CHALMERS
UNIVERSITY OF TECHNOLOGY

Design of an Industrial Scale Algae Cultivation System

A product development project

Master's thesis in Product Development

Karin Dankis

Department of Product and Production Development
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2016

Master's thesis 2016

Design of an Industrial Scale Algae Cultivation System

A product development project

Karin Dankis

Department of Product and Production Development
Division of Product Development
Chalmers University of Technology
Gothenburg, Sweden 2016

Design of an Industrial Scale Algae Cultivation System
A product development project
Karin Dankis

Supervisor and Examiner: Lars Almefelt, Department of Product and Production Development

Master's Thesis 2016
Department of Product and Production Development
Division of Product Development

Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: Render of the product platform designed.

Typeset in LaTeX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2016

Abstract

The company Swedish Algae Factory (SAF) advertised a master thesis project opportunity with the department of Product and Production Development at Chalmers University of Technology in 2015. This was the initiation of the project recapitulated in the following report. SAF is a small start-up company that was created at the Chalmers School of Entrepreneurship together with algae researchers from the University of Gothenburg. The company are still growing their business and looking for potential markets to enter into. The algae that they work with has many potential value adding uses which allows them to cater to a vast array of customers.

To be able to accommodate the potential customers that they are looking into, an industrial scale-up of their existing algae cultivation module is imperative. This is where the development project began. The objective of the project was to develop a new design of the existing cultivation module that would be able to be scaled into a cultivation system that could be used in a commercial endeavour. The module had to use the space and light efficiently, maximise the algal growing area and have a modular design that allowed for upgrades and large scale usage. The module had to be safe for both the users and the algae throughout the product's life cycle.

Simultaneously as the master thesis project was under way, an additional project together with the municipality of Sotenäs and the company Rena Hav AB had been initiated. The project is part of a program called "Sotenäs Symbios" that promotes an environmental way of conducting commercial endeavours. Rena Hav AB are building a pisciculture plant that is completely on land to minimise any pollutants contaminating the surrounding sea water. Rena Hav AB are interested in implementing an algal based water treatment plant that purifies a portion of the pollutants generated from the fish tanks. This project was used as a case study to be able to design the product after real life specifications and dimensions.

The project commenced with a thorough data collection phase resulting in information input that was used in the concept generation and selection phases. The final chosen concept was refined and fully detailed design and dimensioned. The result of the project is a complete design of an industrial algal cultivation module and system. The module is a cost effective platform based product that is prepared for future updates in the form of complete automation as well as control and monitoring programs.

Keywords: Algae cultivation, Industrial scale, Platform, Pisciculture, Case.

Preface

This following report is a summary of the master thesis project that was conducted at the department of Product and Production Development at Chalmers University of Technology for the company Swedish Algae Factory. The project was divided into two parts for the first half took place during the summer of 2015 and the second half was completed in the spring of 2016. This project completes my Master of Science degree in Product Development.

First of all, I would like to thank everybody at Swedish Algae Factory for their support and insight into the project. Without their expertise none of this would be possible.

I would also like to thank my supervisor and examiner Lars Almefelt at the department of Product and Production Development for his guidance in this project.

A special thanks to Jan Bragee and Reine Nohlborg at the prototype lab at Chalmers for the immense help in building my prototype and for allowing me to use the facility.

Finally, a huge thanks to my family and friends without whom I would never have been able to do any of this. Especially Martin, who never let me quit.

Karin Dankis
Gothenburg
April 2016

Contents

List of Figures

List of Tables

Glossary

cultivation system A group of modules arranged in succession. v

module The algae cultivation unit which entails cultivation surfaces and support structures. v

pisciculture Breeding fish in a controlled environment for commercial purposes. v

1
Introduction

The following report is a summation of a master thesis project that was conducted at Chalmers University of Technology in accordance with the company Swedish Algae Factory (SAF). The focus of the project was to put forth a design for an industrial scale algae cultivation plant. The project covered all parts of the product development process from concept, detailed design, cost analysis and implementation strategy.

1.1 Background

1.1.1 Swedish Algae Factory

The company Swedish Algae Factory (SAF) is a small "start-up" that was generated from the Venture Technology programme at Chalmers School of Entrepreneurship in 2013. Researchers at the department of Biological and Environmental Sciences at Gothenburg's University found an algae deep in the polar ice caps during an expedition. They then brought this algae to Chalmers and introduced it to the Venture Technology programme to initiate a commercially viable opportunity. SAF was then created and led by the CEO Sofie Allert along with a board of directors and industry advisors.

