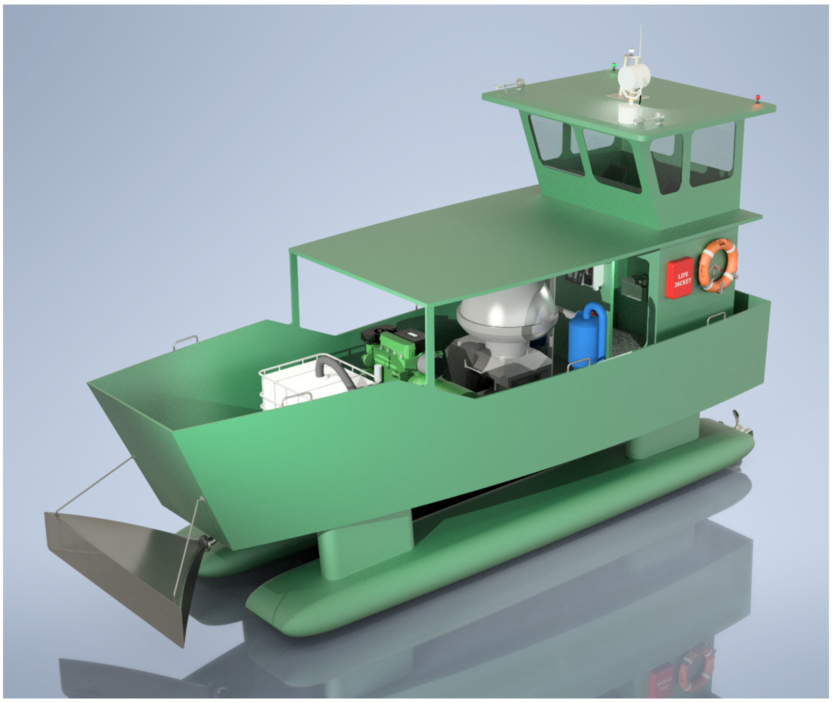

Design of a Toxic Algae Harvester

Collaboration between Chalmers University of Technology, Pennsylvania State University and Volvo Penta

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BACHELOR'S THESIS 2020

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Cover: Rendering of the design of the Toxic Algae Harvester made with Autodesk Inventor Professional 2020.

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Abstract

Harmful algae blooms in lakes and seas are increasing every year. Still, sufficient technology for removal and cleanup in lakes and seas are lacking. The entailing consequences of harmful algae blooms are not only the intoxication of both humans and animals, but also the creation of hypoxic dead-zones in waters around the world. Therefore, this study aimed to explore the possibility of creating a system able to remove wild algae from lakes and seas. Additionally, the potential of producing different products based on the harvested algae was investigated.

The study was divided into two parts, concept generation and algae product research. The resulting Toxic Algae Harvester features a centrifuge for separation of algae and water and a funnel combined with a pump for collecting the algae and water. Furthermore, a suitable vessel has been designed to fit all the necessary components, making it a complete system. Additionally, a rough cost analysis has been conducted and the environmental impact of operating the system has been estimated. As for the algae product, the only feasible solution with the present research was production of biogas. The reason for this being that the algae species and composition does not have to be considered when producing biogas.

The combined results from this study provides a solution that can separate algae during algae blooms in an efficient way and therefore contributes to lessen the environmental impact these blooms cause. Furthermore, it reduces the economic damage on society that would otherwise result from a decrease in fishing and tourism industries caused by algae blooms. However, the economic and environmental benefits are limited in this configuration but could be increased by further development and possibly upscaling of the Toxic Algae Harvester.

Sammanfattning

Varje år ökar antalet giftiga algblomningar. I dagsläget finns det ingen teknik för borttagning och sanering av dessa alger i sjöar och hav. Giftiga algblomningar leder till hälsorisker för människor och djur, samt uppkomst av hypoxiska zoner runt om i världen. Denna studie syftade därför till att undersöka möjligheten att skapa ett system som kan avlägsna giftiga alger. Dessutom undersöktes möjligheten att använda algerna för att framställa olika produkter.

Studien delades upp i två områden, det ena behandlade konceptgenerering och det andra behandlade framställningen av alg-baserade produkter. Den resulterande produkten utför separering av alger och vatten med hjälp av en centrifug och algerna samlas in med hjälp av en pump och ett munstycke. Dessutom har ett fartyg designats speciellt för denna applikation där alla komponenter och stödsystem samspelar optimalt. Därtill genomfördes en övergripande kostnadsuppskattning samt produktens miljöpåverkan under användning uppskattades. Resultatet av undersökningen av alg-baserade produkter var att framställning av biogas är den mest lämpliga användningen av giftiga alger med nuvarande teknik.

De kombinerade resultaten från denna studie tillhandahåller ett system som på ett effektivt sätt avlägsnar alger under algblomningar. Genom att göra detta minskas den negativa miljöpåverkan som algblomningar orsakar. Dessutom mildras samhällsekonomiska förluster från fiske- och turistindustrin som orsakas av algblomningar. Dessa positiva effekter är begränsade i produktens nuvarande form men kan utökas genom vidareutveckling och utvidgad design.

Acknowledgements

This project would not have succeeded without the help and contributions from the multiple external sources which have been involved in the project and therefore, we would like to express our gratitude to you all. Our supervisors Mikael Enelund, Erik Hulthén, Daniel Humberto Cortes and examiner Ola Isaksson deserves a special thanks for their continuous support and feedback throughout the entire project.

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Although the outbreak of Covid-19 made it impossible to fulfill, a special thanks is given to Herbert and Karin Jacobssons Foundation for offering funding for the Chalmers students to travel to Pennsylvania State College for collaborative work.

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Alda Chau, Edwin Eliasson, Olle Haglund, Daniel Hozouri, Jason Johnson, Forest Ledrick, Julianne Martinez, Carlos Molina & Henrik Wahrén.

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Abbreviations

AHP Analytic Hierarchy Process

CAD Computer Aided Design

COD Chemical Oxygen Demand

DAF Dissolved Air Flotation

DFA Defatted Algae

GMAW Gas Metal Arc Welding

HDPE High Density Polyethylene

HVO Hydrated Vegetable Oil

IBC Intermediate Bulk Container

LCA Life Cycle Analysis

LD50 Lethal dose 50%

NPSHA Net Positive Suction Head Available

NPSHR Net Positive Suction Head Required

NRLE U.S. National renewable energy laboratory

PDP Positive Displacement Pump

SWATH Small Waterplane Area Twin Hull

TAH Toxic Algae Harvester

UPS Uninterruptible Power Supply

USDA U.S. Department of Agriculture

USDOE U.S. Department of Energy

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1 INTRODUCTION

In a rapidly advancing technological world where the amount of harmful algae blooms is increasing by the year due to overuse of fertilizers, a method to clean and separate algae efficiently is urgently needed. Algae bloom is a process when microalgae increase their populations rapidly to the extent that entire lakes and coastlines are covered by a layer of algae, which results in huge imbalances in those ecosystems. The algae blooms will not only create hypoxic dead-zones, but some species will also produce deadly toxins affecting both the aquatic life as well as humans. Thus, an efficient solution to clean and separate microalgae is essential.

1.1 Background

Overuse of fertilizers in farming, industrial and human waste not being purified, and emissions from combustion of fossil fuels, all increase the amount of nutrients, especially nitrogen and phosphorus, in waters, also known as eutrophication. This occurs in fresh-, salt-, and brackish water and it increases the primary production, later on resulting in overgrowth of algae (NOAA, 2020). It is, however, important to understand that it is the overgrowth of algae that is problematic, not the algae itself – it is estimated that 50 percent of all produced oxygen on earth stems from algae through photosynthesis (Chapman, 2013), which means that it also acts as a very large carbon sink by converting atmospheric carbon dioxide to biomass.

Originally, algae mostly grew in temperate and tropical regions, but this is now changing because of global warming. A warmer climate leads to warmer water temperatures and loss of sea ice in the Arctic, which results in a more favorable environment for algae growth in northern regions (Lefebvre, et al., 2016). An environmental study initially proposed in 2009 called “Planetary Boundaries” brings up 9 different aspects of environmental impact, with “nitrogen and phosphorus cycles” being one of them (Rockström, et al., 2009). An update of the study was published as an article in the magazine “Science” in 2015. At this point the boundaries for nitrogen and phosphorus flow were measured to be highly exceeded causing a major risk of environmental problems. According to the article the boundaries for both phosphorus and nitrogen flow were more than twice as large than what was considered safe (Steffen, et al., 2015).

The overgrowth of algae causes an imbalance in the ecosystem in which it is present in two primary ways. The algae blooms block sunlight and thereby inhibit photosynthesis for other plants. This is leading to fish needing these plants for their survival to ultimately starve and die. Furthermore, oxygen is consumed when these algae are decomposed by bacteria, creating hypoxic dead zones which are leading to death of aquatic life. As of 2008, dead zones have appeared in continental seas, such as the Baltic Sea, the Kattegat, the Black Sea, Gulf of Mexico, and East China Sea. All these seas contain major fishery areas and, therefore, the algae blooms have a big impact on the fishing industry (Diaz and Rosenberg, 2008).

The death of different species that results from eutrophication is a severe problem since it reduces marine biodiversity. Loss of biodiversity is harmful for the functioning of the ecosystem in which it occurs and decreases its ability to provide important ecosystem services such as carbon sequestration and clean water (Cresswell and Murphy, 2016). Periods of hypoxia leads to changes in the ecosystem energetics; energy that in normal conditions would move up to higher trophic levels is instead moved towards microbial secondary production. This reduces the amount of biomass in the form of food energy (Diaz and Rosenberg, 2008).

This is a grave problem; according to FAO (Food and Agriculture Organization of the United Nations), fish provide more than 3.2 billion people with nearly 20 percent of their average per capita intake of animal protein (FAO, 2018).

Further, some species of algae produce harmful toxins that negatively affect the health of fish and shellfish, as well as humans. Cyanobacteria, for example, is a type of algae that produce microcystins which can be harmful for the human liver and can even be deadly (Chorus and Bartram, 1999). Along the west coast of North America, the neurotoxin domoic acid has caused illnesses and even death of mammals. The neurotoxin saxitoxin has been found in shellfish in Aleutians and Gulf of Alaska, the human consumption of which can result in illness and deaths (Lefebvre, et al., 2016). This makes it very clear how important and relevant it is to prevent algae blooms and developing techniques for removing them, thus removing part of their harmful effects.

Decreasing the emergence of dead zones needs a multifaceted problem-solving approach. The preventive part of the approach is to reduce the flow of nutrients from agricultural systems into waters by making the cycle of nutrients circular, thus re-using nutrients instead of it leaving the agricultural system to waters (Diaz and Rosenberg, 2008). This can be achieved by applying agricultural management strategies such as crop rotation and using cover crops (Weathers, et al., 2013). In the Black Sea, a hypoxic dead zone developed from 1973 to 1990. After fertilizer use was significantly reduced in 1989, the hypoxic dead zone was gone by 1995. This shows the significant effects strategies to prevent nutrient flows to water ecosystems can have on the development of hypoxia. Another example is the Northern Gulf of Mexico that receives large amounts of nutrients from U.S. agriculture from freshwater discharge from the Mississippi River. During years with high river flow, the area of hypoxia is more than 15000 square kilometers, while in years with low river flow, the area of hypoxia is less than 5000 square kilometers (Diaz and Rosenberg, 2008). The corrective part of the multi-facetted approach mentioned earlier is removing already existing algae blooms in the most effective and sustainable way possible. It is this part that this project is focused on.

The discussion of the problem at hand can be extended to the common denominators across all environmental problems we face; namely that a growing global economy and increased human consumption have only been possible through rapid technological advancement in all areas as well as increased use of natural resources, often at the expense of the environment. For example, global crop production has nearly tripled over the past 50 years (Weathers, et al., 2013). This has only been possible using chemically produced fertilizer, as opposed to manure that has historically been the fertilizer used in agriculture. Hence, increased food production and a higher standard of living globally have not been possible except by paying the price of the consequential environmental problems that occur with the use chemical fertilizer. Humans directly and indirectly constantly pollute the environment using different technologies, the previous example being only one of them. It could be deemed unethical for human beings to exploit nature and, as a result, destroy it, solely for the fulfilment of their own goals. This would naturally lead one to hold the view of humans having a moral duty to preserve nature, and in the case of already having imposed harm on it, to try to fix it as efficiently as possible. Whether this is something that one believes or not, developing a system removing algae blooms is good both because it preserves the environment and reduces the harm on it, as well as reduces the harm it has on the health of human beings.

The difficulty of removing wild algae is not merely harvesting it, but also separating the algae from water and other objects that might have come along with the harvesting, in order to acquire pure algae mass. Examples of different technologies in use for the separation of microalgae are centrifugation, membrane filtration, and flocculation. In the study conducted by Bosma et al. (2003), the use of ultrasound to harvest microalgae is tested and compared to older technologies, such as those previously mentioned. It was shown that that for large scale operation, centrifuging microalgae is more energy efficient than the use of ultrasound, but that ultrasound is more suitable for laboratory purposes.

There are a few companies existing today that are working with harvesting and refining algae, although they do not harvest wild algae, but solely focus on growing a specific alga, often genetically modified, in controlled environments, and using it to produce different kinds of products. One example is the company ExxonMobil (2018) that grow genetically modified species of algae with high lipid content to make biofuel. ExxonMobil managed to increase the oil content of an alga strain from 20 to 40 percent through cell engineering. The reason that they do not use wild algae is because of too low lipid content and too much uncertainty of the content to efficiently produce biofuel.

As the end customer of this product is most likely a governmental institute or an organization, the profitability is not as important as the function, even though it would increase the value of the product. Volvo, on the other hand, a global company that does require profit, has no intention of manufacturing and selling the final product that this project intends to develop, but rather to give the specifications away for others to produce. The way this will become profitable for Volvo is by designing the Toxic Algae Harvester to use a Volvo Penta propulsion system.

If this project is successful in all of its undertakings it will be beneficial for Volvo and the end user as well as the environment. The environmental effect of a successful project is minimizing the harmful effects caused by algae blooms such as dead zones and the spread of toxins. Harvesting wild algae and refining it into something usable is a short-term solution connected to the problem of eutrophication. As long as an excess of nutrients is present in lakes and oceans there will be a need for collecting algae blooms to reduce their harmful effects. When the root cause is solved, the principles of the system could still be used, but instead for efficient harvesting of cultivated algae in a controlled environment. Thus, in total, this project contributes to long-term benefits in several ways.

1.2 Purpose

Through a collaboration between Chalmers University of Technology and Pennsylvania State University on behalf of the global company Volvo Penta of the Volvo Group, the purpose of this project was to develop a device for removing and separating toxic algae from lakes and seas. To fulfill this purpose, the following objectives are outlined:

- Designing a device for removing algae blooms
- Investigating the possibilities of using the harvested algae
- Assessing whether the developed system is environmentally beneficial as a whole or not
- Assessing the cost of producing the system

1.3 Limitations

The final design is limited to not including a physical prototype but includes detailed CAD models that incorporate the algae separation method, the power source, the propulsion system and the floating device that holds all the working parts. Because of limited time and unique circumstances due to Covid-19, functional models were not built either, although they were initially part of the team's plan. In addition, the final design incorporates specific materials needed and an approximate cost to build the device. The size of the Toxic Algae Harvester, the capacity and the storage tank volume are also outlined in the design. This study is unable to encompass the harvesting of algae blooms far out in the ocean but only those in lakes and along coastlines. This study only considers the strategy of removing algae blooms and does not engage in studying preventing strategies such as increasing the efficiency of nutrient-use in agricultural systems.

1.4 Clarification of the problem statement

Today, sufficient technology and knowledge about purifying water from harmful wild growing algae blooms are not commercially available. For that reason, these algae blooms remain in seas, lakes and rivers and cause a number of environmental problems. Since the purpose of the project is to develop a Toxic Algae Harvester that captures microalgae as efficiently as possible, it is natural that the first stage in this project would be to investigate existing products and their characteristics. As mentioned earlier, there are some existing methods for harvesting specific algae grown in controlled environments which have been studied. This was done in order to see what in these products renders each of them insufficiently efficient for them to solve the problem of algae growth on a large scale. Additionally, their positive characteristics were identified for these aspects to be used in the Toxic Algae Harvester. Since the TAH is to be used in fresh-, salt-, and brackish-water, the quest of extracting the best available characteristics from existing products was a complicated one, considering that most products have been developed for running in one type of water only. An example of this not being the case is the Mobile Harvester developed by Rob Falken. He and his team harvest blue-green algae and convert them into polymers. The conversion to polymer becomes difficult if there is salt in the algae, making it only suitable for freshwater lakes. However, for the harvesting, the type of water, whether it is fresh-, salt-, or brackish-water, does not matter. In other words, the harvester works in all kinds of waters (Shoot, 2016).

Further, the collected algae becoming landfill is undesired even though it captures the carbon dioxide fixed in the algae, so therefore the possibility of using the harvested algae in different ways have been investigated. Besides contributing with the environmental benefits from a closed ecological system, the biproduct of harvested algae can provide an economical value if processed into a product. By achieving this, a greater market value is created since the running cost could thereby be reduced or even eliminated. Today, research is done to cultivate different types of algae, harvest them and from them produce biofuels (Adeniyi, et al., 2019), biomaterials (Mahmood Zia, Mohammad and Muhammad, 2017), and animal feed (Garlapati, et al, 2019). These examples show what opportunities there are for using algae to provide sustainable alternatives to products currently not being produced in an environmentally sustainable way. The problem with using these examples as sources of inspiration for using the algae is that the most widespread approach is to cultivate and harvest a single type of alga. This differs from the case which this project investigates; namely clusters of algae probably consisting of different species, some of them being toxic. This makes using these algae blooms for production purposes after harvesting much more difficult than it is in a controlled environment. An example of an application which could potentially eliminate this problem is to use algae for wastewater treatment. Wastewater typically contains high amounts of nitrogen and phosphorus, thus, causing eutrophication in the waters it is emitted to. This enhances primary production which damages aquatic ecosystems. By taking advantage of this, algae can be made to grow more efficiently when exposed to wastewater, thereby both increasing the output of biomass which can be used for the production of different types of products, as well as lessening the damaging effect that these nutrients contained in the wastewater have on aquatic ecosystems in which they end up (Deviram, et al., 2019). Now, going back to the problem at hand, the question is whether already harvested algae are fit for use in this situation or not, considering that it is the growth of algae that consumes nutrients and thereby purifies wastewater and not their mere presence. Perhaps already harvested microalgae could continue their growth when exposed to wastewater, either simply because of the high amounts of nutrients in the wastewater as opposed to the ocean or lake from which it was harvested, or because part of the harvested microalgae have not yet grown to their full extent, and can therefore continue to grow when exposed to wastewater.

1.5 Social, ethical and environmental aspects

There are several actors involved in this project: the two universities, Chalmers University of Technology and Pennsylvania State University; the project proposer, Volvo Penta; and the two teams consisting of students from the two universities. This means that there are both cultural aspects and ethical foundations of the two universities and the company Volvo Penta which have had to be followed. As well as following ethical values, team members on both sites have done their very best to deliver a satisfying result and thereby maintain the reputation of the universities and the company.

1.5.1 Social aspects

Algae blooms have several negative social consequences that the TAH is intended to mitigate. When a toxic algae bloom occurs, it does not only damage the environment by creating dead zones, but it also damages it by filling ocean currents along the coast with toxins, which results in the closing of beaches and a decrease in tourism. The Swedish Environmental Protection Agency has conducted interview studies to assess the importance of the state of the marine environment to the tourism industry in the Baltic Sea. The study analyzed different fields - among which were beach tourism, cruises, recreational fishing, boating and real estate - in the nine countries with coastlines in the Baltic Sea. The conclusion was that out of all environmentally related problems, the blue-green algae blooms have the biggest impact on these industries. Besides causing the largest impact, the conclusion indicates that an increase in algae blooms would cause a severe harm on these industries (Hasselström, et al., 2008). Besides impacts on tourism related industry, algae blooms also cause an economic and social impact on the fish industry and the society as a whole. With the 59,6 million people employed globally by the fish industry (FAO, 2018), algae blooms causing large amounts of fish deaths would naturally result in large amounts of people becoming unemployed. The fact that algae directly cause high fish mortality has been proven, for example in a brackish water-lake on Åland (Lindholm, et al., 1999). Furthermore, algae blooms cause drinking water pollution, rendering the water harmful for human beings (Falconer, 1998). Everyone is in need of ecosystem services from lakes and seas, e.g. source of food, drinking water and recreation, to mention a few. The Toxic Algae Harvester contributes to maintaining but also increasing these ecosystem services by supporting the work in reaching the planetary boundary goal regarding eutrophication (Steffen, et al., 2015), as well as removing all the mentioned social harms.

1.5.2 Ethical aspects

Since the main purpose of this project is to design a system for removing toxic algae causing numerous environmental problems in seas and lakes, there are no obvious negative ethical aspects linked to it. Still, it has always been made sure that the work of the project team has been conducted in an ethical manner with respect to laws and regulations. Decisions have been thoroughly reviewed throughout the project and they have been based on facts while always keeping ethics in mind. The Toxic Algae Harvester needs to be completely safe to operate for the driver and it is not allowed to harm any aquatic animals inhabiting the operating space. This have been made sure by risk assessment and the use of safety standards.

1.5.3 Environmental aspects

The environmental benefits of the project are obvious considering the great environmental harm that algae blooms cause. However, the environmental harms to be mitigated are originally caused by humans, through human and industrial waste, fertilizers etc. Removing these toxic algae blooms in fact only works to rectify the harm already caused, thereby not working in any preventive way, only a repairing one. In other words, harvesting algae does not go to the root cause of the problem, which is the human and industrial waste emitted to waters.

Regardless of whether the algae collected is valuable and useful in a refinement process or will be considered as toxic waste, the question of to whom the algae belong is important. The ownership or responsibility of the algae must therefore be established before the system is operated. There are probably also protected areas in which the system should not be used and these need to be defined. If toxins are extracted while harvesting the algae, these toxins will have certain environmental and health-related effects based on where they end up. Even though the project's purpose is solely to develop an algae harvester and not attempt to analyze and improve the material flows in a system wherein toxic algae is a part, the fate of these potential toxins is considered to be part of the project teams' responsibility. Another aspect that is considered in this project is the fuel consumption and the resulting emissions from running the Toxic Algae Harvester. This is analyzed and discussed in an environmental analysis.

During the time of the project, the majority of the participants from Chalmers were supposed to travel to Penn State in the U.S. by flight in order to meet and work together with their teammates. However, due to Covid-19 the trip was unfortunately cancelled. Although it was planned, traveling by flight impacts the environment in several negative ways (Fahey and Lee, 2016), and should therefore be avoided as much as possible. However, the team reasoned that the expected positive outcome of the project could be seen as outweighing the negative aspect of this journey, and, in addition, a physical meeting with the whole team would most probably contribute to a better result. Therefore, according to a utilitarian ethical perspective (Hansson, 2009), the project was still considered to be beneficial for the environment.

1.6 Thesis structure

This thesis has been organized in the following way. Chapter two outlines the general method implemented in the project. Chapter three addresses costumer needs. The thesis then moves on to the actual concept selections in chapter four and five. Chapter six is concerned with toxins in the algae and the possibility of their removal. In chapter seven, visualizations of the final design of the product are presented and described. Chapter eight deals with the different potential uses of the harvested algae. Chapter nine presents the environmental analysis of the product and chapter 10 the manufacturing and cost analysis. Finally, the last section of the thesis consists of a discussion, a conclusion and recommendations to the client in chapters 11, 12 and 13.

2 METHOD

The general method that has been used throughout this project is inspired by The Value Model (P. Lindstedt, J. Burenius., 2004). The Value Model is used in product development projects where customer value is the main factor to maximize. The definition of customer value according to European standard (EN: 12973) is shown in *equation 1*.

$$\text{Costumer value} = \frac{\text{satisfaction of needs}}{\text{use of resources}} \qquad (1)$$

Per definition there are two ways to increase the customer value, either by increasing the satisfaction of the customer needs or by decreasing the use of resources. *Figure 2.1* is a schematic that describes the methodology which was intended to be followed throughout the project.

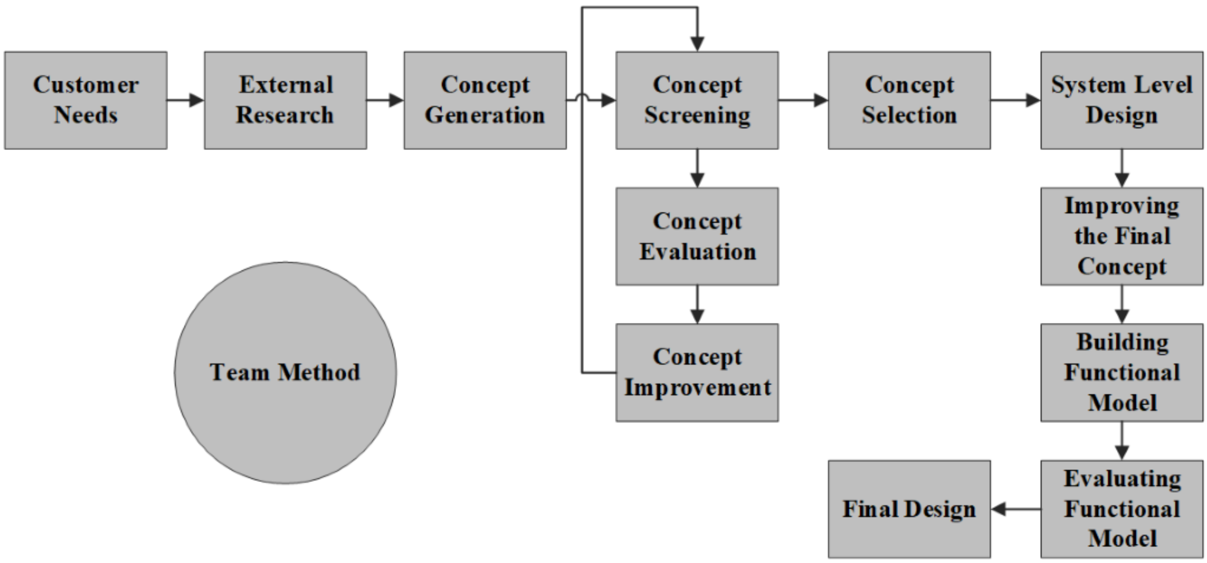

Figure 2.1: Schematic figure of the planned project methodology

2.1 Team method

A unique part of this project was that five members of the team were based at Penn State, U.S and four members of the team were based at Chalmers, Sweden. Getting the whole team to work as one unit has been a challenge during this project. One way of handling this challenge has been to divide the team into subgroups, each working on a specific part of the project. In this way, the students have had the chance of getting to know each other better as well as benefitting from the diversity of the group. In the weekly meetings, discussions have been held on what tasks have been completed in each subgroup and what problems have arisen.

The overall aim has been to make this project as collaborative as possible between the two universities. This is part of the reason why subgroups were created - the intention with these groups were mainly to increase the level of collaboration by each team consisting of at least one member from each university. However, some parts of the process needed a closer collaboration, and hence, most of the CAD-design and chapter *6 Toxins*, was made by group members from Chalmers. Furthermore, chapter *10 Manufacturing Analysis* was mainly conducted by group members from Penn State. To maintain a properly divided and collaborative work, individual weekly progress reports were written throughout the project. These progress reports included both information about accomplishments, encountered problems and need of future work.

2.2 Customer needs and Target specification

Due to this project being performed on behalf of Volvo Penta with the objective of using it as a product for their customers, according to the value model, Volvo Penta is referred to as the Client and Volvo Penta's customers that will use the product are defined as the end user or end customer.

When brainstorming ideas during the concept generation, many factors were considered, both the requirements and needs set by the client, as well as the needs of the end users. The requirements and needs from the client have continuously been noted and evaluated during the weekly skype meetings, whereas for the end user needs, a more widely spread analysis has been performed by contacting organizations and companies that are already using existing products to get an understanding of the advantages and disadvantages related to different harvesting methods and products, and also by discussing within the team the possible problems of each harvesting method for the users. Furthermore, identifying people who are not necessarily working directly with algae has been proven valuable; for example, people familiar with marine applications of different kinds have been considered able to provide useful information and inputs.

It has been considered that there most probably will be conflicting needs and requests among different end customers. For example, a government responsible for cleaning big lakes or even parts of oceans would most likely require a product with a high separation rate and large storage tank to be able to clean massive volumes in a short amount of time. This would result in a product having large dimensions and a high cost to produce. On the other end of the scale of customers there might be small organizations that have their main focus on local lakes, rivers and ponds. These types of customers might value the ease of use, ease of transport and a low cost more than a fast clean-up. Hence, it has been considered crucial to receive input on specific needs from all possible sorts of end customers in order to be able to weigh the conflicting needs and conduct decisions on specifications. Furthermore, different end customers might intend to use the system in different types of water. A solution for this is to design the system to be capable of use in all three types of water mentioned earlier.

To start with, some initial, general costumer needs were listed. Target specifications were then created by translating the customer needs into numerical values and establishing limits. The resulting target specifications are shown in *Table 2.1*. Important to note is that these target specifications were only preliminary since this was in the beginning of the project before contacting organizations and companies.

Table 2.1: Initial target specification with the importance graded.

Specification No.	Specification	Importance (1=not very, 5=very)	Threshold Value	Objective Value	Units	Specifier
1	Storage Tank Size	4	>1000	>1500	L	End user
2	Motor Output	4	<100	<50	kW	End user
3	Machine Perimeter	3	<136.6	<74.3	m^2	End user
4	Durability	2	>1	>2	Years without maintenance	End user
5	Algae Harvesting Rate	5	>150	>200	m^3/day	Client
6	Algae Separation Rate	3	>150	>200	m^3/h	Client
7	Ease of Use	4	<8	<5	Hours of training required	End user
8	Salinity Tolerance	3	>0.5	>35	g/L	Client
9	Operator Safety	5	2	3	Life preservers onboard	End user
10	Maximum Speed	1	>1	>2.5	m/s	End user
11	Cost	4	<10	<3	US$ million	Client

One method to compare the difference in importance between categories for target specifications is to create a weighted hierarchal customer needs list and use the analytic hierarchy process (AHP). A preliminary AHP was created by the team members with input from the client and the results are displayed in *Table 2.2.*

Table 2.2: Analytic hierarchy process with initial customer needs and given weight.

Degree of Importance	Storage Tank Size	Motor Output	Machine Perimeter	Durability	Algae Harvesting Rate	Algae Seperation Rate	Ease of Use	Salinity Tolerance	Operator Safety	Maximum Speed	Cost	Total	Weight	Weight (%)	Cumulative
Storage Tank Size	1,0	3,0	1,0	0,5	0,5	0,3	1,0	3,0	0,5	2,0	2,0	17,8	0,122	10,7%	10,7%
Motor Output	0,3	1,0	0,5	0,3	0,3	0,3	0,3	0,5	0,3	1,0	0,5	8,5	0,058	5,1%	15,8%
Machine Perimeter	2,0	2,0	1,0	0,5	0,5	0,5	2,0	2,0	0,5	2,0	2,0	18,0	0,123	10,8%	26,7%
Durability	2,0	3,0	2,0	1,0	1,0	1,0	3,0	3,0	1,0	3,0	2,0	4,0	0,027	2,4%	29,1%
Algae Harvesting Rate	2,0	3,0	2,0	1,0	1,0	1,0	3,0	3,0	1,0	3,0	2,0	28,0	0,192	16,9%	45,9%
Algae Seperation Rate	3,0	3,0	2,0	1,0	1,0	1,0	3,0	3,0	1,0	3,0	2,0	24,0	0,165	14,4%	60,4%
Ease of Use	1,0	3,0	0,5	0,3	0,3	0,3	1,0	2,0	0,5	2,0	0,5	14,5	0,099	8,7%	69,1%
Salinity Tolerance	0,3	2,0	0,5	0,3	0,3	0,3	0,5	1,0	0,3	0,5	0,5	7,0	0,048	4,2%	73,3%
Operator Safety	2,0	3,0	2,0	1,0	1,0	2,0	2,0	3,0	1,0	3,0	3,0	24,0	0,165	14,4%	87,8%
Maximum Speed	0,5	1,0	0,5	0,3	0,3	0,3	0,3	0,5	0,5	1,0	0,5	6,3	0,043	3,8%	91,6%
Cost	0,5	2,0	0,5	0,5	0,5	0,5	0,5	2,0	2,0	2,0	1,0	14,0	0,096	8,4%	100,0%

Direct Input

Calculated, do not input data

Ranking: 1 is equal, 2 is more important, 3 is much more important (reverse ranking: inverse)

The results established from the AHP indicated that "Algae Harvesting Rate" is the most important aspect, followed by "Algae Separation Rate" and "Operator Safety". Given that the focus of the project is to separate toxic algae during blooms it is appropriate that the weight of harvest and separation of algae score highly.

