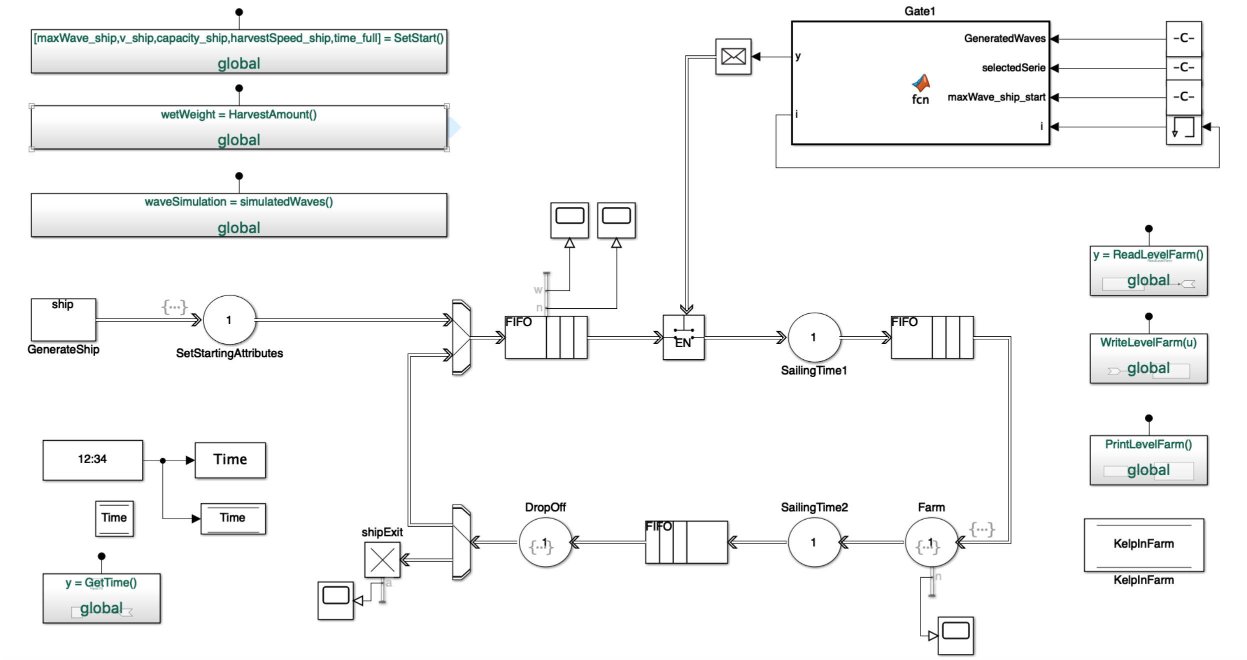


Figure 7.2: Simulation model from Simulink

The different blocks of the simulation model will be explained in the different sections below. The only block not mentioned below is the entity queues, marked with FIFO in figure 7.2. The entity queues are there to make sure entities are queued up, instead of falling out of the system, in front of servers and other blocks that only accept one entity at the time. The queues can also be used to measure the waiting time for the entities before they can enter a block. In the system used in this thesis, there are only one entity, which is the vessel generated. However, with simple changes the model could be changed to allow several entities, and here the queues would be needed.

One of the main simplification this model have is that it operates continuously, meaning that there are no specific work hours. This will have a large impact on the model, as there are no specific requirement to not harvest during the night or given shifts in terms of the crew on board.

Global variables and Matlab function blocks

In the simulation there are several values that are used in different parts of the model, and that also changes values. To make this accessible, the values have been made into global variables, which means that the data is available globally. For the simulink model there are two of these, time and the amount of kelp in the farm. The variables will be described in the blocks they are used. There are also four Matlab functions that uses input from Matlab workspace to provide input to the simulation. These functions will also be described when used.

7.1.1 Generating vessels

The first part of the model is the entity generator that generates entities, in this case the different vessels in the model. The generator is set to generate only one vessel at the start of the simulation with the desired attributes, for example speed, capacity and harvesting-speed. The attributes are only defined in the entity generator, and the entity moves to the next box. This is an entity server, and in this case the values of the different attributes are set here. This server used a global function to set the values for the specific vessel. The vessels and the values are defined in the Matlab-script found in appendix B, and makes it easy to switch between the different size and types of vessels. The attributes used and their function can be found in the list bellow.

- *Exit* - attribute changes when farm is empty and allows vessel to exit system.
- *maxWave* - defines the maximal wave the ship can operate in.
- *capacity* - defines the maximum capacity the vessel can carry per round-trip.
- *speed* - transit speed of the vessel.
- *harvestSpeed* - the speed of harvesting
- *load* - the amount the vessel actually carries per round-trip.
- *stopHarvest* - the time the vessel can harvest before it is stopped be weather conditions above tolerated.

- *timeFull* - time the vessel harvests before reaching full capacity.

7.1.2 Sailing

Before the vessels enters the block that controls the sailing time, they have to pass through a gate. This gate determines whether the weather for the next three hours, in this case the significant wave height, is bellow the maximum height set by the vessel. The reason for this gate is to stop the vessel for going out if the weather changes right away, as this means no harvesting. The gate uses the selected wave-series from Matlab workspace and sends a positive signal to the gate when the conditions are fulfilled.

There are two entity servers that functions as the sailing-time to and from the farm. The sailing-time is calculated using the attribute for vessel-speed along with the selected distance. In this case the three vessels operated under the same speed with the same distance to travel. With the given distance and speed the sailing time amounted to one hour each way for all vessels. With potential round-trip times of 18, 45.5 and 91 hours, for vessel 1, 2 and 3 respectively, the sailing-time only amount to 11, 4 and 2 percent for each. Given these values no form of speed-reduction was implemented in the simulation, as the reduction in time would not have significantly affected the total time. The vessels also traveled in relative sheltered waters.

