Exploring Mechanisms for Harvesting of Farmed Seaweed

by

Ali Badr

Submitted to the
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ABSTRACT

In this thesis, I explore different harvesting mechanisms for farmed seaweed off of a line. The seaweed market is large and growing globally, and currently relies heavily on manual labor and coastal waters for the farming process. The main goals of the designed mechanisms are to achieve a simple, reliable system that can be implemented on seaweed farms and allow off-shore farming as well as increase overall efficiency by reducing the reliance on manual labor. Alongside a colleague, we designed and built three iterations of the mechanism and I propose a fourth design that we will be exploring in the future. The three designs center around different actuation and cutting methods. The first design uses a ski lift actuation method and a circular saw blade as the cutting instrument. The second design uses the same cutting method but a spool method for actuation (described in more detail in paper). The third design uses a suction method for cutting and has multiple actuation methods. The designed mechanisms are then tested with live seaweed. By comparing the results of these tests and evaluating each design across a few metrics that we learned by speaking to seaweed farmers and throughout the process of building the mechanisms, I propose a fourth theoretical design that aims to improve on all previous designs and meet the proposed design requirements.

Thesis Supervisor: Ahmed Ghoniem
Title: Professor of Mechanical Engineering

ACHKNOWLEDGEMENTS

I would like to thank my colleague, Chris Goul, for working on this project with me and for creating an environment where we always push each other to achieve more. I would also like to thank the Dan and Greg Martino, who always helped with any seaweed farming related questions we had and provided us with the live seaweed to do our tests. Finally, I would like to thank my thesis advisor, Dr. Ghoniem, for guidance throughout the process and pointing me towards resources that were extremely useful throughout the design and testing process.

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Chapter 1

The Problem

In recent years, the demand for seaweed has been growing due to its widespread use in the manufacture of hydrocolloids, in animal feed, and for human consumption. There are also many potential applications of seaweed such as biofuel generation and alginate-based building materials[1]. Due to the large amounts of manual labor required in the farming process, the only way for farmers and suppliers to meet this increase in demand is to hire more seasonal workers (the harvest season is mainly during the winter months). This heavy reliance on manual labor means that most farms are started and operate in areas with cheap labor prices. This is why the leading producers of cultivated seaweed are found in Asia (namely China, Indonesia, South Korea, Japan and Phillipines)[2] However, virtually all available farm locations in China and Japan (which dominate the seaweed production market) have been taken, as they require shallow coastal waters. Additionally, due to the reliance on manual labor, the farms have larger overall production times and smaller margins. Upon analysis of many different seaweed farms and their different cost structures, it is quite clear that labor accounts negate a large portion of farm revenues, with labor costs ranging from 20-61% of the overall farm revenue.[3] The lack of mechanization and automation in this industry also prevents farms from reaching true economies of scale, keeping overall costs high and their margins low.

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[1] "Seaweed.Ie :: Uses and Utilization," accessed April 23, 2019, http://www.seaweed.ie/uses_general/.

[2] "The Global Status of Seaweed Production, Trade and Utilization - Volume 124 | GLOBEFISH | Food and Agriculture Organization of the United Nations," accessed April 23, 2019, http://www.fao.org/in-action/globefish/publications/details-publication/en/c/1154074/.

[3] Sander W. K. van den Burg et al., "The Economic Feasibility of Seaweed Production in the North Sea," *Aquaculture Economics & Management* 20, no. 3 (July 2, 2016): 235–52, https://doi.org/10.1080/13657305.2016.1177859.

1.1 Current Farm Designs

Many different commercial farm designs exist and they vary factors such as size, method of harvesting, method of anchoring, location of seaweed relative to ocean floor, and many other aspects. The three most common farm designs are the off-bottom, floating raft, and floating line design. The off-bottom and floating raft design can be seen in Figure 1-1 below. The floating line design is extremely similar to the floating raft except that each individual line that has seaweed growing on it has a separate anchor and buoy to keep it anchored and floating near the surface of the water.

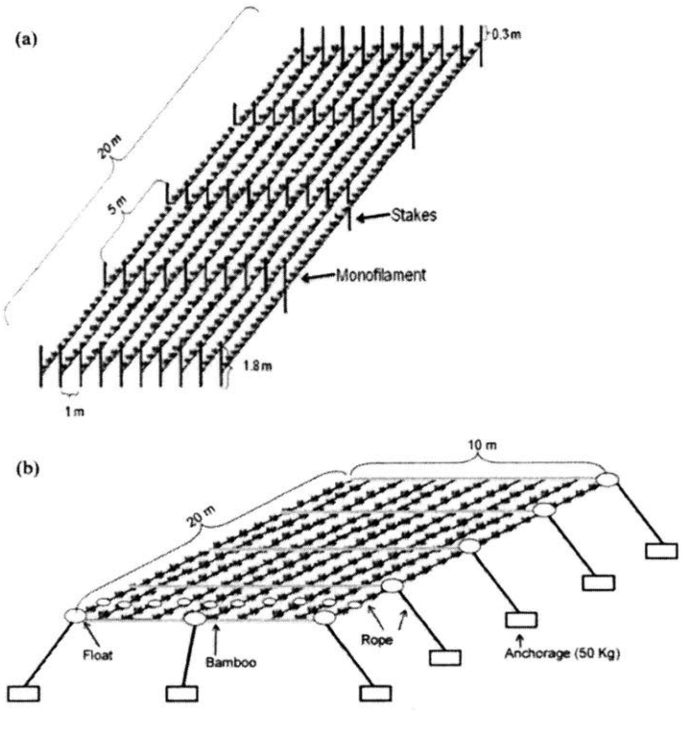

Figure 1-1: (a) shows the off bottom design where the lines with the spores and seaweed are held to the ocean floor by stakes or some other anchoring system. (b) shows the floating raft system where the seaweed is growing on a line at the surface of the water and is held together by a raft

made of a floating material (in this case, bamboo) and the raft is then anchored at the ends by several weights.[4]

Analyzing these three farm designs alone shows varying levels of productivity and economic efficiency depending on the location of the farm, who is running it, and the method of harvesting that is used. Many studies have analyzed the economic efficiency of these farming systems and some of the results of these studies are shown in Figure 1-2 below. This figure shows a large spread of efficiencies depending on the type of farm but also on the overall size of the farm and the lifespan of that given farm design.

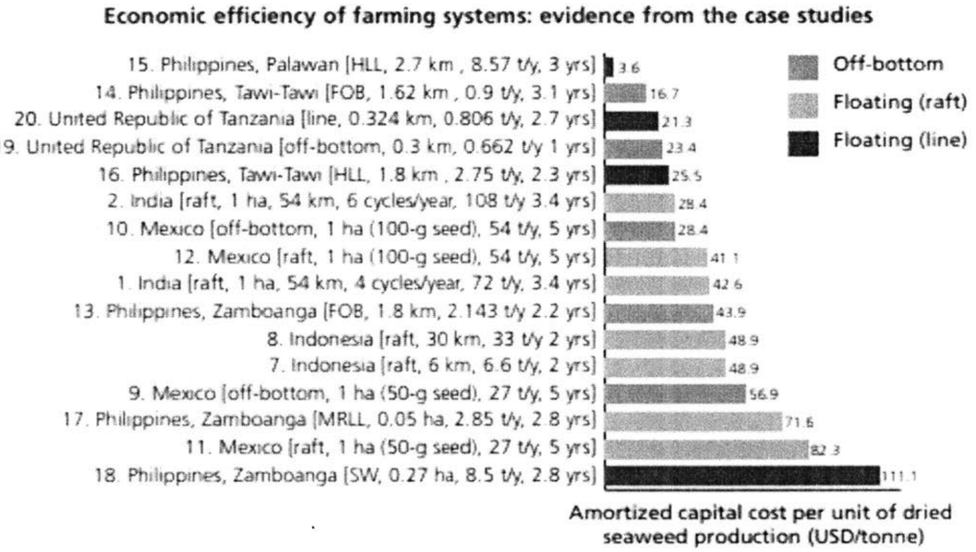

Figure 1-2: Economic efficiency here is defined by the amortized capital cost per unit of seaweed production to account for trade-offs between the productivity of a farming system (how much it produces per unit hectare) and the amortized capital cost. The labels on the y axis indicate the location of the farm, the length of the cultivated lines in km, the tonnes/year produced (t/y), and the lifespan of that farming system.[5]

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[4] Diego Valderrama et al., "The Economics of Kappaphycus Seaweed Cultivation in Developing Countries: A Comparative Analysis of Farming Systems," *Aquaculture Economics & Management* 19 (May 11, 2015): 251–77, https://doi.org/10.1080/13657305.2015.1024348.