2.3 External research

To get information on what is available on the market at present, research on available products and patents was conducted. The available products' characteristics, as well as their advantages and disadvantages, were studied. This informed the team of what functions and characteristics today's available products lack in order to remove algae effectively. Also, the team learned about their positive aspects that they could implement in the TAH and their negative aspects that they needed to avoid. This accomplished gaining inspiration for the concept generation and making sure no patent infringement is done. As mentioned in section *2.1 Team Method*, the team was divided into subgroups. The task of one subgroup was decided to be researching existing products. The plan was to investigate multiple different products and patents in order to gather enough information on algae harvesting systems.

2.4 Concepts

After the external research, a concept generation was conducted. In a concept generation the group brain-storms different solutions to the problem at hand and have a discussion about them to further inspire new solutions and ideas in the group. After the concepts had been generated, a concept selection was conducted. The first step was to either eliminate or improve concepts that do not fulfill the customer needs, which was done using an elimination-matrix or screening-matrix. The second step was to evaluate the remaining concepts using a Pugh-matrix, also called a scoring-matrix, which ranks the different concepts from best to worst. Thereafter, the team investigated the weaknesses of the concepts and tried to improve them before again using the Pugh-matrix to evaluate the improved concepts. This was an iterative process that finally led to the best concept being singled out and continued to work on until it reached its full potential.

2.5 System level design

When a concept has been singled out it is described in detail using a system level design model called black box. The black box model visualizes all subsystems, inputs, outputs, and how they interact. The system level design is used to improve the concept by reducing complexity and finding weak points. An initial sketch of the system level design is shown in *Figure 2.2*.

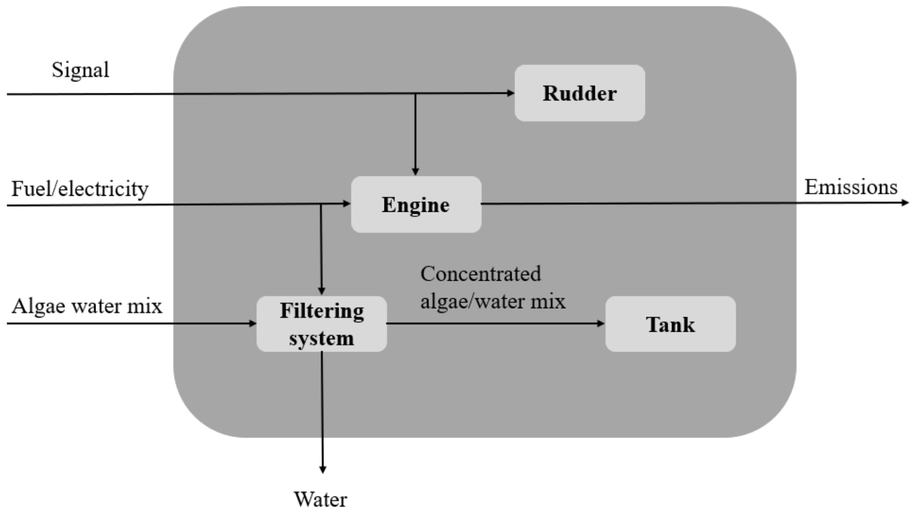

Figure 2.2: Schematic example of the system level design

In the previous example, the overall system has four important inputs: the signal from the operator of the TAH, fuel, electricity, and the algae water mix coming onto the TAH. The input from the operator of the TAH will go to two different locations within the main system, the first being the rudder which will guide it and the second being the engine thus controlling the speed. Fuel and electricity are led to the engine and the filtering system respectively providing both with energy. The algae mixed water will enter the filtering system and be separated sending the concentrated algae to a storage tank while the remaining water will be flushed out of the system back into the water source that is being cleansed. The only other output of the system other than the water is the emissions from the engine into the surrounding environment.

2.6 Improvement of final concept and final design

As for the concept improvements, the final concept was optimized and fine-tuned in both performance and cost based on customer needs, with the aim of raising the customer value described in the Value Model when the final concept is re-evaluated.

The final design and the improvements of the final concept overlapped quite a lot and became an iterative process meaning that an early model of the final design was made before the improvements were finalized. When the second final design was made in CAD, even more improvements had to be made until the result was satisfactory. It was a more time-consuming way of designing the final product than doing all the improvements first and having a better understanding of what the final product should be before designing. Although it was more time consuming, the iterative process was beneficial since more issues were brought up and fixed so that the final design became a successful product. When the design had been specified and approved by all members of the team, renderings were made in order to improve the visualization of the product.

3 CUSTOMER NEEDS

Besides having had joint brainstorming sessions regarding customer needs specifications, the group has also reached out to potential customers, people working in a similar environment that the Toxic Algae Harvester is supposed to be used and professionals in various fields connected to the project. Since the Toxic Algae Harvester is supposed to be used in lakes and oceans, information about important aspects for a vehicle operating in these environments had to be identified. Therefore, a meeting with senior lecturer in Maritime Science Per Hogström was held. During this meeting, information about safety equipment, environmental aspects and some guidelines for ship design was acquired. An explanation on how to comply with the regulatory framework documents SOLAS (Safety of Life at Sea) and MARPOL (International Convention for the Prevention of Pollution from Ships) established by the United Nations was also given. In order to get a better picture of how it is like for the people working in these environments and what aspects that are important regarding the work environment, a meeting with the fisherman Dan Kristensson was held. He provided insight in general safety measurements implemented on the fishing boat and what is important for the fisherman to be cautious with to achieve a safe working environment. He also emphasizes the importance of radiocommunication and that all fishing boats use the same radio channel to communicate.

Furthermore, a meeting with Lars Åkesson and Philip Axe from the Swedish Agency for Marine and Water Management was held. They state that cyanobacteria are present in all levels of depth in lakes and oceans, but that they float up to the surface at the end of their life-cycle. They then become concentrated in a section from the surface down to a depth of 0.5 m. This is positive from a harvesting perspective. However, the high concentration of cyanobacteria in this section necessitates harvesting the same area several times as algae continuously age and float up to the surface. In this section little or no amounts of other important species like zooplankton or fish are present, which, together with low harvesting speed, makes the risk of collecting fish and other aquatic animals low. The Swedish Agency for Marine and Water Management safety state that the only restriction for people swimming in lakes and oceans is that they are advised against it if there is visible green algae sludge in the water. Because the water could still contain toxic algae even when there is no visible green algae sludge in it, the Swedish Agency for Marine and Water Management requests a very high separation level, specifically 99% separation of water and algae. In addition, clear instructions to the operator of the harvesting system needs to be given about harvesting the same area several times. The Swedish Agency for Marine and Water Management are not themselves interested in becoming a direct costumer to a system of the order of magnitude which is presently being designed due to them operating on a regional scale and hence would need a larger product. However, they state that this is a very interesting solution with a high potential, and that they could be interested in a scaled-up version of it. They are also interested in financing municipalities for buying the smaller present system, because of the benefit on a local scale. Lastly, The Swedish Agency for Marine and Water Management points out that this system is sufficiently beneficial in its function of harvesting algae for it to be useful even if the algae are not processed into another product, like biofuels or polymers, because of the huge local impact the algae blooms have on the tourism revenues (Axe, P., and Åkesson, L., 2020, personal communication, 18 March).

To summarize, customer needs related to level of separation, collection depth, safety measurements, environmental regulations and capacity of the system were identified with help of the potential costumers and professionals.

4 SEPARATION CONCEPTS

Due to the relatively low total proportion of pure algae in the water, a method of separating the algae from the water is needed in order to maximize the amount of collected algae in each run. Therefore, this chapter intends to give an in-depth description of identified concepts for separating algae from water. The separation process can be done in multiple different ways, including: mechanical, electrical, chemical and biochemical methods. Many possible methods have been researched and each method's advantages and disadvantages have been listed. Furthermore, numerical values regarding different performance aspects of each method was compiled into a table which was later used for eliminating substandard solutions.

4.1 Concept description

In order to accurately evaluate the different concepts, each of them needed an in-depth description based on facts and numbers. The separation rate was a very important criterion and therefore the main function to evaluate. In the cases of discontinuous separation concepts that uses a tank there is a need for two tanks in order for the system to be continuous - one tank that is being filled and one tank where the water and algae are being separated. In those cases, the tank volume was evaluated instead of the separation rate.

4.1.1 Centrifugal separation

Separating algae from water can be done using a centrifuge. A company that produces such a centrifuge is Alfa Laval. Their model Clara 701H (Alfa Laval, 2015), for example, is designed for the wine-making industry to filter out small yeast particles after the fermentation process. In this process the centrifuge is fed water mixed algae from the bottom and transport the solid algae particles to the sides of the centrifuge bowl by the centrifugal force produced by spinning at a rate of 4800 rpm. The algae are then discharged from the bowl by a hydraulic system. The clean water is pumped out from the top of the centrifuge using a built-in pump.

The *Clara 701H* is 1.73 meters long, 1.75 meters wide and 1.823 meters high. It weighs 2800 kg when in use, and is fitted with an electrical motor providing a power of 37 kW. It is capable of separating particles in the range 0.4 to 200 µm with a throughput rate of 75 cubic meters per hour. The price of a *Clara 701H*, according to the area sales manager for the food and wine division at Alfa Laval, Mattias Von Knorring, is US$282,000. A sketch of the separator is shown in *Figure 4.1*. A disadvantage of the centrifuge, besides the price, is that the rotating bowl creates a large angular momentum due to the fact that it is very heavy and that it rotates quite fast. The bowl in the *Clara 701H* weighs 1150 kg and reaches a rotating speed of 4800 rpm or 502.7 rad/s. If the axis which the centrifuge rotates around is changed by a wave, for example, the angular momentum will change, which will result in a torque being introduced from the centrifuge to the TAH. That might cause problems with the handling and the stability of the TAH and might in addition cause stresses on the structures of it.

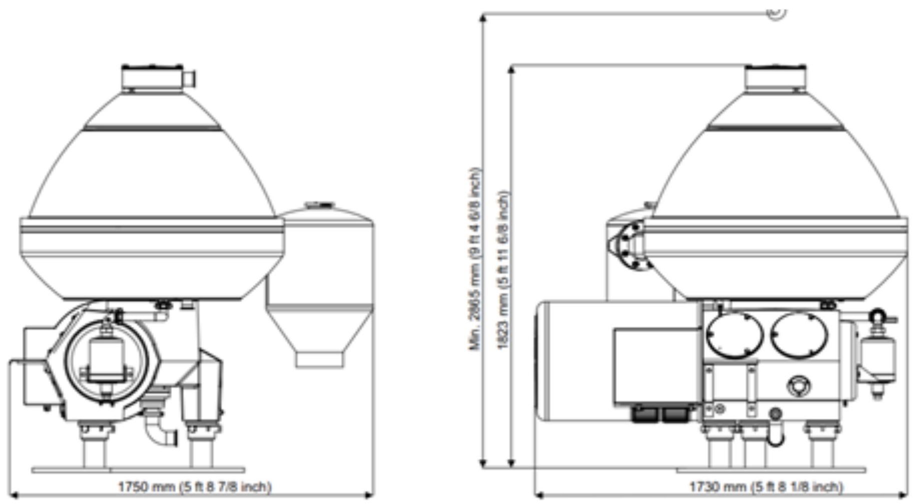

Figure 4.1: Alfa Laval separator (Alfa Laval, 2020)

4.1.2 Inorganic Chemical Flocculation

Inorganic Chemical Flocculation consists of using inorganic flocculants to induce chemical flocculation in microalgae. There are many possibilities for the chemical flocculant, and different chemicals have different benefits ranges. The process of chemical flocculation is rather simple and efficient (Bevi, et al., 2017). Furthermore, it is a well-documented and widely used method; it is, for example, often used in wastewater treatment.

However, there are some obvious disadvantages related to this method. The most significant one is the fact that chemicals are used, which entails the risk of secondary pollution. Additionally, the medium cannot be reused, resulting in the need to store the used chemical on the mobile vehicle. The running cost of this method mainly consists of the cost of the chemical flocculant. A commonly used flocculant is Poly Aluminum Chloride, the cost of this chemical when buying bulk size is approximately US$1.84 per cubic meter of separated water (Pelendridou., et al, 2014).

The fastest chemical flocculation available today separates 90% of the material in 15 minutes (Matter., et al, 2019). If the maximum tank size allowed by the system is estimated to 2000 liters, the maximum throughput-rate would be 133 L/min or 8 m^3/h. Even so, in order to make this method continuously separate algae, there is a need for having two tanks of the size mentioned before, namely one tank doing flocculation while another is filling or emptying water. The estimated power requirement is 1 kW. This power is used for stirring the water when doing flocculation.

4.1.3 Bioflocculation

The method of bioflocculation is similar to the more widespread method of chemical flocculation with the difference that the flocculant is organic. There are several types of organic flocculants, of which some are bacteria, plant-derived flocculant, self-aggregating alga, fungus and microbial based flocculants (Bevi .U., et al, 2017). Advantages of this method are mostly environmentally related; the energy consumption is low and the flocculants are not harmful to the environment. Although biological flocculants are typically more expensive than chemical flocculants, bioflocculation is still considered a cost-efficient method (Matter., et al, 2019).

The primary disadvantages of bioflocculation are the following. First of all, different species of alga require different types of flocculants for the flocculation to be efficient. For that reason, considering that wild algae probably consist of different species, bioflocculation is not an appropriate solution. Second, bioflocculation is a relatively slow process that requires a controlled environment to reach its full potential. Last of all, there is also a need for a secondary process to remove the flocculated algae.

The most successful result when using this method for separation was accomplished when separating the Chlorella alga with a self-aggregating alga as flocculant. With this method, 100% of the material was separated within 5 minutes (Matter., et al, 2019). If this could be matched, the minimum tank size required to separate at the rate of 360L/min would be 1800 liters. If the maximum tank size allowed by the system is estimated to 2000 liters, the maximum throughput-rate would be $400\ \mathrm{L/min}$ or $24\ \mathrm{m^3/h}$. In the same way as in the case of inorganic chemical flocculation, there is a need for having two tanks of the size mentioned above, that is one tank doing flocculation while another is filling or emptying water. The estimated power requirement for this method is also 1 kW. This power is used for stirring the water when doing flocculation.

4.1.4 Electrocoagulation

As specified by Vandamme, D., et al. (2011), electrocoagulation is an efficient way to harvest microalgae that uses less energy than the microalgae contain. The method is based on releasing positive iron or aluminum ions into the dirty water. These ions then attract the negatively charged algae and agglomerate them into bigger chunks that are eventually extracted. Electricity is used to induce electrolytic oxidation from a sacrificial anode in order to release the ions into the water (Matter., et al, 2019).

Alfafara CG, et al (2002) studied the removal of algae from lake water using electrocoagulation, both continuous and batch reactors. The results are shown in *Figure 4.2.*

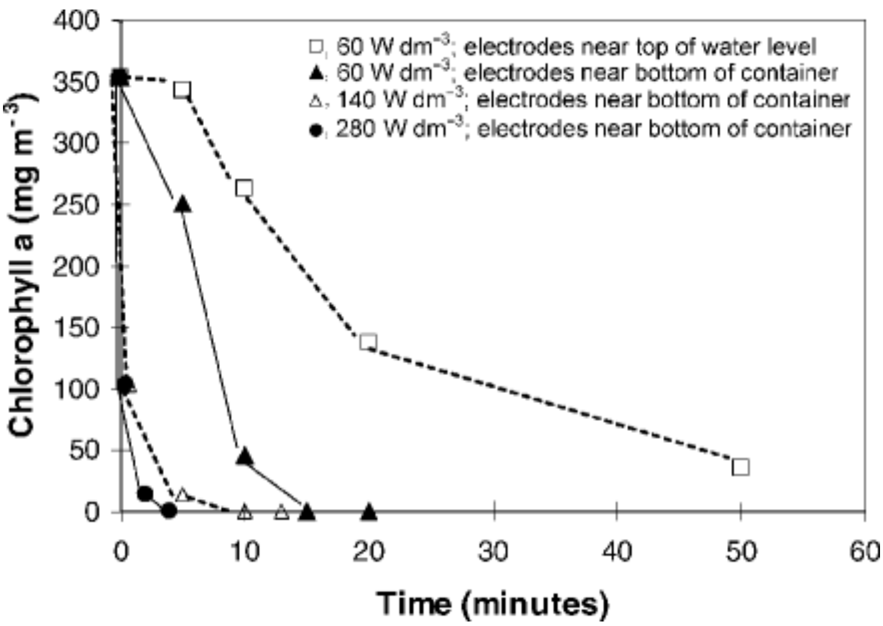

Figure 4.2: The concentration of chlorophyll over time in four different testing conditions (Alfafara, et al., 2002)

This shows the possible efficiency that electrocoagulation can bring about. In the paper by Alfafara CG et al. (2002), the optimum charge dose to achieve high algal removal efficiency with minimum release of excess aluminum was 250 coulombs [mg-chlorophyll a].

Besides from having the potential to be very efficient, the method has been proven to be suitable for most species of algae, and, additionally, there is no need to add any chemicals in the process (Matter., et al, 2019). Under optimal conditions, electrocoagulation has been demonstrated to carry out separation at a 100% rate with an energy consumption of only $0.4\ \mathrm{kWh/m^3}$(Gao., et al, 2010). This makes it a potentially cost-efficient and environmentally friendly alternative. Nevertheless, this method does have its disadvantages, of which the most considerable one is the risk of the effluent water being contaminated by ions from the sacrificing anode. This could occur when too much power is applied to the process (Matter., et al, 2019). Furthermore, there is a need for periodic change of the offering anode due to dissolution, which could potentially decrease the capacity of the system by an amount depending on the length of the change interval, in addition to increase costs. Moreover, an extra step to remove contaminating metal ions from the dissolving electrodes would be an added expense.

The best solution available requires three minutes to fulfill the separation of a tank. In order to meet the throughput requirement of 360 $\mathrm{L/min}$, a tank with the capacity of 1080 liters would be needed. If the maximum tank size allowed by the system is estimated to 2000 liters, the maximum throughput-rate would be 666.7 $\mathrm{L/min}$ or 40 $\mathrm{m^3/h}$.

4.1.5 Magnetic flocculation

Magnetic flocculation, also known as magnetic separation, according to Wang, S. K., et al. (2015), essentially consists of utilizing a flocculant together with magnetic nanoparticles by letting the particles stick to the algae, and then using a magnetic field to attract the particles and thereby remove the algae. Magnetic flocculation shows strong potential with several advantages such as low energy consumption, rapid separation, and the re-usability of medium and magnetic particles, which lowers its cost. According to Wang, S. K., et al. (2015), the total cost of cleaning a cubic meter of fresh water was US$0.13. Depending on the precision of the flocculant dose and the material of the nanoparticles, more than 99% harvesting efficiency has been proven to be possible (Lee., et al, 2013). Despite the advantages mentioned, it must be taken in account that the method is in an early stage of development. A study by Matter., et al. (2019) has shown magnetic flocculation to be successful in harvesting cultivated algae grown for biofuel production as well as to clear a lake from a harmful algae bloom, but these attempts have only been on a small scale.

A simplified sketch explaining the process of magnetic separation is shown in *Figure 4.3*.

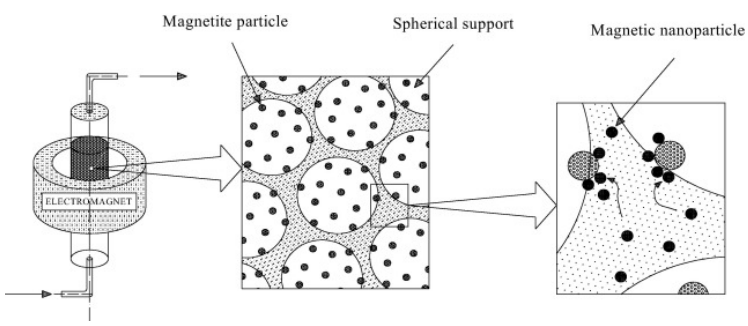

Figure 4.3: Principles of magnetic flocculation (Ebner and Ritter, 2000)

One disadvantage of magnetic flocculation is the proven difficulty in the separation of the nanoparticles from the harvested algae, which is something that could affect the use of the harvested algae (Matter., et al, 2019). Another disadvantage is that the need to separate the nanoparticles will most probably give rise to a need for a separate processing machine stationed on land. Further, there is a lack of research on this technology being used on a mobile vehicle; in its past and present applications, it has only been used on land. By applying this technology to a floating system, there might appear a substantial risk of metallic nanoparticles leaking into the surrounding environment.

Hereby follows an analysis of the possible throughput-rate using magnetic flocculation. The suitability of the nanomaterial depends somewhat on the algae specie being separated. Two materials which have proved successful are magnetite ($\mathrm{Fe_3O_4}$) and yttrium iron garnet ($\mathrm{Y_3Fe_5O_{12}}$). The use of coated nanoparticles has proved even more efficient (Matter., et al, 2019). When using a coated nanoparticle called $\mathrm{Fe_3O_4}$-chitosan for harvesting the toxic blue-green algae Chlorella, 99% of the material was separated within 2 to 5 minutes using $1.4\ \mathrm{g/L}$ of flocculant (Lee., et al, 2013). With this method the throughput-rate is limited by the size of the tank wherein the flocculation is conducted. To accomplish a throughput rate of $360\ \mathrm{L/min}$ the tank size required is:

$$360 \cdot 2\ \mathrm{L} = 720\ \mathrm{L}\ \text{to}\ 360 \cdot 5\ \mathrm{L} = 1800\ \mathrm{L} \tag{2}$$

If the maximum tank size is estimated to be 2000 L, the potential throughput rate is 500 L/min to $1000\ \mathrm{L/min}$ or 30 $\mathrm{m^3}$/h to 60 $\mathrm{m^3/h}$. Just like the other flocculation methods, in order to make this method continuously separate algae, there is a need for having two tanks of the size mentioned before.

4.1.6 Fine mesh filtering

Fine mesh filtering is a method of separating algae from water using a very fine net that is dragged in the water either by a boat or by hand with a smaller net connected to a long handle. Fine mesh filtering is a very simple, cost-effective and fully mechanical method of separating algae from water.

One commercially available product that implements the fine mesh filtering method is the parachute skimmer (Weiss, 2011). The parachute skimmer is a fine meshed net that collects algae both on and below the surface using a floating top part and a weighted bottom part to make the net stretch and cover as large an area as possible. The list price of a parachute skimmer is US$140. The parachute skimmer is dragged behind a boat and when the net is full it is pulled up to the back of the boat using a rope to then empty the net into tanks on the boat. The manual emptying of the net is a limiting factor on the size of the net.

A considerable problem with the fine mesh filtering method is that the holes in the net must be very small for the product to be able to filter out small algae particles, and if the holes are small enough they will get clogged very fast, which will lead to the water flowing around the net instead of through it until the net is emptied. An efficient method of removing the clogging materials also poses an issue. Thus, the fine mesh filtering system can theoretically have a very large throughput rate ($\mathrm{Area} \cdot \mathrm{Velocity}$) if the holes are big enough for the water to flow through the net. It can thereby be used to filter out large algae, wildlife, and other debris, but is not suitable for harvesting microalgae. An approximative value for the throughput rate $\dot{V}$ can be calculated as:

$$\dot{V} = v \cdot A = 2\ \mathrm{m^3}/s = 7200\ \mathrm{m^3/h} \tag{3}$$

where v is the velocity of the TAH and A the area of the net. It has been assumed that $v = 1\ \mathrm{m/s}$, A=2 m^2, that all water passes through the filter and that no water flows around - the holes in the net are large - and that no time is needed to empty the net. These assumptions represent ideal conditions which makes the calculated throughput rate a rough estimate.

4.1.7 Pressure filtering

Pressure filtering is a method of separating algae from water by forcing the water-mixed algae through a very fine filter through which the water passes but the algae does not. It works by a cylinder being filled with the water mixed algae, and a piston with a filter cloth, normal to the cylinder's centerline, is forced through the mix. Since the filter needs to be very fine in order to separate the microalgae from the water, the pressure needs to be high and maintained for several hours, according to (Show and Lee, 2014). When the pressure filtering process is finished, a solid algae cake is what is left. Since the time under pressure is several hours, the cylinder volume would need to be very large in order to fulfill the throughput requirement.

To reduce the time under pressure and, by extension, the cylinder volume, the algae mixed water could first be coagulated so that the algae clump and becomes large. In that way the holes in the filter would not need to be as small as for filtering un-coagulated algae, allowing a reduction in both pressure and time under pressure. Although, a reduction in time under pressure is demanded in this application, it would lead to a two-part system that is more complex, takes up more space and is more prone to failure. An approximate tank size required to fulfill the $360\ \mathrm{L/min}$ throughput rate would be: $V = 43.2\ \mathrm{m}^3$. If “several hours” is set to two hours. Note that two of these tanks would be required for the system to operate continuously. With the same assumption of time under pressure and a more reasonable tank volume of two cubic meters, the throughput rate $\dot{V}$ would be:

$$\dot{V} = \frac{V}{t} = 1\ \ \mathrm{m}^3/\mathrm{h} \tag{4}$$

where t denotes time in hours.

4.1.8 Tangential flow filtration

Tangential flow filtration is a method of separating algae from water by letting a turbulent flow of algae-mixed water flow through a horizontal filter. The algae pass through the filter and some of the water is filtered out by gravity through the bottom of the filter and let out in the lake or sea. The algae water mix is re-circulated through the filter until a desired concentration is obtained. The re-circulation process is shown in *Figure 4.4*. When the desired algae concentration in the water has been obtained the concentrated algae tank can be emptied into a second tank and the re-circulation process can begin again with a new batch of algae-mixed water. For this method to operate continuously, two continuous re-circulation systems would be needed, one of them concentrating the algae mixed water, and the other being filled, as visualized in *Figure 4.5*.

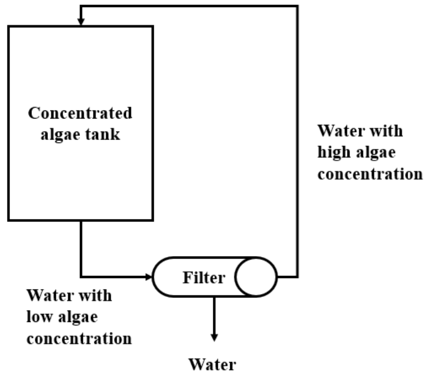

Figure 4.4: Re-circulation process

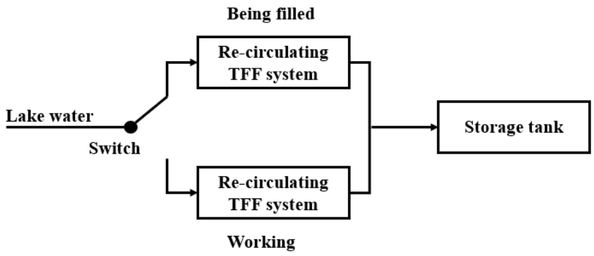

Figure 4.5: System level design

In a study conducted by Petruševski, et al. (1994), they concentrated a 200 L tank of water mixed algae using a tangential flow filtration system with a flowrate of 3 to 3.5 $\mathrm{L/min}$. The algae concentration could be increased by about 5% after one iteration and up to 98% after 40 iterations, depending on the algal species. The study also shows that a loss of algal mass between 10 and 30% occurs due to some algae being let out with the water. If the throughput rate is similar to what it was in the study of Petruševski, et al. (1994), the total throughput rate would be:

$$\dot{V} = \frac{3.5\ \mathrm{L}}{40\ \mathrm{min}} = 0.0875\frac{\mathrm{L}}{\mathrm{min}} = 0.01\ \mathrm{m^3/h} \qquad (5)$$

4.1.9 Dissolved Air Flotation (DAF)

The way a DAF system operates is by algae mixed water being fed into the system joined by a stream of recirculated clarified water that is saturated with dissolved air, called whitewater. Microscopic bubbles from the whitewater attach to solid particles in the wastewater and give the particles buoyancy to float to the surface of the DAF tank. As a layer of the particles accumulate on the mixture surface, a skimmer moves the sludges towards a discharger. Solids that do not float sink to the bottom of the V-shaped tank and are discharged with a pneumatic drain valve (Bondelind, 2011).

The DAF system has several advantages. The first is the established experience available of using it to clean algae contaminated water in wastewater management systems (Vlaski., et al, 1996). The second is the large flowrate it can achieve - up to $29.5\ \mathrm{m^3/h}$ for a $18.8\ \mathrm{m^2} \cdot 2.8\ \mathrm{m} = 52.64\ \mathrm{m^3}$ system - as shown by Ecologix Systems' model E-405C (Ecologix, 2020). The third is its ability to function in very contaminated water. A blueprint and additional information are shown in *Figure 4.6.* Due to the fact that the technology is mature and that there are many companies that manufacture DAF systems, the price is relatively low. The company FRC manufacture a DAF system called PCL-15. PCL-15 is capable of a flowrate of

37 m^3/h, and the cost of it is around US$125,000 (CRF, 2020). However, there are some obvious disadvantages, including most of the use cases being for stationary systems, the size of the system being large and the fact that it is heavy. Furthermore, the system is not designed to be mounted in a vehicle.

There is no reason the system would not be able to be attached to a moving vehicle. The extra turbulence from being attached to a moving vehicle should not be an issue since there is a high inherent turbulence from the whitewater being pushed into the tank. The overall angle, however, may be an issue since the scrapper mechanism relies on the tank being upright, so a stabilization system may be needed if the TAH is found to achieve extreme inclinations. Still, there is the risk of unforeseen events since there is no precedent case of DAF being used on a boat, but the most probable issues have been considered.

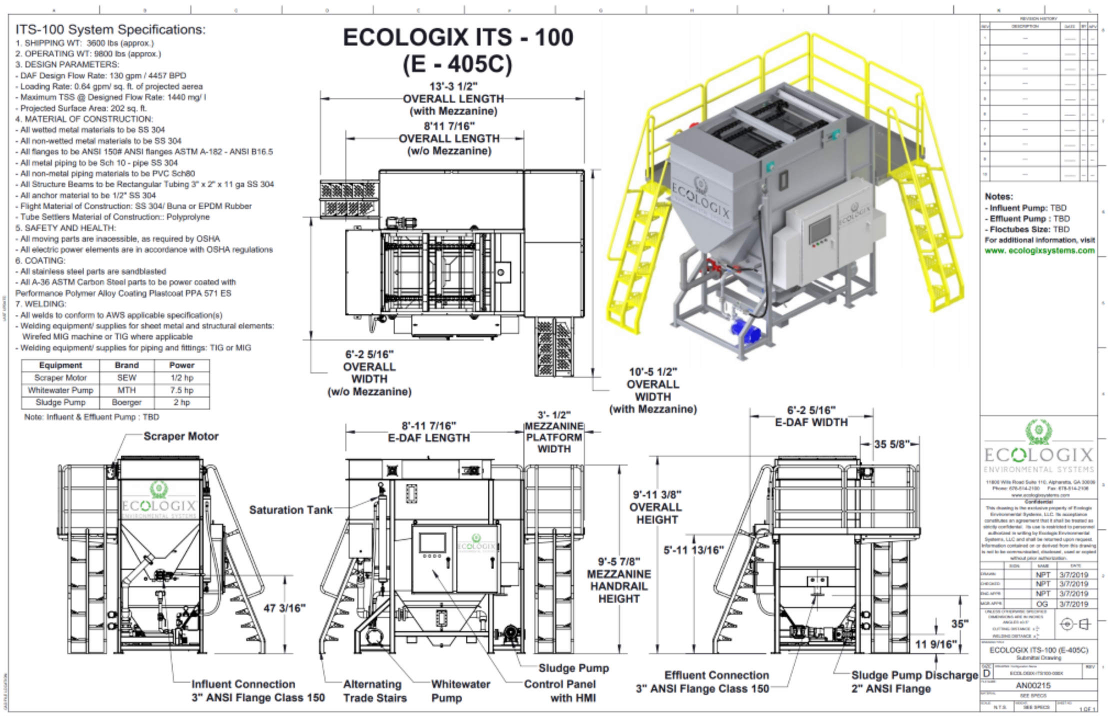

Figure 4.6: Blueprints of Ecologix Systems' DAF model E-405C (Ecologix, 2020)

4.1.10 Roller separation

Roller separation is a method of de-watering highly concentrated algae mass, that is, algae mass in the form of sludge. The algae sludge is fed in between two high precision rotating rollers that squeeze the water from the algae. The separated algae and water then fall down on to a conveyor belt that lets the water through and back into the lake and transports the algae to a final storage tank, as visualized in *Figure 4.7*. In this way less water needs to be transported onboard the TAH, reducing both tank size and power requirement.