7.1.3 The farm

When the vessel enters the entity server that functions as the farm, the first thing the block do is note the time of entry. The server uses time as a global variable to do this, and for the first entry the amount of biomass is read through a global function. Every vessel have a specific set of hours before the vessel is fully loaded, presented under the entity *timeFull*. The server uses the time of entry to check the weather conditions for all the hours it takes to load the vessel. This can be done as the significant wave-heights are a global variable. If all the significant wave-heights are bellow the vessels limit the harvest time is set as the time for a maximal capacity load. If not, the time is set as the amount of time before the waves reaches above the accepted limit.

After the harvest time is set, the server uses the global variable to notice how much kelp are available for harvesting. The amount harvested is based on the time available for harvest and the harvesting speed of the vessel. When the vessel is loaded the new value of kelp is read and stored in the variable.

7.1.4 Off-loading

The simulation uses another entity server to work as an drop off, where the vessel is unloaded. The off-loading time will be decided based on the storing-method on board and the amount of harvested biomass. The storage on board can, and probably will, be different for the different vessels, as the amount of space and equipment is a decisive factor in how the seaweed is harvested. Since it is hard to say exactly what these values would be, the off-loading time have been estimated based on the amount harvested. The simulation assumes that unloading the smallest vessel of 40 tonnes takes approximately one hour, and from this unloading the largest vessel, at maximum capacity, will take 5 hours.

This entity server reads the level of kelp in the farm every time the vessel passes. Since the level of kelp in the farm is a global variable it is accessible in every server. If there are no more kelp to be harvested the vessel is terminated and does not continue the round-trip. This is done by changing the value of the entity Exit.

Chapter 8

Results

This chapter will present the results from running the simulation model in Simulink.

8.1 Vessel 1

The first vessel in the simulation have a restriction of 1.5 meter significant wave height. When analyzing the weather data for the 40 simulations, using probability plots, it became clear that the probability of the significant wave height over 1.5 meters were 0.5 percent. This amounts to one in every 200 waves, and from figure 5.2 in chapter 5 this trend is visible. From the probability matrix in the same chapter, it is estimated that the probability of staying in state 8, the state that includes a height of 1.5 meter, is only 28 percent. This means that in the majority of cases the weather will change to an acceptable state within few hours.

When looking at the model in simulink, the ship were only stopped by the initial gate two times out of the 40 simulations. Since the majority of the round-trip is spent harvesting, it makes sense that this number is low, as the probability of the wave being in the 2 hour sailing period is low.

This ship had the smallest capacity, and it could be fully loaded in 17 hours. During this loading period, each simulation had one or two instances in which the vessel left the farm early. This resulted in a difference in harvesting time for the entire cycle is 18 hours, with 412 hours being the shortest harvesting cycle and 430 hours being the longest. This corresponds to 18 days of continuous harvesting. Figure 8.1 shows the harvesting scenario for the 40 simulations done for vessel 1.

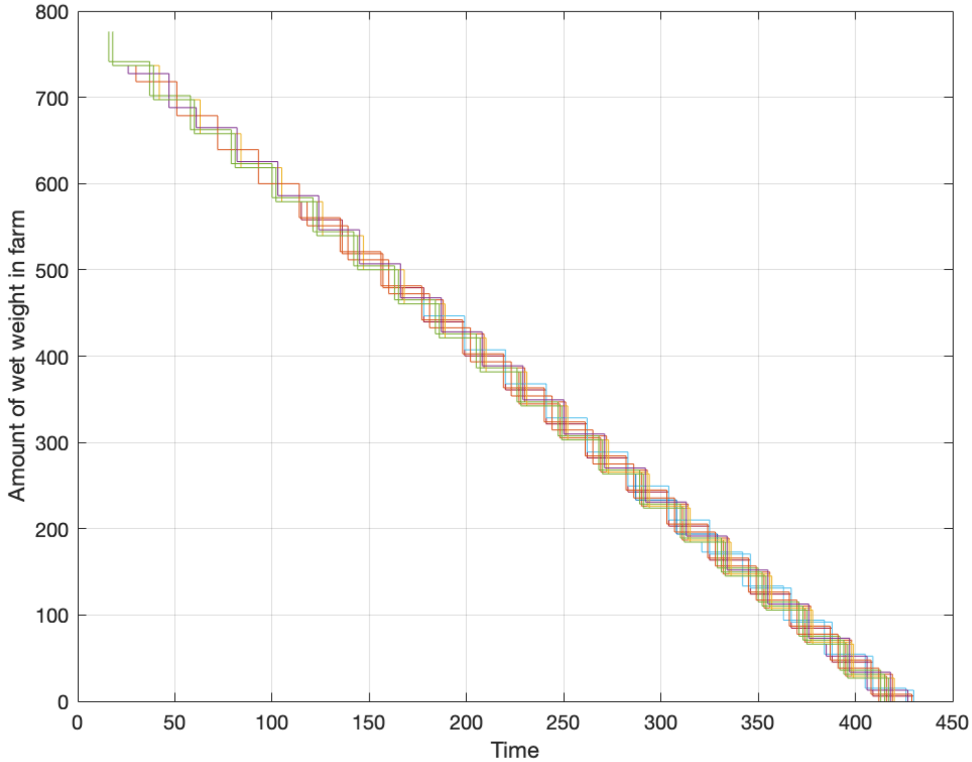


Figure 8.1: Harvesting scenario for 40 simulations, Vessel 1

The average cycle allows the vessel to empty the farm in 20 round-trips, giving a potential collection of 800 tonnes. The collected amount in the simulation is 776 tonnes, meaning that the vessel harvests at 97 percent capacity.