[5] Flower Msuya, "Social and Economic Dimensions of Carrageenan Seaweed Farming in the United Republic of Tanzania," 2013.

The floating line design clearly has extremely high efficiency, which can be seen by the three red lines at the top of the graph with very low amortized capital cost per unit of dried seaweed production. The off-bottom systems analyzed from Mexico and the Philippines also perform quite well. It is interesting to see that in the Philippines, the same floating line design in two different implementations (and locations) results in both the best and the worst economic efficiency. Overall, the evidence from this figure as well as the rest of the paper analyzing farm designs indicated that the floating line design was very efficient. After conducting some user interviews here in the US on the types of farm designs used and learning that most farmers also use a floating line design, we chose to design a harvesting mechanism for the floating line farm design.

1.2 Current Methods of Harvesting

Within the realm of floating line farm designs, most farmers harvest seaweed using rakes, scythes or other sharp blades to remove the seaweed from the line. The commercial seaweed farming industry has not seen innovation in harvesting technologies for decades, and any new ideas are rare and often small upgrades from the original method. This traditional method of harvesting can be seen in the top picture of Figure 1-3 below.[6,7]A modern implementation that still requires manual cutting of the seaweed off of the line can also be seen below.

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[6] "Seaweed: The next Big Step for Irish Food and Farming?," accessed April 23, 2019, https://www.irishtimes.com/life-and-style/food-and-drink/seaweed-the-next-big-step-for-irish-food-and-farming-1.2859853.

[7] "What You Need to Know about South Korea's Seaweed Farms," MNN - Mother Nature Network, accessed April 23, 2019, https://www.mnn.com/your-home/organic-farming-gardening/blogs/what-you-need-to-know-about-south-koreas-seaweed-farms.

Figure 1-3: This figure shows two different methods used to harvest seaweed. In the top picture, the person harvesting the seaweed manually removes the line from the water to cut off pieces from the line and deposit them on their vessel. In the bottom picture, the line is held up by the boat, and the person is only in charge of removing the seaweed from the line.

While both harvesting systems require the farmer to physically cut the seaweed off of the line, the more modern version shown in the lower picture eliminates the time needed for farmers to raise the line above the surface of the water and allows them to more quickly move down the length of the line while cutting the seaweed. This minor adjustment alone results in higher levels of efficiency and many commercial farms use this harvesting method. However, while this system is slightly more optimized than the default one that has been used since the dawn of seaweed farming, it still has major areas of improvement. Replacing the farmer with an autonomous system that can cut the seaweed off the line will allow for scalability while under the management of fewer people. Such a system would trade off the initial higher capital cost to build the system and get it started for higher levels of productivity, efficiency and scalability in the long run. Furthermore, such a system would allow for farms to exist further offshore because, increasing potential farming land for the industry.

1.3 Harvesting designs from related industries

The two main industries that farm in similar ways to seaweed are the mussel and oyster industries. Both industries rely on farm setups revolved around a line in water that the aquaculture product then grows around. However, the commercial harvesting systems that are used for oysters cannot be applied for seaweed because although the oyster grows off of a line, it grows in bundles or nets so the harvesting process comprises mostly of emptying those containers that are submerged in the water onto a processing line that then cleans and processes the oyster depending on its final destination. While mussel farming also uses a similar harvesting and processing system as oyster farming, an interesting design concept can be learned from their anchoring system. Figure 1-4 below shows a diagram of a surface longline mussel farm[8]. To maximize the efficiency of this farm setup, the droppers (lines that the mussel actually grows on) hang from the backbone (the main rope that can be seen on the surface). The mussel longline attaches on one side and then loops again to the other side of the backbone. This allows a much production line to be farmed using a shorter backbone (supporting rope). However, because the mussel production lines grow vertically while seaweed lines are typically horizontal (because of many factors such as the buoyancy of seaweed as well as the required sunshine for their growth), this looping is not possible with a seaweed farm design. Nevertheless, analyzing this farm design did

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[8] Nils Goseberg et al., "Technological Approaches to Longline- and Cage-Based Aquaculture in Open Ocean Environments," in *Aquaculture Perspective of Multi-Use Sites in the Open Ocean*, ed. Bela H. Buck and Richard Langan (Cham: Springer International Publishing, 2017), 71–95, https://doi.org/10.1007/978-3-319-51159-7_3.

lead to an alternative buoy and anchoring design that would make harvesting seaweed easier.

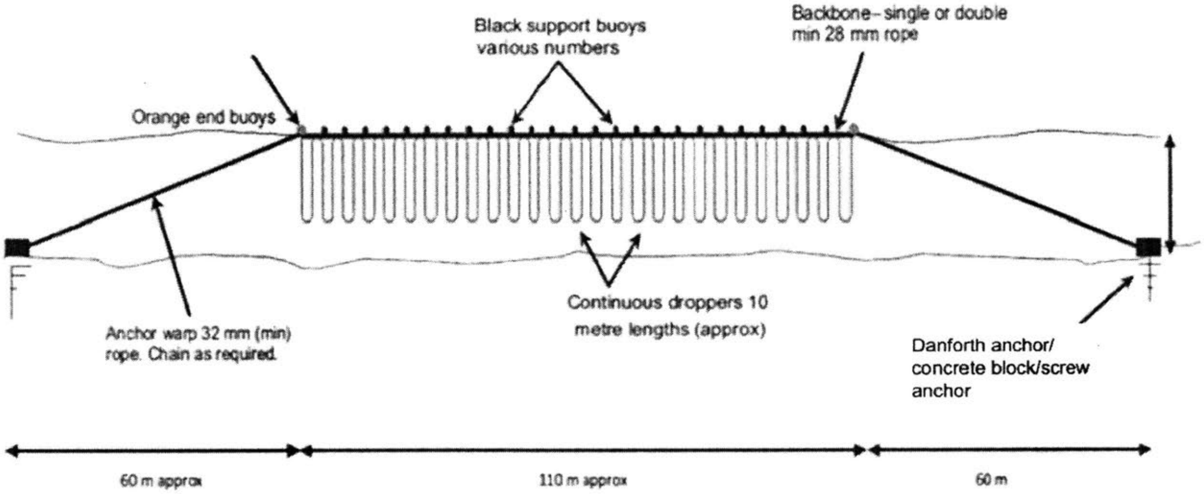

Figure 1-4: The diagram above shows a cross section of a surface longline mussel farm. The main components of this farm are the anchor, the "backbone" which is comprised of rope that the mussel lines loop around for maximum efficiency of materials and space, and the buoys (the large orange buoys at the end and the support buoys in the middle).

A major problem with many of the attempts at automating the seaweed harvesting process is the interference of buoys with the designed mechanism. Buoys are an integral part of the line because they keep the line at a fixed distance from the surface, ensuring that the seaweed is exposed to sunlight. However, since the buoy is in series with the rope and the seaweed growing on the line, any proposed mechanized solution would have to interact with the buoy and make sure not to damage it. The design shown above in Figure 1-4 employs two different kinds of buoys. There are large orange buoys at either end of the line and then smaller support buoys throughout the line. A similar concept can be applied to a seaweed farm. In this case, large buoys can be placed at either end of the line, and then smaller buoys can be laid out along the line but in parallel with the remainder of the setup. A sketch of this farm design can be seen in Figure 1-5 below. The main advantage of this farm design over current the current design where the buoy is in series with the growing line is the simplification of the buoy-harvester interaction. This farm setup change will allow any harvesting mechanism to run down/operate on the line without interfering with the buoys.