In 2014, SAF developed a cultivation system and module that mimics the natural environment that the algae were exposed to in nature before discovery. Until recently they were testing this system in a project with wastewater from Renova, the primary waste management company active in the western parts of Sweden. They are currently researching different potential customers and uses for the algae and system. SAF are aiming to commercialise their product and introduce it into the industrial market in the near future. [18] Therefore, they are interested in looking into optimising the system to be suitable for a mass algae production plant.

1.1.2 A Breif Diatom Algae Theory

The algae that SAF work with is a type of diatom algae which are in turn a type of siliceous microalgae. Contrary to how many macroalgae are cultivated, these types of algae do not grow in suspension but instead colonise on surfaces in what is called a biofilm. These diatoms use a gravitational pull to sediment on a surface and grow exponentially by cloning themselves [8]. The algae, grows extremely well in low temperatures with little access to light which makes it ideal for the Nordic climate. Compared to other energy crop algae, this algae is much more efficient as it grows a total of 22 hours per day while others grow around 16 hours per day. This shortens the cultivation period drastically. The algae feed on three natural substances; phosphorus, nitrogen and carbon dioxide. All of these matters can be found in common wastewater plants, therefore this is an optimal growing environment for the algae. As the algae grows it depletes the water from of these waste materials, which simultaneously cleans the water. Once the algae are fully grown, it can be harvested to create biomass that can be converted into biofuel, among other things. [10]

1.1.3 Rena Hav AB

In the summer of 2015, SAF entered into a project together with the company Rena Hav AB and the municipality of Sotenäs in Sweden. The project is part of a program called "Sotenäs Symbios" that was started by the municipality of Sotenäs to bring companies and interested parties together to create a "no-waste" industry. The idea is that the waste generated from one commercial company can be used by another company to create value products. Rena Hav AB are working on building a pisciculture plant that has zero pollutant emissions. To achieve this they are building an entire fish farm on land and working with a set of denitrification processes to purify the water that has been in the fish tanks before they let it out in the sea again. The algae system design in this project is deemed to be part of the water purification process. This project was used as a case study for this master thesis project. The full case description can be reviewed in chapter 2.

1.2 Purpose of project

The purpose of the master thesis project is to further develop and optimise the company's existing algae growing module and cultivation process so that it can be implemented into an industrial algae growing plant. The project will enable SAF to evaluate the way in which an industrial scale-up will affect their business and what steps are necessary to achieve their goal of commercialisation. The project can be denoted as a "platform or next-generation project" as it entails an entire redesign for a system to be created that supports future upgrades. These types of projects often offer companies a competitive advantage as the outcome has a longer life span than a single product [23].

1.3 Research driving questions

As this is a product development project and not a purely experimental and investigative project there was no hypothesis to be tested in the classic sense. However, a set of driving issues was identified that encapsulated the uncertainties of the project that were to be resolved. They are as follows:

- How can the existing modules be redesigned to work on a larger scale?
- What additional features are imperative to the scale up (monitoring system, nutrient feeding etc..)?
- How can a harvesting system be implemented that allows for regrowth and as little disturbance to the growing cycle as possible?
- What is the optimal layout of modules in a cultivation plant that utilises resources as efficiently as possible?
- How can the new design of module be cost efficiently produced to be sold to potential customers?

1.4 Project Scope

The goal of the project is to provide SAF with a design that can be used as a foundation for their industrial ramp-up plan for their product. The design entails both the cultivation module and layout of industrial cultivation plant.

1.4.1 Objectives

The following objectives were formulated as to fulfil the final goal.

- Increased efficiency of algae growing space and light utilisation
- Increased modularity in the design of the cultivation system to allow for industrial ramp-up
- Design to keep the algae in the exponential growth phase despite harvest
- Platform based design to allow for gradual upgrades
- Design of how to implement automated harvesting system
- Manufacturing plan with a cost analysis of all parts
- Materials and designs that are cost effective

1.4.2 Deliverables

The following deliverables were provided to the company by the completion of the project:

- Design and drawings of algae cultivation module
- Design and drawings of algae cultivation plant
- Cost analysis
- Manufacturing plan

1.4.3 Limitations

Initial limitations were set to make the project tangible for all parties involved. The limitations set are in accordance with the desired improvements to the existing module that have been presented by the research team at SAF and the company's plans on industrialisation in the near future. Certain delimitations were set due to the project being conducted by a single master thesis student and therefore time constraints were taken into account. Some delimitations were set due to the fact that previous work was done on the subject and thus it was not to be investigated further. The limitations listed below were used as a framework for the project.