8.2 Vessel 2

Vessel 2 is the most sensitive to the wave height restriction, with a maximum wave height at 1 meter. The probability of the significant wave height of being under 1 meter is 0.87, meaning that nearly 1 out of 10 waves is above the given criteria. This can be seen easily in figure 8.2 as the spread between the different simulations are much larger than for figure 8.1. The difference in total harvest time is 97 hours, where the lowest total time is 380 hours and the highest is 480 hours.

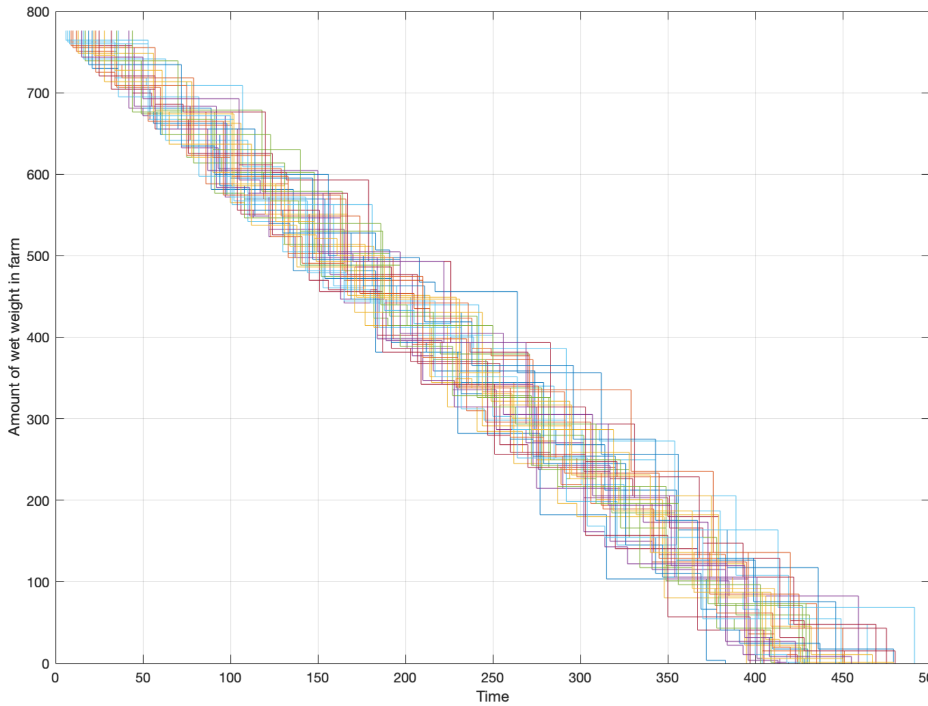


Figure 8.2: Harvesting scenario for 40 simulations, Vessel 2

The vessel is also much more sensible in regards to the gate allowing vessels to start each round-trip. An example of such a waiting time can be seen in figure 8.3, where the y-axis shows the waiting time in hours over the total time. If the vessel experience an 8 hour waiting period, it would increase the round-trip time by 17 percent affecting the total harvesting cycle by a lot.

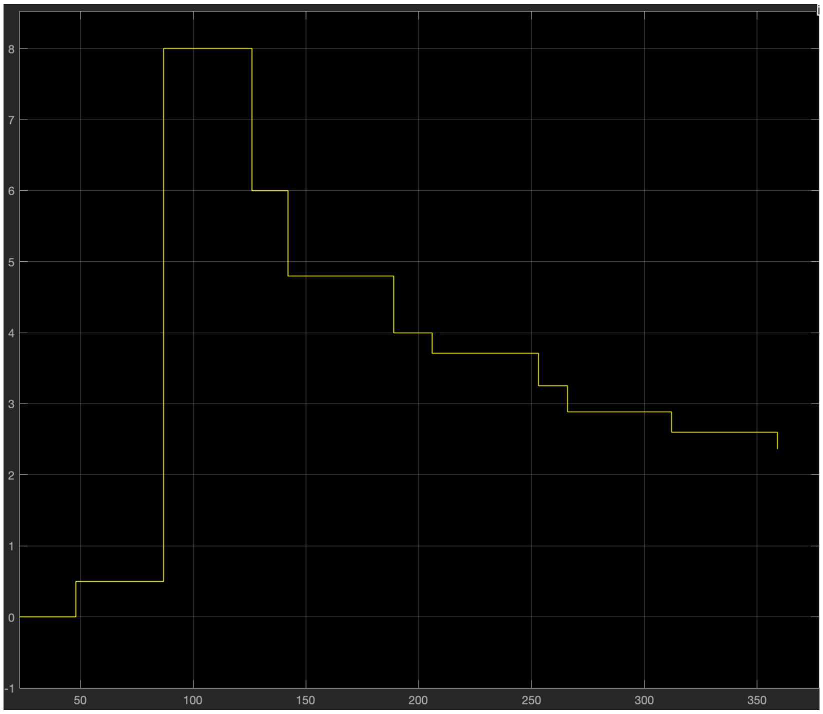


Figure 8.3: Waiting time shown as a function of time for vessel 2

Vessel 2 performs a total of 11 round-trips in each simulation. With a capacity of 100 tonnes per trip, this amounts to a potential harvest of 1100 tonnes. Given that the vessel here harvest 776 tonnes, the capacity for one cycle is at 70.5 percent. From the probability matrix it is shown that for a significant wave height at 1 meter, it is a 50 percent chance of the next step is the same. This means that the periods of waves over the critical height would last longer than it did for vessel 1.

8.3 Vessel 3

The third vessel were the biggest, and were also not affected by the wave restriction, as the maximal wave tolerated were at 2.5 meters. This meant that the vessel could harvest continuously for the full cycle. With an harvesting speed at twice the other two ships, it managed to harvest the entire farm in 185 hours, or nearly 8 days. The vessel used 4 trips, to collect the 776 tonnes of sugar kelp. With the potential capacity of four trips at 800 tonnes, the last trip would result in a vessel not fully loaded. The harvesting cycle for all 40 simulation can be seen in figure 8.4. There are only one curve line visible, given that the weather does not affect the run.