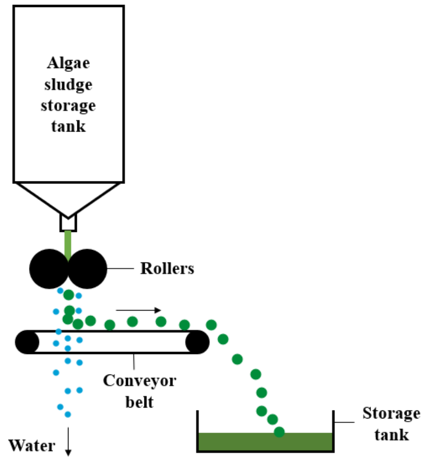

Figure 4.7: Principles of roller separation

The roller separation method is probably not a good way to separate water with low algae concentration; it will simply pass right through the conveyor belt. Nonetheless, it could be used as a secondary process to reduce water weight and tank size.

4.1.11 Specifications of the concepts

The most important specifications for each separation method were identified and the values for each concept were summarized in *Table 4.1* and *Table 4.2*.

Table 4.1: Table for comparison of the different concepts.

Concept	Max through-put rate [m^3/h]	Level of separation	Length [m]	Height [m]	Width [m]
Centrifugal separation	75	99%	1.75	1.823	1.73
Bioflocculation	24	99%	2	2	1
Electrocoagulation	40	99%	2	2	1
Inorganic Chemical Flocculation	8	90%	2	2	1
Magnetic flocculation	30-60	99%	2	2	1
Fine mesh filtering / parachute skimmer	7200	~50%	0.1	1	2
Pressure filtering	1	99.99%	2	2	1
Tangential flow filtration	0.01	98%	1.5	1	0.5
Dissolved Air Flotation	29.52	99%	2.5	2.8	1.6

Table 4.2: Table for comparison of the different concepts (continued).

Concept	Gross-weight $[\mathbf{kg}]$	Energy requirement $[\mathbf{kWh/m^3}]$	Running cost $[\mathbf{US\$/m^3}]$	Price $[\mathbf{US\$}]$	Level of contamination
Centrifugal separation	2800	0.5	Energy requirement	282,000	Non existing
Bioflocculation	4800	~0.04	~3.68	~50,000	Minor
Electrocoagulation	5000	0.4	Energy requirement	~100,000	Moderate
Inorganic Chemical Flocculation	4800	~0.125	1.84 + Energy requirement	~50,000	Moderate
Magnetic flocculation	4800	~0.2	0.13	~100,000	Moderate
Fine mesh filtering / parachute skimmer	10	N/A	0	140	Non existing
Pressure filtering	5000	Unknown	Energy requirement	Unknown	Non existing
Tangential flow filtration	500	~0.1	Energy requirement + filter replacement	~20,000	Non existing
Dissolved Air Flotation	4445	0.26	Energy requirement	125,000	Non existing

4.1.12 Elimination

In the first round of elimination three concepts were deemed unfeasible to use in this project. The most considered specification was the throughput rate which has a very important role in the success of this project. The limit was set to $360\ \mathrm{liter/min}$ or $21\ \mathrm{m^3/h}$. The three concepts that did not meet this specification and that seemed unable to do so even with improvements were: Inorganic chemical flocculation, Pressure filtering and Tangential flow filtration. These three concepts were therefore eliminated and the remaining concepts and their specifications are summarized in *Table 4.3* and *Table 4.4*.

Table 4.3: Concepts left after first elimination.

Concept	Max through-put rate $[m^3/h]$	Level of separation	Length $[m]$	Height $[m]$	Width $[m]$
Centrifugal separation	75	99%	1.75	1.823	1.73
Bioflocculation	24	99%	2	2	1
Electrocoagulation	40	99%	2	2	1
Magnetic flocculation	30-60	99%	2	2	1
Fine mesh filtering / parachute skimmer	7200	~50%	0.1	1	2
Dissolved Air Flotation	29.52	99%	2.5	2.8	1.6

Table 4.4: Concepts left after first elimination (continued).

Concept	Gross-weight $[kg]$	Energy requirement $[kWh/m^3]$	Running cost $[US\$/m^3]$	Price $[US\$]$	Level of contamination
Centrifugal separation	2800	0.5	Energy requirement	282,000	Non existing
Bioflocculation	4800	~0.04	~3.68	~50,000	Minor
Electrocoagulation	5000	0.4	Energy requirement	~100,000	Moderate
Magnetic flocculation	4800	~0.2	Energy requirement +0.13	~100,000	Moderate
Fine mesh filtering / parachute skimmer	10	N/A	0	140	Non existing
Dissolved Air Flotation	4445	0.26	Energy requirement	125,000	Non existing

4.2 Concept evaluation

To evaluate all concepts, a Concept-scoring Matrix was used with weighted evaluation criteria to make a just and factual assessment of all concepts, shown in *Table 4.6*. The weights in the Concept-scoring Matrix were generated by comparing the importance of each criterion to the rest of the criteria in an AHP (Analytical Hierarchy Process) matrix, shown in *Table 4.5*. The AHP matrix was created by the team members with input from the client taken into account.

Table 4.5: Analytical Hierarchy Process Matrix.

	Max Throughput	Level of Separtion	Dimension	Weight	Power Consumption	Operation Cost	Level of Contamination	Sunk Cost	Total	Weight	Weight (%)
Max Throughput	1,0	1,0	3,0	3,0	2,0	2,0	1,0	3,0	16,0	0,191	19,1%
Level of Separtion	1,0	1,0	3,0	3,0	2,0	2,0	1,0	3,0	16,0	0,191	19,1%
Dimension	0,3	0,3	1,0	1,0	0,5	0,5	0,3	0,3	4,3	0,052	5,2%
Weight	0,3	0,3	1,0	1,0	0,5	0,5	0,3	0,3	4	0,052	5,2%
Power Consumption	0,5	0,5	2,0	2,0	1,0	1,0	0,5	2,0	9,5	0,113	11,3%
Operation Cost	0,5	0,5	2,0	2,0	1,0	1,0	0,5	2,0	9,5	0,113	11,3%
Level of Contamination	1,0	1,0	3,0	3,0	2,0	2,0	1,0	2,0	15,1	0,179	17,9%
Sunk Cost	0,3	0,3	3,0	3,0	0,5	0,5	0,5	1,0	9,2	0,110	11,0%

Table 4.6: Concept-scoring Matrix

		Centrifugal Separation		Bio Flocculation		Electro Coagulation		Magnetic Flocculation		Fine Mesh Filtering		Dissolved Air Flotation	
Evaluation Criteria	**Weight %**	**Score**	**Weighted Score**	**Score**	**Weighted Score**	**Score**	**Weighted Score**	**Score**	**Weighted Score**	**Score**	**Weighted Score**	**Score**	**Weighted Score**
Max Throughput	**19,1**	4	0,764	2	0,382	3	0,573	3	0,573	5	0,955	3	0,573
Level of Separation	**19,1**	5	0,955	5	0,955	5	0,955	5	0,955	1	0,191	5	0,955
Dimension	**5,2**	4	0,208	4	0,208	4	0,208	4	0,208	5	0,26	3	0,156
Weight	**5,2**	3	0,156	2	0,104	2	0,104	2	0,104	5	0,26	2	0,104
Power Consumption	**11,3**	3	0,339	5	0,565	3	0,339	4	0,452	5	0,565	4	0,452
Operation Cost	**11,3**	3	0,339	1	0,113	3	0,339	3	0,339	5	0,565	4	0,452
Level of Contamination	**17,9**	5	0,895	4	0,716	3	0,537	3	0,537	5	0,895	5	0,895
Sunk Cost	**11**	1	0,11	3	0,33	2	0,22	2	0,22	5	0,55	2	0,22
Total Score		3,766		3,373		3,275		3,388		4,241		3,807	
Rank		3		5		6		4		1		2	

The concept scoring matrix resulted in four concepts being kept for further analyzing and development, namely Fine Mesh Filtering, Dissolved Air Flotation, Centrifugal Separation and Magnetic flocculation.

Fine mesh filtering, although having the highest score, cannot be expected to be used as a primary way of separating the algae from the water due to the existence of small particles of microalgae that would become clogged in the filter. Still, it might be used for pre- and post-processing of the water. The other filters could be damaged by debris, which can be filtered out using the fine mesh filtering system. Moreover, the filtered algae might still contain a large amount of unnecessary water that, if the algae are large or coagulated enough, could be filtered out using a fine mesh filter.

The second-best rated concept was the Dissolved air flotation system, which is a feasible option. The feasibility of this concept is strengthened by the fact that is has been thoroughly tested and designed specifically to separate algae from water. Even so, there are no documented records of a Dissolved air flotation being used on a boat. Therefore, there are many uncertainties regarding the effects that the unstable support will have on the mechanical parts of this system and whether the general working principle is still valid.

The centrifugal separator was rated as the third best concept, and it is regarded as a suitable concept for filtering out algae from water. There are two major issues with the centrifuge that need to be addressed before being able to use it on the TAH. The first issue is that there are no records of it being tested on a boat, and, therefore, the effect that the angular momentum has on the boat is unknown. The second issue is also associated with using it on a boat. The effect that the boat's rocking and turning has on the centrifuge is unknown. It will most likely have a negative impact on bearings and other mechanical parts that would need to be upscaled.

The lowest ranked concept that is still being kept for improvement is the Magnetic Flocculation. As opposed to the other concepts, it does not seem to be any problem regarding using Magnetic Flocculation on a boat. Moreover, the reason that the Magnetic Flocculation ranked low in the scoring matrix was due to the throughput rate, level of contamination and operation cost, some of which could be improved, rendering Magnetic Flocculation a considerable option still.

4.3 Concept improvements

In this subchapter, each concept that has passed through the concept elimination and evaluation successfully is improved in its function and properties.

4.3.1 Dissolved Air Flotation

The dissolved air flotation system scored highest of all remaining concepts and would be ideal if the sunk cost, weight and dimensions could be improved. Besides these, the criterion with the most impact is the throughput rate, which can be improved at the expense of increasing the weight, dimension and sunk cost by selecting a larger model.

The use of a dissolved air flotation system on a boat has, as mentioned earlier, not been documented formerly, which might lead to unexpected problems if it is implemented on the TAH. One example of these unexpected issues could be that the water in the large tank moves around to a great extent, which would cause the scrapers to lose their function of scraping algae off of the surface, and, in addition, generate a lot of instability when the TAH turns and accelerates.

The DAF system could possibly be damaged by non-algal debris found in the water. A mechanism to filter out large particles and debris before the algae mixed water is let into the DAF system would therefore be required. A fine mesh filter could be utilized for this purpose; it could be used both in pre- and post-processing of the water mixed algae.

A dissolved air filtration system with the desired throughput sold by *Yosun Environmental* has an operating weight of 18000 kg. This is a major obstacle to overcome if this concept is to be implemented. This large operating weight originates from the amount of water the system holds, since the rest of the system only weighs 2200 kg.

To solve this, the team could take inspiration from other vessels that carry large amounts of liquid, such as tankers. Tankers manage to carry large weights in liquid with efficiency and stability.

4.3.2 Centrifugal Separation

The centrifuge scored second best of all the remaining concepts. The weak points of the centrifuge are its dimension, weight, power consumption, sunk cost and operating cost. The sunk cost score has the possibility of improvement. The investment cost used in the calculations as of now is for buying a single centrifuge. The investment cost per centrifuge could most likely be reduced if several centrifuges were purchased simultaneously. Another possibility would be to select a larger centrifuge and scale up the whole operation in order to reduce cost per total volume harvested, leading to a smaller operating cost but a larger investment cost. The rest of the disadvantages of the centrifuge - that is the dimension, weight, power consumption and operating cost – do not have any room for improvement.

Regarding the issues of operating a centrifuge on the sea, bearings and other mechanical parts that would suffer from fatigue could be upscaled to become more durable. Furthermore, the fact that gyroscopes, which are components that rotate with about the same mass and speed as the centrifuge, have been used in different types of vessels and even on commercial boats proves that they can handle the large forces created by the centrifuge (Perez, 2009). The whole centrifuge could also be mounted on a damped platform so that most of the torque would be absorbed by springs instead of being directly transferred to the ship. The centrifugal separation system would most likely benefit from implementing the fine mesh filtering in both pre- and post-processing of the water mixed algae. Since the centrifuge cannot handle large debris, and the centrifuge not being able to deliver completely dry algae, implementing fine mesh filtering or a similar system in pre- and post-processing would be a large improvement.

4.3.3 Magnetic Flocculation

The Magnetic Flocculation would need to be improved in multiple different areas to be a valid contender for use in the end product. The throughput rate and operating cost are two big aspects that would need to be improved. The throughput rate could easily be improved by flocculating larger amounts of water at a time which would necessitate a larger and heavier machine.

Furthermore, the magnetic flocculation system requires a secondary process to remove the sedimented algae from the water. One secondary process that could be implemented, if the algae are large enough, is the fine mesh filtering system. If the flocculated algae are not large enough for the fine mesh filtering system to be implemented, a DAF or Centrifuge could be used, giving an improved efficiency.

4.4 Re-evaluation

To make a fairer judgement between the three remaining concepts, a DAF-system which matches the throughput rate of the centrifuge is used in the second scoring matrix. The DAF-system used in the specifications is the model PCL-30 manufactured by the company FRC. The magnetic flocculation method has a similar throughput rate and, thus, will not be scaled up. The new specifications are shown in *Table 4.7* and *Table 4.8.*

Table 4.7: Specifications.

Concept	Max through-put rate $[m^3/h]$	Level of separation	Length [m]	Height [m]	Width [m]	Gross-weight [kg]
Centrifugal separation	75	99%	1.75	1.823	1.73	2800
Magnetic flocculation	30-60	99%	2	2	1	4800
Dissolved Air Flotation	74.9	99%	3.8	2.4	3.15	12,250

Table 4.8: Specifications (continued).

Concept	Energy requirement $[kWh/m^3]$	Running cost $[US\$/m^3]$	Price [US$]	Level of contamination
Centrifugal separation	0.5	Energy requirement	282,000	Non existing
Magnetic flocculation	~0.2	0.13	~100,000	Moderate
Dissolved Air Flotation	0.45	Energy requirement	250,000	Non existing

With the addition of a criteria for the separation method's impact on the stability of the TAH, the improved concepts are evaluated once more using the Analytical Hierarchy Process matrix in *Table 4.3*, and the Concept-Scoring Matrix in *Table 4.9*.

Table 4.9: Second Concept-Scoring Matrix

		Centrifugal Separation		Magnetic Flocculation		Dissolved Air Flotation	
Evaluation Criteria	**Weight %**	**Score**	**Weighted Score**	**Score**	**Weighted Score**	**Score**	**Weighted Score**
Max Throughput	**16,9**	5	0,845	4	0,676	5	0,845
Level of Separation	**16,9**	5	0,845	5	0,845	5	0,845
Dimension	**5,9**	5	0,295	5	0,295	2	0,118
Weight	**5,9**	5	0,295	4	0,236	2	0,118
Power Consumption	**11,7**	3	0,351	5	0,585	4	0,468
Operation Cost	**11,7**	4	0,468	3	0,351	5	0,585
Level of Contamination	**16**	5	0,8	3	0,48	5	0,8
Sunk Cost	**9,1**	4	0,364	5	0,455	4	0,364
Impact on Vessel Stability	**5,8**	4	0,232	3	0,174	2	0,116
Total Score		4,263		3,923		4,143	
Rank		1		3		2	

4.4.1 Selection

Based on the scoring in *Table 4.9* the final decision was to use the centrifuge as the separation method for the algae-harvesting system. The main advantages of this method are its large throughput rate, its relatively small size and low weight. These positive attributes of the centrifuge enhance the efficiency of storage capabilities of separated algae, which renders the need to return to the shore for unloading less frequent.

4.5 Laboratory experiment

To confirm that the centrifugal separation method would work for separation of wild algae and not just for food processing, a minor experiment was conducted. However, due to Covid-19 the available laboratory equipment was limited to only a centrifuge which reduced the experimental extent.

4.5.1 Method

To start growing wild algae, three samples were taken at three different places around Gothenburg with a volume of approximately 0.5L each. Thereafter, 10 ml of flower fertilizer was added, which contained approximately 0.5 g nitrogen, 0.2 g ammonia, 0.1 g phosphorus and 0.4 g calcium, after which the bottles were placed on a window counter to grow for six weeks.

For centrifugation, a 15 ml falcon tube was used and filled with algae from the sample with the highest cell concentration. The concentration was estimated by eye since equipment such as a spectrophotometer were unavailable. The bottle with the sample was mixed before filling each tube. The tubes were filled to a total weight of approximately 19 g before centrifugation at 4800 rpm for five minutes. The results were analyzed and the same procedure was repeated two additional times, with the centrifuge at 4800 rpm for 10 minutes as well as 3800 rpm for five minutes. The results were analyzed and the supernatant was collected in a separate container.

Since the efficiency of the centrifuge was not being measured during the experiment due to limited equipment available, the supernatant was collected and cultivated an additional three weeks. The supernatant was then analyzed and compared to the used sample.

4.5.2 Results

The number of wild algae that had grown after the cultivation period differed depending on the origin of the sample. Two of the different samples are shown in *Figure 4.8*, and it is clear that bottle number 2 contains more algae. Therefore, the experiment was performed using the sample from bottle 2.

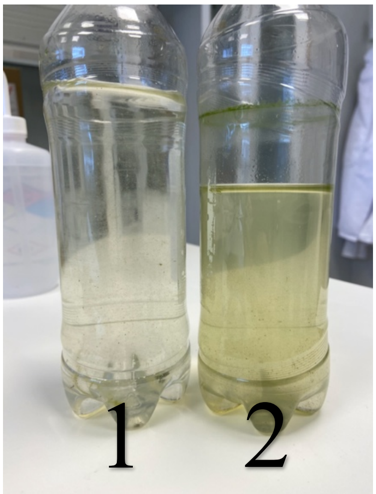

Figure 4.8: Two samples with different origin after cultivation

The results from centrifuging the algae at 4800 rpm for five minutes are displayed in *Figure 4.9*, where the pellets are distributed over the entire side of the tube due to the tube station in the centrifuge being in a fixed position.

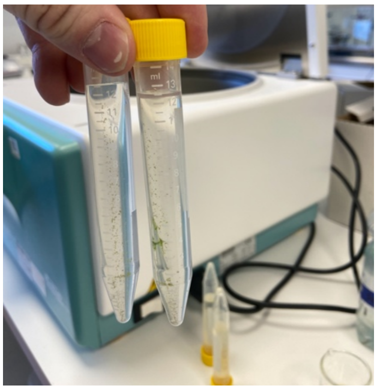

Figure 4.9: Results after centrifugation at 4800 rpm and five minutes

Figure 4.10 shows the sample before and after centrifugation, where tube number 1 has not been centrifuged yet while tube number 2 has been centrifuged at 4800 rpm for five minutes. The liquid in tube 1 and the supernatant in tube 2 do not differ in clarity even after algae separation.

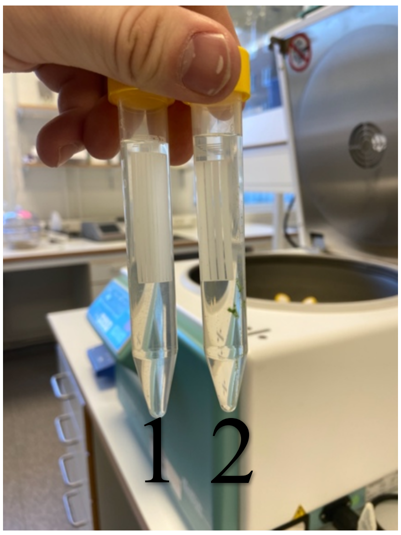

Figure 4.10: Tubes before (nr 1) and after (nr 2) centrifugation at 4800 rpm for five minutes

The tubes that were centrifuged at 4800 rpm for ten minutes are shown in *Figure 4.11* with the pellets collected more towards the bottom of the tube.

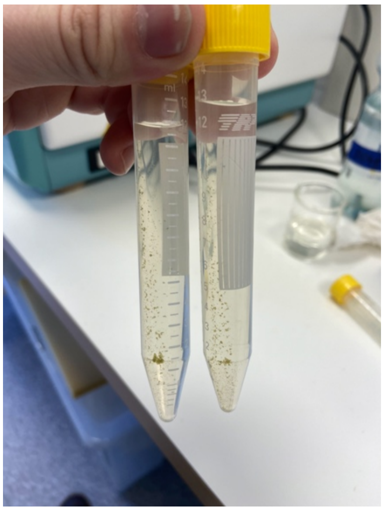

Figure 4.11: Results from centrifugation at 4800 rpm for ten minutes

Figure 4.12 displays the results after centrifuging the sample at 3800 rpm for five minutes. Although both tubes are from the same sample there still is a difference in the amount of pellets.

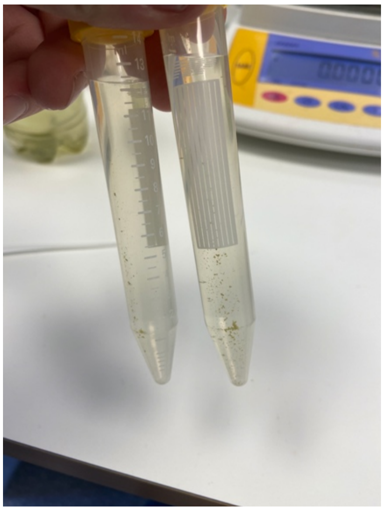

Figure 4.12: Tubes after centrifugation at 3800 rpm for five minutes

The supernatant from each tube was collected into bottle 1, while bottle 2 contains the sample used. This is displayed in *Figure 4.13*. There is a visible difference in cell concentration where bottle 1 is almost completely transparent.

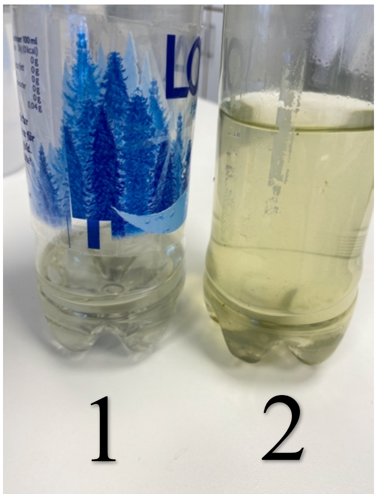

Figure 4.13: Collected supernatant in bottle 1 and sample used in bottle 2

After the laboratory part of the experiment the supernatant and the sample were allowed to grow an additional three weeks, the results of which are given in *Figure 4.14*. The bottles were flipped for better visibility. There are a lot of visible cells in bottle 2, which is the regular sample, while there are almost no visible cells in bottle 1, which contains the supernatant.

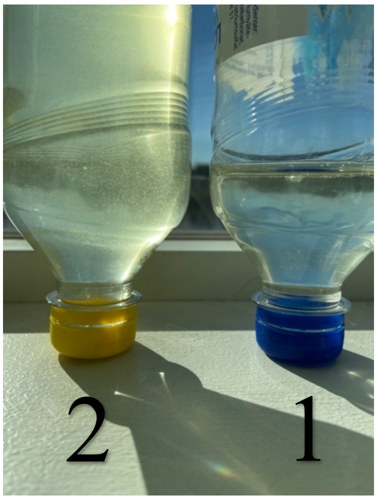

Figure 4.14: Collected supernatant and sample after a three-week cultivation

4.5.3 Conclusion

Due to the fact that the microorganisms in the samples were not analyzed there might be other species present and not just algae. However, the focus of this project is on wild algae, and during wild algae blooms there are more than one species present, for which reason it was not necessary to analyze the sample content further. For simplicity, the microorganisms are referred to as algae or pellets. The decided 4800 rpm was used because it is the maximum speed the chosen centrifuge to be used on the TAH can achieve, with the difference that the one on the TAH would be a continuous centrifuge while the experimental one used tubes. Still, the principle is the same.

When comparing the tubes in *Figure 4.10*, there is no difference in clarity between the sample and supernatant, but as seen in tube 2 there are a lot of pellets stuck on the wall. The same amount should be present in tube 1, but due to the size and volume of the tube it is not visible to the eye. This also indicates that the centrifuge is able to separate microalgae that is not visible in small volumes, but not to which extent. When comparing the results from the different centrifugation values, which are given in *Figure 4.9, Figure 4.11* and *Figure 4.12*, there is a distinct difference in amount of pellets present. Especially when analyzing *Figure 4.12* where the centrifuge was put to 3800 rpm, the number of pellets is clearly less than in the other samples, from *Figure 4.9* and *Figure 4.11*, which indicated that the centrifuge on the TAH should be kept at maximum speed.

There are two distinct differences between *Figure 4.9* and *Figure 4.11*, namely the amount and location of the pellets. There are more visible pellets in the tubes in *Figure 4.11* and in addition they are located more towards the bottom of the tube than for the tubes in *Figure 4.9*. However, due to the dry weight not having been noted it is not possible to guarantee that there are more pellets in the tubes that were centrifuged for ten minutes than the tubes that were centrifuged for 5 minutes, even if it most likely is so.

A way of analyzing the efficiency of the centrifuge was to cultivate the supernatant separately, for the reason that if algae are present in the solution they would keep growing. However, as seen in *Figure 4.14*, there are no tracks of cellular activity after cultivation, which most likely would indicate that the centrifuge was very successful in removing the algae. Another possible reason could be that the algae did not survive the centrifugal force or that the nutrients were not enough for growth, although this is not very likely due to the fact that no cells or sedimentation were observed in the solution.

In summary, the experiment was successful, the centrifuge separated the algae from the water with a high efficiency if used at maximum speed, and could therefore be used on the TAH.

5 HARVESTING CONCEPTS

This chapter describes the process of creating, eliminating, improving and selecting one concept for transporting algae mixed water from the lake or sea onto the TAH for separation. Numerical values were calculated and researched for each concept in order to compare them in a fair manner. The concepts were evaluated and improved and finally one of them was singled out to be used on the TAH.

5.1 Harvester Concept Generation

The following concepts were created in two steps – first, in a brainstorming session conducted by a part of the team and, second, by an external search on similar or competitive products.

5.1.1 Super scooper

A source of inspiration is the mechanism for water collection on the firefighting plane Bombardier 415 "Super Scooper" shown in *Figure 5.1*. The water collection mechanism on the Super Scooper works by flying "into" the water at a speed of roughly 160 km/h and opening flaps on the bottom of the plane that lead into a tank capable of holding 6000 liters of water. The process of filling the tank only takes 12 seconds (Pröckl, 2014).

As the TAH being designed is not nearly as fast as the Super Scooper is, the exact same mechanism would most likely not be a feasible option. However, the principle of using the kinetic energy of a moving vessel as a way of transporting water could be implemented, and, even though it in itself might not be sufficient, could make the system require a smaller pump since some of the kinetic energy is utilized.

Another part of the Super Scooper-mechanism that could be used in the TAH is the option to open and close the flaps. A way of both reducing drag when not harvesting algae by closing the collection mechanism and adjusting the depth of collection would be beneficial for the end user. The major benefits of the Super Scooper collection mechanism are the fact that it is very fast and its possibility to adjust depth and reduce drag. The main disadvantages of the Super Scooper collection mechanism, if it were to be implemented on the TAH, are that it might not work at such low speeds, and that it might be difficult to pre-filter the water so that large debris and marine life do not get stuck in the separator at the required speed.

Figure 5.1: Bombardier 415 "Super Scooper" (Wikimedia, 2015)

5.1.2 Funnel

When doing product development, observing animals and nature is a great way of gathering inspiration. The process of taking inspiration from nature is called biomimetics (Bhushan, 2016). When observing marine life, the basking shark was identified as an interesting source of inspiration, shown in *Figure 5.2*. The basking shark with its funnel shaped mouth filters out 2000 tons of water per hour, well exceeding the throughput-rate requirement for the algae Toxic Algae Harvester (Knickle, Billingsley & DiVittorio., 2020).

Figure 5.2: Basking shark (Stafford-Deitsch, n.d)

One problem to overcome using this method is the need for elevating the water up on the TAH where the algae will be separated from the water. There are several different solutions to this problem, one of which is to simply implement a pump to get the required amount of water on to the TAH. Another solution might be to let the cross-sectional area decrease - i.e. make the funnel tapered - so that the velocity increases. A simple CAD-model of this is shown in *Figure 5.3*.

In order to control when to collect water, decrease drag and adjust the depth of collection, the funnel could have the ability to open and close. By deciding a moving speed for algae collection, the size of the funnel can be designed to meet the through-put rate requirements.

With an assumption of a constant flow of mass and everything actually flowing through the funnel, the volume flow rate $\dot{V}$ can be calculated as the cross-sectional area A times the velocity v.

$$\dot{V} = A \cdot v = 1\ \mathrm{m}^2 \cdot 1\ \mathrm{m/s} = 1\ \mathrm{m}^3/\mathrm{s} = 3600\ \mathrm{m}^3/\mathrm{h} \quad (6)$$

Note that 3600 cubic meters per hour is a maximal value and most likely a lot larger than the actual throughput since water will get slowed down due to the added potential energy and then the flow of mass will no longer be constant.

Another way of calculating if this concept could work on its own is to assume that all the kinetic energy of the water turns in to potential energy by elevating the water. That leads to the equation:

$$0.5\ \mathrm{mv}^2 = mgz \rightarrow z = \frac{0.5v^2}{g} = 0.05\ \mathrm{m} = 50\ \mathrm{mm} \quad (7)$$

where z is the elevation in meters, v is the velocity in meters per second, m is the weight of the lifted water in kg and g is the gravitational acceleration. This way of analyzing the concept concludes that the maximal possible elevation at a speed of 1 m/s is 0.05 m or 50 mm, which is not nearly enough to get the algae mixed water onto the TAH for separation. The required speed V for elevating the water two meters, assuming no loss, can be calculated as:

$$V = \sqrt{2gz} = \sqrt{2 \cdot 9.81 \cdot 2} = 6.26\ \mathrm{m/s} \quad (8)$$

A speed of 6.26 m/s is way too fast and, hence, the conclusion is that this concept would require a pump in order to be feasible.

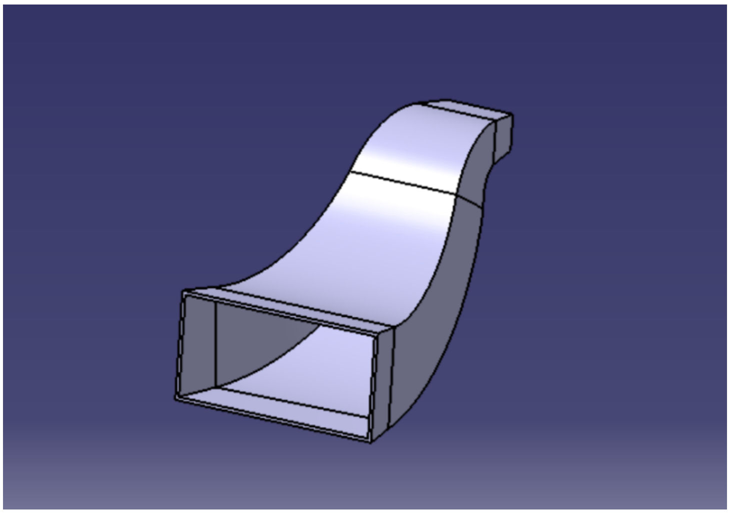

Figure 5.3: CAD-drawing of funnel.

The main advantages of the funnel concept are the possibility of a very large through-put rate, its simple design, the ability to adjust the collection depth and the simple implementation of a pre-filtering system. The main disadvantages are that the required velocity to elevate the water enough is too high, which, firstly, necessitates the use of a pump and, secondly, causes the large opening of the funnel in the water to increase the drag force on the TAH a lot.

5.1.3 Paddle wheel with buckets

This concept is inspired by the old paddle wheels used to generate energy prior to the invention of steam engines in the late 17th century and that were implemented in industrial use in the mid 18th century (Palermo, E. 2014). An example is shown in *Figure 5.4*.

This concept would be an inverted paddle wheel that instead of generating energy from the moving water, would use energy to move water. The paddlewheel would be mounted on the TAH in a way so that the energy input is not only used for collecting water but also to provide propulsion for the TAH. To make sure no water leaks out of the paddle wheel when it rotates, it would be enclosed with holes in the enclosure only for filling and emptying each compartment of water, as visualized in *Figure 5.5*.