The following aspects were handled in the project:
- Redesign of the existing algae growth module to be able to be implemented for an industrial scale cultivation plant
- A concept design of a harvesting system
- A proposed design of future upgrades
- Proposed layout and implementation of an industrial scale cultivation plant
- A cost analysis of both the redesign of the module and cultivation plant
- Design that keeps the algae in an exponential growing phase

The following aspects were not part of the project:
- A complete automatisation of the harvest system, nutrient control and monitoring system
- Design for implementation of modules for private non commercial use
- Market analysis of algae growing plants
- In-depth optimal algae growth condition investigation
- Complete green-house design

1.5 Mission Statement

The mission statement below was formulated to summate the key aspects of the project and how it fits into the company strategy.

Table 1.1: Mission Statement

Product Description	Algae cultivation system that promotes fast regeneration of algae to ensure an even water purification.
Benefit Proposition	Modular design with high level of flexibility for the customer Purifies water while generating biomass that can be used for several value products
Key Business Goals	Rena Hav AB project completion First commercial order Achieve economy of scale
Primary Market	Biomass production sector
Secondary Market	Silicon production plants
Assumptions and Constraints	Platform design Modular design Upgrades such as fully automated harvesting system and monitoring/control to be designed at a later date Use of as many standardised parts to keep costs down A level of manual handling in the form of cleaning, harvest collection and water regulation
Stakeholders	Swedish Algae Factory Rena Hav AB Manufacturers Service operators

By request of SAF, the following has been excluded from the report:

- *Specific designs used in the experiment and subsequent results*
- *The cost analysis*
- *The type of algae*
- *Any algal production rates*
- *Exact drawings of the designs*

2
Case Description

The master thesis project is centred on a project that SAF are participating in that will be in practice in the beginning of 2017. The project, named "Sotenäs Symbios", is in association with the company Rena Hav AB and Sotenäs Municipality. The purpose of the project is for companies with industrial interests on the subject to come together and work in a circular economical fashion to both create profit and participate in the creation of a sustainable future. Rena Hav AB are building a pisciculture plant with zero waste being unused. Their business plan entails breeding fish for commercial purposes in onshore tanks and then reusing the waste created by both the fish and process in other applications such as biofuels and food for the fish.

Swedish Algae Factory's part in the project is to assist in the purification of the water from the fish tanks. The water that comes directly from the fish tanks contains high levels of nitrogen, phosphorus and carbon dioxide, which creates ideal growing conditions for algae. The algae will deplete the water of these nutrients and create biomass that can be used for biofuel, fish feed and silicon. The algae growing plant will be constructed on the roof of the pisciculture building on an area of 3000 m^2.

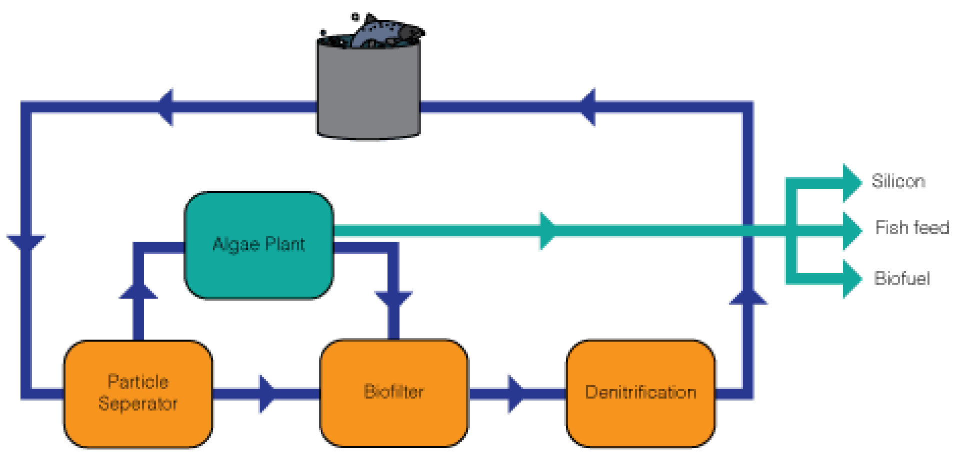

Figure 2.1: Illustration of the pisciculture case project.