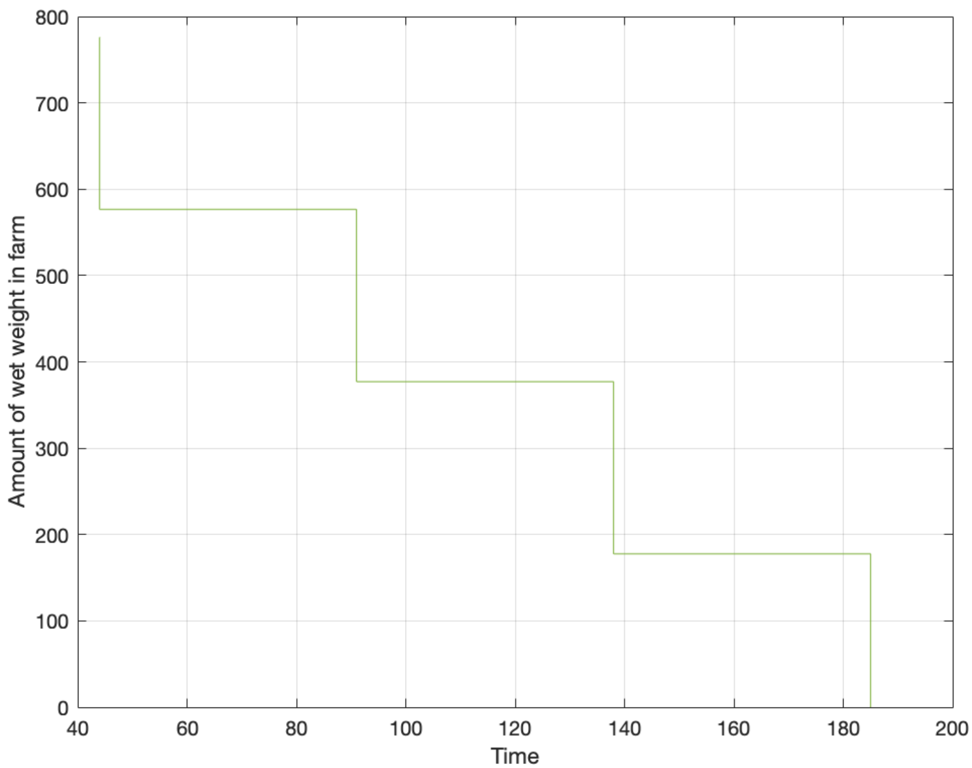


Figure 8.4: Harvesting scenario for 40 simulations, Vessel 3

Chapter 9

Discussion

9.1 Growth

When comparing the results of the growth model to recent studies, the produced amount is consistent within the estimates set for the location. When comparing the produced biomass to the estimates found in Broch et al. (2017, 2019), it is clear that while the location does not have maximum biomass yield, it still have good potential. The location used in this thesis is placed on a fish-farm site, due to available data, and is therefore not technically available for production. However, with the way the model is designed, it is easy to change the input. This means that the model is applicable for every location where data is available.

9.1.1 Integrated Multi-trophic Aquaculture

In the article *"The potential for upscaling kelp (Saccharina latissima) cultivation in salmon-driven integrated multi-trophic aquaculture"*, several estimated productions have been done in close proximity to a fish-farm. The article concludes that the relations between the fish and the kelp can lead to more uptake of nutrients, enhancing the potential growth for the sugar kelp (Fossberg et al., 2018). The accessibility of nitrogen could therefore be increased by utilizing IMTA. On the other hand can this limit the possible biomass production at each location due to limited space in the fjords. While IMTA have not been considered in this thesis, it is clear from the growth-model that increasing the amount of nutrients will increase the production.

The amount of nutrients available for the farm is constant, with the value as mentioned in section 6.3.1, 0.3 mmol/L. This value is higher than the value for optimal growth set by Broch et al. (2017). In this article the nutrient content should exceed 4 mmol/m^3, equivalent to 0.04 mmol/L.

9.1.2 The farm

The farm was, as described in section 3.1.2, decided based on the similar environmental conditions for the area, and the available data, both in terms of sizes and with the estimated production. When looking at the estimated production in Bak et al. (2018), compared to the results in this thesis, there is a slight difference. For the rig in the Faroe Islands multiple partial harvesting have been used, meaning that instead of harvesting the total amount of kelp, it have been cut and allowed to grow back out. From the model in Broch and Slagstad (2012) the specific growth rate depend on the size of the plant, meaning a smaller plant grows faster. By this standard, the plants will have a higher specific growth rate after being cut, and therefore have the potential to produce more biomass.

With the level of biomass in the farm decided at simulation start, there could potentially be more sugar kelp than estimated. This is because the sugar kelp will continue to grow for the duration of the harvesting cycle. From the results in chapter 8 this will be between 8 and 20 days.

Another reason for the difference in biomass could be that the rig from Ocean Rainforest uses vertical lines, instead of horizontal lines, utilizing a larger part of the water column. While this is also usable in Norwegian waters, it is an important factor that the Faroe Islands have especially clear water. This allows the light to penetrate further down the water column allowing production at a deeper level. Along with the clear water, the location in the Faroe Islands have a much higher level of irrandiance, giving a higher level of photosynthesis, again contributing to increased growth. The result from the numeric ocean model, SINMOD, show that the potential at the coast of Norway is higher offshore then closer to the coast. The lights penetrates further down the water column in offshore waters, making the cultivation near shore dependent on the top layers (Broch et al., 2019). This could be another advantage with moving the production further from the coast.