If both the propulsion and collection part of this concept work well, it would have a major advantage compared to other concepts. However, the beauty of this concept is also its main disadvantage; achieving both collection and propulsion in the same system will require a lot of moving parts, and to fulfill the throughput requirement, the size of the wheel would need to be very large and complex, leading both to high energy consumption and to the system being more prone to failure. Further, the flow of water would not be constant and would in addition have zero pressure, leading to the need of a buffer tank and a pump which in total makes a large and heavy system.

Figure 5.4: Waterwheel at Watermill, NY (Ruffins, 2018).

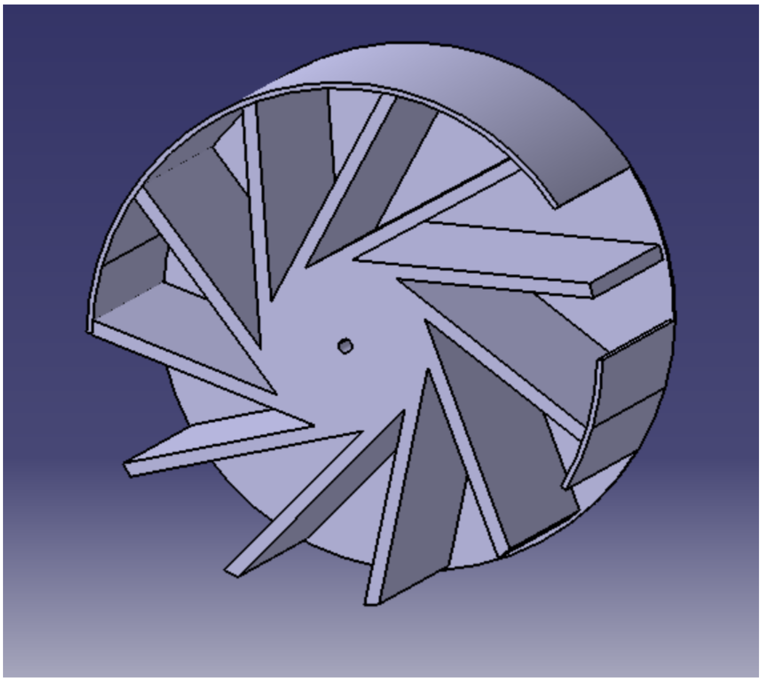

Figure 5.5: Sketch of paddle wheel for harvesting

5.1.4 Pump

A simple, tested and proved way of moving water is to use a pump. Pumps are commercially available in a multitude of different models and sizes. There are two main types of pumps, dynamic change pumps and positive- displacement pumps (PDPs). A PDP delivers the flow by trapping the fluid and displacing the fluid out through the discharge opening. These pumps have the advantages of being able to handle any viscosity, as well as being self-priming - i.e. they do not need to be filled with liquid upon startup. However, a notable disadvantage is the fact that they are sensitive for blocking in the discharge pipe. If the discharge pipe would be blocked by debris, for example, or if the separation machine would be shut off, a huge pressure would build up in the pump, which would lead to damages. Therefore, it is necessary that pressure relief valves be installed in the system if this kind of pump is to be used. The other type of pump, the dynamic change pump, works by adding momentum to the fluid by fast moving blades. This type of pump has the advantage of being simple, robust and being able to adjust the flow rate by changing the rotational speed. Disadvantages include the lack of ability to handle high-viscosity fluids and the need of priming (White, 2016). *Figure 5.6* shows a schematic sketch of a dynamic change pump.

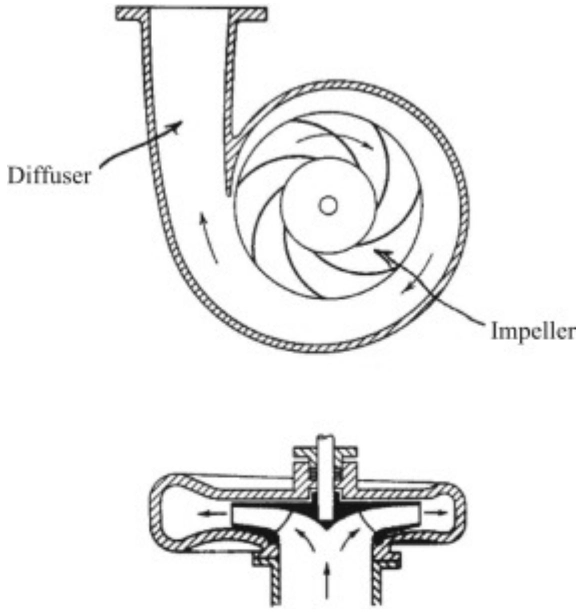

Figure 5.6: Dynamic change pump (Guo, Liu and Tan, 2017)

A problem that the pump would need to overcome is that there are not only algae in the water but also larger debris, particles and marine life that could damage the system. The inlet of the pump would need a small enough filter to separate large debris but large enough to let algae through fast enough. One problem with a pump just fitted with a hose in the water is that it only sucks up the fluid at that exact spot, which at times could consist of only water. It is preferred that the collection area is more diverse to make sure there are always algae entering the separator and, therefore, it needs to be fitted with some kind of funnel.

5.1.5 Submerged tank

In the brainstorming session, a different way of looking at the problem was identified: instead of elevating the water, which consumes a lot of energy, there is the possibility of moving the separator below the surface in order to minimize energy consumption.

With this idea in mind, a new concept was generated called the submerged tank. A simple design of how the submerged tank could be outlined is visualized in *Figure 5.7* with both flaps closed, and in *Figure 5.8* with the back flap closed. The water would be retrieved by opening flaps on the front and back of the tank to let the cleaned water out and new water in.

There are three major problems with this concept that would need to be solved. First of all, it would be a quite complex design whether the separator needs to be submerged or not. Second, it would have a negative impact on the dynamics of the TAH and increase the drag force. Last of all, it could prevent the TAH from being able to go on shallow depths near the coast.

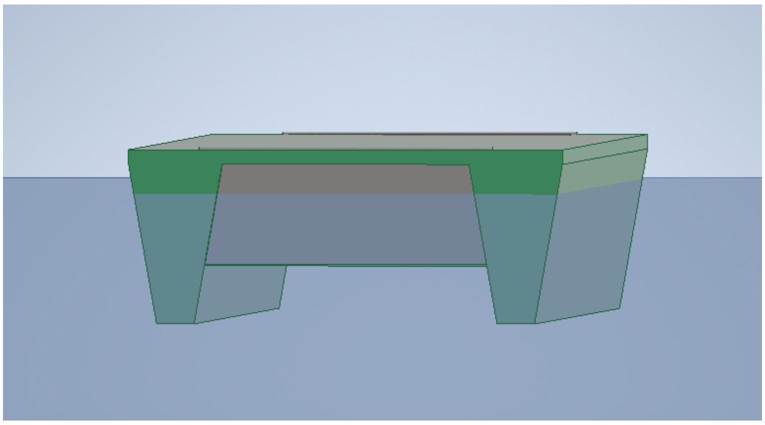

Figure 5.7: Submerged tank with flaps closed

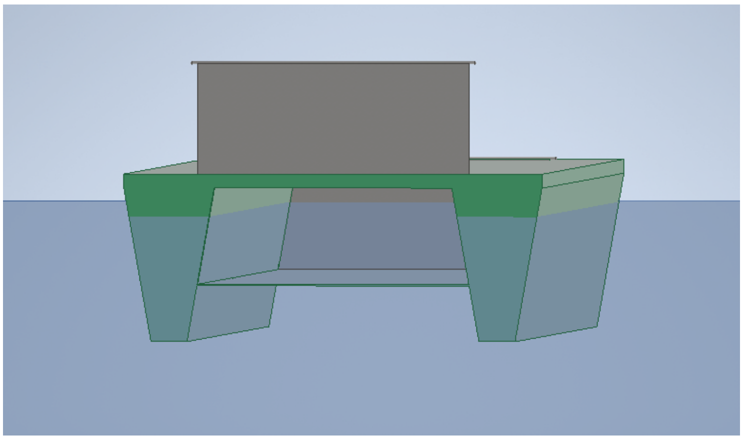

Figure 5.8: Submerged tank with back flap closed

5.1.6 Conveyor belt

The conveyor belt design is a widespread method for harvesting macroalgae from oceans. *Figure 5.9* shows an existing harvester using this concept. This concept is not suitable as a harvester design in this project because of the large holes in the belt through which the microalgae would slip. One possibility to make this system work would be to mount scoops on the belt– instead of the holes on it - and collect the water in a way similar to the paddle-wheel concept. Advantages of this method are that some aspects of the design could be re-used from existing solutions and that it has the ability to include an adjustable depth for collection. Disadvantages include the uneven flow of fluid because of the scoops on the belt, and that in order to meet the throughput requirements it would need to be large, and, therefore, heavy.

Figure 5.9: Harvester with conveyor belt (Aquarius Systems, 2010)

5.2 Concept Evaluation

The first step in the concept evaluation was to identify the necessary evaluation criteria and evaluate how well each concept fulfills the criteria. This step is listed in *Table 5.1* and continued in *Table 5.2*.

Table 5.1: Concept evaluation

Concept	Flow rate [m^3/h]	Flow	Added drag force	Power Consumption	Added propulsion	Collection depth
Super Scooper	Unsatisfactory	Steady	Moderate	Moderate =added drag force	None	Adjustable
Funnel	Unsatisfactory	Steady	High	High =added drag force	None	Adjustable
Paddle wheel	Satisfactory	Unsteady	Low	High	Yes	Depends on design
Pump	Satisfactory	Steady	Low	Moderate	Low	Depends on design
Submerged tank	Stationary	Unsteady	High	High	None	Depends on design
Conveyor belt	Satisfactory	Unsteady	Moderate	Moderate	Low – none	Adjustable

Table 5.2: Concept evaluation (continued)

Concept	Collection width	Weight	Cost	Complexity	Risk of harming marine life	Need of maintenance	Compatibility with centrifuge
Super Scooper	Depends on design	Low	Low	Low	Moderate	Low	High
Funnel	Depends on design	Moderate	Moderate	Moderate	Moderate	Low	High
Paddle wheel	Depends on design	High	High	High	Moderate	Moderate	Low
Pump	Low	Low	Low	Low	Moderate	Low	High
Submerged tank	Depends on design	Moderate	Moderate	High	High	Low	Low
Conveyor belt	Depends on design	Moderate	High	High	High	High	Low

The second step of the concept evaluation was to evaluate each criterion and assign a weight to it. This was conducted in the same way as for the separation concept evaluation, with an AHP matrix created by the team members with the client's input taken into account, shown in *Table 5.3*.

Table 5.3: Analytical hierarchy matrix

	Flow Rate	Flow Type	Added Drag force	Power Consumption	Added Propulsion	Collection Depth	Collection Width	Weight	Cost	Complexity	Risk of Harming Marine Life	Need of Maintenance	Compatibility With Centrifuge	Total	Weight	Weight (%)
Flow Rate	1,0	0,5	2,0	1,0	3,0	1,0	1,0	2,0	3,0	0,3	0,3	2,0	0,3	17,5	0,077	7,7%
Flow Type	2,0	1,0	2,0	2,0	2,0	1,0	1,0	2,0	2,0	0,3	0,3	2,0	0,3	18,0	0,079	7,9%
Added Drag force	0,5	0,5	1,0	1,0	2,0	0,3	0,5	1,0	1,0	0,5	0,3	1,0	0,3	10,0	0,044	4,4%
Power Consumption	1,0	0,5	1,0	1,0	2,0	0,5	1,0	1,0	2,0	0,5	0,3	2,0	0,3	13,2	0,058	5,8%
Added Propulsion	0,3	0,5	0,5	0,5	1,0	0,3	0,5	0,5	0,5	0,5	0,3	0,5	0,3	6,3	0,028	2,8%
Collection Depth	1,0	1,0	3,0	2,0	3,3	1,0	3,0	3,0	2,0	2,0	0,3	2,0	0,3	24,0	0,105	10,5%
Collection Width	1,0	1,0	2,0	1,0	2,0	0,3	1,0	2,0	2,0	0,5	0,3	2,0	0,3	15,5	0,068	6,8%
Weight	0,5	0,5	1,0	1,0	2,0	0,3	0,5	1,0	1,0	0,3	0,3	2,0	0,3	10,8	0,048	4,8%
Cost	0,3	0,5	1,0	0,5	2,0	0,5	0,5	1,0	1,0	0,5	0,3	0,5	0,3	9,0	0,039	3,9%
Complexity	3,0	3,0	2,0	2,0	2,0	0,5	2,0	3,0	2,0	1,0	0,3	1,0	0,3	22,3	0,098	9,8%
Risk of Harming Marine Life	3,0	3,0	3,0	3,0	3,0	3,0	3,0	3,0	3,0	3,0	1,0	3,0	1,0	35,3	0,155	15,5%
Need of Maintenance	0,5	0,5	1,0	0,5	2,0	0,5	0,5	0,5	2,0	1,0	0,3	1,0	0,3	10,7	0,047	4,7%
Compatibility With Centrifuge	3,0	3,0	3,0	3,0	3,0	3,0	3,0	3,0	3,0	3,0	1,0	3,0	1,0	35,3	0,155	15,5%

The criteria with the greatest influence are compatibility with centrifuge and risk of harming marine life. When all criteria had been weighted, the last step of the concept evaluation process was to evaluate all concepts using the weighted values from *Table 5.3*. The concept evaluation was done using a concept scoring matrix, shown in *Table 5.4*.

Table 5.4: Concept-scoring matrix

		Super Scooper		**Funnel**		**Paddel Wheel**		**Pump**		**Submerged Tank**		**Conveyor Belt**	
Evaluation Criteria	**Weight %**	**Score**	**Weighted Score**	**Score**	**Weighted Score**	**Score**	**Weighted Score**	**Score**	**Weighted Score**	**Score**	**Weighted Score**	**Score**	**Weighted Score**
Flow Rate	**7,7**	1	0,077	1	0,077	5	0,385	5	0,385	5	0,39	5	0,385
Flow Type	**7,9**	5	0,395	5	0,395	3	0,237	5	0,395	1	0,08	3	0,237
Added Drag Force	**4,4**	4	0,176	1	0,044	1	0,044	3	0,132	1	0,04	3	0,132
Power Consumption	**5,8**	2	0,116	3	0,174	5	0,29	3	0,174	4	0,23	3	0,174
Added Propulsion	**2,8**	1	0,028	1	0,028	5	0,14	2	0,056	1	0,03	2	0,056
Collection Depth	**10,5**	5	0,525	5	0,525	3	0,315	2	0,21	3	0,32	4	0,42
Collection Width	**6,8**	3	0,204	4	0,272	2	0,136	1	0,068	3	0,2	3	0,204
Weight	**4,8**	5	0,24	3	0,144	1	0,048	4	0,192	2	0,1	3	0,144
Cost	**3,9**	5	0,195	3	0,117	1	0,039	2	0,078	3	0,12	1	0,039
Complexity	**9,8**	5	0,49	3	0,294	1	0,098	5	0,49	4	0,39	5	0,49
Risk of Harming Marine Life	**15,5**	3	0,465	3	0,465	3	0,465	4	0,62	2	0,31	1	0,155
Need of Maintenance	**4,7**	5	0,235	5	0,235	3	0,141	4	0,188	4	0,19	1	0,047
Compatibility With Centrifuge	**15,5**	4	0,62	4	0,62	2	0,31	5	0,775	1	0,16	2	0,31
Total Score		**3,766**		**3,39**		**2,648**		**3,763**		**2,545**		**2,793**	
Rank		**1**		**3**		**5**		**2**		**6**		**4**	

The concept scoring matrix resulted in three concepts being kept for improvement. The remaining concepts scored too low and are deemed unworthy of improvement. The remaining concepts in descending order based on total score are: Super Scooper, Pump and Funnel. Although the Super Scooper concept was ranked the highest, it was eliminated based on it not being feasible because of its unsatisfactory flow rate. This means that the Pump concept is the highest ranked of the remaining concepts and will therefore be chosen.

The pump is not perfect and scored low in a few criteria, some of which could be easily improved. A new concept can be created by combining the pump and the funnel, increasing the collection depth and width of the pump and giving the funnel a satisfactory flow rate. Further, the power consumption of the pump would be somewhat decreased but at the cost of an increased drag force.

To conclude, the final collection concept was chosen to be a combination of the funnel and the pump, taking the best parts of each concept to get a concept that fulfills all requirements in a satisfactory manner. A rough model of the final design is visualized in *Figure 5.10*.

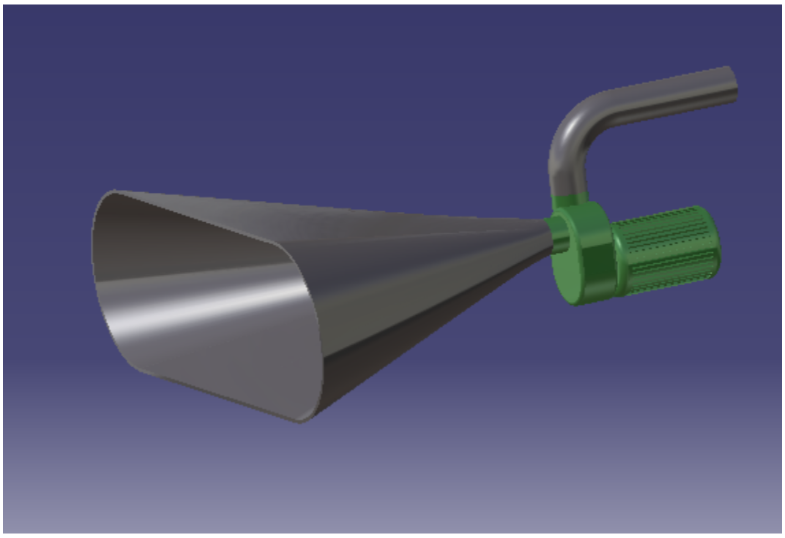

Figure 5.10: Rough model of the final design

5.3 Pump Sizing

After the decision had been made that a pump combined with a funnel would be used to harvest the algae, a suitable pump needed to be chosen. With the help of the information about different types of pumps concluded in section *5.1.4 Pumps,* the team considered that a dynamical change pump would be the most suitable option. The reason was the robustness of this type of pump which is important since it will be used in harsh environments, combined with the relatively compact size and its ability to adjust the flow rate.

To find a suitable dynamic change pump, some fluid-mechanic calculations were conducted. The theoretical power requirement and the NPSHA (Net Pressure Suction Head Available) were calculated and these can be found in *Appendix A*. After some research, a pump with a satisfactory flow rate and a NPSHR (Net Pressure Suction Required) matching the NPSHA was found.

The pump chosen is a Victor S85K312T and the total specifications can be seen in *Appendix B*. Apart from being made of Stainless Steel and being relatively compact, it has the ability of handling solids of sizes up to 40 mm in diameter.

5.4 Algae Storage Tank Design

After the algae is harvested from the body of water, and concentrated through the centrifuge, it must enter a storage facility on the TAH as temporary storage before it can be transported off the TAH to the shore.

In order to evaluate the storage tank size, many factors were taken into consideration. First, the total time of harvesting was evaluated at a four-hour time slot. Since the overall harvesting design revolves around an eight-hour harvesting day – that is two 4-hour time slots - the maximum number of algae that the tank should be designed for is a four-hour period.

The second variable that was taken into consideration was the inflow of water that the pump transports to the centrifuge. This flow of water was determined based on the maximum intake of water that the centrifuge could handle, which was a flowrate of $75\ \mathrm{m^3/h}$. Another factor involving the centrifuge is the efficiency. Assuming that the centrifuge is 99% efficient, the storage tank still needs to account for that extra 1% of the volume.

The third variable that was evaluated was the algae characteristics. Cyanobacteria (blue-green algae) is the most common algae seen in these algae blooms. They can range from 0.5 to 60 micrometers in diameter (Huang, 2014). When conducting the volume calculations, instead of using a spherical cell shape, a cube shape was assumed in order to simplify the volume calculations, thus overestimating the size. Cubes can be fit tightly into a fitted space, as opposed to spheres which have a volume of negative space when in contact with one another.

The last component analyzed for the volume of the storage tank was the concentration of algae in the water where the blooms take place. It was determined that a typical algae bloom has a maximum concentration of $1 \cdot 10^7$algae cells per liter of water (Huang, 2014).

Combining all these factors, the total volume of the storage tank - including an extra 1% due to the 99% efficiency - was determined to be 655 liters. Overall, the final volume determined was rounded up to 1000 liters for two reasons. First, the assumptions made might not be completely consistent with reality, and adding volume might serve to counteract that. Second, a 1000-liter storage tank size is a common, standardized and low-cost storage tank. Because of this an IBC (Intermediate Bulk Container) tank was chosen to be used onboard the TAH.

6 TOXINS

In this chapter the most common toxic molecules are described more in-depth to be able to determine if there is a need for a toxin separation method onboard the TAH. Not all toxins are cell-bounded to the algae and would therefore not be picked up by the centrifuge due to the small size. It could therefore be a need for a separation method to handle the toxins after separation.

6.1 Microcystin

Microcystins are a family of chemical toxins with a cyclic heptapeptide structure that are produced from Cyanobacteria. There are more then 80 naturally occurring variations of the molecule within the family, where the most common one is microcystin-LR (Deon van der Merwe, 2015), which is regarded as a hepatoxin - a toxin that damages the liver (National Center for Biotechnology Information, 2020a).

Studies on microcystin-LR have shown that it is not only toxic with a lethal dose of 50% (LD50) at 5 mg/kg given orally to rats (U.S. National Library of Medicine, 2020) but it has also shown irritant effects on skin and eyes (National Center for Biotechnology Information, 2020). Because of the molecules' high toxicity, the world health organization (WHO) has decided on a guideline that drinking water should not contain more than a total of 1 µg/L microcystin-LR, which includes cell-bunded molecules (World Health Organization, 2008).

The molecule does not show potential of bioaccumulative characteristics due to the low log P (Octanol-water partition coefficient) ranging from 1.67 to -1,41; If log $P<3.5$ it is most likely not bio-accumulative (McCord et al, 2018). However, the molecule does show persistent characteristics within the liver when tested on mice, without a major change in concentration over a 6-day period (National Center for Biotechnology Information, 2020).

However, microcystins' half-life in reservoir waters is reported to be less than one week, due to the fact that other microorganisms are able to break down the molecule. Another factor that could contribute to the results are that sunlight have shown a minor ability of breaking down the toxin (National Center for Biotechnology Information, 2020).

Instead of waiting for the toxin to degrade itself, scientists have shown that exposing the molecule dissolved in water to UV light increases the decomposition at 36% compared to normal sunlight. The use of a Carbon filter showed even higher efficiency where only 0.05 to 0.3% of microcystin-LR passed through (National Center for Biotechnology Information, 2020).

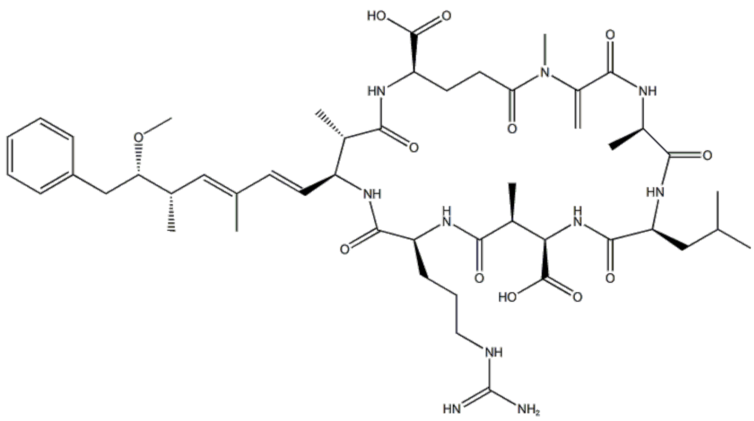

Figure 6.1: Molecular structure of microcystin-LR (Chemical book, 2020)

6.2 Anatoxin-a

Anatoxin-a is a natural neurotoxin produced by many species in the domain cyanobacteria. It is a highly toxic compound that has caused the death of domestic animals and wildlife within hours of exposure due to inhibition of neuron receptors, which leads to overstimulation and later on to respiratory paralysis (National Center for Biotechnology Information, 2020b). Real-life events and laboratory studies have therefore classified anatoxin-a as irritant and health hazardous with a LD50 at 5 mg/kg when given orally to mice (National Center for Biotechnology Information, 2020b), which have led to regulatory guideline of anatoxin-a in drinking water to range from 3 to 6 µg/L depending on country (Vlad, et al. 2014).

When observing the molecular properties, the toxins are not likely to be bioaccumulative, due to a log P value at around 1.12. It is also not considered persistent due to half-life ranging from 5 to 21 days in reservoir water depending on pH and presents of sedimentation (National Center for Biotechnology Information, 2020c); molecules are considered persistent if half-life > 60 days in water (Vallero, DA., 2005). The lowest half-life at 5 days were observed when a bed of sedimentation was present in the water which suggests that biodegradation is an important factor for the half-life - biodegradation is when microorganisms break down organic matter (National Center for Biotechnology Information, 2020c). However, there are also records of anatoxin-a having a half-life less than 24 hours in natural blooms in eutrophic lakes (Trainer & Hardy, 2015).

Furthermore, researchers have studied methods on how to degrade or remove the toxins faster where one of the methods used UV light to create an oxidation agent to break down the toxin. The results varied depending on UV light used, but when exposing anatoxin-a for 300 s to Vacuum UV light (VUV) it degraded by 70 and 85% depending on if natural water or synthetic water was used, which correspond to a high UV exposure of 193 mJ/cm^2 (Afzal, et al, 2010); UV light with wavelength <200 nm (Pile, D.F.P, 2018).

The use of a wood-based carbon filter is considered the most efficient method for filtrating microcystins and have shown great potential in absorbing other toxins such as anatoxin-a. There is, however, not enough research on the effect carbon filter has on anatoxin-a specifically, and it is not appropriate to use the well-studied microcystins as an indicator of the absorption potential carbon filter as on anatoxins-a (Vlad, et al, 2014a), which is mainly due to the difference in chemical structure and size. Therefore, it is more proper to compare it with similar molecules, such as 2-methylisoborneol and geosmin (Vlad, et al, 2014a), where one study showed that by using granular active carbon and sand as a filter could remove 47 to

100% of 2-methylisoborneol and 76 to 100% of geosmin (Alhadi, Huck & Slawson, 2004). The use of carbon in a filter to remove anatoxin-a could therefore be a feasible solution, but a specific study would be needed for confirmation (Vlad, et al, 2014b).

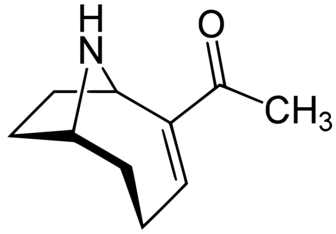

Figure 6.2: Molecular structure of anatoxin-a (Yikrazuul, 2009)

6.3 Saxitoxin

Saxitoxin is a highly toxic compound classified as a neurotoxin that is produced by cyanobacteria and dinoflagellates (National Center for Biotechnology Information, 2020c). It has the ability to block specific sodium channels which will disrupt ordinary cellular functions and lead to paralysis (Huot & Armstrong, 1989). However, saxitoxin is only one out of over 50 neurotoxins that is produced by cyanobacteria and dinoflagellates that are both structurally and functionally related (The European Bioinformatics Institute, 2016).

The molecule is regarded as acutely toxic as it is regarded as fatal if swallowed, inhaled or made contact on skin due to results from several studies. The toxicity corresponds to the recorded LD50 which is as low as 192 µg/kg, when given orally to rats (National Center for Biotechnology Information, 2020d). However, the lethal dose for humans have been recorded to range between 1 to 4 mg depending on age and physical conditions (Al-Tebrineh, et al, 2010). Because of its high toxic properties, the recommended health alert concentration is set to 3 µg/L in drinking water (Al-Tebrineh, et al, 2010).

Saxitoxin is also not likely to possess bio-accumulative abilities with the Log P value being -4.6 (National Center for Biotechnology Information, 2020f). The molecule is also not rather persistent because of the fact that the half-life of most saxitoxins varies from 9 to 28 days in natural waters (Trainer & Hardy, 2015). However, the cause of paralytic shellfish poisoning is toxins, such as saxitoxins, which are located in the shellfish tissue and depending on species can be conserved for several weeks up to nearly a year (Watkins, et al, 2018). With controversial results from calculations and historical events, the given octanol-water partition coefficient should not be used to predict the bioaccumulative ability of the compound, while the half-life of the compound at the same time only can be applied to natural water.

Because of the fact that saxitoxin is highly toxic for humans as well as the possibility that an algae bloom creating these compounds may contaminate water reservoirs, scientists have researched water treatment methods for toxins, a few of which focus specifically on saxitoxins. One approach was to use a chlorine concentration at 0.5 mg/L during a 30 min interval to break down the molecules, with results of breaking up to around 90% depending on pH. Adding ozone stock solution was also one approach. This solution was not very efficient in breaking down saxitoxins. This was due to the fact that it only decreases the compound with 30%. The last method used powder and granular activated carbon for absorbing the toxins over a 6-month time period, where approximately 70% of the saxitoxins were removed (Newcombe & Nicholson, 2002).

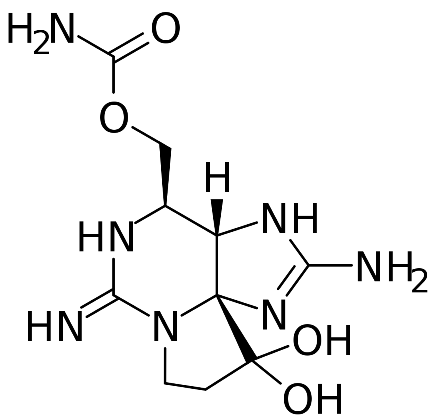

Figure 6.3: Molecular structure of saxitoxin (Edgar, 2016.)

6.4 Evaluation

The main points when evaluating the importance of having a method to separate toxins from the water are mainly the half-life time of the molecules, bioaccumulation and persistency, as well as the efficiency of being able to remove the toxins. With regards to the toxins microcystin, anatoxin-a and saxitoxin that have a half-life time less then 30 days in reservoir water for almost all of the variants of the molecules, which does not make any of them persistent. If left untreated, the compounds would decay a few weeks after the algae removal. There is a risk that wildlife such as fish or shellfish would absorb the toxins into their tissue if the toxins are left untreated. However, if referring to the log P value it is not likely that any of the toxins possess bioaccumulative abilities, with the exception for some saxitoxins that have proven otherwise in shellfish. However, this is based on that the shellfish filter the algae that contain the saxitoxins from the water and not the toxins dissolved in water. Therefore, the likelihood that the toxins are absorbed into wildlife is relatively low and even less so for humans to get intoxicated by eating the wild animals.

Based on these factors it would be preferable if the toxins could be removed onboard the TAH because the water would be unusable for a few weeks after algae separation. However, the research on how to remove toxins did not provide a feasible solution for all compounds and the few methods with high efficiency were either very focused on one compound or the water needed to be treated for a longer period of time.

Therefore, before deciding if the toxins should be removed onboard the TAH and how it is supposed to be done more research is needed. To begin with, it is necessary to analyze the effect of removing the algae has on the water-soluble toxins. But also, to design a compact and feasible separator that work on multiple toxins and fits on the TAH. For now, it is not critical to have a method to remove the toxins due to the relatively short half-life time most molecules possess and the fact that toxins are also cell bounded.

Lastly, it is, however, important that the water is tested for toxins after harvesting the algae so that the guideline levels for the toxins are not exceeded. This is because there is a risk that the water will look clean when the algae is removed, while toxins possibly are present.

7 PRODUCT DESIGN AND SPECIFICATION

In this stage of the project, all parts of the system, both the components that are bought and the components that are developed in the project, were designed in the commercial CAD-software Autodesk Inventor (Autodesk, 1999). The reason for including all parts in the design was to give a visualization of the complete system. The main focus of the final design was to make everything fit together well and make the TAH a viable workspace. Not as much focus was pointed towards the strength and efficiency, although it was considered in every step of the design process. The final design of the TAH, visualized in *Figure 7.1,* contains all the necessary components needed to harvest algae from lakes and seas. The TAH measures 9.4 m in length including the funnel, 3.0 m in width and 5.07 m in height including the pontoons, 3.97 m excluding the pontoons. The height might be a problem during transportation but no way of designing the TAH was found that could lower the height enough without exceeding the length and width limits.