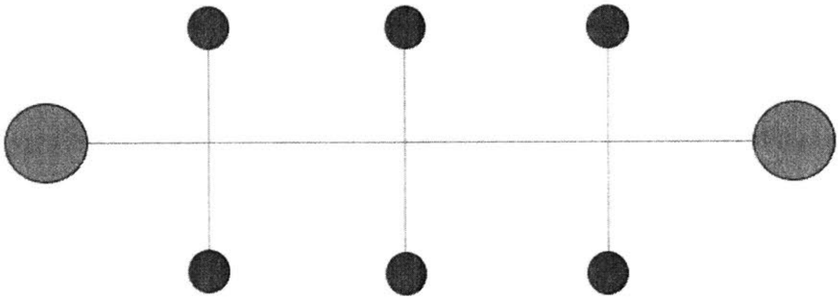

Figure 1-5: In this farm design, the orange circles represent the large buoys at each end of the line. The blue circles represent smaller buoys that are placed in parallel with the growing line (in green here). This prevents the buoys from interfering with any potential harvesting mechanism that runs down the line.

1.4 Patent research

There have been dozens of thousands of patents issued covering the seaweed industry and every aspect of the process, such as cultivation, seeding, harvesting, etc. Most of the patents that are issued regarding seaweed harvesting or devices that accomplish that task come from Asian countries such as Japan, China and Korea. Furthermore, most of these patents lack a real design process or a functioning design to accomplish the task. For example, Figure 1-6 below shows a figure of the design presented in a patent for a seaweed farming system coming from Bangalore, India.[9] The general design concept is that of an assembly line where the growing line moves down this assembly process while being harvested and reseeded. However, the design and patent never discuss the specifics of how these mechanisms operate and the imagery of the design lacks a lot of the details associated with a farm setup such as the buoys, the anchors, how the system is constrained, moved, etc.

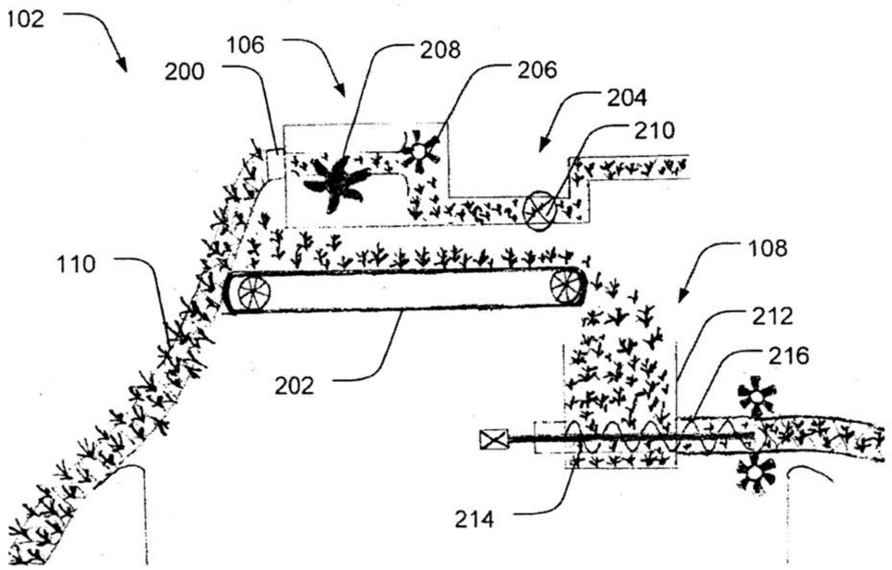

Figure 1-6: This is the figure presented in the patent of their design of a seaweed farming system.

One of the Chinese patents that I analyzed presented another interesting variation of the farm setup. While the intent of the patent was to cover a seaweed farming boat design, the farm design portrayed could actually pair well with the design from Figure 1-5 to reduce initial capital costs further and require less buoys and

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[9] Nitish KATI et al., Seaweed farming system, United States US20160219811A1, filed September 12, 2014, and issued August 4, 2016, https://patents.google.com/patent/US20160219811A1/en?q=seaweed&q=farming&oq=seaweed+farming.

unused lines overall for higher margins and a more compact design. This farm design is shown in Figure 1-7 below.[10]

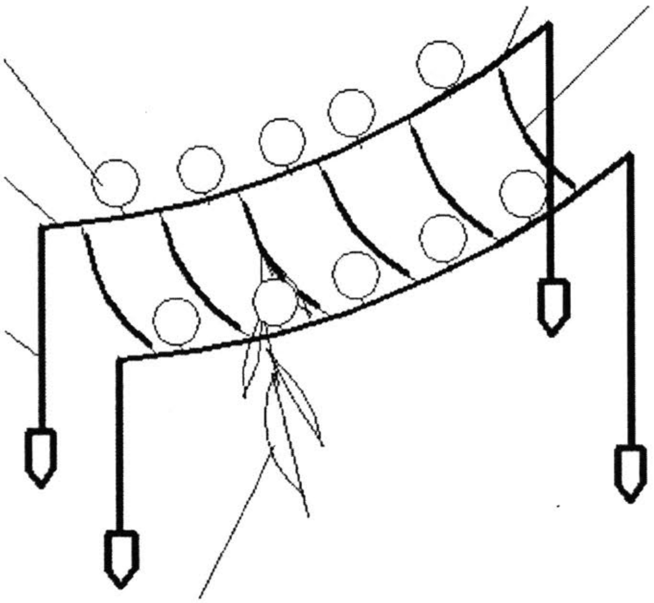

Figure 1-7: This farm design would provide the benefits of a parallel buoy system similar to Figure 1-5 while requiring less buoys/line by connecting all the lines together and then anchoring at the ends of each set of lines.

While the actual harvesting system discussed in the patent presents many design problems that are hard to overlook, the suggested farm design is quite clever when compared with current industry standards. Currently, each growing line is independent and has its own buoys/anchors, which means that the number of buoys and anchors used per line is quite high, increasing costs. A farm design like the one above would limit the number of buoys necessary and share them across multiple lines, meaning the design is much more economically efficient.

The final patent that presented another unique design came from Japan and presented a suction pump seaweed harvester. This design inspired the V3 design that is talked about in the next chapter. While the full patent is not actually shown

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[10] "CN103477796B.Pdf," accessed May 11, 2019, https://patentimages.storage.googleapis.com/0a/11/41/02f95b56a61679/CN103477796B.pdf.

online and neither is any of the associated imagery, the online translation of the patent discusses the use of a pump that uses suction to remove the seaweed from a farmed line by sucking in the seawater and seaweed and pumping it into a collecting area on the boat.[11] While this mechanism is very unique and presents a different approach to harvesting seaweed compared to the other used mechanisms, the system still relies heavily on a diver (manual labor) to aim and guide the suction valve to remove the seaweed from the line. In version three, we attempt to use similar fundamental principles but remove the manual labor necessary to guide it down the line.

1.5 Design Requirements

As we set out to answer the problem of a lack of automation in the industry, my colleague and I performed many user interviews with seaweed farmers across the nation to attempt to really understand what their farming experience is like and to better understand the design requirements of the mechanism we had set out to build. We asked them as many questions as possible such as their farm design, the species they were cultivating, their method of harvesting, the rates at which they harvest, the times at which they harvested, the economics behind their business, and also what they personally struggled with the most throughout their time farming seaweed. From these discussions and our own vision of what we want the mechanism to be capable of, we set out 5 design criteria: complexity, economic feasibility, scalability, usability and the level of autonomy of the design. A successful design would perform well in each metric.