The water will flow from the fish tanks into a particle seperator, then the algae plant and then into a series of denitrification processes to ensure that all nutrients that are harmful to the fish are removed before going back into the fish tanks or into the ocean. Those algae will not be able to handle the entire amount of nitrogen and phosphorus in the wastewater, but the amount taken up by the algae will minimise the use of alternative non-sustainable purification processes.

The figures provided by Rena Hav AB were used as customer specifications that the design was built on in order to facilitate the theoretical foundation of a scale-up design.

- Area: 3000 $[m^2]$
- Water: 1500 $[m^3/day]$
- Nitrogen concentration in water: 65 $[mg/L]$
- Phosphorus concentration in water: 7 $[mg/L]$
- Roof dimensions: 41 x 75 $[m]$
- Keep weight as low as possible
- Keep height around 2 $[m]$
- Keep steady rate of nutrient depletion

3
Methodology

The project was divided into three stages; concept generation, concept selection and a final detail design. Each stage involved several methods used to systematically examine, define and propel the project forward.

3.1 General Development Approach

The approach to the development process was heavily influenced by the type of product that was to be designed. As the project is centred on a platform type product that is part of a larger system with several subsystems, the development process was modelled after the "complex development process". In this type of development process the system level design phase plays a big part. This is where the system is broken down into smaller subsystems that are to be designed independently while taking into account the design choices of the other subsystems. The "complex development process" used in this project was laid forth by Karl Ulrich and Steven Eppinger. [21]
The project development process flow chart along with all the according development methods can be seen in Figure 3.1.

3.2 Methods used for Concept Generation

In the concept generation phase the project goes from a raw data input to a wide range of concept solutions. The methods can be categorised into three different categories; data collection, idea generation and concept synthesis. Once the concept generation phase is completed a large amount of potential concepts are ready to be evaluated.

3.2.1 Data Collection Methods

Method: Literature Study
Purpose: Collect existing information on all parts of the project
Desired result: Greater understanding of subject matter and investigation of the level of uncertainties in the project

A thorough study of peer reviewed scientific journal articles, trade journals and published reference material was conducted at the initiation of the project. The