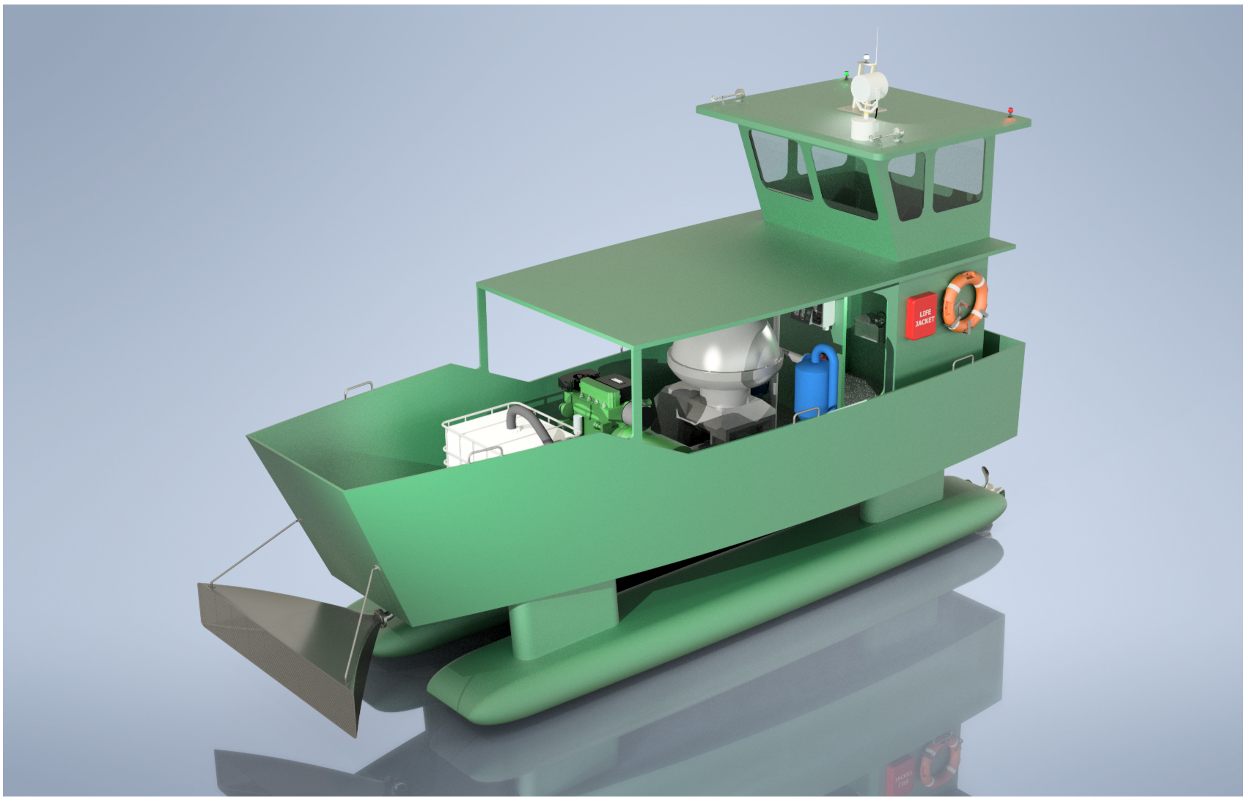

Figure 7.1: Final Design of the Toxic Algae Harvester

The layout of the TAH is best represented by a section view from the top. *Figure 7.2* shows this view with names of the major components. The placement and functions are described further on.

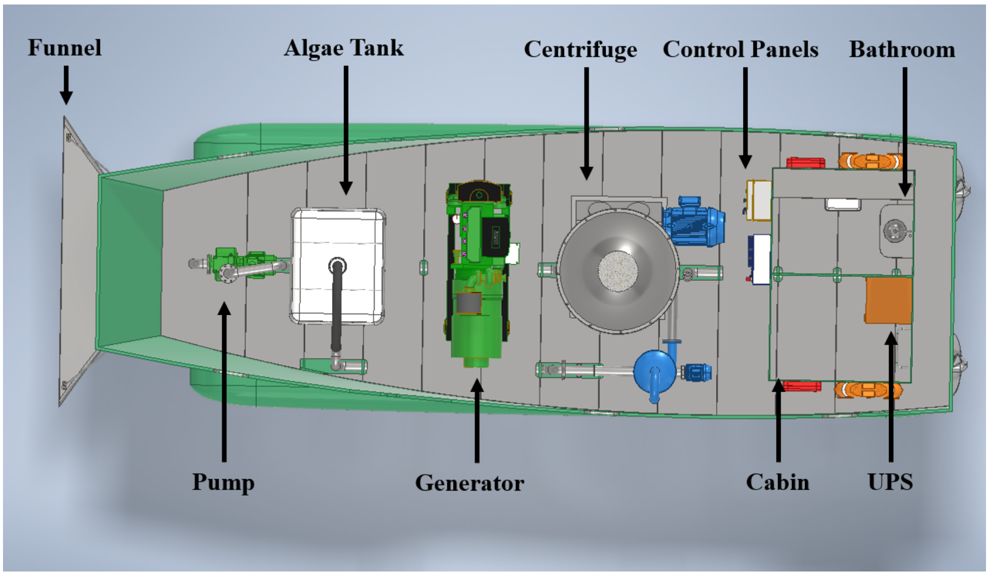

Figure 7.2: Layout of the TAH

The TAH is fitted with a double floor function to hide pipes, wires and other components that do not need to be easily accessed and would otherwise be in the way. The double floor is shown in *Figure 7.3* with a section view from the left side. The covering floor is made from aluminum treadplate for better traction and corrosion resistance and it is divided into sections so that it can be easily lifted to access pipes and wires without moving all machines of the floor.

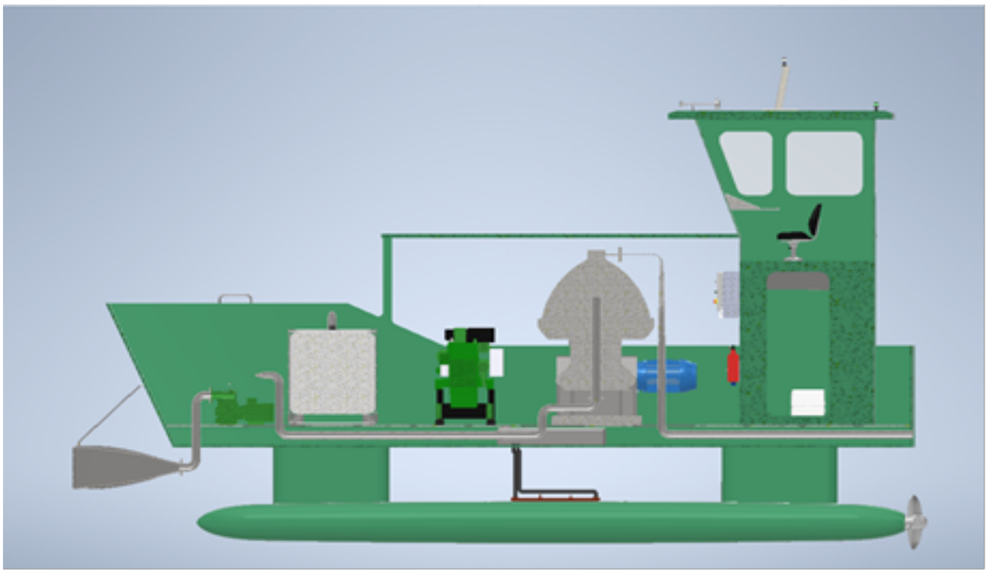

Figure 7.3: Section view from the side

A few components like the funnel, the centrifuge and the propellers require a specific location on the TAH and, thus, there is not much that can be done about their placement. Less critical components were placed to allow for easy access, comfort and safety. Starting from the front of the TAH, the funnel used to collect algae and water, visualized in *Figure 7.4*, is mounted on the TAH with two supports and connected to the pump with a pipe which also increases the rigidity. The funnel is also fitted with a mesh to ensure that no animals or large debris gets into the system and get hurt or risk damaging components. The funnel is made of stainless steel in order to reduce risk of corrosion and still be strong enough to withstand small hits. The funnel could easily be removed for transport by loosening 12 bolts. The pump is an electrically powered dynamical change pump with specifications concluded in *Appendix B*.

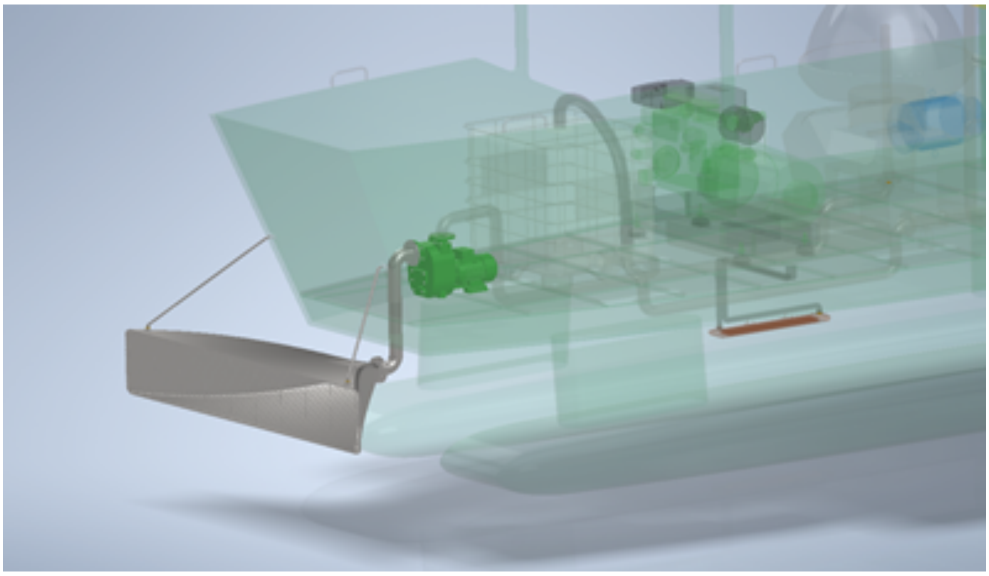

Figure 7.4: CAD model of the funnel, mesh, pump and supports

After the algae mixed water has been retrieved, the next step is to separate the algae from the water. This process is shown in *Figure 7.5*. The algae mixed water is therefore pumped back to the centrifuge were the water and algae are separated. The clean water is let out of a drainpipe in the rear and the concentrated algae is transported to the algae tank. The centrifuge is located in the center of the TAH in order to minimize the impact of the rocking motion of the waves. The centrifuge used is the Alfa Laval model Clara 701H that has a throughput of 75 cubic meters of water per hour and require 37 kW of power.

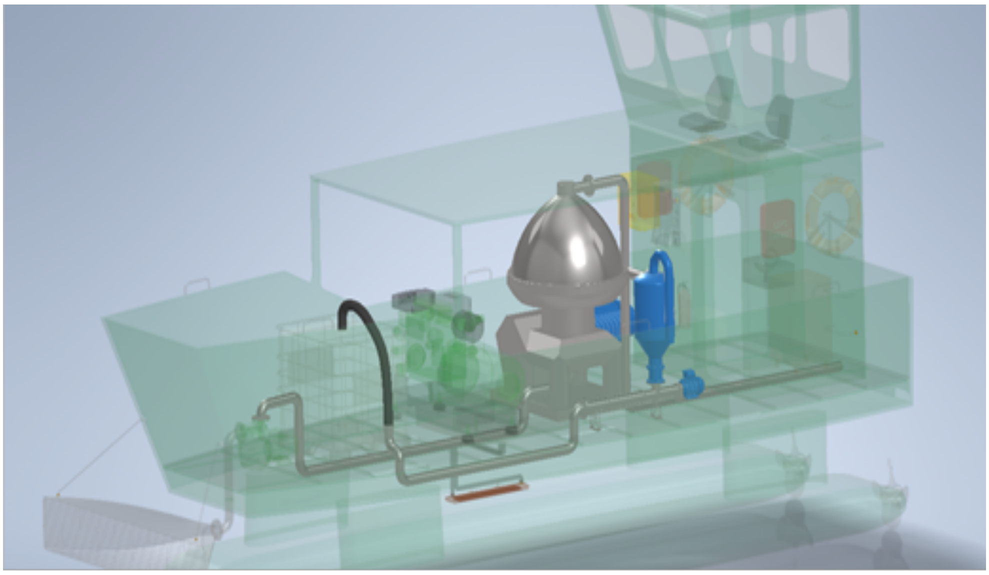

Figure 7.5: CAD-model of the centrifuge with connected pipes

As previously mentioned, after separation the concentrated algae is pumped to the algae tank in the front for storage, as visualized in *Figure 7.6*. The algae tank can either be emptied by connecting a hose to the bottom of the tank or simply lifting the whole tank out of the TAH and replacing it with an empty tank. The filling pipe is made of rubber so that it can easily be disconnected and re-connected when replacing the tank. The algae tank is not a crucial component location-wise, but it was placed in the front for multiple reasons, mainly, to even out the weight distribution and to allow it to be lifted of the TAH without hitting the roof. The tank used is a called an IBC tank which has a low cost, is commercially available and robust.

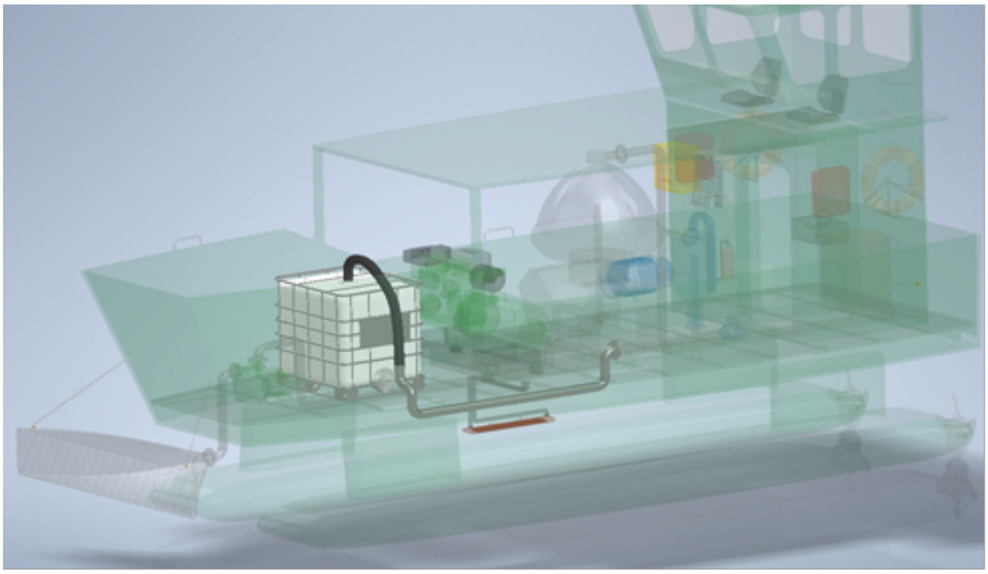

Figure 7.6: CAD-model of the algae tank and connected pipes

To power the TAH and all its components a generator is used. Since this project is sponsored by Volvo Penta the natural choice was to use a Volvo Penta generator, more specifically a Volvo Penta HED5A TA / UCM274E-1 Genset with an output of 400 V and 86 kW. The generator is placed between the algae tank and the centrifuge, shown in *Figure 7.7*. Further, the generator is connected to three crucial subcomponents. First, a fuel tank located under the floor containing biodiesel to fuel the engine. Second, a keel cooler located on top of the right pontoon of the swath hull to cool the engine using the water from the lake or sea and, last of all, a UPS (Uninterruptable Power Supply) located in the bottom floor of the cabin. The UPS is manufactured by the company APC and the specifications of it can be found in *Appendix E*. The reason that a UPS is installed is because it evens out and distributes the current produced by the Genset. Furthermore, it has a built-in battery and can power the system for a short time in case there is a problem with the Genset. The UPS also protects the components on the Toxic Algae Harvester from voltage spikes and voltage drops.

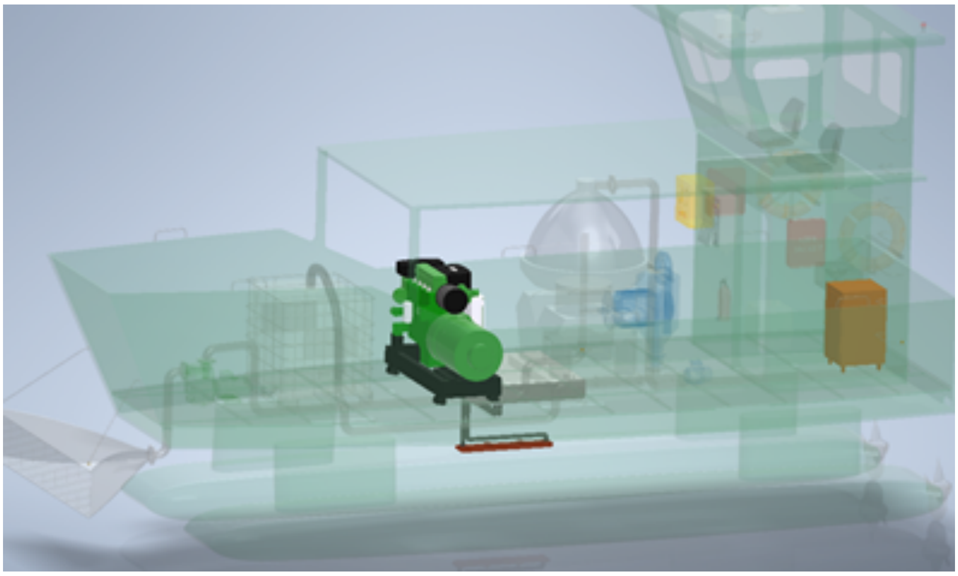

Figure 7.7: CAD-model of the generator and connected components

In order to utilize the limited space as efficiently as possible, the cabin is designed in a two-story configuration, shown in *Figure 7.8*. Besides the two floors, the cabin also includes a superstructure that protects some of the more sensitive components from water and wind as well as providing shade for the operators working on the floor. The sides and the roof of the cabin are used to hold control panels, life jackets, lifebuoys, a fire extinguisher, lights, horns and an antenna. The two control panels are used to control the generator, the pump and the centrifuge. The cabin is made of an aluminum structure lined with aluminum sheets. Aluminum is used since it is light weight, corrosion resistant and quite strong.

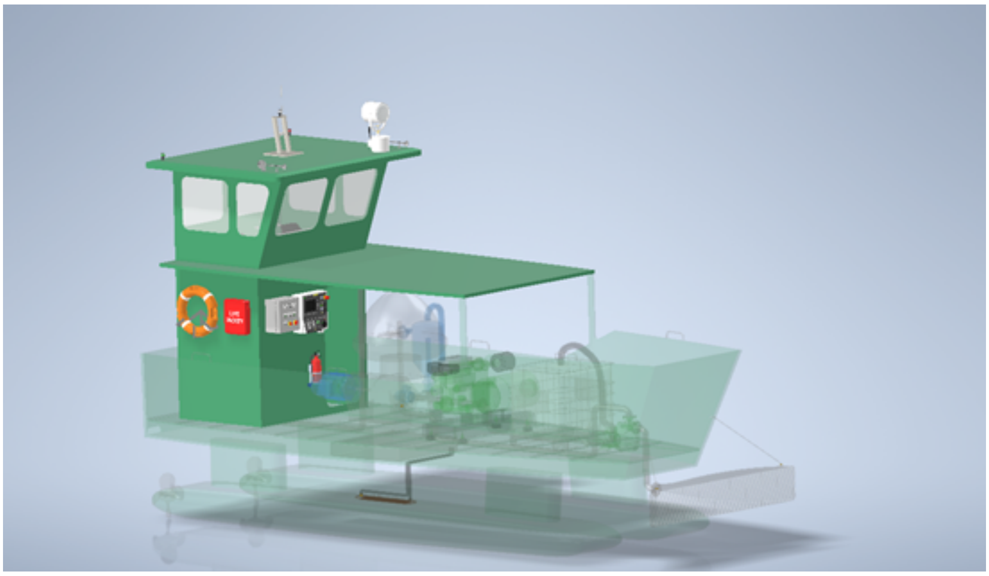

Figure 7.8: CAD- model of the cabin

In the bottom floor of the cabin, shown in *Figure 7.9*, there is a bathroom, the UPS and room for some minor storage. The bathroom contains a toilet, a sink and a clean water tank.

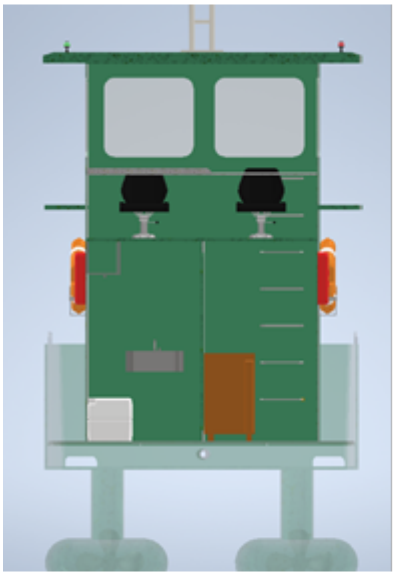

Figure 7.9: Cross section view from the front showing the bottom floor of the cabin

The top floor of the cabin, shown in *Figure 7.10*, is accessed by a ladder from the bottom floor and contains two seats for the operators. The control panel on the top floor is mainly used to steer the TAH and control the different machines but it can also be utilized as a table where food can be consumed. The top floor has a total of eight windows that provides an all-around vision.

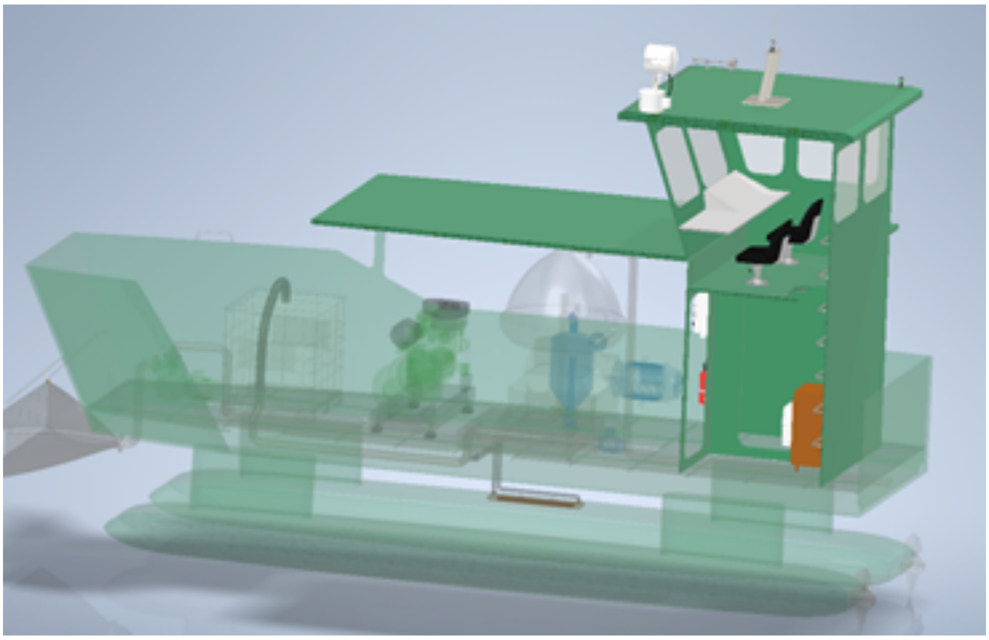

Figure 7.10: Cross section view from the left side showing the top floor of the cabin

Regarding the hull of the Toxic Algae Harvester, the team was tasked with choosing a hull design that makes use of a dual-hull design at the request of the client. After researching the different types of dual-hull designs that are available on the market, the team concluded that there are generally two types of dual-hull styles. The catamaran design is considered to be the traditional style of dual-hulls. Most people would be familiar with this style from pontoon boats. The other style of dual-hull is known as a SWATH (Small Waterplane-Area Twin

Hull) which is considerably more complex than the catamaran. The two types of dual-hull is displayed in *Figure 7.11*. The main advantage that the SWATH style has over the catamaran style is that it has a high resistance to rocking and swaying (Kos, Brčić & Frančić, 2010) which is crucial for boats that are operating with sensitive machinery, like the centrifugal separator. One other advantage that the SWATH design has is that it has increased maneuverability due to the control fins located on the ballast tanks. This helps with the customer need that the TAH needs to be more maneuverable due to the fact that the intended location of use includes lakes, which are considerably more difficult to navigate compared to the ocean. Another fact to consider is that there is much more room between the pontoons at sea-level for the SWATH hull than the catamaran. This extra space makes it possible to fit a wider funnel and, thus, increasing the area that can be harvested per hour.

Even though the SWATH style dual-hull is more complex than the catamaran it was selected to use on the toxic algae TAH due to its many advantages.

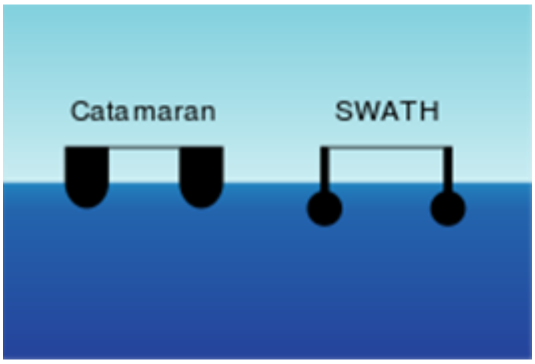

Figure 7.11: Catamaran vs. SWATH hull design (Wikimedia, 2009)

The deck of the TAH, shown in *Figure 7.12*, utilizes a kind of SWATH hull design with propellers mounted on the back of each pontoon. Further, the front of the deck is designed with quite an aggressive angle to prevent splashing water from getting on to the TAH but rather splash away from the sides. This preventative measure reduces the amount of water on the TAH but does not eliminate it and, therefore, there are two holes in the back of the deck from which water can escape from.

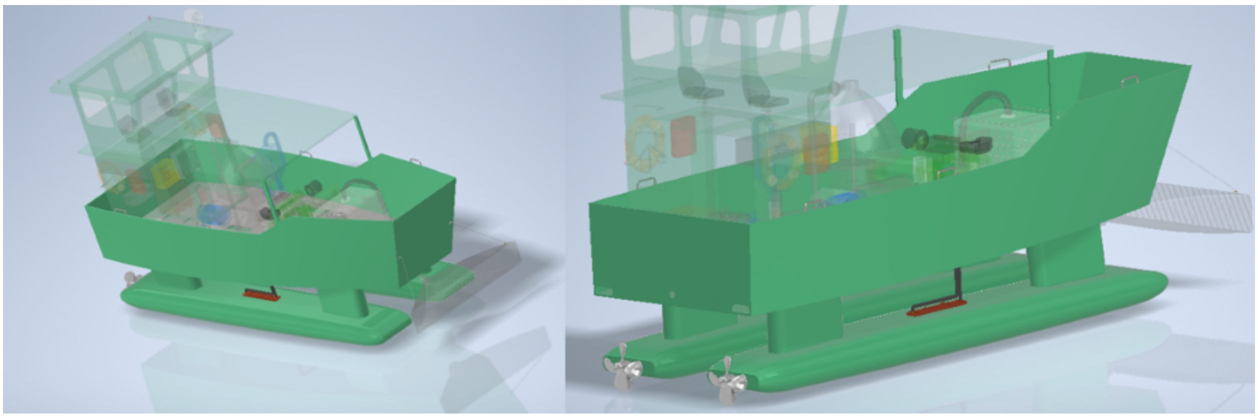

Figure 7.12: CAD-model of the deck and hull

The top of each side is equipped with three rails which work both as something to hold on to and fasteners for ropes when the TAH is docked. Both the deck and the hull are made of an aluminum structure lined with aluminum sheets that makes it corrosion resistant and strong, and at the same time keeps the weight of the TAH down.

The pontoons of the swath hull are hollow and as previously mentioned built around a solid structure in order to reduce weight. This is shown in *Figure 7.13*. The structure is sectioned with eight watertight compartments so that if there is a rupture in a pontoon, only one section will be filled with water and the TAH could still be able to float and get back to land.

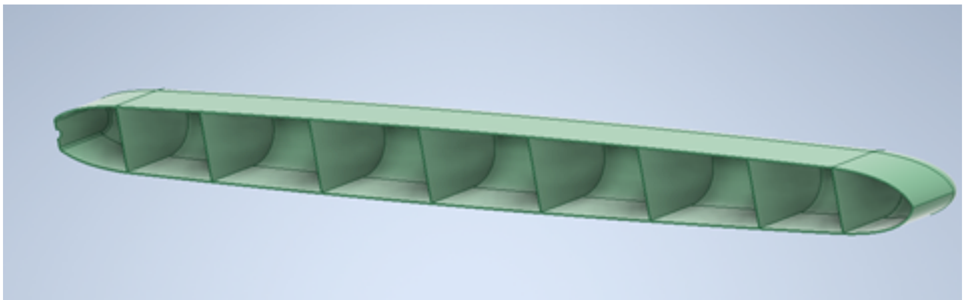

Figure 7.13: Section view of the pontoon showing the watertight compartments

Most of the materials used on the Toxic Algae Harvester were selected due to their anti-corrosive properties. To further reduce the risk of corrosion sacrificial anodes are placed on components that run a higher risk of suffering from corrosion. There is no generic type of anode that works efficiently for all metals in all environments and, therefore, the anodes will differ for each part they intend to protect and they also need to be selected for which environment the TAH is intended to be used in - fresh-, salt- or brackish water. Since the TAH is intended to be used in all kinds of water and offers the possibility to be moved to different locations, the anodes need to be easy to change depending on which type of water it is used in.

8 USE OF HARVESTED ALGAE

After the separation of algae from the water, there are possibilities of using it for the production of different products, extending the environmental benefit of algae harvesting even further beyond mitigating the harmful effects of algae blooms. There are many different ways of processing the algae into a product, but the mutual foundation is to work from the high content of lipids, protein and carbohydrates that algae consist of. Most research has been strictly performed on specific species of algae that have been cultivated in a controlled environment, instead of wild algae which is the scope of this project. Therefore, the possibility of producing each product has been researched and followed up by a discussion of advantages and disadvantages.

8.1 Biofuel

Some of the most common types of algae include *Euglenophyta* (Euglenoids), *Chrysophyta* (Golden-brown algae and Diatoms), *Pyrrophyta* (Fire algae), *Chlorophyta* (Green algae), *Rhodophyta* (Red algae), *Paeophyta* (Brown algae), and *Xanthophyta* (Yellow-green algae) (Bailey, 2010). Within that, some of the most common algae that cause blooms include Diatoms, Cyanobacteria, Euglena, Golden algae, and Green algae (Graham, 2013).

One of the attributes that makes algae a good candidate for producing biofuels is the growth rates being faster than terrestrial crops (Fikes, 2018). Different algae have different growth rates. Most species experience two doubling times per day, while some species have doubling times in as short time as 6 hours (Hannon, 2010).

One potential biofuel that could be produced by algae is biodiesel. Biodiesel is a diesel fuel derived from animal or plant lipids - oils or fats - which are found in algae. *Scenedesmus obliquus, Chlorella kessleri, Botryococcus braunii,* and *Chlorella vulgaris* - all green microalgae - were found to be some of the most suitable algae types for biodiesel production (Brennan, 2010). Their high lipid contents make them ideal for making biodiesel (Leckey, 2011). In order to extract these oils, a process similar to the way vegetable oil is extracted is required (Fikes, 2018). Another biofuel that can be created using algae is bioethanol or butanol fuel. These can be created by fermenting the carbohydrate content in the algae. Biobutanol can also be formed from algae using only a solar powered biorefinery. Biobutanol can be used as a direct replacement in most gasoline engines, meaning that the engines do not need to go through any modifications. That being said, butanol can also be combined with gasoline, providing better performance and corrosion resistance compared to ethanol (Fikes, 2018).

Although algae can technically be processed and turned into various biofuels, there are many specific characteristics to algae, in addition to growth rate, that would allow them to be productive in creating biofuels. The most important attribute would be their oil content. The higher the lipid productivity, the more beneficial the algae would be in producing biofuel. In addition, algae have the capability of having a much higher fraction of their biomass as oil compared to most conventional crops. For example, algae can reach 60% as opposed to soybeans which average to about 2 to 3% (Fikes, 2018). According to the U.S. National renewable energy laboratory (NRLE), *genera Chlorella* (green algae) potentially has a good source of oil from algae (Schuh, 2011). In addition, the U.S. Department of Energy (USDOE) conducted an experiment of over 3000 strains of oil producing organisms, and out of the algae candidates, mostly green algae and diatoms were among the top results (Brennan, 2010).