The complexity design criterion is a measure of how feasible the design actually is when built for the open ocean and how complicated the design was to

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[11] 牧権六, 海苔採取装置, JPH0621304Y2, filed April 11, 1991, and issued June 8, 1994, https://patents.google.com/patent/JPH0621304Y2/en?q=seaweed&q=harvesting&oq=seaweed+harvesting.

implement. The economic feasibility criterion measures how economically viable the design would be when scaled to current commercial farm sizes and how much of a cost reduction farms would see upon implementing the technology. The scalability metric measures how the actual technology would scale to a full-size commercial farm and beyond. For example, as you will see below, the first version required major changes to the farm setup and would have been extremely difficult to scale to farm sizes in the dozens of hectares. Usability is a measure of how easily a farmer can use the technology with their current farm design or how much a farmer would have to change to learn to use and implement the technology. It also looks at if the technology provides all of the needed features that farmers require. A large factor that we had not considered until doing the user interviews was that some farmers chose to trim the growing lines every short period of time while other farmers would leave the seaweed out for a full cycle and fully clear the line when they performed the harvest. Any successful solution would have to allow for both options without too much of a hassle. The level of autonomy simply measures how much the technology has improved efficiencies in terms of labor hours needed to manage a farm.

Ultimately, our discussions with farmers also confirmed our initial goal to design a system that would be capable of both harvesting and growing (seeding) at the same time to result in even more efficiencies. For every one of the design iterations below, there is a growing system that integrates with the harvesting side to perform both at the same time. However, for the sake of this thesis, I will be analyzing only the different harvesting mechanisms and the optimal design from a harvesting standpoint.

Chapter 2

Design Iterations

2.1 Version One

After deciding that the mechanical system we are designing is for floating line farms setups, the design of the actual system was underway. The first version that was built, shown in Figure 1-9 below, works similar to a ski lift, where the farm is comprised of many ovular floating lines that are rotated by this wooden star that is connected to a rotating shaft powered by a motor. As the line is rotated, the seaweed at a certain height from the line can be cut off the line and stored. The whole design is meant to be attached to a floating system (such as a boat) that can be driven around the farm to harvest each set of lines. In this case, the only interaction that the farmer would have with the line is that they would need to initially place the line of seaweed on the pulleys shown in the figure and in the notched gaps in the wooden star. After the seaweed is cut, it can either be deposited on the boat where the mechanism is or in a net in the water which can be tied up after and dragged back to shore. Before the design was completed, an analysis of the required motor power necessary to rotate the line was performed. In this case, the motor had to overcome the drag force that worked against the direction the seaweed is being rotated in.

$$R = \frac{1}{2}pCAv^2$$

The equation above can be derived from Bernoulli's equation for pressure in a fluid and the definition of a pressure as force per area. In this equation, R denotes the drag force, p is the density of the fluid, C is the coefficient of drag, A is the area (which I limited to the cross-sectional area of the seaweed for my analysis) and v which is the speed.

$$P = F * v = R * v = \frac{1}{2} pCAv^3$$

To get to power from the drag force, I simply multiplied by the velocity again, resulting in a relationship that scales with the velocity cubed. Due to the largely changing value of P depending on the v, my colleague and I decided to look at the power requirements for a rotation velocity of 1 m/s. A plot of the power required for the area of the seaweed is shown in Figure 2-1 below.

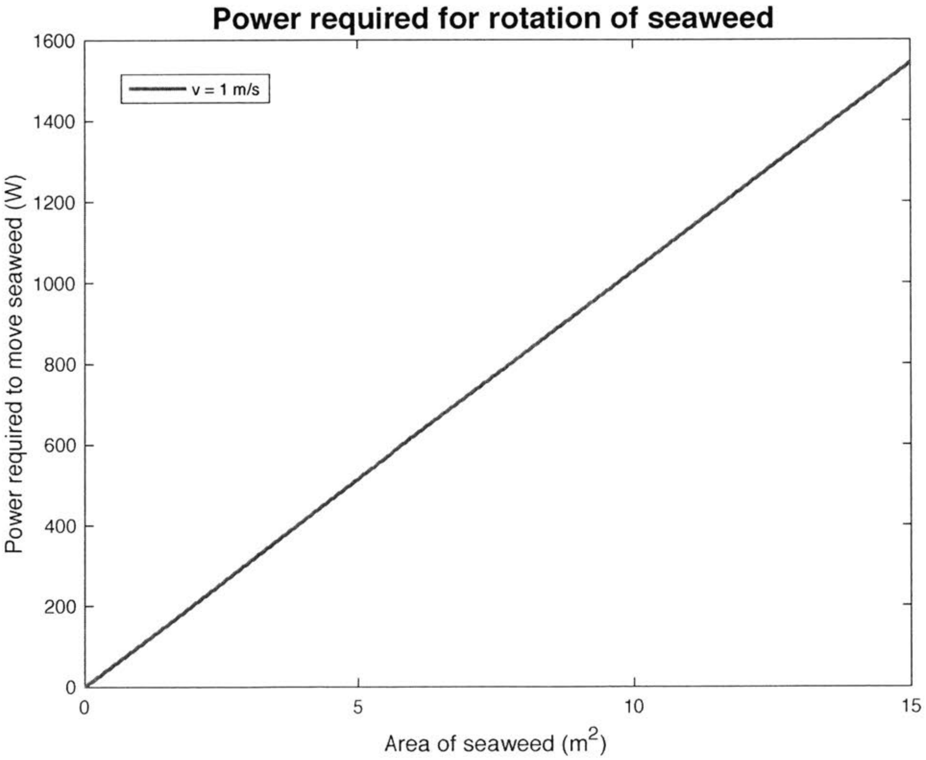

Figure 2-1: The plot above shows the power required for rotation of seaweed in W relative to the frontal area of the seaweed in m^2.

The area is highly variant depending on the species of seaweed being cultivated, with some species growing up to 30m long (giant kelp) and some growing to only a few centimeters. However, for the sake of testing, we concerned ourselves with seaweed that would be readily available in the New England area, which was typically under the 5 m^2 range. Therefore, as shown by the graph, this meant that our power requirement was under 500W.

After doing this basic analysis, we built a model of the design using a CAD software. Looking at Figure 2-2 below, this floating line setup is quite different from some of the other floating lines shown in Figure 1-3 and even Figure 1-1. In our version, there are two lines that are connected by a piece of metal. The line on top is used to actuate and move the entire line and also connect to a buoy, whereas the bottom line has the spore line and the actual seaweed on it. If only one line was used, the harvesting mechanism would interfere with the buoys and the seaweed growing on the line would also interfere with how the line is actuated.