In equation 6.6 the nutrient uptake is calculated. The uptake rate used current speed as an input, and for this thesis, the current speed at 7 meters have been used. Ideally a function of speed over the different levels of the water column should have been used, but here a simplification have been done.

From analysis done by Broch et al. (2017) there are little to no tide in the area. This makes the placement of the farm easier, at the vertical lines does not move with the tide. The farm should therefore be angled with respect to the direction of maximal current, and the mooring system adapted to this. The farm in the Faroe Islands operate at similar depths, and the mooring component should therefore be decided based on the bottom condition, and the total size of the farm.

9.2 Vessels

The model used in van der Molen et al. (2018) suggests that there are an optimal window for harvesting the kelp. This is based on the results that the kelp experiences in the early summer a high growth rate and increased content of carbohydrates. However, along with this growth, mortality are also increasing. This is in line with results from existing farms, but more studies should be done in regards to how much biomass is gained and lost in this period. The important factor do draw from this is that to have an efficient harvest, the vessels and equipment should be optimized for the given location.

The vessels selected for this thesis is based on estimates done by the project *Taredyrkningsfartøy 2020*, and information from the Norwegian company Seaweed Energy Solution AS in regards to the limitations they face. Here, the most important factor is the wave restriction, as this will have the largest influence in the simulation model. It was difficult to select these values for the three vessels, as it would depend on harvesting equipment that does not yet exist. The values selected should therefore not be used as fixed values for the vessel sizes, but more as a guide for further work in this field. The maximum wave-height value could greatly affect the performance for the vessels, as whenever the vessels have to abort the harvesting, time and resources are lost.

The significant wave height was selected as the restriction factor in regards to harvesting. On the other hand, it would be interesting to look at the effect of wind. From correspondence with Seaweed Energy Solution, it was mentioned that the sugar kelp could, with sufficient wind, fall of the lines during harvest. However, this would depending a lot on selected harvesting equipment, and for this thesis the significant wave height was deemed the most important factor.

9.3 Simulation

The most important simplification done in the model is to make it a continuous process. Meaning that the vessels are harvesting 24 hours per day. Initially the model tried to separate the day into shifts, where the vessel only operated during a given time-period. However, this significantly complicated the model, making it less user-friendly, and was not applied to the final version of the simulation. Given that this is a time-critical process it is interesting to see how fast the harvest cycle is for the different vessels. For a vessel with continuous harvest, it would therefor be necessary to hire several shift of workers, making it into a comparison of the cost of operation versus the profit from the end product.

When running the simulation for the three vessels, it became clear that the wave height restriction greatly affected both the waiting time and the amount of interruption in the harvest process.

The first vessel had a maximum wave restriction in the highest state of the probability matrix. This meant that while there are some waves that interrupts the harvesting cycle, it is not likely that the weather will stay bad for longer periods. Depending on the harvested amount before such an interruption, it could be interesting to implement a function comparing the cost of waiting with the loss of not loading the vessel to full capacity. This would therefore be an issue of cost, something that is not considered in this thesis.

Another issue that occurs while waiting is the degradation of the biomass. Depending on the method of storage, the loss of quality could be significantly more important. However for this vessel, the maximum wave requirement is a good fit for the wave-series, given operations at 97 percent capacity.

The second vessel had the lowest limit for the wave restriction, and this was clearly seen in figure 8.2. The vessel operated on average with a load of 70 percent of the total capacity. Along with this, there were long waiting times in regards to start each round-trip. The gate allowing the vessel to pass if the next three hours were bellow criteria was selected as an estimate that the weather could be predicted for this time-period. This also guaranteed a period of harvest before a potential interruption. The length of this interval could be changed based on how long the specific vessels have to harvest before making profit, and with this stopping the vessel from starting a round-trip where it have to return early.

As mentioned in section 8.3 the third vessel were not affected by the weather conditions due to the high maximal wave restriction. This meant that the vessel could harvest uninterrupted, and the round-trip times only depended on the harvest speed and the sailing time.

A recurring trend for the three vessels are the relatively high harvest time for full capacity. With the harvest speed selected in this thesis the uninterrupted round-trip have a harvest period of 17, 43 and 43 hours respectively for the three vessels. The reason vessel 2 and 3 have the same loading time with different capacities, is the assumption that vessel 3 can harvest two lines at the same time. The harvesting time is based on the time estimated for the Macroalgae Cultivation Rig, by Ocean Rainforest, using a semi-automatic process involving both the use of harvesting equipment along with some manual labour. To develop a sustainable industry the first step would be to develop a fully automatic harvest process that can harvest more efficiently than described in this thesis. Estimated values from *Taredyrkningsfartøy 2020* assumed a harvest-speed of 1 m/s using rope, but it is hard to verify if this is possible as no such equipment exist. For the future estimated production by Olafsen et al. (2012) where Noway is producing 20 million tonnes of kelp, the new harvest-method would need to be far superior to the one used in this thesis.

Given the rapid decomposition of the biomass after harvesting, the time before conservation need to be minimized. A solution could be a vessel with the dimensions and limitation as given by Vessel 1, where the harvest speed allowed for 1-2 loads per day. This would mean rapid delivery, and allow for a product of higher quality. The equipment for storing and preserving the sugar kelp on board would also play a significant part in preserving the biomass. For a larger vessel, like vessel 3, the available space on board could provide available room for different preserving methods such as refrigerated sea-water tanks. On the other hand, the different preserving equipment, along with a larger vessel, could turn out more expensive even if the end-product have a higher value.

When selecting the desired vessel, one of the most important factors will be the occupation outside the harvesting period. If not renting the vessel just for the possible 6-8 weeks of harvesting, the vessel should have another occupation. Depending on the vessel size, hull and equipment on board, there are several possible solutions. Both vessel 1 and 2 are similar sizes to service-vessels for the aquaculture industry, and could be applied there. Another possibility is to trawl wild-growing kelp using the crane on board. What type of equipment the vessel have will also play an important part, and it would probably be an advantage if the storage equipment can be easily changed with regards to equipment for other types of operations.