On the downside, although algae have the capability of reaching an oil to biomass percentage of 60, this is usually due to genetic and metabolic modifications of algae strands, specifically targeting this characteristic (Brennan, 2010). The algae strains used today for specific purposes have undergone improvements through breeding, selection, and random mutagenesis. Specific strains are engineered to grow under conditions that require low input (Hannon, 2010).

Outside of the specific strains, the most effective method found for improving the lipid accumulation in microalgae is through nitrogen limitation (Brennan, 2010). This method not only increases the lipid content, but also produces more triacylglycerol (TAG) from the free fatty acids, resulting in an easier conversion to biodiesel. The reason why depriving the microalgae of nitrogen is helpful is because lipid accumulation occurs when a nutrient is exhausted from the medium (Brennan, 2010). Unfortunately, this method would be very difficult to control considering that the wild algae harvested from the blooms are often caused by a plethora of nutrients.

Overall, the harvested wild algae are grown through an "open loop" system where variables are not able to be controlled. Factors such as temperature fluctuation, carbon dioxide deficiencies, inefficient mixing, and light limitations all can cause an inconsistency in the outcome of the algae. These factors can change the characteristics of the algae (Brennan, 2010).

In addition, this high oil content brings another challenge which is extracting or removing the oil (Brennan, 2010). Extracting the oil requires expensive equipment as well as lots of energy (Hannon, 2010). The amount of raw algae that would be needed in order to fill one barrel of diesel oil might require up to 20 times the amount of raw algae by volume. This means that the extraction process must have the ability to move large amounts of materials in small amounts of time in addition to being safe and low cost in order to be efficient (Schuh, 2011). There are two process techniques used for extracting oil which have been tested in lab settings at small scale. One is mechanical and the other is chemical. The mechanical process is more widely used. During the mechanical process, the algae are treated similarly to seeds from row crops or orchards. The pre-pressing operations include grinding or flaking, followed by cooking the pre-cleaned raw material (Schuh, 2011). Specific variables such as pressure, temperature, pressing time, and moisture affect the overall oil yield. Once the oil is extracted, algae oil conversion is chemically similar to crude fossil fuel oil where there is already an efficiently established process (Hannon, 2010). This means that the most difficult part is the extraction of the oil in the algae. The processing of the oil after the extraction will not be as large of a cost burden due to there already being designs and mechanical processes for these steps.

8.2 Fertilizer

Even back in 1979, the potential of using algae as wastewater treatment, and after that as fertilizer, was being discussed. Nitrogen is not a limiting nutrient except in marine environments, where only bacteria and blue-green algae fix nitrogen. As a natural result, blue-green algae are very effective in fixing nitrogen, and they in fact stand for fixating almost all nitrogen in the biosphere, excluding chemical fertilizers.

Benemann (1979) studied in 1979 a certain type of blue-green algae that is a very effective nitrogen-fixator by nature, in producing nitrogen fertilizer by absorbing the nitrogen in wastewater. In this study, the algae are cultivated, and not harvested in wild form, which makes it different from the case which the project seeks to address. Wuang et al. (2016) studied the use of the cyanobacteria *Spirulina platensis* produced from purifying wastewater as agricultural fertilizers. It was shown that it had an enhancing effect on several plants. In another study, it was shown that agricultural use of microbial fertilizers obtained from microalgae increased soil organic matter and the water holding capacity (Uysal, Uysal & Ekinci, 2015). Moheimani and Borowitzka (2010) report that the nitrogen-fixing algae (heterocystous cyanobacteria) such as *Anabaena* have been cultivated for the production of fertilizer. It is already used in India as biofertilizers for rice paddies. It is also reported in the same study that after extracting lipids from the algae for the production of biofuel, the biomass remaining contains high amounts of nitrogen and phosphorus. Moheimani and Borowitzka think that the capture and recycling of this residual nitrogen and phosphorus is more important for the production of biofuels than for other alternatives such as animal feed. Most likely, according to Moheimani and Borowitzka, the method used to recover these nutrients is anaerobic digestion which produces methane. The idea is to use this methane to supply the algae plant with the energy it needs, to use the CO_2 produced to enhance growth in the algae cultivation, and to return the effluent containing ammonia and phosphorus to the algae ponds to recycle at least part of the amount of its nutrients. In other words, the fertilizer produced, which is the effluent, is used as fertilizer in the algae cultivation it originally stems from, creating a nutrient cycle. They also report that using the residual algae as a slow fertilizer in agriculture is possible, having the capacity to improve soil quality. Whether the algal fertilizer is used in agriculture, or in the algae cultivation itself as in the first example, it will reduce the need for chemical fertilizers and hence reduce the emission of CO_2 among other gases that are emitted through the use of chemical fertilizers. A problem that might arise, though, is that if the algae are grown in saline water, its residual biomass might still contain salt, which can be a problem when used in agriculture.

Abdel-Raouf, Homaidan and Ibraheem (2012) state that Diazotrophic cyanobacteria only require sunlight to supply its energy requirement for it to fixate carbon and nitrogen. This makes them a very effective nitrogen fixator having great potential for being used as agricultural fertilizer. In China, Egypt, Philippines and India, paddy soils with appropriate cyanobacterial strains are used as fertilizers in rice fields. One of the problems of this technology is that agrochemicals applied in agricultural fields, especially herbicides, inhibit cyanobacterial diazotrophic growth. Therefore, selecting suitable diazotrophic strains that tolerate the concentrations of herbicides normally applied in agriculture is required. El-Khawaga (2011) reports that combining inorganic nitrogen with humic acid and *Spirulina Platensis* significantly improves the quality of the fruits and increases its biomass. Algae Production Systems (Algae Production Systems) is a company that produces biofuels from algae, while processing the biomass that remains into organic fertilizer. A microbiologist with the U.S Agricultural Research Service showed that algae can recover close to 100% of nitrogen and phosphorus nutrients from manure and concluded that dried-out-algae can, thus, be used as slow-release agricultural fertilizer. It has also been shown in experiments conducted by U.S. Department of Agriculture (USDA) on four dairy farms that algae can capture 60 to 90% of nitrogen and 70 to 100% of phosphorus from a mix containing manure and fresh water. A USDA microbiologist Walter Mulbry showed that corn and cucumber seedlings could thrive on a fertilizer produced from the dried-out algae (Hsu, 2010).

Algae can contain high amounts of metals, thus posing a risk to agricultural land when used as fertilizer. Instead, using wild harvested macroalgae seems to be more fitting for the production of biogas (Submariner). Melin (2010) reports that anaerobic digestion of algae together with municipal waste showed that the process would not be stable except by adding extra calcium oxide (CaO). Another problem with using algae as fertilizer is its content of cadmium, lead and nickel. These are heavy metals that are very toxic to human beings. There are regulations concerning the maximum amounts of, for example cadmium, relative to phosphorus or nitrogen, that fertilizers are allowed to contain. This makes these heavy metals limiting factors for the use of algae as fertilizer. Different algae have different abilities in taking up heavy metals from water. Thus, it is important to take this into consideration for using them as fertilizer. That being so, Melin recommends that algae be used in non-eatable crops instead.

In the province of Skåne, located in the south of Sweden, for example, a lot of industrial fertilizer, containing high amounts of cadmium, is used in the agricultural fields. This heavy metal then leaks into the sea. When harvesting algae in the coasts of Skåne, high levels of cadmium are in fact found, originally stemming from agriculture. This was confirmed through a phone interview with Fredrik Gröndahl, the project leader of Seafarm (Gröndahl, F., 2020, personal communication, 19 March). In the province of Gotland, on the other hand, high amounts of cadmium are found in lakes but not in the sea. Hence, what the algae contains and does not contain is very location specific (Franzén, Infantes and Gröndahl, 2019).

Positive results are found in the reports about the use of algae as fertilizer. Most of the findings and reports, though, have shown specific algae species, often cultivated and not harvested in wild form, being used as fertilizers. This is fundamentally different than the issue at hand, namely harvesting wild algae. Further, the problem of heavy metals contained in wild algae has been clarified, together with the location dependency of the problem. The project intends to harvest algae blooms and microalgae on the same run. This means that several different species, each having unique characteristics and posing unique problems, will have to be dealt with at once. This makes the complexity of the task extremely high, rendering it unfeasible for it to give useful results on a large scale.

8.3 Animal feed

A potential algae product that has been studied by many scientists around the world is animal feed, due to the high contents of important minerals and vitamins within algae (Christaki, Florou-Paneri and Bonos, 2011). Research shows that including microalgae into animals' diet could improve growth and meat quality, although these discoveries are highly dependent on the algae species, compositions and amount in the diet (Madeira, et al., 2017).

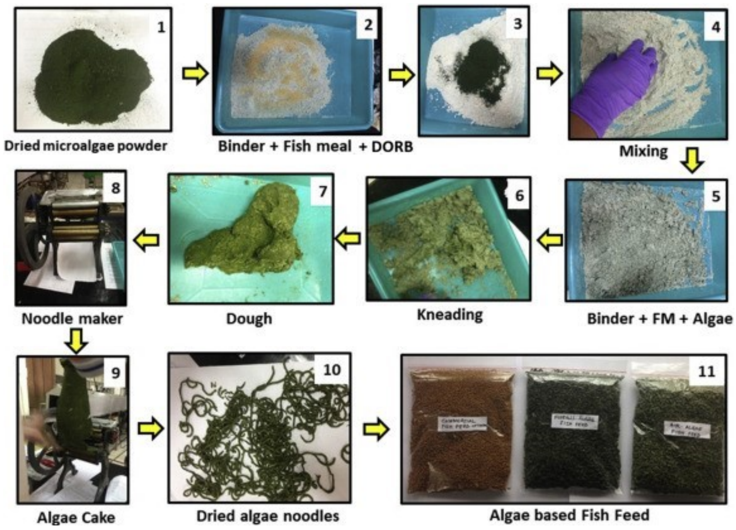

Figure 8.1: Schematic preparation of fish meal based on microalgae (Yadav, 2020)

The algae content characteristics with a high amount of protein, lipids and carbohydrate has resulted in a production of animal feed done in two ways. The first and most common one is to dry and use the microalgae as they are in the animal feed mix, shown in *Figure 8.1*. The second way is to first extract lipids from the algae, defatted algae (DFA), for production of mainly biofuels before the remaining biomass will be used as an animal feed ingredient.

One study conducted by (Madeira, et al., 2017) showed that when mixing microalgae with the animal feed there was an overall increase in growth performance and meat quality for ruminants, pigs, poultry and rabbits. The performance and quality did however vary depend on the algae species and the percentage of algae in the feed. For example, to achieve the best grow rate for ruminants the microalgae *Arthrospira plaatensis* should be used at a 10% level in the feed, but for the meat quality a diet enriched with a 4% *Isochrisys* sp. showed the best results (Madeira, et al., 2017). Another case is that the poultry meat quality varied depending on the algae used in the feed. *Arthrospira* sp. affected both the yellowness and redness of the fillet, while *Arthorospira platensis* did not affect the color but increased valuable fatty acids. (Madeira, et al., 2017)

The use of microalgae as an ingredient in animal feed has shown great potential in aquaculture, where studies have shown that algae can increase the growth rate of the fish and also reduce the costs of the feed (Meena, et al., 2020). One study showed that by mixing the microalgae *N. oceanica* at 22.5 to 30% in regular fishmeal for spotted wolfish the fish would increase in weight by 26% on average (Knutsen, et al., 2019a), while another study showed a maximum weight gain of 55% when using a mixed fishmeal with the microalgae *Chlorella* sp. at 15% for juvenile- common Carp, compared to a regular fishmeal. Additionally, the cost of the algae mixed feed was 26.1% less than the regular fishmeal (Meena, et al., 2020). However, the use of microalgae in fishmeal does not always result in increased growth or weight. One example is a study that used the microalgae *Scenedesmus obliquus* at a maximum 50% in fishmeal for spotted wolfish, were carotenoids appeared in the skin of the fish without increasing its weight (Knutsen, et al., 2019b).

For optimization of cultivated biomass, biorefineries use algae to produce biofuels and animal feed, where the lipid extracted algae are used as feed. Algae are generally rich in lipids, proteins and carbohydrates so when the lipids are removed the remaining biomass consists of mostly protein, carbohydrates and ash, which results in a valuable ingredient for animal feed.

Therefore, many studies have been conducted on this topic where one of them used *Staurosira* sp. in the animal feed for pigs, broiler chicks and laying hens, with a concentration of algae at 7.5 and 15%. Overall, there were no differences in growth rate, weight or egg quality when comparing the broiler chicks and laying hens that received the 7.5% mixed animal feed and the control feed, which was not the case with the 15% mixed feed, where both growth rate and egg yolk quality were affected badly by the feed. Regarding the pigs, both the 7.5 and 15% algae mixed feed decreased their growth rate by 8 and 11%, respectively (Gatrell, et al., 2014).

Another study used the defatted microalgae *Nannochloropsis* sp. as a protein source in fishmeal for European sea bass. They used three experimental diets containing 5%, 10% and 15% of DFA during a 93-day period. After the 93 days there were not significant differences in fish growth performance, whole body composition and nutrient gain between the three diets (Valente, et al., 2019). One additional study on DFA in fishmeal for aquaculture used the microalgae *Haematococcus pluvialis* in a feed for Pacific white shrimp. Five diets with similar protein, lipid and other nutrients but different algae concentrations, 0, 3%, 6%, 9% and 12%, were used. After an 8-week period all the feed resulted in a higher growth rate than the commercial/control feed, however the feed with 3% algae showed a significantly higher growth rate than the other diets (Ju, Deng and Dominy, 2012).

The usage of algae as animal feed or fishmeal appears to be possible with varying results depending on species of algae and species of test animal. Some research papers also indicate that it is possible to use the co-product from biofuel, which is a defatted algae biomass, as animal feed. This, however, does not give the same efficiency as normal algae biomass with a higher lipid content even if there are some beneficial results. The main problem with using the harvested algae as animal feed is that it is wild algae, which have a huge variety in nutrients depending on species and area of bloom. It might still be possible to mix the algae biomass into the feed depending on the concentrations, because none of the papers showed any negative effects in either body mass of digestibility when a low concentration was used. Even if it is possible to use the algae one problem still remains unsolved, which is how to remove the toxins some algae product.

8.4 Biogas

Seafarm is an organization that works with harvesting macroalgae and microalgae on Sweden's coasts for the production of biogas, food, animal feed, biobased materials and fertilizer. They use algae that have been washed up on the shore (Seafarm). One of their projects involves collecting a mixture consisting of algae and other seaweeds that accumulates on the shores of Gotland. Fredrik Gröndahl, the project manager of Seafarm, states that this accumulated mixture suits perfectly to the production of biogas (Biogas2020, 2016).

Biogas is an energy-rich gas that is made up by methane and carbon dioxide. It can be produced from all sorts of organic material through anaerobic digestion. Algae, combined with municipal waste and other agricultural waste, is used to produce biogas. Many buses and some cars use biogas as fuel today, and for more vehicles to be able to do the same, more biogas is needed. (Trelleborgs kommun, 2015).

Mostly, today, microalgae are just used as one of the ingredients in anaerobic digestion, and not as a single ingredient. Forkman (2014) studies the potential of biogas production by anaerobically digesting microalgae together with drainage slit. Because of the high carbon content in drainage slit, it contributes to a higher C/N-ratio (carbon to nitrogen-ratio), especially since microalgae often have a lower C/N-ratio than what is optimal, thus making mixed digestion more beneficial than digesting algae alone. At the same time, algae contain more soluble COD (Chemical Oxygen Demand) - which is a measure of the amount of oxygen consumed for complete chemical digestion or the amount of organic material that remains after digestion - than slit does, thus rendering mixed digestion more beneficial than only digesting slit. Thus, algae increase the organic material. Additionally, mixed digestion gives a higher efficiency and better utilization of the substrates contained. Digesting slit together with microalgae has shown to give increased methane-content. Forkman states that the amount of fuel that can be produced by algae is up to 20 times more than what can be produced by soybeans, African oil palm, and sunflower, measuring liter per planting area and year. The energy content of a normalized m^3 biofuel in the form of biogas is approximately the same as in 1.1 liter gasoline. There are, however, problems with digesting algae. It gives off high amounts of unsaturated fats. Also, digesting algae does not always give higher production of biogas because of the algae cells' thick walls which make them hard to break down. Some pre-treatments are possible to avoid this. Heating the algae to 100 °C during a couple of hours, chemical treatment, or treatment with ultra-sound, are possible treatments. It is not known yet, though, if pre-treatment results in higher revenue than the cost of it. It is also possible to use the decayed residuals, after the biogas is produced, as fertilizer, but a problem that can arise with that is that the decayed residuals might contain too much metals to be allowed to be used as fertilizer (Forkman, 2014).

Anaerobic digestion of algae for the production of biogas is not dependent on the algae's lipid-content. Algae with lipid-content of 2 to 22% has produced biogas containing $0.17 - 0.45\ m^3\ CH_4/kg\ VS$ (Larsson, 2014).

In the municipality of Trelleborg, the biogas that is produced is to be used mainly as transportation fuel. This is done by the biogas being upgraded. Biogas contains 60 to 70% methane and the rest CO_2. Upgrading it means purifying it from CO_2, and then mixing it with natural gas to produce transportation fuel. When the biogas has been produced, a residual material is left, which can be used to produce biofertilizer. This can be used in agriculture and works very well according to Samhällsbyggnadsförvaltningen (2013). When combusted, biogas emits much less of the dangerous emissions that fossil fuels emit, like nitric oxides, toxic hydrocarbons and soot particles. Additionally, no carbon dioxide is emitted, so it is completely CO_2-neutral. Biogas production contributes to the continued survival and development of the countryside, by giving value to their residue products through enabling them to produce biogas from it. Before, three types of algae have been used in the biomass production, they are: Bladder wrack, Toothed wrack and Seawrack. Now, more fine-threaded algae are emerging, and they are trying to harvest these, but using them to produce biogas is not a very easy task due to them containing a lot of salt and gathering a lot of sand on the shore. Therefore, they employ a method of dry anaerobic digestion. This has gone well during 2011-08-15 until 2012-12-31 (Samhällsbyggnadsförvaltningen, 2013).

Bearing the possibilities and problems of biogas production in mind, it is clear that biogas production from algae poses a great opportunity that seems both technically and economically feasible.

8.5 Polymer

From the 359 million tons of plastic that is produced annually only about 1% represent the category of bioplastics (European Bioplastics, 2019a), shown in *Figure 8.2*. However, the rapidly increasing demand from society for sustainable degradable plastics (European Bioplastics, 2019b) have opened up a new possibility for development and research on bioplastic.

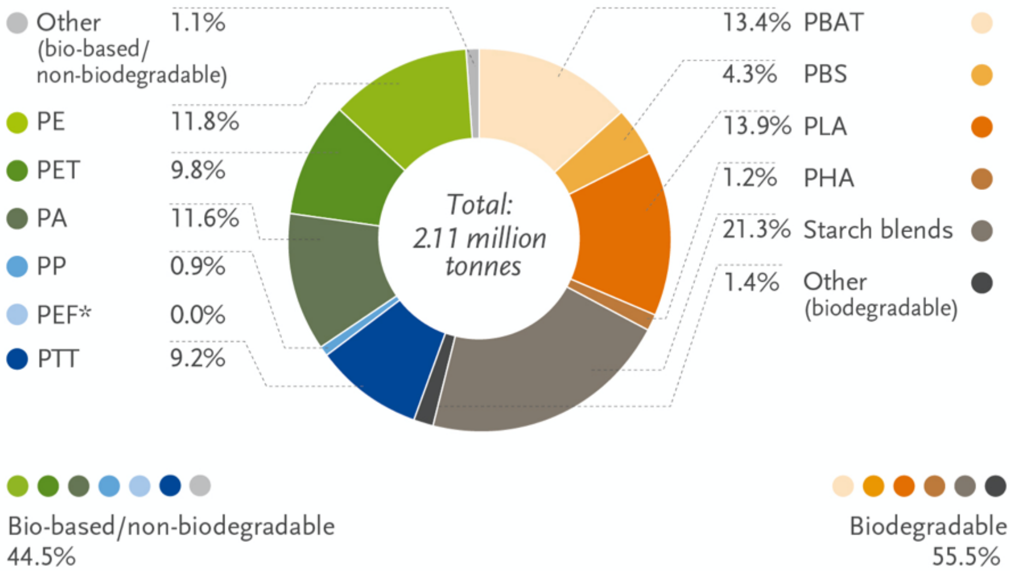

Figure 8.2: Global production capacities of bioplastic in 2019 from European Bioplastic, nova-institute (European Bioplastic, 2019c)

Protein from plants such as wheat and soy are used as a source for bio-based polymers, such as edible films, microencapsulation agent and biodegradable films (Swain, et al., 2004). Due to the fact that the proteins used are also found within algae, the algae can be considered as an optional source for production of bioplastics (Zhang, Show and Ho, 2019).

With carbohydrates or polysaccharides as a source for creating biopolymers without cultivating the algae through anaerobic fermentation there are two main biopolymers that are produced (Zhang, Show and Ho, 2019). The first one is a starch-based polymer that is constructed by disintegrating the starch crystals extracted from the algae with high temperature before gelatinization with water (Zhang, Show and Ho, 2019) and plasticization to retrieve the biopolymers (Mathiot, et al., 2019). The second one is a polymer based on cellulose. Due to the cellulose content in algae such as *Ulva fasciate* and *Lyngbya* is around 14 to 17% there is a possibility to extract and crystalize the cellulose before turning it into polymers (Calvino, et al., 2020).

In general microalgae also have a high lipid content which is usually extracted for biofuel production, whereas the remaining biomass either ends up on land fields or are used directly as animal feed (Kumar, et al., 2020). However, for biorefineries to be able to ensure economic profits from cultivated algae a further refinement of the lipid extracted algae are being researched, with the general process shown in *Figure 8.3*. As a result, producing polymers is a natural field of research due to the extra high amount of carbohydrates after lipid extraction (Kumar, et al., 2020). The carbohydrates in the remaining biomass will undergo a series of treatment for its polysaccharides to break down into smaller components of monosaccharides, which is then used for production of bioplastic, where the primary way is to use the extracted sugar as a carbon source for biopolymer producing microbial organisms (Kumar, et al., 2020).

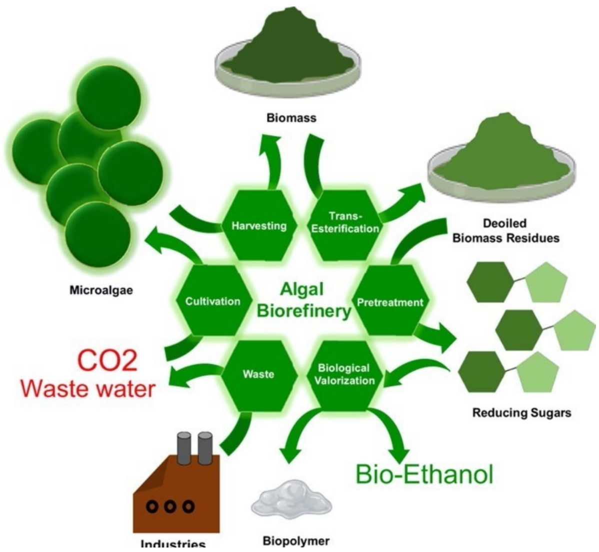

Figure 8.3: Overview of the process in a Biorefinery for production of biopolymers (Kumar, et al., 2020)

Although the use of wild algae for biopolymer production might not be as beneficial as when an optimized cultivated strand is being used, it is still a possible product to achieve. However, for all the existing methods lysing the cell wall is required and due to the high variety of species during a wild harvest it will be difficult for an efficient solution.

8.6 Discussion

From the research conducted on the different products possible to produce from harvested wild algae and the different advantages and disadvantages of each of them taken into account, the one product that seems feasible to produce from harvested wild algae on a large scale is biogas. This is related to its simplicity in that the algae do not need any engineering procedures before being anaerobically digested, and because the great use there is for biogas, both for transportation and heating. Lastly, the main reason why biogas is to be considered the most practical solution is due to the specific characteristics needed in order to achieve feasibility on the other researched products. Biofuels, fertilizers, and animal feed all require much more specific attributes in the algae for them to be made efficiently. Some of these characteristics include higher oil content, lowered metal percentages, specific nutrients, and an easily breakable cell wall. Biogas has the least amount of specifications in order for it to be successfully produced. This does not mean that it is impossible to produce the other studied products from the algae; on the contrary, the research has shown that it is possible indeed. Nevertheless, their production is problematic, firstly because companies having an interest in harvested wild algae for the production of these products have not been found; there is no market for it, as it seems today. Secondly, because of the lack of demand for harvested wild algae for the production of biofuel and polymer, there is very little research on it. More research is needed in order to be able to fully assess the feasibility of biofuel and polymer production. One solution could be to combine different products from the same harvest, where the first procedure would be to extract the oil for biofuel, then use the remaining biomass for another co-product such as polymers and then use the non-usable biomass for biogas production. However, due to the lack of conducted experiments and research for this solution this has not been considered a possible solution. Another thought is that this problem could be solved by installing a miniature refinery on the TAH or on shore in order to produce the products immediately after harvest, and not selling it, but this solution is not considered a possible one either because of lack of resources in this study.

Thereby, it is concluded that the production of biogas is the most feasible option. It is found in the research that after the production of biogas, the residuals can be used as fertilizer. The problem with this is, though, that heavy metals from the sea is contained within this residual of the algae and will then be leaked into agricultural fields, making this unsustainable. The team thinks that more research is needed in order to assess the feasibility of using the residuals from anaerobic digestion as fertilizer, and more industrial capacity and market demand is needed in order to produce biogas from harvested wild algae.

9 ENVIRONMENTAL ANALYSIS

This chapter contains an environmental analysis of the TAH. Since the purpose of the project is to reduce environmental harm, analyzing the impact of the product on the environment is considered necessary and relevant. Inspiration is taken from the famously known LCA, which stands for Life-Cycle Assessment. The chapter begins by briefly describing the LCA. Thereafter, it describes what parts of the LCA are implemented in this environmental analysis. Lastly, it presents an analysis and a discussion.

9.1 Introduction to the LCA

The LCA is an analysis of the life-cycle of a product and its environmental impact during its production, use and disposal. Thus, it studies a product during its whole lifetime, famously expressed as 'cradle-to-grave'. An LCA can be illustrated visually as in *Figure 9.1.*

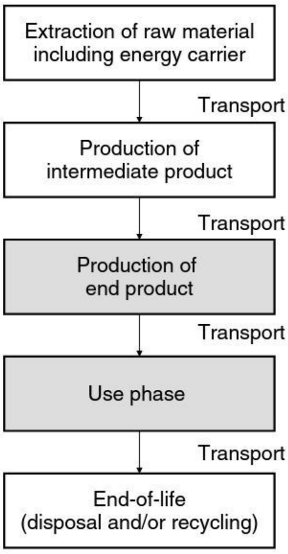

Figure 9.1: Simplified LCA of a product (Klöpffer & Grahl, 2009)

A "product" can be a product, process, service, or, in the widest sense, a human activity. In the LCA, the product analyzed serves a specific function, technically defined as the functional unit, which is used as the standard of comparison between products (Klöpffer & Grahl, 2009). A functional unit describes the utility of a product, which means proceeding with the question: "What does the product do?" instead of: "What is the product?". A functional unit usually includes something about time, quantity and quality (Jönbrink, Norrblom and Zackrisson, 2011). An LCA consists of four parts. The first part is to define the goal and scope of the study. Herein the purpose of the study is stated, and for whom the study is conducted. It is stated if the LCA is intended for marketing purposes, or if it is only aimed internally. It is also specified if only one product is to be analyzed or if it is a comparative LCA. The second part is to perform a life-cycle inventory analysis. Herein all the inputs and outputs to the system, including the materials and energy used for production, use and disposal, as well as the emissions in these stages, are quantified and presented in sheets, and also in diagrams, if needed (Klöpffer & Grahl, 2009). The third part is to conduct an impact assessment, which means that the results from the inventory analysis are used to assess the environmental impact of each material and process of the cycle on different impact categories, such as greenhouse effect, eutrophication, ozone depletion, and acidification (Jönbrink, Norrblom and Zackrisson, 2011). There is the possibility of using a weighting system called Eco-99 (Ministry of Housing, Spatial Planning and the Environment, 2000), where the environmental impact of each material and process is assessed according to a weighting system used to obtain a total environmental impact of the system (Ministry of Housing, Spatial Planning and the Environment, 2000). The weighting system is a simplification that is to be used with care and common sense, but can provide a good basis for comparison. The last and forth part is interpretation where the environmental impacts are discussed and potential improvements are proposed.

9.2 Inspiration from the LCA and the scope of the study

In this analysis, the impact of running and operating the TAH is assessed, as well as the production of biogas from the harvested algae. As is known, an LCA considers the operation, production and disposal of a product. Due to the limited time-scope of this project, the production and the disposal of the product are not included in the analysis, only the operation. Still, this environmental analysis is considered of value due to the fuel consumption being rated as causing the most considerable impact on the environment.

When conducting the analysis, the concept of a functional unit is taken from LCA, described before. The functional unit is in this analysis running the TAH for a day, which consists of two four-hour shifts, making up a total of 8 hours.

The system under study is the whole TAH with all its included parts. The system boundary is, thus, drawn at the outlets of the TAH, with the water under it and the air above it as its surroundings.

9.3 The life-cycle of the system

The construction of the TAH begins with the production of the raw materials. Many of the items in this design were bought as an already put together working system such as the centrifuge and the pump. Other raw materials that were added for the design include stainless steel, plastics, metals etc. These materials are then manufactured and pieced together in the first production assembly. This creates individual components such as the funnel, piping, and bathroom. After that, these materials then join the assembled bought systems such as the genset and centrifuge, and come together to form the final assembly making the TAH system as a whole. These steps are demonstrated in *Figure 9.2*.

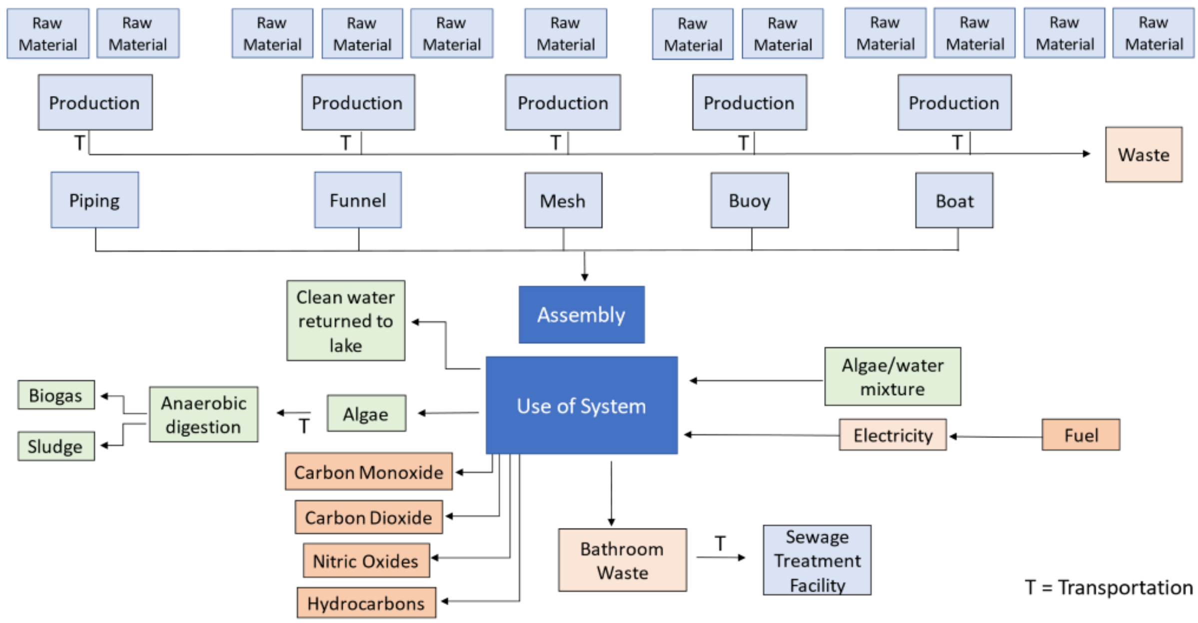

Figure 9.2: Flow Diagram of system

Overall, the TAH requires various inputs in order to operate. For one, there is a fuel source required to operate the Genset generator. This generator then provides the system with electricity. In addition, as the TAH operates, it takes up the mixture of algae and water from the body of water it is cleaning.