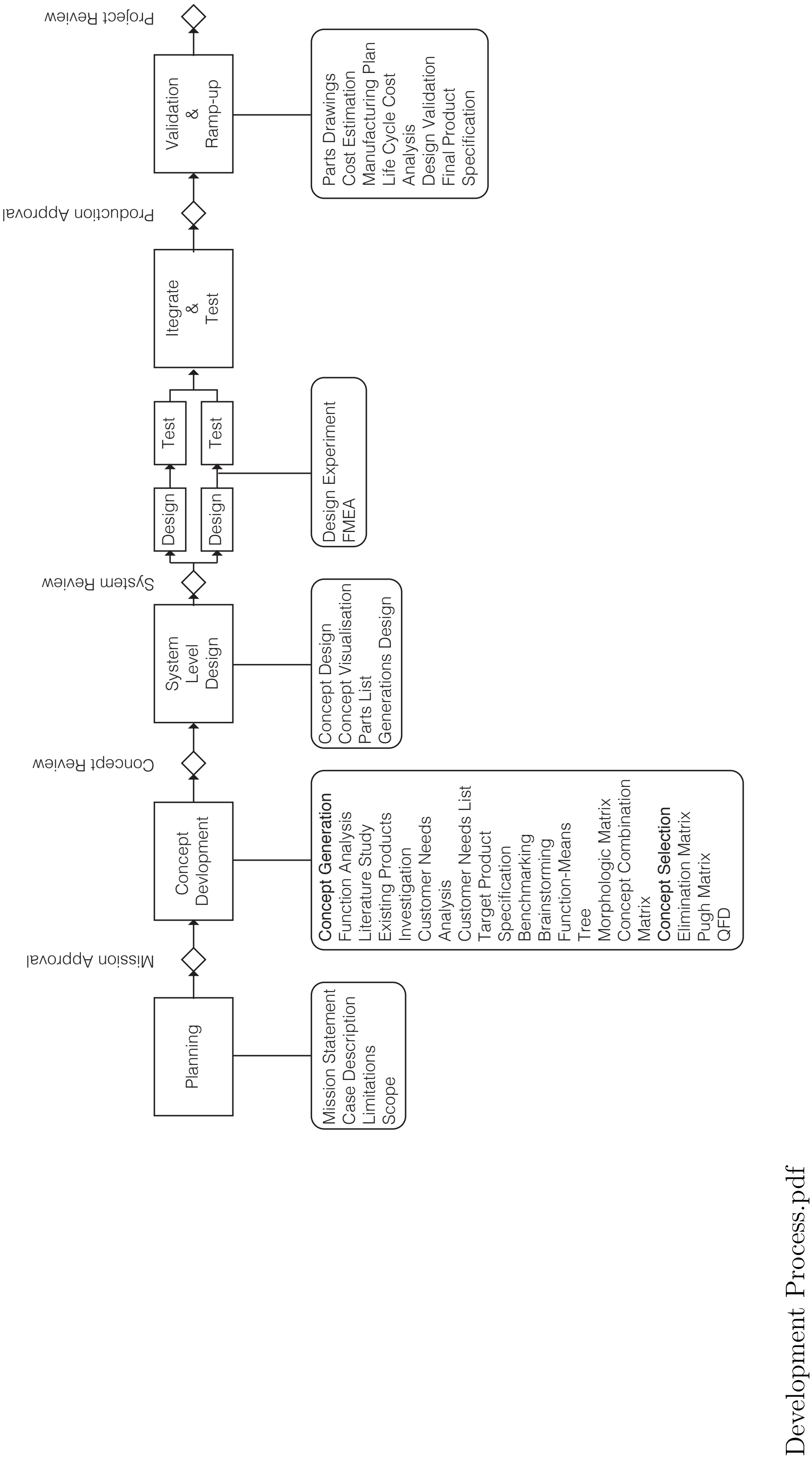

Figure 3.1: The product development process with according methods.

information gathered was used as an evidence base for either strengthening the need statements as well as filling in knowledge gaps. As algae are a relatively unknown product to the master thesis student, a great deal of information on the growth cycles and conditions was gathered. The literature search was done on databases that are available to Chalmers students through the library server in addition to Google Scholar.

The main areas of study were

- Algae growth conditions and cycle
- Material properties
- Cultivation plant layout planning
- Production process planning

Method: Case description
purpose: model concept with real life input and dimensions
Desired result: Outline of product use and dimensioning input

A case study as part of the master thesis was developed as SAF became more involved with the Sotenäs Symbios project during the beginning of the master thesis project. The case study methodology is common for applied disciplines and is often used for both building and testing a research theory to facilitate knowledge creation [11]. The use of a case study allows for a closer investigation of complex details on an isolated series of events. Placing theoretical research into a real life situation can increase the strength of the teachings through applied use [20]. The Sotenäs Symbios project enabled design choices to be made with appropriate industrial scale dimensions and applications.

The complete case description can be found in Chapter 2 of this report.

Method: Stakeholder interviews
Purpose: gather pertinent information about the existing product, algae growth cycles and the needs of the customer
Desired result: a documentation of interview statements that can be used for target product specifications

The problem is defined by the stakeholders of the project, which lays the foundation for a concept that solves said problem. The people that were interviewed were employed by or had an association with SAF. The interviews were semi-structured, which entailed that a list of topics with open-ended questions were prepared before the interviews to make sure that no information was neglected [22]. The questions were formulated as such to allow for the interviewee to offer new information that was unbeknown to the interviewer. However, each question posed aimed to have a purpose and possible hypothesis of the answer [9]. All interviews were conducted individually so that other parties would not influence the answers.
The structure of the interview followed a process of introduction, warm-up, main interview, cool down and closure. The introduction consisted of the interviewer pro-

viding information of why the interview was held and a short recap of the project. The warm-up had unobtrusive questions about the interviewee and their interest in the project. This was then followed by the full interview, were the bulk of the information gathering took place. Finally a cool-off posed more summarising questions followed by a short closure. [16]

The audio from the interviews was recorded and transcribed to create a documentation of the interview in order to trace the future decisions back to the initial information gathering. These transcripts were also used as the foundation for the customer need analysis, which will be discussed in a later section.

The interview subjects were:

- Sofie Allert - CEO of SAF
- Mikael Hedblom - Algae researcher at SAF
- Justin Pearce - Process engineer at SAF

The transcripts of the interviews have been excluded from the report by request of the company.

Method: Observation of existing product and future industrialisation site
Purpose: Understand how the existing process is designed and how this process is to be implemented at the industrial site
Desired result: foundation for target product specifications

At the initiation of the master thesis project, the existing algae cultivation module was in use in a test environment at the Gothenburg University Botanical Garden campus. The existing module was placed in a small greenhouse in a courtyard strategically placed to maximise the use of natural light. The first preliminary objective of the visits was to understand how the algae grow and how SAF had simulated an optimal growing condition on a lab-scale. The visits were of the unstructured kind of observation, by simply viewing the module and understanding how the process worked.