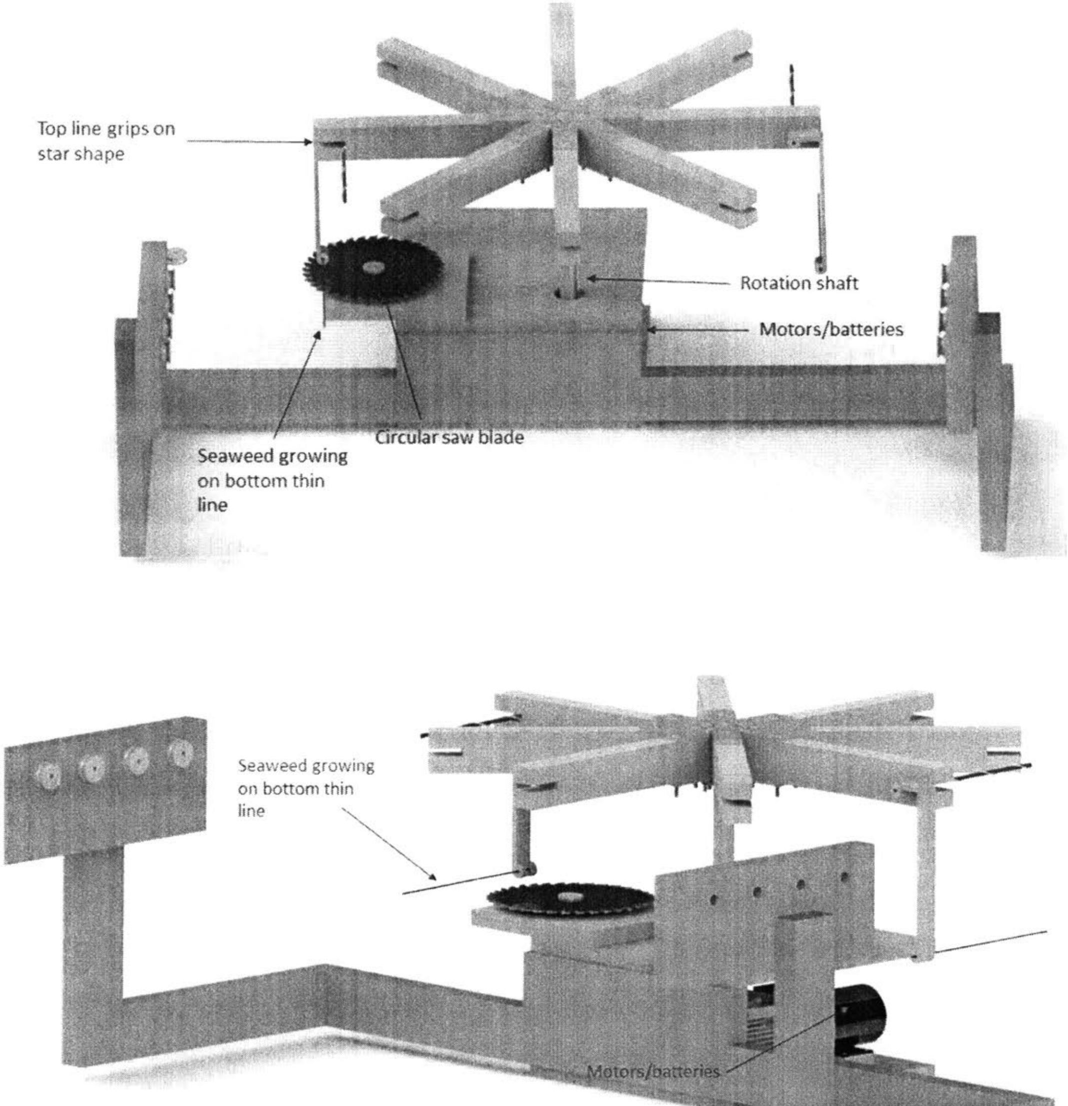

Figure 2-2: This figure shows the first version of the harvesting mechanism, which we called the ski lift design. The seaweed grows on the labeled thin line that is then connected via this metal connection to another line at the top that is actuated by the rotating system. The circular saw blade cuts the seaweed at a specified length and deposits it into a net or on the boat.

The physical version of this design is shown in Figure 2-3 below. After building this iteration and testing it with a very short line, we immediately realized some of the flaws of the design. We were unable to actually test the cutting mechanism in this iteration because of the lack of tension while the shaft was rotating. In its ideal implementation, there would be two of these mechanisms, one on each side of the farm. In our physical tests, we attempted to maintain tension using various methods ranging from people actually pulling on the line to having something on the other side serving as a pulley for the line.

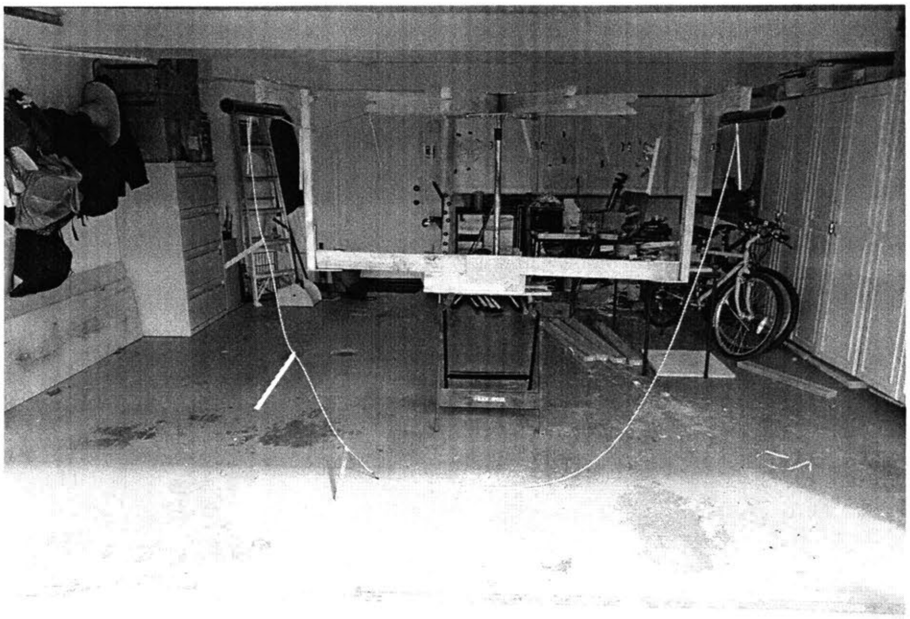

Figure 2-3: This figure shows the physical implementation of Figure 2-2.

The lack of tension meant that the line was very loose in certain areas and that the cutting mechanism would not cut at the correct height and could potentially even cut into the line if there was enough slack. This lack of tension would be further exaggerated if the system was to be tested in the water where nothing is actually stationary as in the land case, making the lack of tension extreme even more disastrous. After some time modifying the design (such as the black PVC pipes in Figure 2-3 above that aimed to straighten the incoming line so that it caught onto the gaps in the wooden star), we decided to move on to the next version.

2.2 Version Two

This second version, shown below in Figure 2-4, used the same rotating shaft design and motor as the first version described above. This meant that the same underlying motor power analysis applied. The only difference was that now instead of rotating the seaweed in a circle, a single line was being reeled in (which required even less power). The main difference was that instead of having this star shape serving as a ski lift rotating the line in an ovular motion, the setup would consist of a single line that would be reeled in at one end while being harvested and another spool of line would be released at the other end to replace the harvested line.

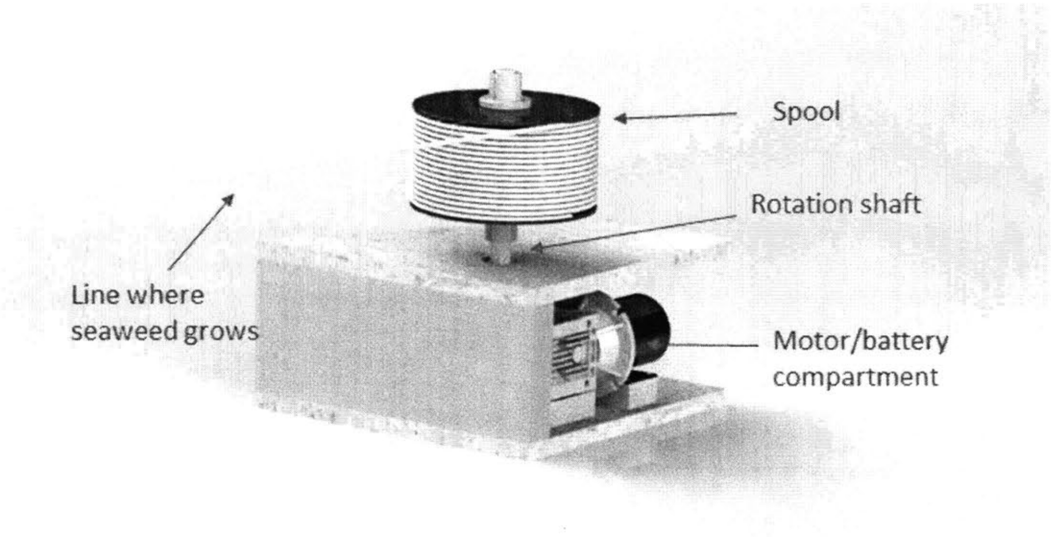

Figure 2-4: Version two of the harvester design. This method is known as the spool method. It works by having this spool design at both ends of a line. This reels the line in on one side where it is harvested, while the other line reels out a fresh new reseeded line as the harvest is happening.