With these inputs, the system then computes a handful of outputs. The first, and the most important, is the 99% filtered algae which is held in the storage tank. These algae are then transferred off the TAH for the purpose of anaerobic digestion where it turns into two more products of biogas (methane) and then sludge. The methane can be harvested and repurposed for transportation or heating. The sludge could possibly be used as a fertilizer, or disposed of at an incinerator or landfill. The remaining clean water that was filtered from the TAH is returned to the body of water it was removed from. The transfer of water mixed algae onto the TAH, the separation of the algae, and the flow of water back to the water it was removed from, all happen as the TAH is running, with the inflow and outflow occurring simultaneously. Another output in the design consists of the products from the combustion of the fuel. Carbon monoxide, carbon dioxide, nitric oxides, and hydrocarbons are all produced from the combustion of the fuel. The last output is the waste from the bathroom. Both the sink drainage as well as the toilet will produce a waste which is held in an enclosed compartment but needs to be emptied and treated at a sewage treatment facility.

Overall, this environmental analysis focuses the emissions from the combustion of the fuel and the production of biogas.

9.4 Analysis

The main user of power for the entire algae separator system is the Genset. The Genset converts fuel into electricity. Then, the electricity is provided to the pump, centrifuge, electric motor etc. The overall power producer that needs to be analyzed is the Genset, and the fuel that it uses to provide electricity. The fuel used is Hydrated Vegetable Oil (HVO) due to its smaller negative impact on the environment compared to conventional diesel. HVO is a liquid fuel that is composed of many kinds of vegetable oils such as rapeseed, sunflower, soybean, and palm oil (Dimitriadis, et al., 2018). The main emissions due to the combustion of fuel include CO_2, NO_x, CO, and HC (Bortel, 2019). Hydrated Vegetable Oil is able to drastically decrease the emissions on a few of these main components.

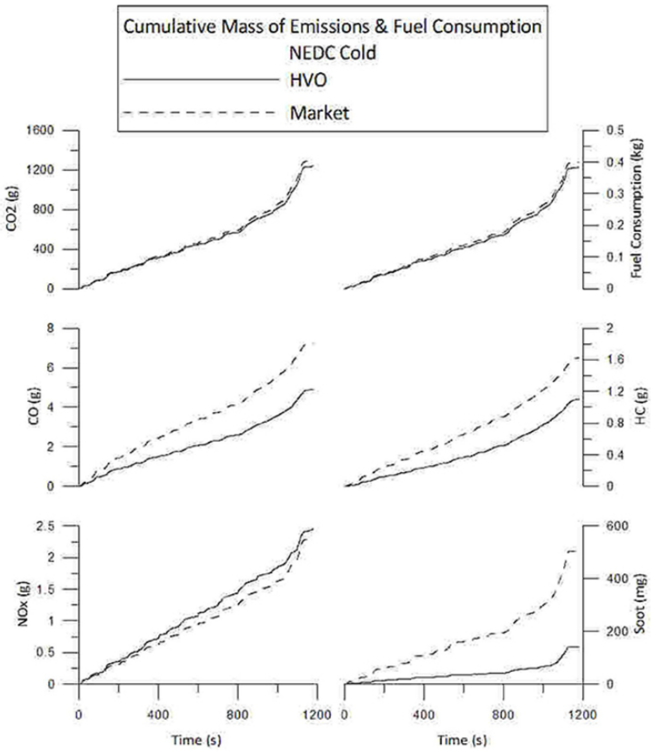

Figure 9.3: Fuel Emissions HVO compared to market fuels (Bortel, Vavra and Takats, 2019)

As seen in *Figure 9.3,* emissions of carbon monoxide as well as hydrocarbons are much lower using HVO compared to diesel.

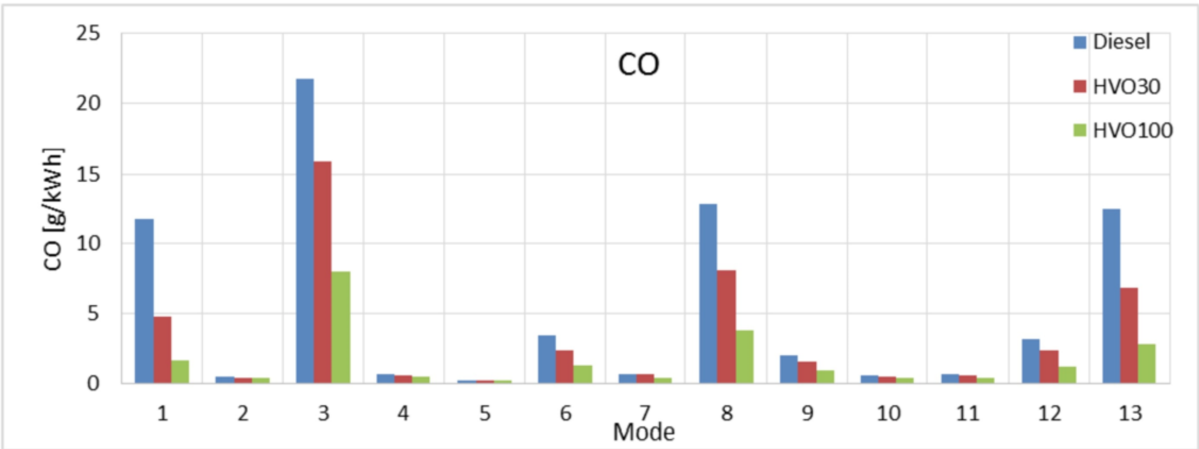

Figure 9.4: CO emissions using HVO compared to Diesel (Bortel, Vavra and Takats, 2019)

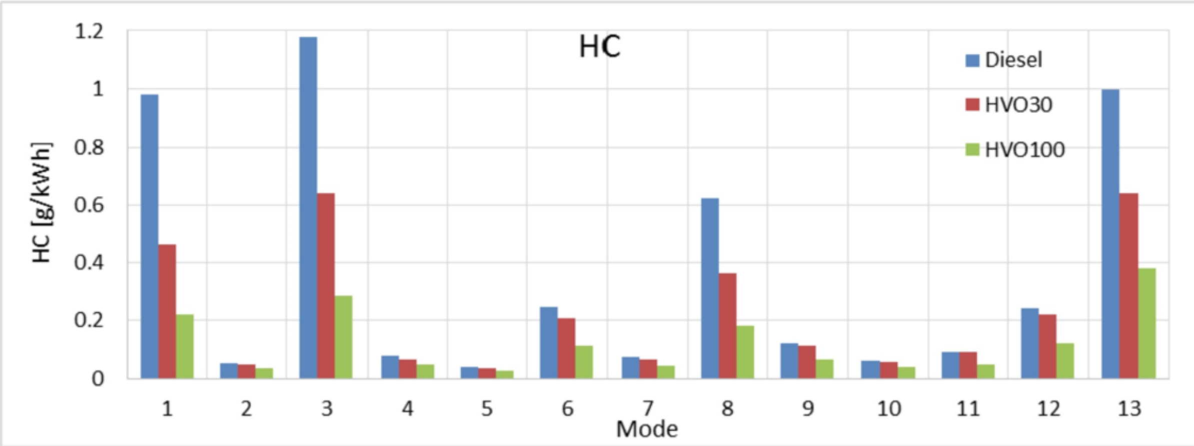

Figure 9.5: HC emissions using HVO compared to Diesel (Bortel, Vavra and Takats, 2019)

Again, seen in *Figure 9.4*, pure HVO decreases the Carbon Dioxide emissions by over half, and *Figure 9.5* shows the Hydrocarbon emissions being cut by about 75% (Bortel, 2019). On the x-axis, the modes represent different engine modes which mimic real usage conditions. These modes were defined by World Harmonized Stationary Cycle test (WHSC) which include 13 modes of engine operation in order to get a larger understanding of the impact (Bortel, 2019).

Table 9.1: Emissions for HVO in grams

Name of gas	Chemical formula of gas	Unit measurement in g/kWH	Total grams for Genset/h	Total grams for an 8-hour day
Carbon Dioxide	CO_2	575	49450	395600
Nitric Oxides	NO_x	5	430	3440
Carbon Monoxide	CO	0-5	430	3440
Hydrocarbons	HC	<.2	17.2	137.6

Overall, the analysis for the HVO emissions is analyzed in *Table 9.1*. The total emissions released per day of usage is shown in the far-right column. Again, the carbon monoxide and hydrocarbons are much smaller using the HVO fuel compared to normal diesel oil.

9.4.1 Biogas calculations

In the experiment by Forkman, an average value of $176.7\ \mathrm{cm^3/gVS}$ of methane was produced from the microalgae. The algae had a TS, which is the amount of dry substance, that is the amount of algae when all its containing water has dried, of 8.43%. The VS, that is the organic part of the algae that is of value in producing methane, is 59.16% of the TS. This gives a yield of:

$$176.7\ \mathrm{cm^3/g_{VS}} \cdot 0.0843 \cdot 0.5919 = 8.817\ \mathrm{liter/kg_{algae}} \tag{9}$$

As seen, an estimated amount of 1296 liters of algae are harvested each day. Using the density of cyanobacteria, 0.87 kg/liter (Hu, 2014), this gives an amount:

$$1296\ \mathrm{liter} \cdot 0.87\ \mathrm{kg/liter} = 1127.52\ \mathrm{kg} \tag{10}$$

of harvested algae per day. This gives a methane-production of:

$$1127.52 \text{ kg} \cdot 8.817 \frac{\text{liter}}{\text{kg}_{\text{algae}}} = 9934.7 \text{ liter per day} \quad (11)$$

With a methane density of $0.000656 \text{ kg/liter}$, the weight of methane produced per day is:

$$0.000656 \text{ kg/liter} \cdot 9934.7 \text{ liter} = 6.517 \text{ kg} \quad (12)$$

The reaction formula for combusting methane is:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \quad (13)$$

Hence, the only significant gas emitted is carbon dioxide. The same molar amount of carbon dioxide is emitted as the molar amount of methane that is combusted. The molar amount of methane produced per day is:

$$\frac{6.517}{0.016} \frac{\text{kg}}{\text{kg/mol}} = 407.3 \text{ mol} \quad (14)$$

The weight of this carbon dioxide is:

$$407.3 \text{ mol} \cdot 44 \frac{\text{g}}{\text{mol}} = 17921.2 \text{ g} \quad (15)$$

Therefore, 17921.2 grams of carbon dioxide is emitted when combusting the methane that is produced in one day.

Methane has a heat content of 55 MJ/kg. This gives a total heat content of:

$$55 \text{ MJ/kg} \cdot 6.517 \text{ kg} = 358.44 \text{ MJ} = 99.5 \text{ kWh} \quad (16)$$

in the methane produced in one day.

As previously mentioned, in this analysis it is assumed that the produced methane, and the resulting emissions from its combustion, is to replace an amount of HVO corresponding to the same amount of energy. Therefore, the emissions that the production of methane replaces is evaluated in terms of the data for HVO. This is presented in the *Table 9.2*. For carbon dioxide, the amount replaced is the emitted amount of combusting the same energy-amount of HVO minus the amount emitted by combusting the methane produced. This gives:

$$57212.5 \text{ g} - 17921.2 \text{ g} = 39291.3 \text{ g} \quad (17)$$

For the rest of the gas, the net amount replaced is the same as the amount emitted by the same energy-amount of HVO, since the methane does not emit anything of these gases.

Table 9.2: Environmental impact of fuel and biogas

Name of gas	Chemical formula	HVO emissions [g/kWh]	Boat emissions in one day [g]	Emissions by HVO replacing biogas produced in one day [g]	Emissions by methane produced in one day [g]	Net amount of emissions replaced [g]	Proportion of emissions replaced
Carbon Dioxide	CO_2	575	395600	57212.5	17921.2	39291.3	9.9%
Nitric Oxides	NO_x	5	3440	497.5	0	497.5	14.4%
Carbon Monoxide	CO	0-5	0-3440	0-497.5	0	0-497.5	0-14.4%
Hydro-carbons	HC	<0.2	<137.6	19.9	0	19.9	<14.4%

Table 9.2 shows that the production of methane replaces 9.9% of the carbon dioxide emissions, 14.4% of the nitric oxides, between 0 and 14% of the carbon monoxide, and up to 14.4% of the hydrocarbons resulting from running and operating the TAH.

9.5 Discussion

To run the complete TAH, a large amount of fuel is consumed, and as a result a large amount of emissions is emitted. Producing methane gas by anaerobic digestion from the harvested wild algae produces environmentally friendly fuel which could be used for either transportation, municipal heating or to replace an alternative fuel. In this analysis, it is assumed that the fuel that is replaced by the methane is the HVO used to operate the TAH. The results of the calculations reveal that a fair share of the emissions produced from running the TAH is replaced by the production of methane. This result can be considered low for a system that is developed for the benefit of the environment, and it might be expected that emissions be completely balanced out to demonstrate a net balance of zero environmental footprint, but it should be considered that the major environmental benefit of this system is not in its fuel economy, but in removing harmful algae blooms. Mitigating a considerable share of the emitted gases from running and operating the TAH - 9.9% in the case of carbon dioxide, 14.4% in the case of nitric oxides, and up to 14.4% in the case of carbon monoxide and hydrocarbons - can be considered an extra environmental benefit added to the fact that the problem of harmful algae blooms are removed from a specific area.

10 MANUFACTURING ANALYSIS

A plan for the production and an assessment of the manufacturability of the Toxic Algae Harvester were done to get a clear view of how it can be produced and to find weak points that can be eliminated by improving the design. As can be seen in *Table 10.1* the overall manufacturing process is focused on being as simple and as inexpensive as possible when taking into account that this product will mostly be manufactured in very small batches. Therefore, besides the hull, deck and cabin, the components for the TAH are mostly sourced from various suppliers.

Table 10.1: *Manufacturing Process*

Assembly Name	Material Type	Raw Stock Size	Operations
Continuous Centrifuge / Alfa Laval Clara 701H	Cast Iron and Stainless Steel: SS 2347 SS 2333	Weight 2,800 kg, Volume 10 m^3	Sourced from Supplier
Centrifugal pump / Victor S85K312T	Stainless Steel: SS316	Weight 114 kg, Volume 0.18 m^3	Sourced from Supplier
Funnel	Stainless Steel SS2333	5.5 m^2 of 3 mm thickness stainless steel sheet	Cut metal sheets into shape, and weld together.
Web Wire Mesh / 1mm slot flat wedge wire screen	Stainless Steel SS2332	500x3000mm	Sourced from Supplier, but must then be cut to fit Funnel using a Circular Saw
Volvo Penta Electric Sail Drive	No Public info available*	No Public info available*	Sourced from Supplier
Volvo Penta Marine Genset	No Public info available*	Weight 1310 kg, Volume 3.25 m^3	Sourced from Supplier
APC Silcon 80kW 400V UPS	No Public info available*	Weight 463.18 kg, Volume 0.896 m^3	Sourced from Supplier
SWATH Hull	Aluminum sheets and square hollow section aluminum. Aluminum Sheet SS4125.	56.5 m^2 of 5 mm thickness aluminum sheets and 20 m of 25 mm square hollow section aluminum	After a frame is made of square hollow section aluminum, sheets can be cut to shape and welded to the frame.
Storage Tank	Plastic within Metal cage	Weight 65 kg, Volume 1.398 m^3	Sourced locally
Deck	Aluminum sheets and square hollow section aluminum.	52 m^2 of 3 mm thickness aluminum sheet and 60 m of 25 mm square hollow section aluminum	After a frame is made of square hollow section aluminum, sheets can be cut to shape

	Aluminum Sheet SS4007.		and welded to the frame.
Floor	Aluminum Treadplate SS4125	22 m^2 of 5 mm thickness aluminum treadplate sheets	Aluminum sheets are cut to shape and mounted to the deck
Piping	Stainless Steel SS2333	13.25 m of 100 mm diameter stainless steel pipes	The pipes are cut and bent to connect the different components
Fuel Tank	High density polyethylene (HDPE)	Weight 20 kg, Volume 0.4 m^3	Sourced locally
Cabin	Aluminum sheets and square hollow section aluminum. Aluminum Sheet SS4125	60 m^2 of 3 mm thickness aluminum sheet and 40 m of 25 mm square hollow section aluminum	After a frame is made of square hollow section aluminum, sheets can be cut to shape and welded to the frame.
Cabin components	Sink, toilet, clean water tank, life jackets, life buoys, horns, lights, antenna, seats, windows and control panel	Weight 400 kg, Volume 2 m^3	Sourced locally
Control Panels	Steel box and copper wire	Weight 30 kg, Volume 0.05 m^3	Sourced from Supplier

*This information was to be provided by the sponsor, but given the current situation the information could not be acquired

10.1 Sourcing from Suppliers

Most of the components of the Toxic Algae Harvester will be sourced from different suppliers and the manufacturing will be more of an assembly than actually making different parts. The three main suppliers for the Toxic Algae Harvester: Volvo Penta, Alfa Laval, and Web Wire Mesh. If the customer is producing a large quantity, shipping and buying negations become an option. This option is helped by the fact that some components share suppliers.

10.2 Manufacturing of funnel, hull and deck

There are four main components that are special for this product that cannot be purchased and therefore need to be manufactured by the producer. These four components are the funnel, the SWATH hull, the deck and the cabin. All these components are made in a similar way, meaning they can be produced in the same facility and they can be made using very few tools and machines in a simple factory or workshop.

For the manufacturing of the funnel sheets of metal should be cut and bent to the shape specified by Volvo and then welded by GMAW (Gas Metal Arc Welding) to get the final component. The specific type of Stainless steel is to be decided by the manufacturer of the TAH in order to reduce cost and logistic complications.

The manufacturing of the SWATH hull begins by cutting, bending and welding the square hollow section aluminum to a frame according to specifications laid out by Volvo. Thereafter the aluminum sheets for the eight watertight sections can be cut and welded to the frame. Last of all, the aluminum sheets covering the pontoons can be cut and welded to the frame, all according to specifications. Since it is critical that the pontoons are watertight, they should be tested under pressure to make sure all welds are completely sealed.

Similar to the building of the SWATH hull, the process of manufacturing the deck and cabin begins by cutting the square hollow section aluminum and welding it to a frame. From that point all the aluminum sheets can be cut and then welded to the frame in order to complete the deck and cabin. Then all the piping and wiring can be completed prior to the cutting and fitting of the aluminum treadplate floor. All the steps will be done according specifications defined by Volvo. It is not as crucial for the deck and cabin to be watertight as the pontoons of the SWATH hull but all welds should still be checked visually or by using ultrasound to make sure the welds are good.

10.3 Possibility of Mass Manufacturing

The current method to manufacture the TAH lends itself for easy mass production. It is mostly made from outsourced parts which come from four major manufacturers. This cuts costs on deliveries and makes buying in bulk negotiations easier. Additionally, it simplifies the supply chain massively by lowering the number of suppliers from six to four.

Another benefit of the Toxic Algae Harvester when considering mass manufacturing is the low need for precise production of the main hull. The main design of the Toxic Algae Harvester allows for certain give which makes the manufacturing of the hull much less demanding. Aspects which require more precise measurements such as piping should be left until the end to make any small adjustments.

The best place for the mass manufacturing of the TAH would be somewhere in Sweden. The low lead times resulting by having two of the major suppliers nearby could be very helpful for making production leaner and having just-in-time production.

10.4 Cost Analysis

A cost analysis was conducted through identifying the economic value of different components towards manufacturing, producing, and delivering the TAH. These costs were then split into different sections: vessel materials, labor, transportation, and fuel, and their percentages were placed on a pie chart which is shown in *Figure 10.1*. The total cost of the entire build for one unit and one year's worth of usage is estimated to be around US$837,000 and the cost of developing the TAH was estimated to US$96,768 - the calculations are shown in *Appendix F*. It should be noted that the costs of Volvo Penta's Genset and Sail Drive are estimates since they could not be obtained from Volvo Penta because of the lockdown due to Covid-19.

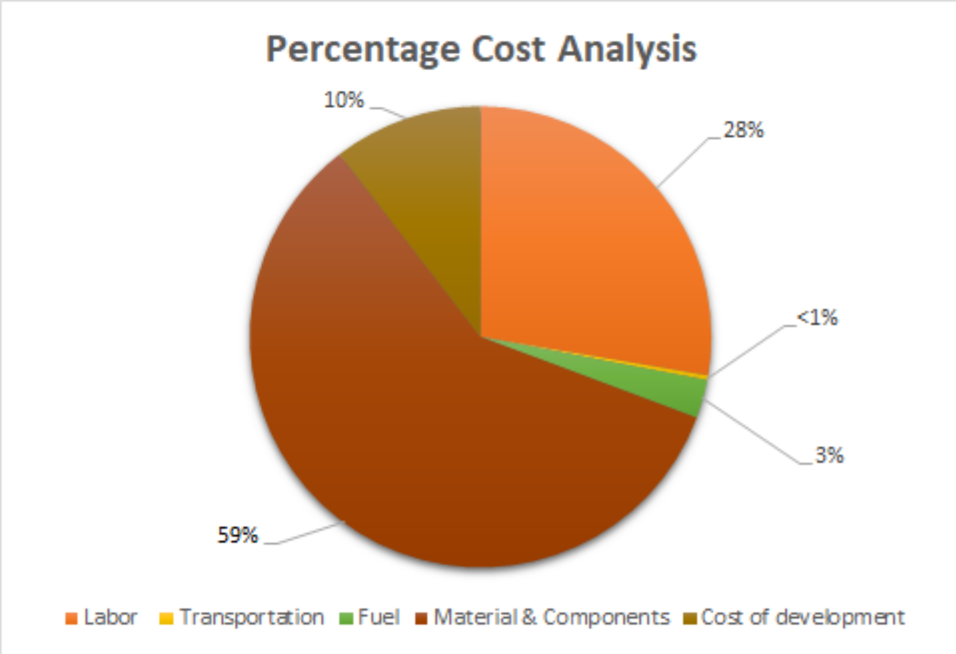

Figure 10.1: Pie chart showing percentage costs of TAH production, development, transportation, and usage on one unit in one year's time.

The running cost was simplified to consist of only the cost of the consumed fuel. This was calculated by using the Volvo Penta Genset fuel consumption of 20 liters per hour and the cost of HVO estimated to US$1.78 per liter. An assumption that the TAH will run for 8 hours a day during spring and summer months (26 weeks) and 5 days a week finally resulted in a running cost of US$37,024.

A very rough estimate was done for the labor cost for building the TAH. An analysis provided by Naval Sea Systems Command shows the labor cost percentage of the total build cost of different vessels. Since the Naval Sea Systems Command builds military vessels, the vessel with most similarity to the TAH was chosen and its labor cost was declared as equal to 32% of the total building cost (Arena, 2006) which resulted in a labor cost of US$256,138 for this project.

In terms of benefit, the TAH is able to improve two main factors. The first one is in the reduction of the economic damage that harmful algae blooms brings to the society. An estimation of the cost of these damages is difficult to perform, but one study estimated that harmful algae blooms result in an economic damage of US$100 million per year, for the dollar value 2012 (Davidson, et al., 2014). Another study in 2019, estimated a US$5.3 billion of economic cost in only the Lake Erie basin over 30 years (Smith, et al., 2019). However, these values are rough estimates since that information is not well documented in the US and throughout the world. The second factor is also an added environmental benefit by removing and using the algae to produce biogas, as described in chapter *9 Environmental Analysis*. The amount of biogas produced each day was calculated in section *9.4.1 Biogas calculations* to 6.517 kg per day. With the current selling price of biogas at US$1.99 per kg, this amount of gas would generate a modest US$1,686 of profit per year. This would not be enough to pay for the cost of building the TAH in a reasonable time, but it will have a positive impact on the environment.

10.5 Market Analysis

Since the algae blooms and their associated problems are extensive and present all over the world, the potential market for the TAH is very promising. For example, Lake Erie is one of the larger lakes in the U.S. and has over the years suffered from a lot of algae blooms, the cost of which has been calculated to US$5.3 billion over the last 30 years (Smith, et al., 2019). In 2015, Lake Erie had a massive algae bloom covering 777 square kilometers of the lake's surface (Swanson, 2018). With the current configuration of the TAH, 50 units would be required to harvest all the algae in that season. With an estimated retail price of US$2 million, providing a profit of US$1 million per unit, the investment cost of 50 Toxic Algae Harvesters would be US$100 million, less than 60% of the average cost caused by algae blooms annually. In an ideal case, the US$100 million investment could save roughly US$180 million yearly.

In summary, considering that the need of algae harvesting in only one lake in the U.S. could render a profit of US$50 million, the world wide algae harvesting business has huge potential. A problem with this kind of service is that it is a one-time deal, once the TAH is sold there is no more profit to be made besides spare parts and repairs. Perhaps a better alternative is to sell a clean-up service, providing the necessary tools and knowledge and in that way have a lower but steady income.

11 DISCUSSION

In this part of the text are there a few main points that are being discussed. These consists of the cost of running the TAH compared to the economic damage it could prevent, and whether it is possible to say that there is a positive impact on the environment by removing the algae while at the same time releasing carbon into the atmosphere. Lastly, the working method of the team during the time of the project will be discussed.

The cost of both producing and running the TAH are, as already known, considerably high. This is not a surprise considering the high weight of the TAH, as well as the heavy and expensive machinery onboard. To compare the cost of producing and running the TAH to the economic damage it could prevent is difficult mainly because of the information on how much it costs to run the TAH being very exact, while there is little and insufficient information on what economic damage the Toxic Algae Harvester could prevent. To predict this is truly a complex task, first of all because of not knowing before the commercialization of the product in exactly how big of a scale it will be used, and as a result how much algae it will actually come to harvest. Secondly, it is difficult to assess the economic damage in the algae blooms in themselves. In this study, the effect that harmful algae blooms have had on tourism activities has been recognized, although this is only one type of economic damage that it can be imagined to inflict. Many other types of damages that these blooms cause are possible. For example, the harm they cause on marine life brings by itself a range of economic damages, loss of resources through death of a large number of organisms being only one of them. Likewise, its harm on human health also poses a series of economic damages difficult to assess, these mainly being linked to healthcare. Not knowing the extent of the health damage that they might cause un-harvested and the resulting healthcare activities that will be necessarily makes this very difficult to assess. Thirdly, being a novel problem, it is difficult to predict what economic investments will be necessary to remove these algae blooms in the future if they are not removed now. It is possible that the economical investment to solve this problem in the future, if it is not solved now, will exponentially grow with time by one problem causing a number of other problems, which in turn cause a series of problems on their own.

An issue to be discussed regarding the Toxic Algae Harvester is its environmental impact. In the Environmental Analysis, it was shown that the TAH has heavy carbon dioxide emissions, along with other emissions. It was also shown that parts of these emissions can be seen as mitigated by processing the algae into biogas. Still, the analysis does not convince the curious reader that the Toxic Algae Harvester is environmentally friendly – quite the opposite, it created the sense of the harvester being another emission-heavy machine brought onto the market. While this is technically true, the aim of developing the TAH has been to harvest harmful algae blooms to mitigate their harms, this being an alarming problem all over the world. In order to fulfill this difficult task on a scale large enough to provide any environmental benefit, this product had to be heavy, with a high flow-rate of water mixed algae, thus necessitating heavy and efficient machinery onboard. This is what has caused the high levels of emissions of the TAH; namely, what was necessary in order to remove the harmful effects of the algae blooms is exactly what causes the emissions to be high. For this reason, stating the environmental effect of this product is not a solely quantitative activity, but is a qualitative one where one environmental harm is set side-by-side to another one for comparison.

The project team consisted of nine persons, four from Chalmers and five from Penn State. In order to get to know each other better and to benefit from the diversity of the group, subgroups were created, each subgroup working on a specific task. The subgroups consisted of two to four people. Having a subgroup larger than three people made it difficult to assign tasks to every member of the group in a fair manner. Having smaller subgroups of two to three people would be preferred due to it facilitating keeping account of all members in the subgroup and distributing the work-load evenly. This was especially important in this project since the team was stationed in two different countries. Communicating digitally generally makes communication more difficult, and, as a result, creates the risk of not knowing what tasks other group members are currently doing, hence the need for small sub-groups with close and continuous communication. Furthermore, it has been noted during this project that the level of ambition has been different among group members, something that was not foreseen from the beginning. However, measures were taken in the beginning where the ambition of the team members was discussed, but still, these measures did not provide the intended result.

12 CONCLUSION

This study has set out to develop a Toxic Algae Harvester to harvest harmful algae blooms in all types of waters. Several harvesting and separation concepts have been found and analyzed. The study has, by way of weighing, eliminating and evaluating different concepts, identified advantages and disadvantages of different harvesting and separation concepts, and through combining them, reached an optimal solution. This has resulted in the Toxic Algae Harvester being a boat with several components onboard, designed as a system to harvest algae in a fast and efficient way. Through a laboratory experiment, the separation concept chosen – i.e. the centrifuge – has been investigated and the results have been positive. Further, toxins that occur frequently in algae have been researched in order to discern if any device is needed for separation of toxins. Being a study intended for the benefit of the environment, what the best use of the harvest algae might be has been investigated. Among several products the algae could possibly be processed into, biogas has shown to be the most suitable one, being the most practical in terms of production, added to being beneficial for the environment. Finally, an environmental analysis has been conducted where the impact of the operation of the TAH on the environment has been attempted to asses, as well as a cost analysis with the purpose of giving a picture of the cost of its production and operation.

The project is a very complex one, with several factors involved, as seen in the discussion. The most important focus of the project has been the removal of toxic algae blooms in the most efficient way possible. Outside of that, the environmental impact of running the TAH by its emissions, and to counteract that, the production of biogas, has shown that the emissions from it are high, and that part of that is mitigated by the production of biogas. For this reason, the environmental benefit of the product has not been made evident. Adding to this its high cost, it is difficult to state that it is truly advisable for our client to manufacture this product for the removal of toxic algae blooms. Nevertheless, the high emission and the high cost of production can be allocated partly to the limitations of the study. The limited amount of time, as well as the limited amount of experience of the team, has resulted in the team not being able to fully develop and design the product for an efficient production and operation as possible. Hence, the product has turned out very costly and very emission heavy. It is imagined that with more time it would be possible to further optimize the product and by that way reduce its weight, and thereby its emissions and cost. For this reason, the team considers this study to be of high value, having contributed to a solution to harvesting toxic algae blooms in a very efficient way, as is shown in this study, and it is expected that this study will provide inspiration for further developers to further develop and optimize this solution for it to become economically feasible and more eco-friendly.

On a final note, the team, being situated in two different continents, has obtained valuable experience by this unique type of co-operation and are thankful for being able to participate in this study.

13 RECOMMENDATIONS

Due to this project having a rather short time frame, there is a significant potential for improvements to be made on the work done so far if Volvo Penta decides to proceed with the project. There are both several additional recommendations to further enhance the current design and several recommendations to avoid problems. If employed, these recommendations could greatly increase the ingenuity, efficiency, and effectiveness of the design and its components. Furthermore, it is important to clarify that the design of the TAH is not complete and ready to be manufactured, but the design process has come far, and the overall principles of the system has been established.

13.1 Gyroscopic stabilization

Since there is a large and heavy centrifuge mounted on the TAH for separating the algae and water, one recommendation is to design the centrifuge as a stabilizing gyroscope as an additional feature. A stabilizing gyroscope utilizes the angular momentum of a horizontal mass rotating around the vertical axis to counteract the effects of waves on a vessel by rotating the gyroscope around the horizontal axes (Perez, 2009). By rotating the gyroscope around the horizontal axes, the change in angular momentum of the gyroscope induces a torque on the vessel which mitigate the effects of the waves. In *Figure 13.1,* a typical gyroscope used to stabilize a boat is shown. Its angular momentum counteracts the natural rocking of the boat making it much more stable.