Chapter 10

Conclusion

While there are no doubt that there are potential both in available area and good condition for growth, the most important challenge the industry faces is to make it profitable. There are many steps to achieve this, where the most important ones probably are efficient harvest equipment and maintaining the quality of the harvested biomass. The first step involves automation of equipment, making the process of harvesting both efficient and sustainable for a large industry. There are several ways of maintaining the quality of the harvested biomass. The harvesting cycle could be optimized to minimize the time from harvest to preservation. Depending on the location, with regards to traveling time, smaller vessels could perform several round-trips for a given amount of time for weather-conditions suitable to the limitations. For up-scaled farms, with a longer sailing distance, it could be more profitable using a vessel of greater size. The vessel could handle the tougher weather-conditions and use methods of conservation on board, conserving the quality of the biomass.

From the simulation in Simulink it is clear that vessel 3, the largest, have an advantage given no wave-limitation and twice the harvesting speed. However, given the size of the vessel it will be significantly more expensive to operate per round-trip. While vessel 1 have a longer total harvest cycle, it still operates at near maximum capacity. The harvest cycle of vessel 2 is not much longer than for vessel 1, but the vessel operated at an average capacity of only 70 percent, giving a potential loss in profit.

However, with no values for the cost of operation and vessels, it is not possible to draw definite conclusions from this simulation. Despite this, the model presented is user-friendly for both estimating the potential production and a down-stream harvesting process.

10.1 Further work

To improve the model, the first important aspect would be estimating a more efficient harvest speed. While there are, as of now, no existing equipment that satisfies the needs, new technology can be researched and developed.

There are several ways of improving the simulation in Simulink. Firstly, developing a suitable work schedule, resulting in a more realistic model. Secondly, the conclusion can be improved by estimating expenses and income for the different vessels. This will allow an optimization to be made based on cost, and providing a more accurate selection of vessels.