Unlike the first version of the design, this version does not use two lines connected by the metal piece anymore and resorts to the classic one-line floating model that is seen in most farms. A large consideration that was taken into account while making this design was the ease of use for existing farms, meaning that farmers would be able to use this mechanism with their existing farm design and not have to make any major infrastructural changes, which was not the case in the first version. A test of the built physical model is showed in Figure 2-5 below.

Figure 2-5: This figure shows an image of the physical test setup of the second version of the harvester. In this image, we are using a circular blade that is manually operated by my colleague, Chris, to remove the seaweed off of the line and store it in the white bucket shown in the image. The spool and the rotating mechanism can be seen at the end of the line.

In this test, we acquired seaweed off the coast in California and intertwined it with a coated steel wire line so that it would represent an adequate level of attachment to somewhat represent how the seaweed would grow off of the line in the ocean. Then, the mechanism was used to rotate the line and we used a circular blade operated manually to test its functionality. The test was successful on land and we were able to remove the seaweed using the blade and mechanism combination. However, when we reflected on the design, we realized that this mechanism would still require large amounts of human interaction because the spool would either have to be connected to each line in the water which would be quite complex and tedious or each line would require a spool at either end, which would be problematic for the underlying economics of the design as well as its scalability for extremely large farms. Another problem with this design was the power requirement for increasing rotation rates. Figure 2-6 extends the plot shown in version one to encompass rotation and harvesting rates up to 5 m/s.

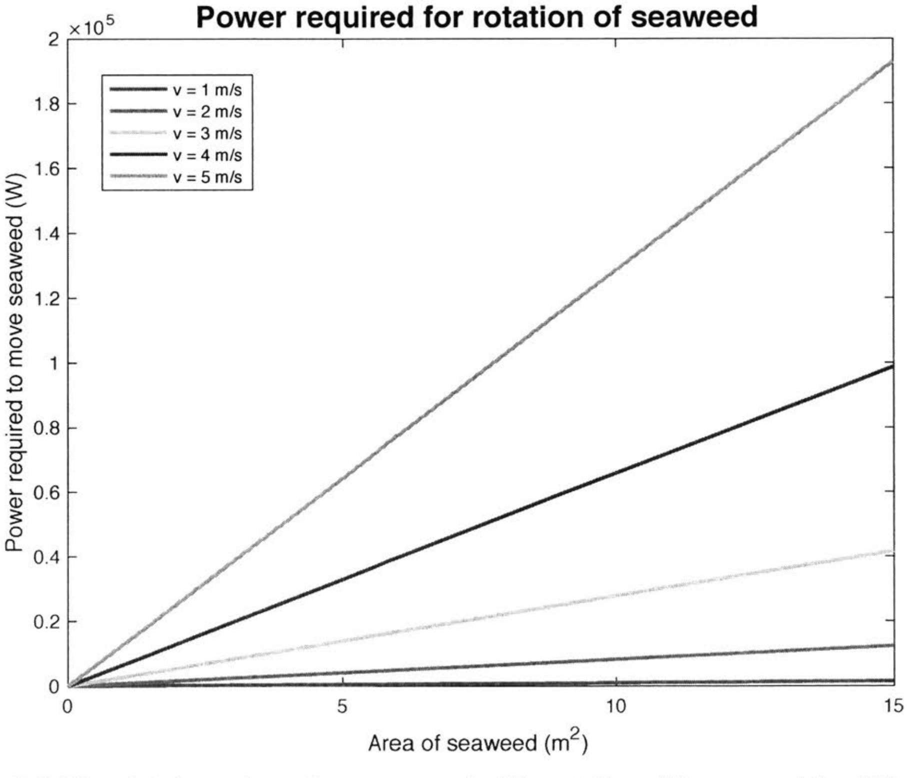

Figure 2-6: The plot above shows the power required for rotation of the seaweed for different rotation rates as well as areas of seaweed (cultivation species).

Due to the scaling nature of the equation with velocity ($P \propto v^3$), the power requirements to rotate the seaweed increase dramatically for every slight increase in rotation rate. To rotate the line at 5 m/s for cultivation species with a frontal area of 8 m^2, a $1 * 10^5$ W motor would be required (which is approximately 134 hp).

1.3 Version Three

After successfully implementing the second version on land, our next major milestone was to build a system and test its success in water. As mentioned previously, the second version would not allow the kind of scalability that was required to truly revolutionize the industry, and this was a major design requirement that my colleague and I had set out initially. Thus, we moved on to a very different style of harvesting that was inspired by the Japanese patent discussed in the introduction. In our third version, we designed a system that would use suction to take the seaweed off of the line in the water and pump it into a storage container or a net. Before designing and testing the system, we performed some basic analysis of the power requirements of the pump that would perform the job.

$$P = Q * p * g * h$$[12]

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[12] "Pump Power Calculator," accessed May 11, 2019, https://www.engineeringtoolbox.com/pumps-power-d_505.html.

In the equation above, P represents the power required in W, Q is the flow capacity in m^3/s, p is the density of the fluid, g is the acceleration of gravity and h is the differential head in meters. The two changing variables in this case are the flow rate and the head. Since the growing line is typically 2-15 feet under the surface of the water, the plot below shows the pump power requirements for different flow rates and differential head in the range of 3 – 11 meters.

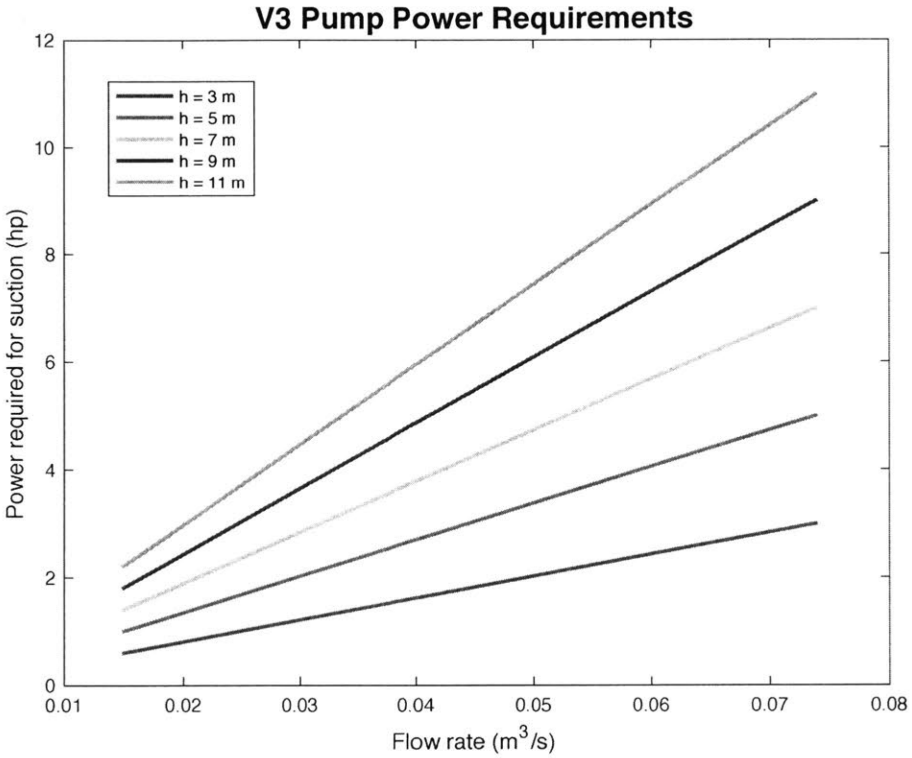

Figure 2-7: This plot shows the pump required (in hp) for various flow rate and differential head conditions.