The visits to the industrial test site in Sotenäs were more like the interview process, semi-structured. Certain aspects that were pertinent to the purpose of the project were observed in more detail and documented after a list of prepared topics [22]. The existing algae cultivation module is at the present date scheduled to be moved into a larger greenhouse outside of the industrial test site. The system is to be connected directly after the test fish tank and a set of denitrification stages. This visit allowed for insight on the way in which the product will be utilised along with an opportunity to pose direct questions on the how the algae system affects the remainder of the fish farm.

Illustrations of the existing module can be found in Figure 4.1.

Method: Customer data template
Purpose: interpretation of customer needs
Desired result: Customer Needs List

After the aforementioned data gathering techniques were completed, the statements made were translated into customer needs that could be quantifiably measured. This was done by using a customer data template. The result of this method is a list of critical need statements that was used as references when considering what areas of research to look into and design parameters. This list also served as inputs into the product specification list. An example of such a template can be seen in the table below.

Table 3.1: Customer data template

Interviewee: Subject A		**Interviewee's statement**
Interviewer: Master thesis student		**Type of stakeholder: Researcher**
Question posed:	**Statement made:**	**Interpreted need:**
Interviewer's question	Interviewee's statement	Interpretation of statement
Interviewer's question	Interviewee's statement	Interpretation of statement
...	...	...

The interpreted needs from the statements were translated and assessed through a set of criteria as follows.

- The needs must be definitive and expressed as to what the product "will" fulfil and not "might".
- The needs must be compliant to the "raw data" to not lose any information.
- The needs must be positively expressed, denoting what the product will do, not what it won't do.
- The needs must be formulated as attributes of the product as much as possible.
- The needs statement should not include the words "must" or "should" for the statement to be as robust as possible.

[21]

By following these guidelines, the interpreted customer needs should be able to be used as inputs into the development phase of the project. These types of data templates often have hundreds of statements and the ranking process is necessary to narrow down the list into "primary need statements". This is mostly relevant when this type of data gathering process is conducted on a wide array of customers and end-users of a product. In this case, the data gathered was from primary stakeholders in the company and case study and therefore the list of needs is not as extensive as in common practice. However, a ranking process of the generated needs was conducted nonetheless. This process entailed the following steps:

- Step one: Print each need on a separate piece of paper.
- Step two: Eliminate any redundant statements.

- Step three: Organise the statements into categories with appropriate labels.
- Step four: Create "super groups" that include several categories.
- Step five: Rank the statements in each group after critical importance as relayed by the frequency of the statement or the implication of importance to the customer.

[21]

The complete customer needs list can be found in Table 4.1 and customer needs statements can be found in Figures A.1 and A.2 in the Appendix.

Method: Function structure analysis
Purpose: Break down the function of the product
Desired result: understanding of the inputs and outputs of the product

A system can be seen as a series of processes that handles inputs and turn them into outputs. A function structure analysis looks at all the inputs of the system, all the desired outputs and what steps are necessary to go from one to the other. The system boundary is depicted by a "black box" with the inputs on the left side and the outputs on the right. Inside the box is a depiction of all sub-functions of the system that transform the inputs to outputs. This method is used to visualise the inside of the system and break down all the functions of the structure. The sub-functions have a very basic annotation of the their function consisting of simply a noun and a verb to not limit the possibilities of development of the function. [14]

The function structure analysis of the system can be found in Figure 4.2.

Method: Preliminary list of target product specification
Purpose: set design target parameters
Desired result: design specifications with values and metrics

The definition of a product specification is the combination of a metric and a value. It is these product specifications that are used as objective inputs into the concept development phase. Karl Ulrich and Steven Eppinger like to denote these specifications as "target specifications" for at this point in the process it is impossible to know the exact figures that the product will have. To create a set of target specifications, the need statements created earlier were reflected upon and interpreted to statements that fulfil the needs. This is called a product "metric". Once the metrics were created, they were assigned a measurable value that was deemed to be possible to fulfil the initial need. [21]
This preliminary list was constantly updated and edited throughout the project resulting in a final product specification.

The target product specifications can be found in Table 4.2.