Appendix A

Matlab script for growth-model

```
%Script for modeling the potential growth

%%%%%%%%%%%%%%%% Constants %%%%%%%%%%%

A0 = 6;  %dm^2 , growth rate adjuststment parameter, used to decide when
    the growth rate drop (relativly small/big plants)
alpha = 3.75*10^(-5); %photosyntetich efficiency
C_min = 0.01;  %minimum carbon reserve
C_struct = 0.2; %amount of carbon per unit dry weight of stuctural mass
gamma = 0.5; %g C /(g sw) , exudation parameter
epsilon = 0.22; % 1/A , frond erosion parameter
I_sat = 200; %irradiance for maximal photosynthesis
J_max = 1.4*10^(-4); %maximal nitrogen uptake rate
k_A = 0.6; %g dm^-2 , structural dry weight per unit area
k_dw = 0.0785; %dry weight to wet weight ratio of structural mass
k_C = 2.1212; %g/(g C) , mass of carbon reserves per gram carbon
k_N = 2.72; %g/(g N) , mass of nitrogen reserves per gram nitrogen
m1 = 0.1085; %growth rate adjustment parameter
m2 = 0.03; %growth rate adjustment parameter
my_max = 0.18; %1/day, maximal area spesific growth ratio
```

```
N_min = 0.01; %g N /(g sw) , minimal nitrogen reserves
N_max = 0.022; %g N /(g sw) , maximal nitrogen reserves
N_struct = 0.01; %g N /(g sw) , amount of nitrogen per unit dry weight of
    structural mass
P1 = 1.22*10^(-3); %g C dm^(-2) h^(-1), maximal photosynthetic rate  at T
    = T^0_P1 K
P2 = 1.44*10^(-3); %g C dm^(-2) h^(-1), maximal photosynthetic rate  at T
    = T^0_P2 K
a1 = 0.85; %photoperiod parameter
a2 = 0.3;  %photoperiod parameter
R1 = 2.785*10^(-4); %g C  dm^(-2) h^(-1), respiration rate at T = T_R1
R2 = 5.429*10^(-4); %g C  dm^(-2) h^(-1), respiration rate at T = T_R2
T_R1 = 285; %kelvin, reference temperature for respiration
T_R2 = 290; %kelvin, reference temperature for respiration
T_AP = 1694.4; %kelvin, arrhenius temperature for photysynthesis
T_APH = 25924; %kelvin, arrhenius temperature for photysynthesis at high
    end of range
T_APL = 27774; %kelvin, arrhenius temperature for photysynthesis at low
    end of range
T_AR = 11033; %kelvin, arrhenius temperature for respiration
U_0_65 = 0.03; %m/s, current speed at which J = 0.65J_max
K_X = 4; %mymol/L , nitrogen uptake half saturation constant
T_P1 = 285; %kelvin, constants for calculating photosynthesis and
    respiration
T_PL = 271; %kelvin, temperatures for the extrame range photosyntesis
T_PH = 296; %kelvin, temperatures for the extrame range photosyntesis

%%%%%%%variables from EXPOSED%%%%%%%%%%%%%
U = full(table2array(rawSeawatchExp1(4915:11319,26))); %current speed at 7
    m, cm/s
```

```
U = U * 0.01;   %changing from cm/s to m/s
T = full(table2array(rawSeawatchExp1(4915:11319,57))); %temperature at 1 m
S = full(table2array(rawSeawatchExp1(4915:11319,55)));  %level of salinity

t = 1:6240;  %length of run

%%%%%initilizing zero matrixes for variables%%%%%%%
derA = zeros(1,length(t)); %rate of change in frond area
my = zeros(1,length(t));  %growth rate
v = zeros(1,length(t));  %frond erosion
f_area = zeros(1,length(t)); %effect of size on growth rate
A = zeros(1,length(t));  %frond area
derC = zeros(1,length(t));  %rate of change carbon reserve
derN = zeros(1,length(t)); %rate of change nitrogen reserve
C = zeros(1,length(t));  %carbon reserve
N = zeros(1,length(t));  %nitrogen reserve
J = zeros(1,length(t));  %nutrient uptake rate
E = zeros(1,length(t));  %exudation rate
R = zeros(1,length(t));  %respiration rate
P_max = zeros(1,length(t)); %maximal photosynthesis rate
beta = zeros(1,length(t));  %variable realated to light inhibition
P_S = zeros(1,length(t));  %variable for calculating photosynthesis
P = zeros(1,length(t));   %gross photosynthesis
I = zeros(1,length(t));   %irradiance
beta_temp = zeros(1,9);  %used in iteration to calculate beta

%%%%%setting initial values%%%%%%%
A(1) = 0.1; %setting start value as the initial value
N(1) = 0.022; %setting starting value for N
C(1) = 0.6; %setting starting value for C
```

```
X =  0.3;  %substrate nutrient consentration

%irradiance
for i = 1:length(t)
    if i >= 1 && i < 690
        I(i) = 57.9;
    elseif i >= 690 && i < 1380
        I(i) = 23.1;
    elseif i >= 1380 && i < 2070
        I(i) = 9.2;
    elseif i >= 2070 && i < 2760
        I(i) = 8.1;
    elseif i >= 2760 && i < 3450
        I(i) = 11.5;
    elseif i >= 3450 && i < 4140
        I(i) = 34.7;
    elseif i >= 4140 && i < 4830
        I(i) = 69.4;
    elseif i >= 4830 && i < 5520
        I(i) = 81;
    elseif i >= 5520 && i <= 6240
        I(i) = 127;

    end
end

%%%%%%%%matrixes for variables not dependent on time%%%%%%%%
f_photo = effect_of_daylight(T);
f_temp = effect_of_temp(T);
f_salinity = effect_of_salinity(S);
```

```
%%%%%%%%%setting inital values%%%%%%%%%%%%%%%
f_area(1) = effect_of_size(A(1), A0, m1, m2);
v(1) = frondLoss (A(1), epsilon); %frond loss
my(1) = spesificGrowthRate (f_area(1), f_photo(1), f_temp(1), f_salinity
    (1), N_min, N(1), C_min, C(1));
J(1) = nitrateUptakeRate ( N(1), U(1), J_max, X, U_0_65, N_min, N_max, K_X
    );
R(1)= tempDepRes (T(1), R1, T_AR, T_R1);
P_max(1) = maxPhotoRate (P1, T_AP, T(1), T_P1, T_APL, T_APH, T_PH, T_PL);
E(1) = carbonExudation(gamma, C_min, C(1));

%%%%%%%%%%%%%
for i = 2:length(t)

    %nitrogen
    derN(i) = 1/k_A*J(i-1) - my(i-1)*(N(i-1) + N_struct);
    N(i) = N(i-1) + derN(i);
    J(i) = J_max*X/(K_X + X) * (N_max - N(i))/(N_max - N_min) * (1 - exp(-
        U(i)/U_0_65));


    %carbon
    P_max(i) = (P1 * exp((T_AP/T_P1)-(T_AP/(T(i)+ 274.15))))/(1 + exp((
        T_APL/(T(i)+ 274.15))-(T_APL/T_PL)) + exp((T_APH/T_PH)-(T_APH/(T(i)
        + 274.15))));

            %making an iteration loop to decide beta
        for j = 1:10
            if j == 1
```

```
                beta_temp(j) = 1*10^(-9);  %initial value
            end

            beta_temp(j+1) = beta_temp(j) - ( ((I_sat*alpha)/(log(1+alpha/beta_temp(j)))...
                * (alpha/(alpha+beta_temp(j)))  * (beta_temp(j)/(alpha + beta_temp(j)))^(beta_temp(j)/alpha) - P_max(i)))...
                / ((alpha*I_sat *   (beta_temp(j)/(alpha + beta_temp(j)))^(beta_temp(j)/alpha - 1)  *...
               (alpha^2 - beta_temp(j)*(alpha + beta_temp(j))*(log(beta_temp(j)/(alpha + beta_temp(j))))^2 )  )     ...
            / ((alpha+beta_temp(j))^3*(log((alpha + beta_temp(j))/beta_temp(j)))^2));

        end

    beta(i) =    beta_temp(9);
    P_S(i) = (alpha*I_sat)/(log(1 + alpha/beta(i)));
    P(i) = P_S(i)* (1 - exp((-alpha*I(i))/(P_S(i))))* exp ((-beta(i)*I(i))/(P_S(i)));
    E(i) = 1 - exp(gamma * (C_min - C(i-1)));
    R(i) = R1* exp((T_AR/T_R1)-(T_AR/(T(i)+ 274.15)));

    derC (i) = 1/k_A* (P(i)*(1-E(i))-R(i)) - my(i-1)*(C(i-1)+C_struct);
    C(i) = C(i-1) + derC (i);

    %frond area
    derA(i) = ((my(i-1)-v(i-1)) * A(i-1));
    A(i) = A(i-1) + (derA(i));
    f_area(i) = effect_of_size(A(i), A0, m1, m2);
```

```
    v(i) = frondLoss (A(i), epsilon);
    my(i) = spesificGrowthRate (f_area(i), f_photo(i), f_temp(i), f_salinity(i), N_min, N(i), C_min, C(i));
end

% the following weights are in grams:

W_s = k_A * A(length(t));%structural weight W_s
W_d = k_A * ( 1 + k_N*(N(length(t)) - N_min) + N_min + k_C*(C(length(t)) - C_min) + C_min) * A(length(t)); %dry weight W_d
W_w = k_A * ( 1/k_dw + k_N*(N(length(t)) - N_min) + N_min + k_C*(C(length(t)) - C_min) + C_min) * A(length(t)); %wet weight W_w

C_total = (C(length(t)) + C_struct) * W_s; %total carbon
N_total = (N(length(t)) + N_struct) * W_s; %total nitrogen


%plotting the frond area
plot(A,'g','LineWidth',2)
xlabel('Time')
ylabel('Frond size [dm^2]')
title('Growth potential')
grid on
```