The flow rates shown here represent a natural range that would occur for harvesting rates on the range of 1-5 m/s (which stays consistent with previous design iterations). Considering the fact that it would be extremely rare to expect a differential head condition that was greater than 7 meters in our test setup, we concluded that any pump in the 5-7 horsepower range would be more than adequate to test the design. The detailed specifications of the chosen pump can be found in Table 1 below.

Type	Centrifugal Pump (water pump)
Power	7 hp gasoline engine
Total Head	92'
Suction Head	26'
Max Pressure	45 PSI
Hose Size	3" Suction and Discharge Fittings
More Details	Cast iron impeller and cast aluminum housing, 2 hour runtime

Table 1: This table lists the specifications of the pump used in the third version of the harvesting mechanism.[13]

A centrifugal pump with an impeller design was chosen because this would allow for seaweed to pass through the pump with minimum quality reduction of the actual product. For this test, we also acquired farmed seaweed on a line by speaking to farmers in Martha's Vineyard, who also provided us with a lot of feedback and allowed us to engage in some user-focused design. Figure 2-8 below shows an image of the seaweed on the line with the suction nozzle in the water in the background and Figure 2-9 shows the actual test set up of the pump.

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[13] "GMC INDUSTRIAL," accessed April 27, 2019, http://gmcindustrial.com/AWG80C.html?fbclid=IwAR1kbpJwiVvQLTRAGP-y59DvRlCuiCLFG0e9f5z8Nze-VGmkGmzaIJYPL3U.

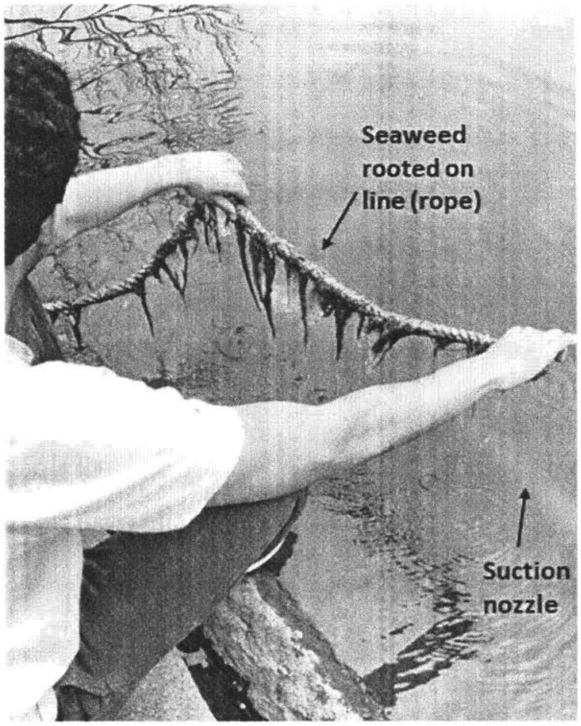

Figure 2-8: This figure shows an image of the line with seaweed on it and the suction nozzle in the background. This is where we conducted the version three test.

From our tests and background research, we know that this method of harvesting is possible for some species of seaweed. However, the major flaw with a design centered around suction was that for different species of seaweed, different pumps are required. For example, some seaweed, such as Mozuku (also known as cladosiphon okamuranus), can be sucked up using smaller pumps because it grows to small lengths and its physical properties allow it to pass through the centrifugal pump's impellers without much harm. However, if the seaweed being harvested is sugar kelp, or some even bigger species, then a much larger and more expensive pump is required (to the extent where the seaweed can grow so large that it would be impractical to keep scaling the pump to match it). This design method also led to the largest amount of potential damage to the quality of the product because it had to pass through a pump and get damaged by the impellers or any design that would pump the seaweed out of the water and into a container.

Other designs simply cut off the seaweed and deposit it into a container with minimal other interaction with the actual product, which preserves its natural shape and quality.

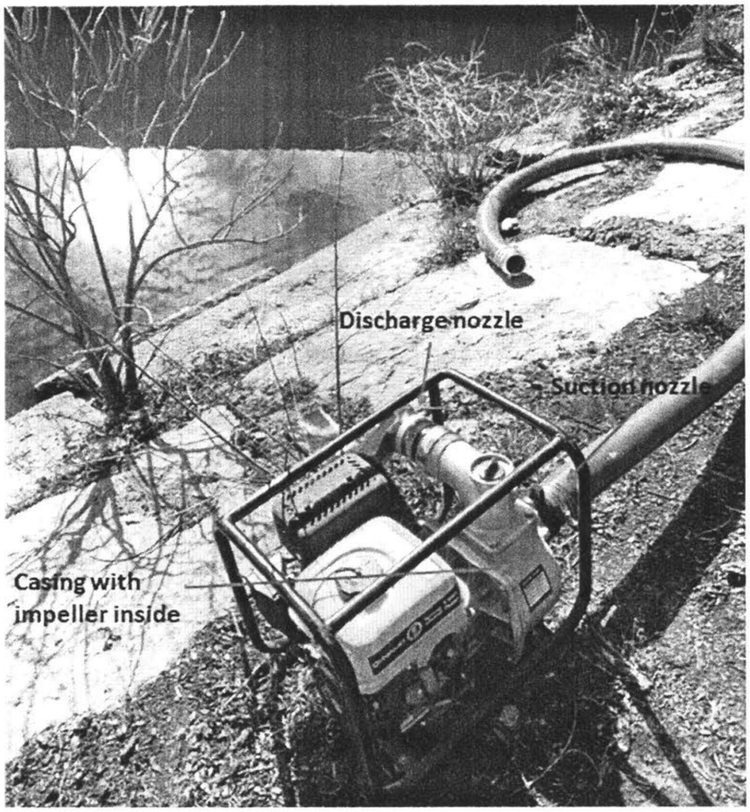

Figure 2-9: This figure shows the majority of the test setup with the pump and the input/discharge nozzles that were setup. The seaweed was sucked off of the line in the river shown in the background.

Furthermore, while this method would be very effective at fully harvesting the line, it would not be as successful at trimming. This feature, which many farmers seemed to think was crucial because this is how they were currently farming, would not be possible with the third version. The suction mechanism meant that the seaweed and its roots were ripped off of the line, meaning that the line would not be trimmed and instead would need to be reseeded if people wanted to keep growing seaweed on it.

2.4 Version Four

This version was designed by combining the advantages of all the previous versions to create one system that would pass all of the design requirements. By returning to a blade cutting system (such as in V1 and V2), the design allows for trimming and also doesn't damage the seaweed while it is being harvested. This system also takes the best part of version three which is the process of harvesting by moving down the line instead of rotating the line towards your cutting source. This will reduce capital costs, enable easier use for any farmer with their current farm design, and enable better farm scalability. While the details of the design have not been worked out to the full extent, a rendered version of the CAD is shown in Figure 2-10.