Method: Competitor Benchmarking Analysis
Purpose: gather information on existing products
Desired result: inspiration from existing products and market positioning

When launching a new product on the market it is imperative to assess where the product will position in the market. A benchmarking analysis is used to compare similar or existing product's performance to each other either on the basis of certain metrics or perceived fulfillment of the customer needs. The benchmarking comparison is conducted in a matrix format with the different products in the columns and the assessing parameters in the rows. The output of the method allows the developer to understand what part of the market the developed product will take and possibly gain some inspiration on how others have solved the same problem. [21]

The benchmarking analysis can be found in Table 4.3.

3.2.2 Methods Enabling Idea Generation

Method: Function-Means tree
Purpose: Break down the entire system into manageable parts and find means to solve the function
Desired Result: function analysis of all subsystems

The purpose of the function analysis was to break down the main function into several sub-functions, which facilitated the idea generation process, as it is easier to generate a solution for a single function instead of an entire system of functions. A function-means tree is a system of functions and according means organised in hierarchical levels starting with the main function at the top. With each descending level of the hierarchy, the level of functions are broken down into more and more detailed parts until the entire system has been handled. The means to a function entails a solution that executes the function. A function can have several defined means with their own descending function, thus the resulting tree can become very large with many branches. [5]

The complete functions-means tree can be found as Figure A.3 in the Appendix.

Method: brainstorming
Purpose: Idea generation
Desired result: several potential concept sub-solutions

Once all sub-functions and means were identified, it was time to generate creative solutions to each of them. This was achieved by brainstorming sessions assisted by sketches and notes. All ideas were considered, however outrageous, to allow for a free flow of ideas that could in a later stage be edited and reconsidered. Brainstorming sessions were intensive and kept to a period of 20 minutes when as many concepts as possible were generated. This is called a "mind-dump". Many small sketches were created for each idea on the same page so that they could be looked at side by side later on and to keep the process as organised as possible. By intensifying the process, critical thinking was eliminated as there was no time for it. [13]

Sketches and notes from the brainstorming sessions can be seen in Figure 4.4.

3.2.3 Systematic Concept Synthesis Methods

Method: Morphological matrix
Purpose: concept synthesis
Desired Result: Several complete concept solutions

As the brainstorming sessions drew to a close, appropriate organisation of the generated ideas had to be carried out. A morphological matrix was created to both visually organise the sub-function solutions and to create complete concepts out of said different sub-function solutions. A matrix was constructed with rows of sub-functions with their corresponding generated ideas. When the matrix was filled in, concepts were created by combining a solution from each row, which ultimately conjured up a set of different concepts that fulfilled the main function that was stated in the function-means tree. [24]

The morphological matrix can be found in Figure A.4 in the Appendix.

method: revised morphological combination matrix
Purpose: Organise the complete concept solutions from the morphological matrix
Desired result: clear visualisation of generated concepts

Upon the completion of combining the different sub-solutions in the morphological matrix a great deal of complete concept solutions were created. The common practice entails drawing lines between different sub-solutions. The finished product becomes very messy and the different parts of the complete solution become hard to read and differentiate. Instead of doing this, the same morphological matrix template was used and then one by one concept combinations were copied into the columns of the new matrix. The rows remained the same, so the result became a column depicting an entire solution that is easy to read. This method is original to this project and was, to the knowledge of the master thesis student, created by the master thesis student.

The morphological concept combination matrix can be found in Figure A.5 in the Appendix.

3.3 Concept Assessment and Selection

After the concept generation phase it is imperative to sift through the large amount possible solutions in a systematic way. The methods used were either used for individual reflection and elimination or for group feedback.

Method: elimination matrix
Purpose: systematic concept elimination
desired Result: eliminate the unsuccessful concept solutions

An elimination matrix helped to narrow down the amount of feasible concepts. The matrix compared each concept in their turn to a set of criteria (commonly the groupings in the product specification list). If the concept fulfilled the criteria, the concept received a "+" in that category of the matrix. If it did not fulfil the requirement, it received a "-". Certain specific criteria fulfilments of a concept was difficult to estimate due to lack of information, in these cases the concept was given a "?" in that category. At the end of each comparative turn, the pluses and minuses were added up and a general score for the entire concept was given. Upon completion, each concept had received a score that allowed for a ranking of the concepts. This allowed for the elimination of concepts with very low scores. [14]
This elimination step was conducted individually by the master thesis student to "weed out" the concepts that were not plausible before including other parties.

The elimination matrix can be found in Table 4.4.