Appendix B

Simulation script

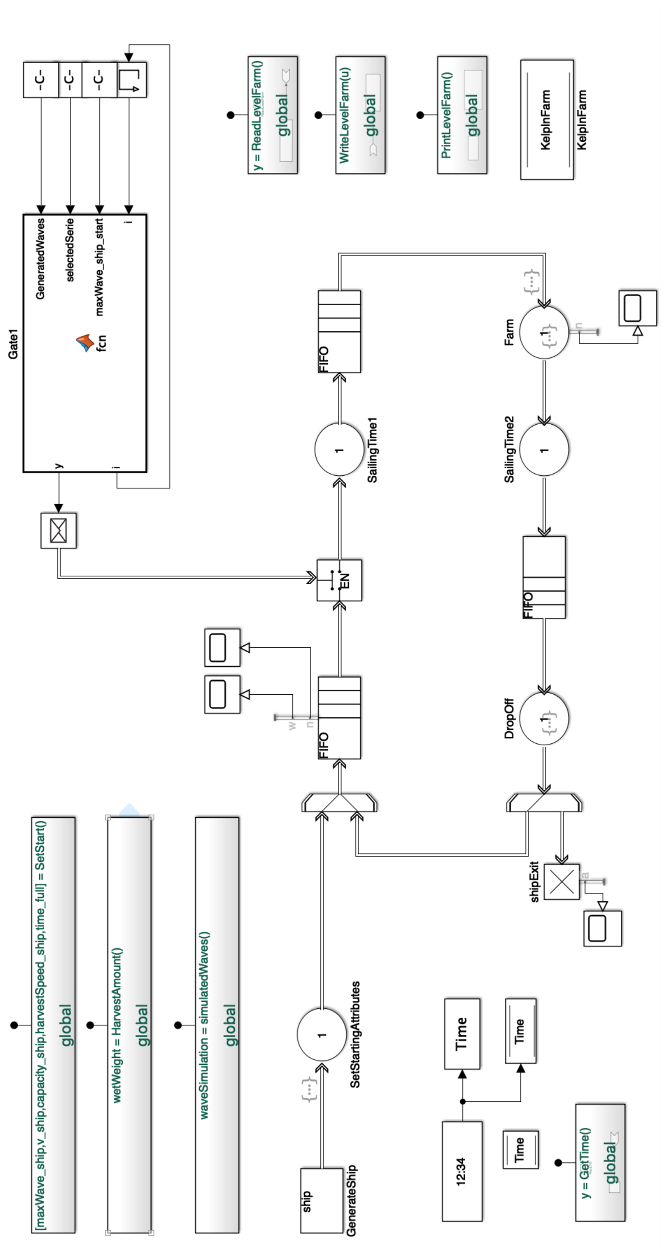
```
%Script used for running simulation from Matlab

k = 40; %number of simulations
number_of_rigs = 10; %number of rigs in model

growth;   %running growth model
W_w_per_system = W_w * 500000 * 0.001; %wet weight per system [kg]
totalW_w = W_w_per_system * 0.001 * number_of_rigs; %calculating total wet
     weight [tonnes]


%running through the number of simulation
for i = 1:k
    tic

GeneratedWaves;  %loading matrix of generated wave heights
selectedSerie = i;   %selecting wave serie
lengthGeneratedWaves = length(GeneratedWaves(selectedSerie,:));

%deciding which vessel to utilize
```

```
vessel = 1 ; % 1 2 3
if vessel == 1;   %values for the first vessel
    maxWave_ship_start = 1.5 ; %meter
    v_ship_start = 16.66 ;   %km/h
    capacity_ship_start = 40 ;  %tonnes
    harvestSpeed_ship_start = 2.32; %tonnes per hour
    full_vessel_time = 17;  %hours
elseif vessel == 2    %values for the second vessel
    maxWave_ship_start = 1 ; %meter
    v_ship_start = 16.66 ;   %km/h
    capacity_ship_start = 100 ;  %tommes
    harvestSpeed_ship_start = 2.32; %tonnes per hour
    full_vessel_time = 43;  %hours
else                    %values for the third vessel
    maxWave_ship_start = 2.5 ; %meter
    v_ship_start = 16.66 ;   %km/h
    capacity_ship_start = 200 ; %tonnes
    harvestSpeed_ship_start = 2 * 2.32; %tonnes per hour
    full_vessel_time = 43;  %hours
end

%loading the simulation model, avoiding opening it
load_system('MasterReal');
%run the simulation
sim('MasterReal');

%plotting the harvested sugar kelp over time
plot(Farm.Time, Farm.Data(:,1))
xlabel('Time')
ylabel('Amount of wet weight in farm')
```

```
grid on
hold on

end
```

Appendix C

Simulink model


Gate1
GeneratedWaves
selectedSerie
maxWave_ship_start
fcn
y = ReadLevelFarm()
global
WriteLevelFarm(u)
global
PrintLevelFarm()
global
KelpInFarm
KelpInFarm
FIFO
SailingTime1
Farm
SailingTime2
FIFO
DropOff
FIFO
shipExit
[maxWave_ship,v_ship,capacity_ship,harvestSpeed_ship,time_full] = SetStart()
global
wetWeight = HarvestAmount()
global
waveSimulation = simulatedWaves()
global
SetStartingAttributes
ship
GenerateShip
Time
Time
12:34
Time
y = GetTime()
global

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