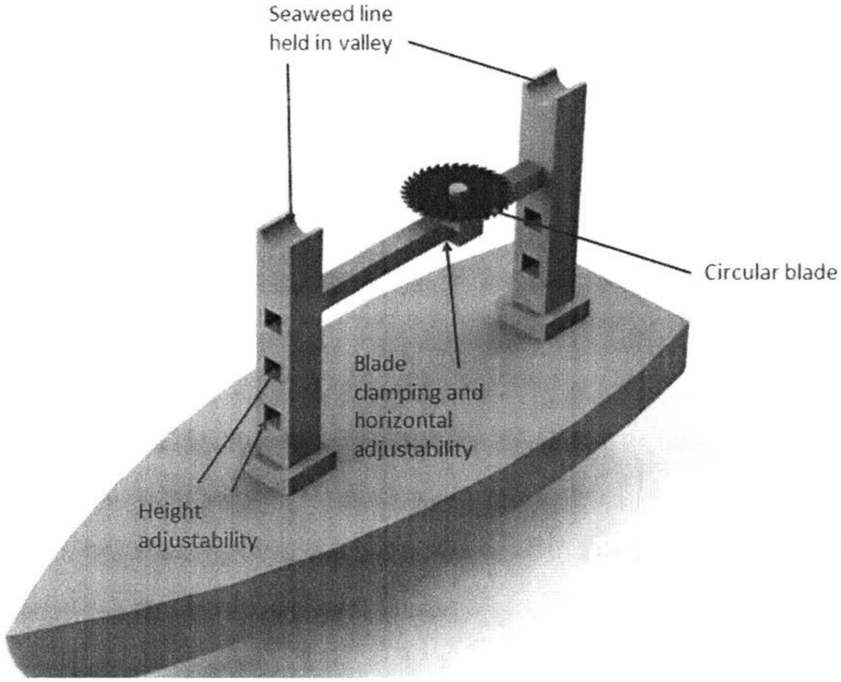

Figure 2-10: This figure shows a very basic render of the fourth version. The design will be integrated into a boat, and this boat will then drive down the line while harvesting the seaweed and depositing it into a net or simply on the boat itself.

As can be seen in Figure 2-10, this mechanism will be integrated into a boat. The line of seaweed will initially be placed by the farmer in the two slots labeled in the diagram. Afterwards, the farmer will have to do nothing except drive the boat down the line. The rate of harvesting will only be limited by the speed at which the farmer can drive the boat (which could also depend on other factors such as external conditions). This theoretical version is designed to be as flexible as possible, allowing farmers to adjust the vertical height (if they want to trim different parts of the line) and the horizontal placement of the cutting tool, which in this case is a circular blade. The design also allows for high future levels of autonomy when paired with the potential of autonomous boats. My colleague and I are also working on an added feature of this design where the farmer would not have to place the line of seaweed on the boat and instead the line can be "picked up" from the water. If this mechanism is successful, the interaction that the farmer has with the line can almost be reduced to nothing and the design could reach the fully autonomous stage.

This is the next design that we are exploring. We plan to build a small-scale version of the boat and mechanism to run down a line before scaling it up to a larger vessel with a full mechanism designed to actually harvest some of the larger seaweed species.

Chapter 3

Evaluation and Conclusion

Overall, it has been very exciting to analyze and try to solve such a unique problem such as the low level of autonomous design in the seaweed industry. It is even more exciting to compare the designs explored in this thesis with current industry standards on an efficiency level. Figure 3-1 below looks at the speed of harvesting for three different systems: a commercial barge system (like the one showed in the bottom of Figure 1-3), a traditional boat system (such as the one shown in the top of Figure 1-3), and possible harvesting rates for V2-V4 (the functioning proposed solutions throughout this thesis).[14] This assumes the average speed of harvesting of the proposed solutions is limited to 1 m/s, even though the discussions above have shown that this can be brought up to 5 m/s in certain implementations through better motors/pumps (depending on the design). The speed for the traditional boat system was determined by analyzing a couple of floating line farm systems and determining the harvesting rate per worker per unit of time from the overall line length, cycle days and labor wages.[15] The speed for the commercial barge system was determined from watching videos of the harvesting as well as speaking with farmers using this process. Overall, the proposed solutions would speed up harvesting times on the order of 40x compared to traditional boat systems and on the order of 10 times compared to commercial barge systems. This would bring down the variable cost of labor significantly by allowing fewer workers to operate larger farms and in turn raise the margins of any farm using these designs.

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[14] Diego Valderrama, "Social and Economic Dimensions of Seaweed Farming: A Global Review," n.d.

[15] Valderrama.

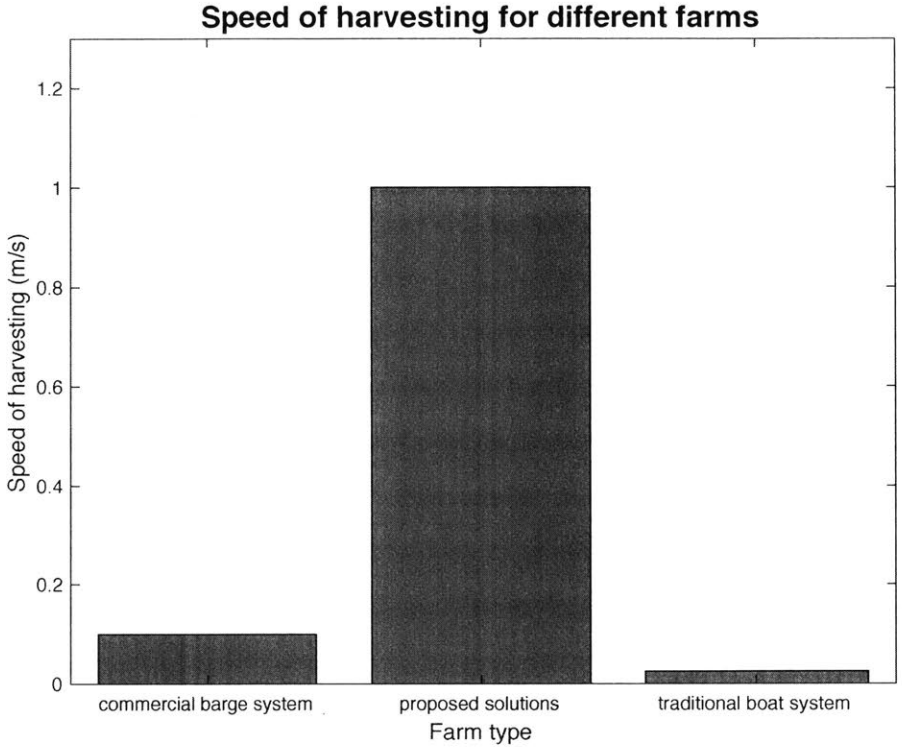

Figure 3-1: This bar graph shows the difference in harvesting speeds for different farm types.

The design criteria discussed throughout the thesis have been listed again below in Table 2. The table compares the various designs across the metrics to see if they pass that requirement. An x in a certain row/column combination means that the version met the standard of that design criteria.

	Complexity	Economics	Scalability	Usability	Autonomy
V1		x			
V2	x				x
V3		x	x		x
V4	x	x	x	x	x

Table 2: A table evaluating the four designs based off of the design criteria established. An x indicates that it meets or exceeds the minimum requirement for that criteria.

As can be seen, the first version (ski lift design), while economically feasible, was not technically feasible and had a lot flaws in terms of its actual functionality and its ability to scale to large farms. Version two (the spool method), the first 'successful' design, was a simple design that worked for our metrics at the time. While it would significantly reduce the labor by speeding up harvesting time as we saw in Figure 3-1, the required fixed costs to build and incorporate spools in each line make it much less economically attractive compared to the other options. At the same time, it did not allow for trimming of the line and also had major flaws in terms of both scalability and economic viability. The third version (suction design), provided major improvements in the scalability and economic viability criteria. However, it did not meet the usability requirement because it wouldn't work optimally for all species of seaweed and also doesn't provide the flexibility for farmers to trim if they would like to. This design also damaged the quality of the seaweed that was being harvested from the farm because of the pump being used. Version four improves on version three by catering to all design uses (trimming and full harvesting) while also allowing for a simpler overall design that can be extended upon to provide greater levels of autonomy. Although it is still in the early design phase and has not been completed, it overcomes many of the major disadvantages of previous designs in terms of autonomy, complexity, scalability and usability while not caving on the economic viability criterion.

From these designs and the thorough testing of each version of the harvester, I conclude that version four is the most promising design to meet all of the design criteria and that can be realistically implemented in commercial farms upon completion. Version four, when integrated with a growing system, will allow farmers to harvest and reseed at a much faster rate while also reducing their operational and variable costs. This is the next step that my colleague and I are working on and we have already established a partnership with farmers to test our design on their farm as soon as it is ready for full scale testing.

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