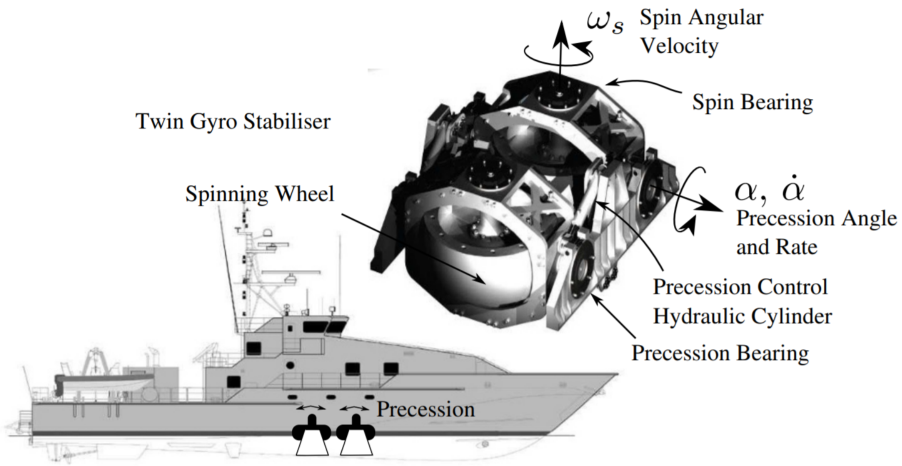

Figure 13.1: Example of a stabilizing gyroscope (Perez, 2009)

The possibility of using the centrifuge as a gyroscope hence becomes evident. The Alfa Laval separator is very heavy and can be mounted on a gyroscope similar to the example shown in *Figure 13.1,* and its angular momentum can definitely be used to help stabilize the TAH. The team could not find any example of a centrifuge being used to power a stabilizing gyroscope; however, this makes sense once one takes into context the lack of centrifuges in locations where a stabilizing gyroscope may be needed. Since there will probably be a person piloting the TAH, the option of a stabilizer with little extra energy cost is definitely to be considered.

13.2 Upscaled bearings in centrifuge

Redesigning the centrifuge to be able to act as both a separator and a stabilizing gyroscope would be a great improvement. A more critical measure would be to upscale the bearings. This is important since the centrifuge manufactured by Alfa Laval is constructed to operate on stable ground and the bearings will probably be worn out prematurely because of the torque induced by the rocking motions caused by the waves. Bearing failure could badly damage the centrifuge causing great costs for repairs besides making the TAH inoperable. It is therefore an important measure to consider, also an estimation needs to be done regarding the life span of the upscaled bearings so that preventive maintenance can be performed with the correct intervals.

13.3 Hull design and simulation

Since none of the team members have any skills in ship design, limited time for strength calculations and the short timeframe of the project, the hull, cabin and superstructure of the TAH has been very roughly estimated and no simulations nor strength calculations have been performed. Instead, focus has been pointed towards how all the different components should fit together and getting the TAH to be a good and ergonomic workspace. The fact that the focus has not been pointed at building a product that is strong enough does not mean it has been discarded completely. During the design phase the team members have used their knowledge to avoid common pitfalls but that is not enough to make sure the TAH is safe to operate and work on. Therefore, before it is able to be manufactured a lot of simulations and testing need to be done. The overall strength of the TAH will need to be assessed, preferably in different environments since it is going to be used in multiple different locations and conditions. The resistance to fatigue due to the rocking motion of the waves will need to be assessed, which could prove difficult due to the torque induced by the centrifuge, especially if it is going to be used as a gyroscope. Further, fluid dynamics simulations need to be performed since the drag force is really sought after to determine if the two motors have enough power to propel the TAH. Last of all, the overall electrical system needs to be revised since none of the group members have any previous knowledge of large electrical systems.

13.4 Functional models and prototype

The initial intention was to create functional models of specific functions of the TAH. This was planned to be able to be done in the limited time, but the outbreak of Covid-19 unfortunately made this impossible. The experiment for testing the suitability of a food-grade separator for separating algae from water was tested but the rest of the functions, like collecting the algae with the funnel and the ability to transport the concentrated algae in the piping still need to be done. After the functional models have been designed, it is recommended to build a prototype of the TAH to test and evaluate the entire system.

One important aspect to test once the prototype has been built is the risk of leftover toxins from the algae left in the water. Thus, it would be recommended to test the water post algae removal to ensure the safety and cleanliness of the water. Clean to the naked eye should not be mistaken as safe of all harmful species.

13.5 Adjustable funnel

As for now, the funnel through which the algae are collected, is completely stationary and held in place with braces. This option was chosen because of the time limit of the project since it was considered the easiest of the options to design. This solution has unfortunately some disadvantages, first of all, the depth of collection is not adjustable and therefore all of the algae might not be able to be collected at all times. Furthermore, the relatively large funnel will always be underneath the surface of the water and, thus, always creating a drag force which leads to an unnecessary increase of energy consumption when algae is not being collected.

A redesign of the funnel including a mechanical vertical adjustability of the funnel would eliminate the problems mentioned earlier. Since there is a generator producing electricity onboard the TAH, the mechanics of the adjustable funnel could be provided power by an electrical motor connected to a gearbox and operated from inside of the driver's cabin.

13.6 Onboard biogas reactor

Since the conclusion was made that the most suitable usage of the collected algae is production of biogas, a recommendation is to make the TAH as self-sufficient as possible by both producing and using the biogas onboard. For this to be possible, the Volvo Penta genset needs to be replaced by a biogas genset. Regarding the gas consumption, the biogas genset would require about 20 to 25 m^3/h (Polprasert and Koottatep, 2017). According to section *9.1.4 Biogas calculations*, the total biogas production from harvested algae is about 10 m^3. Therefore, to be able to keep running the harvester, more algae would be needed which would increase the size of the TAH due to a larger or additional centrifuge.

Since it is possible to increase the amount of collected algae, it could still be a viable future development. If so, to determine the size of a reactor that is able to digest the harvested algae needed, the retention time required needs to be taken into account. The estimated amount of harvested algae is 1296 liters per day and from an experiment by Forkman the retention time of algae is 10 to 15 days. With these values the digestion volume is calculated to be about 13 to 20 m^3. From equations 18 and 19 the following relations are obtained

$$V_\mathrm{d} = V_\mathrm{s} \cdot R_\mathrm{T} = 1296 \cdot 10 = 12960\ liter \approx 13\ \mathrm{m}^3 \tag{18}$$

$$1296 \cdot 15 = 19440\ \mathrm{liter} \approx 20\ \mathrm{m}^3 \tag{19}$$

where V_d stands for the digester volume, V_s stands for the daily substrate input and R_T stands for the retention time. However, there is also a need of a gasholder, the size of which can be determined in different ways. With regards of the high consumption of biogas the harvester has, the size could be determined by the amount of gas needed to be stored when the harvester is not in use. Therefore, the amount of gas produced per hour (G_h) and the maximum amount of zero-consumption time (t_{zero}) is needed. With some rough estimates that one day of harvested algae produces 10 m^3 biogas and a mean value of the retention time at 12.5, the G_h is estimated through:

$$G_h = \frac{10}{12.5}\frac{\mathrm{m}^3}{\mathrm{days}} = \frac{10}{300}\frac{\mathrm{m}^3}{\mathrm{h}} = \frac{1}{30}\ \mathrm{m}^3/\mathrm{h} \tag{20}$$

As the harvester will only be running for 8 hours a day, t_{zero} will be 16 hours. Therefore, the gasholders can be approximated to be 0.53 m^3 from equation 21.

$$G_h \cdot t_\mathrm{zero} = \frac{1}{30} \cdot 16 \approx 0.53\ \mathrm{m}^3 \tag{21}$$

To be able to fit a biogas reactor in the size range of 13 to 20 m^3, the size of the TAH has to be adjusted. If the size of the biogas reactor is instead approximated based on the consumed amount of biogas, the amount of daily needed biogas has to be estimated. As a biogas Genset consumes about 22.5 m^3/h of biogas and with a running time of 8 hours, the total amount of biogas needed per day is calculated as:

$$22.5 \cdot 8 = 180 \text{ m}^3 \tag{22}$$

By mimicking both equation 10 and 11 from chapter *9 Environmental Analysis*, the amount of algae needed is approximated by:

$$\frac{180000}{8.917} \frac{\text{liter}}{\text{liter/kg}_{\text{algae}}} \cdot \frac{1}{0.87} \frac{\text{liter}}{\text{kg}} = 23465.64 \text{ liter} \tag{23}$$

The daily amount of algae is therefore around 23.5 m^3, which is used to approximate the biogas reactor volume:

$$V_d = 23465.64 \cdot 12.5 = 293320 \text{ liters} \approx 290 \text{ m}^3 \tag{24}$$

The size of the biogas reactor needed onboard the TAH to support the current system would therefore need to be larger than 290 m^3 when adding a gasholder.

Furthermore, these calculations are only rough approximations to get an understanding of how large the reactor needs to be to support the harvester. Since all the components are bound together, if one increases so will the others and therefore a recommendation is to research this possibility further. Because to satisfy the current power requirement both the size of the harvester and the amount of harvested algae would have to increase, which would increase the required reactor and so on.

13.7 Overall recommendations discussion

Besides the before mentioned rather crucial aspects, a couple of possible future enhancements have also been identified by the team. If the before mentioned biogas reactor would be implemented, much of the collected algae mass would come to use when generating energy for the TAH. This would decrease the need of returning to land and emptying the algae tank, as well as eliminating the need of returning to land to refuel. This means that the TAH would be able to be out on the water and operating for longer times than the initial four hours. This enhancement would additionally provide the possibility of making the TAH completely autonomous and self-sufficient. An autonomous system has obvious advantages such as lower operating costs since no personnel is needed on board, the possibility of operating for longer times and at different hours of the day, a larger proportion of the available space can be used for machinery since no personnel will be present onboard. Besides the generator running on biogas, solar panels can be installed to support the energy production onboard.

When transporting the TAH to where it will be operated, problems may be encountered. If the TAH is intended to be used in multiple different locations, it needs to be easy to transport. The team tried to accomplish a design that made the TAH easy to transport. The length and width of the TAH pose no problems regarding transportation, all that is needed is a wide load sign on the truck. The height, on the other hand, may be a problem. In Sweden it is difficult to transport cargo higher than 4.5 meters. The final design of the TAH is a total of 5.07 m high including the pontoons, but only 3.97 m excluding the pontoons. Therefore, it might still be possible to transport the TAH using a conventional truck but with a modified trailer, if the trailer is designed to carry the TAH on the bottom of the deck, between the pontoons instead of on the pontoons. This way of transporting is common in wider dual hull ships where distance between the pontoon is wider than the trailer itself. If this way of transporting the TAH is investigated and deemed impossible, there are two less desired ways to make it transportable. First of all, the TAH could be completely re-designed and made sure the height does not exceed the limit. The two-story cabin would have to be excluded in this case since each part could not be tall enough for a human to comfortably move around in. The second way is to divide the TAH into two parts, a bottom plate with the pontoons and top part with the machinery and cabin where the two parts could be transported separately and fitted together in the water. The second method is more complicated and should be avoided if possible.

Furthermore, since most of this projects focus has been on developing the system for collecting and separating the algae from water, this system could probably be mounted on an existing boat. This would decrease costs of building a custom boat design. The versatility and function of different existing boats would also allow the mountable harvester system to be used in different types and volumes of bodies of water. An example of a vessel that could be used for mounting this system is an icebreaker. Algae blooms occur in the summer and icebreakers are mainly used in the winter. Therefore, mounting the harvester system on this kind of vessel would increase the level of utility of the vessel while not interfering with its main purpose.

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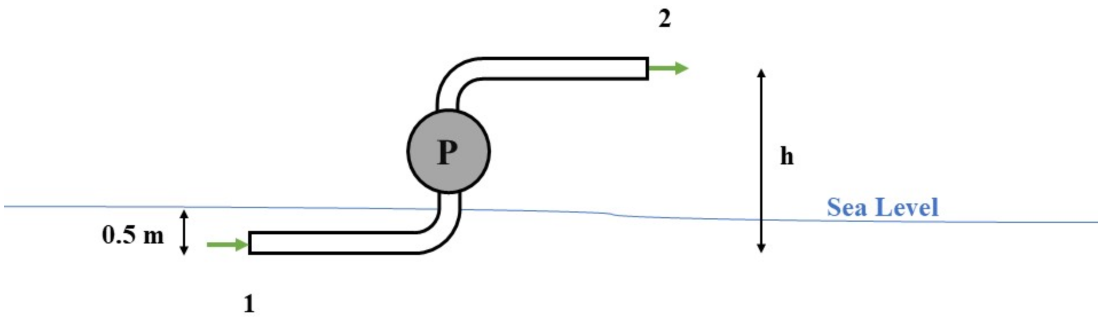
APPENDICES

A. Pump calculations



Known values:

$$Q = 75 \text{ m}^3/\text{h}$$

$$\eta = 50\ \% \text{ (efficiency of an average pump)}$$

$$\rho = 997 \text{ kg/m}^3 \text{ (assuming the density is roughly the same as for water)}$$

$$\text{D} = 100 \text{ mm (assumed pipe diameter)}$$

$$\text{h} = 2000 \text{ mm}$$

$$\text{l} = 5000 \text{ mm (assumed total pipe length)}$$

$$\nu = 1.005 \cdot 10^{-6}$$

Calculations:

$$V = \frac{Q}{A} = \frac{75}{\frac{\pi}{4}(0.1)^2} = 2.65 \text{ m/s}$$

$$\text{Reynolds number} = Re_{\text{d}} = \frac{VD}{\nu} = 2.64 \cdot 10^5 \text{ => turbulent}$$

$$\text{f} = 0.0145 \text{ (from Moody chart with } Re_{\text{d}} = 2.64 \cdot 10^5\text{)}$$

$$K = 0.19 \text{ (Resistance coefficient of 90 degrees bend at 100 mm diameter pipe)}$$

$$h_{\text{m}} = K \cdot \frac{V^2}{2g} = 3 \cdot 0.19 \cdot \frac{2{,}65}{2 \cdot 9.82} = 0.204 \text{ (assumed 3 bends)}$$

$$h_{\text{f}} = f \cdot \frac{LV^2}{d \cdot 2g} = 0.259$$

$$h_{\text{tot}} = h_{\text{f}} + h_{\text{m}} = 0.463$$

Bernoulli:

$$\left(\frac{p_1}{\rho g} + \frac{\alpha_1 V_1^2}{2g} + z_1\right) = \left(\frac{p_2}{\rho g} + \frac{\alpha_2 V_2^2}{2g} + z_2\right) + h_{\text{tot}} - h_{\text{pump}}$$

$V_1 = 1\ \text{m/s}$ (boat harvesting speed)
$V_2 = 2.65\ \text{m/s}$
$z_1 = 0$
$z_2 = 2\ \text{m}$
$\alpha_1 = \alpha_2 = 1$ (because of turbulent flow)
$p_1 = 106205\ \text{Pa}$ (0.5 m below surface)
$p_2 = 101325\ \text{Pa}$

$$h_{\text{pump}} = \left(\frac{p_2}{\rho g} + \frac{\alpha_2 V_2^2}{2g} + z_2\right) - \left(\frac{p_1}{\rho g} + \frac{\alpha_1 V_1^2}{2g} + z_1\right) + h_{\text{tot}} = 2.27\ \text{m}$$

$$P_{\text{pump}} = \frac{\rho g Q h_{\text{pump}}}{\eta} = 923\ \text{W}$$

The theoretical minimum required power is 923 W.

NPSH calculations:
To avoid cavitation of the liquid and thus damaging the pump, the NPSH Required by the pump (NPSHR) must be lower than the NPSH Available in the system (NPSHA). The NPSHA is calculated to approximately 8.67 m. NPSH stands for Net Positive Suction Head and this value is a limiting factor when choosing a suitable pump.

$$NPSHA = \frac{p_{\text{a}}}{\rho g} - Z_{\text{i}} - h_{\text{tot}} - \frac{p_{\text{v}}}{\rho g}$$

$p_{\text{a}} = 101325\ \text{Pa}$

$p_{\text{v}} = 2338\ \text{Pa}$ (vapor pressure water)

$Z_{\text{i}} = 1\ \text{m}$ (heigth of placement of pump)

$h_{\text{tot}} = h_{\text{f}} + h_{\text{m}} = 0.463$

$$NPSHA = \frac{101325}{995 \cdot 9.82} - 1 - 0.463 - \frac{2338}{995 \cdot 9.82} = 8.67\ \text{m}$$

B. Victor S85K312T (Dynamic change pump, centrifugal)

Specifications:

Maximum Flow rate	[m^3/h]	79.8
Power	[kW]	4
Weight	[kg]	117
Dimensions (LxWxH)	[mm]	654x327x412
Maximum allowed viscosity	[cSt]	50
Maximum particle size	[mm]	40
Maximum temperature of fluid	[°C]	70
Inlet Diameter	[mm]	76.2
Outlet Diameter	[mm]	76.2
NPSHR at 75m^3/h	[m]	3.75
Voltage (motor)	[V]	400
Maximum system pressure	[Bar]	6
Pumphouse material		SS 316 (Marine grade stainless steel)
Price	[US$]	5104

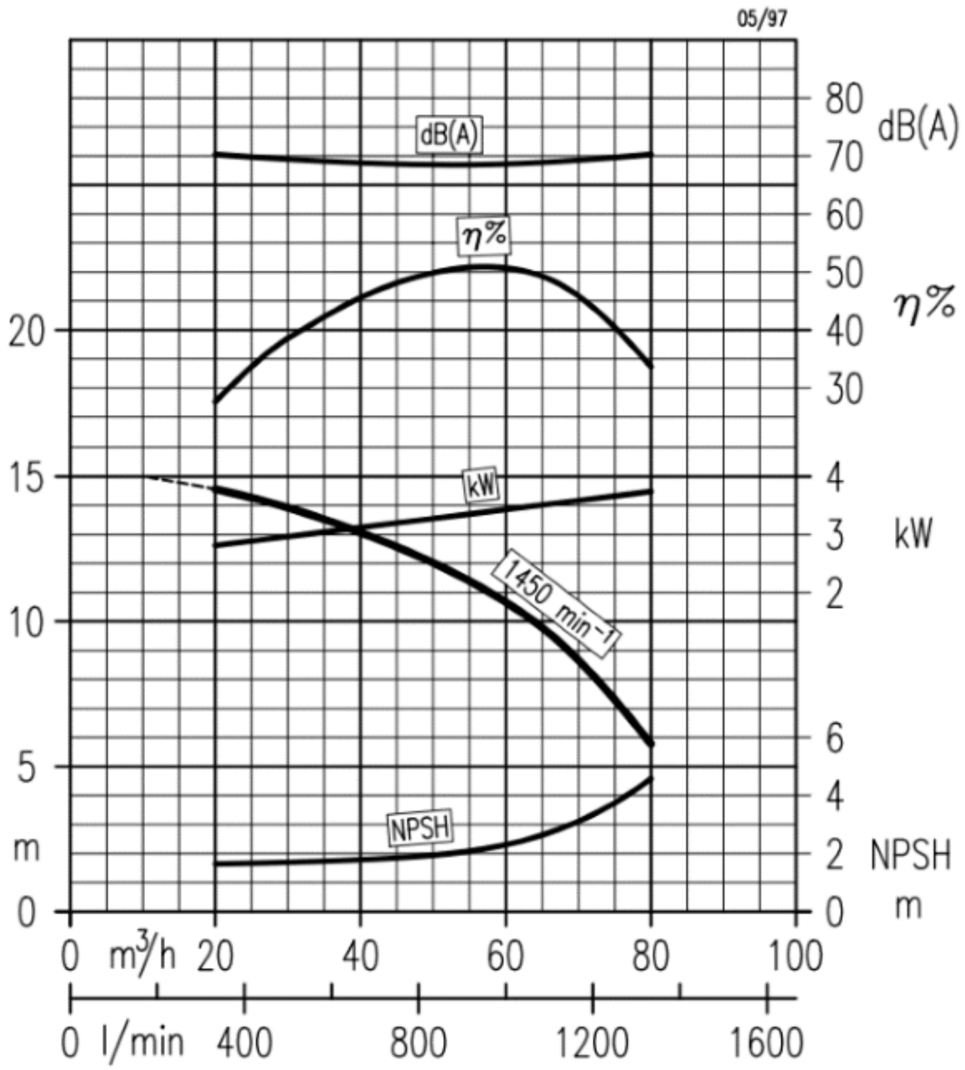
Pump curve:

S Leistungen - Performances - Prestazioni **P-602216**

12/05/00

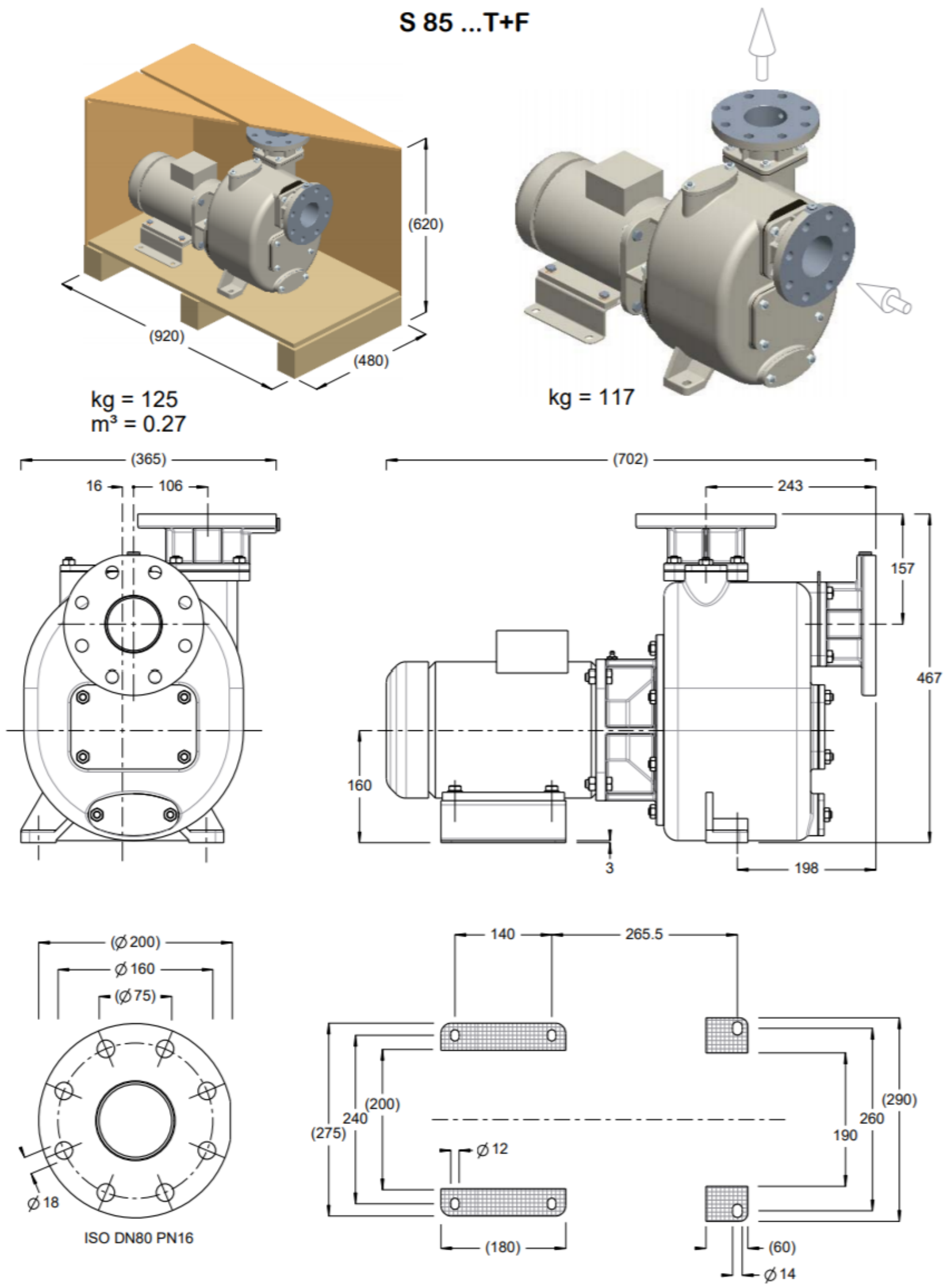
S 85 - 50 Hz

Laufrad: Impeller: Girante:	**220** mm Ø	Feststoffe bis: Solids up to: Solidi fino a:	**40** mm Ø	Umdrehung: Speed: Velocità:	**1450** min^{-1}



GERMANY • Tel. +49 89 9048660 • Fax +49 89 9043447 • germany@victorpumps.com
ITALY • Tel. +39 0498961266 • Fax +39 0498961255 • italy@victorpumps.com

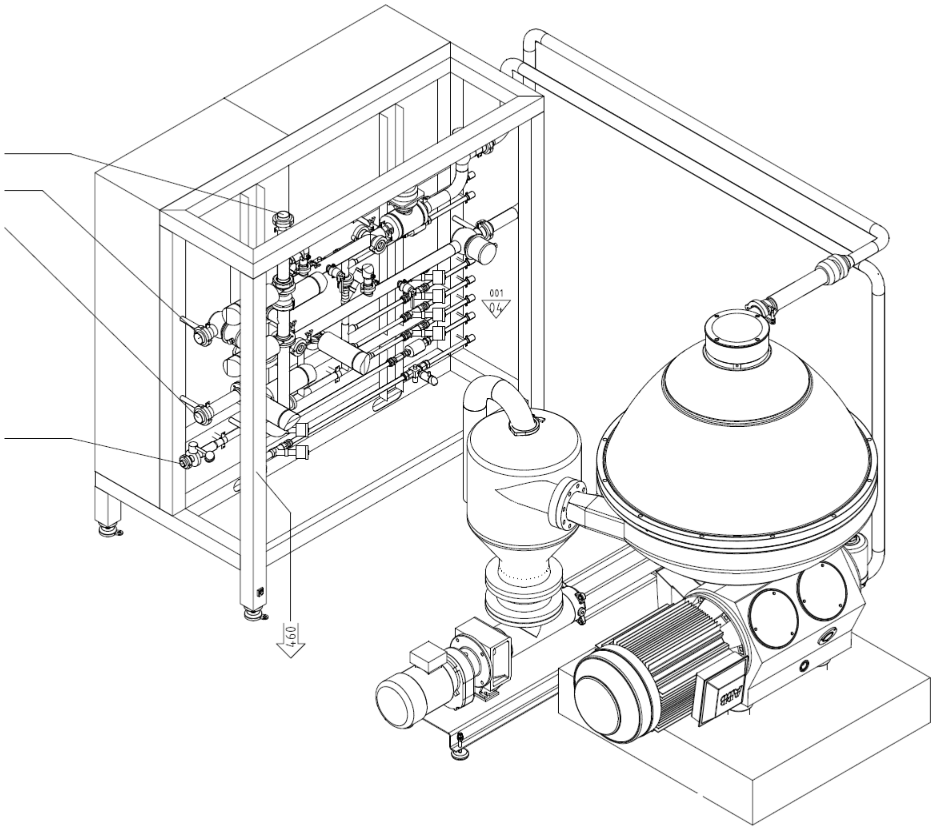
Dimensions:


S 85 ...T+F
(620)
(920)
(480)
kg = 125
m³ = 0.27
kg = 117
(365)
16
106
(702)
243
157
467
160
3
198
(Ø200)
Ø160
(Ø75)
Ø18
ISO DN80 PN16
140
265.5
(275)
240
(200)
Ø12
(180)
190
260
(290)
(60)
Ø14

C. Alfa Laval Clara 701H

Specifications:

Gross Weight	[kg]	2800
Dimension LxWxH	[mm]	1750x1730x1823
Energy Requirement	[kWh]	37
Throughput capacity	[m^3/h]	75
Price	[US$]	282,000



D. Volvo Penta HE D5A TA / UCM274E-1

Specifications:

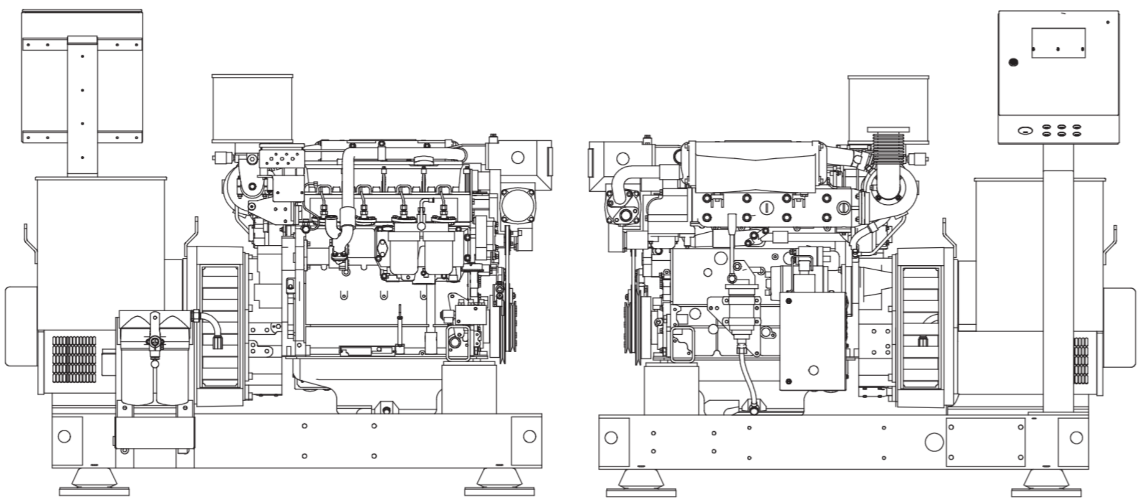
Dry Weight [kg]	1310
Dimension LxWxH1/H2 [mm]	1925x1046x1224/1614
Power output at 1500rpm [kW]	86
Fuel consumption [liters/h]	21.9
Output voltage [V]	3-Phase 400
Recommended fuel	MDO-DMX or MDO-DMA acc. to ISO 8217
Starter battery requirements	12V/140A
Emission level	CCNR Stage 2
Certification level	EU IWW

H1 = Height including exhaust compensator

H2 = Total genset height including control box

HE=Heat Exchanger cooled system

D5A TA



E. APC Silcon 80kW 400V UPS

Specifications:

Output Power	[kW]	80
Input Voltage	[V]	400
Output Voltage	[V]	400
Output Frequency	[Hz]	50 or 60
Weight	[kg]	440.91
Dimensions (LxWxH)	[mm]	800x800x1400
Price	[US$]	55390

F. Cost breakdown of TAH

Material & Components	Details	Provider	Cost [US$]
Centrifuge	Alfa Laval Clara 701H	Alfa Laval	282000
Pump	Victor S85K312T	Telfa	5104
Algae Storage Tank	IBC Tank 1000 liters	Cowab	398
Volvo Penta Genset	Volvo Penta HE D5A TA / UCM274E-1	Volvo Penta	100000
Propulsion system	2 x Volvo Penta Electric Saildrive	Volvo Penta	80000
UPS	APC Silcon 80kW 400V UPS	APC by Schneider	55390
Starter Battery	Varta K8	Autoparts	304
Piping Material	Stainless Steel SS2333 13,25m, r1=50mm, r2=45mm	Stena Stål	298
Funnel Material	Stainless Steel SS2333 5.5m^2 3 mm thickness	Stena Stål	529
Mesh Material	Wire Mesh 1 mm slot Stainless Steel SS2332	Wire Mesh	300
Hull Structure Material	Aluminum Square Hollow Section SS4103 25mmx20m	Stena Stål	327
Hull Material	Aluminum Sheet SS4125 56.5m^2 5mm thickness	Stena Stål	5927.5
Drivers Cabin Material	Aluminum Sheet SS4007 60m^2 3mm thickness	Stena Stål	3515
Deck Material	Aluminum Sheet SS4007 52m^2 3mm thickness	Stena Stål	3049
Floor Material	Aluminum Treadplate SS4125 22m^2 5mm thickness	Stena Stål	660
Fuel Tank	284 liter fuel tank	Transfer Flow	1576
Fresh Water Tank	215 liter tank	Axmarin	200
Septic Tank	Stainless Steel Septic Tank 56 liters	Hjertmans	223
Toilet	Porta Potti 335	Watski	183
Sink	Intra RS72	Ahlsell	300
Searchlight	10W LED searchlight	Watski	360
Life Jackets	4 x Baltic Legend 275n Life Jacket	Crew Safe	980
Lifebuoy	2 x GIOVE Lifebuoy Ring SOLAS	Lalizas	436
Fire Extinguisher	Powder Fire Extinguisher 6 kg (PD 6 G)	Dafo	120
Electric Horn	2 x 12V Electric Horn	Hjertmans	114
Seats	2 x Pilot Chairs	Wholsale Marine	514
Antenna Console	VHF antenna + Console	Westmarine	495

Windows	8 x Windows	Vetus	800
Navigation Lights	Top, sides and sterns	Hjertmans	191
Labor	Estimated as 32% of total building cost		256138
Transportation			3000
Fuel	Estimation of consumption for 1 year of use		37024
Material & Components			544293.5
Cost of Development	Estimation that a newly graduated engineering consultant costs US$71.68 / hour. 9 engineers and 150 hours each		96768
Total			**937223.5**

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