Method: Pugh Matrix
Purpose: concept screening
Desired Result: eliminate the unsuccessful concept solutions with input from stakeholders

After a preliminary concept screening was done by the master thesis student alone, a second round of concept screening was executed. A group of stakeholders were gathered to conduct a session of concept screening with the help of a Pugh matrix. A Pugh matrix is an elimination method that compares concepts to each other. The ultimate goal was to find the dominant concept from a group of concepts. The process is done in several iterations of appointing one concept as a reference to which the remaining concepts are compared to in different categories, just as with the elimination matrix. A concept received a "+" if it was deemed that the concept performs better than the reference in a certain category, a "0" if they were equal and a "-" if the concept performed worse. The optimal result was the one concept that out performed the rest that was then moved into the next stage of developing the concept with a detailed design. [15]

The Pugh matrix can be found in Figure A.6 in the Appendix.

3.4 Detail Design Approaches

When moving into the detail design phase a concept had been selected and ready to be detailed. During this phase the concept was visualised, dimensioned and validated. Continuous refinements were made to the concept in accordance with the results of the development methods.

Method: 3d modeling software (CATIA)
Purpose: design visualisation
Desired Result: 3D model of concept with exact measurements

The selected concept moved into the next stage of development that involved a high level of detailed design. Each sub-function and corresponding components were fully designed to work with the other sub-functions. This was achieved by critically considering the final dimensions and applications of the entire system. This work was conducted by implementing the product specifications and additional acquired information into sketches that were in turn worked into digital 3D model representations. The software that was used was CATIA from the company Dassault Systèmes as this software allows for high levels accuracy and is offered free of charge to Chalmers students. The goal of the detail design phase was to have a complete system fully designed and scaled ready for manufacturing.

The sketches and models can be seen in Chapter 4.

Method: Design experiment/prototype
Purpose: simulate and test design theories
Desired result: validation of theories and input on final design

Due to the large amount of different factors and the high level of uncertainty of the project, a design experiment or prototype was developed. Prototyping is a technical problem-solving tool that allows designers to physically touch and examine their design choices in the real life. This practice is key in the build-test cycle of the product development process [23]. The prototype in this project was also in a design experiment that tested two different kinds of algae regeneration designs along with a simulation of the automated harvesting system. A design experiment created the opportunity to discover the best design choice by trying it out and documenting the effects that it had on the algae. The design of the experiment, despite actually testing two different things (regeneration design and harvesting technique), can be denoted as a one-factor-at-a-time experiment [6]. This is because all the parameters of the experiment were held constant and the only the design of subject varied.

A recount of the experiment can be found in Chapter 5.

Method: Material Properties investigation
Purpose: dimension according to accurate material capabilities
Desired Result: decision on design materials

A materials properties investigation was conducted with the aid of the computer program CES Edupack that was accessed through the computers at Chalmers. The program enabled an investigation into what the appropriate materials to be used for the product were. The program allows the user to enter limitations or product needs such as transparency or UV resistance.

In addition to the material study, non-structured interviews and feedback with professionals was conducted to get more project specific information. The professionals that were sought out were those with specific knowledge such as material manufacturers and retailers. The information gathered was used to dimension the product and form the product specification.

The materials chosen can reviewed in Chapter 5 and the final product specification can be found in Figure A.7 in the Appendix.

Method: Failure mode and effects analysis (FMEA)
Purpose: Risk analysis
Desired Result: reduced risk of failures due to appropriate preventative measures taken

A Failure Mode and Effects Analysis (FMEA) is a common practice in risk analysis. The method is used to examine each part of the system to pinpoint possible failures that could have grave consequences in the future upon construction. The method is qualitative as the consequences are purely speculative. The designer conceives a possible failure, cause of failure and the effect it has on the system. After that, the occurrence, the severity and the detectability of the failure are each given a ranking on a scale of 1-10, that are then multiplied to create a quantitative assessment of the failure called the Risk Priority Number (RPN). A failure corrective action is then identified and assessed on how the action would impact said possible failure by reassessing the occurrence, severity and detectability of the failure once the corrective action has been taken. This creates a new reassessed RPN that can be ranked. [6] The FMEA was created by the master thesis student and then checked and approved by an associate at SAF.

The FMEA can be found in Figures A.8 and A.9 in the Appendix.

Method: Quality Function Deployment (QFD)
Purpose: Quality assurance of design choices
Desired result: validation of quality of design and interaction between parts

Quality function deployment (QFD) is a structured method developed in the Kobe shipyard by Mitsubishi to assess how the most important customer needs affect specific design parameters. The method utilises a tool called the “house of quality” that structures the relationships in a matrix format. The name is derived from the house-like shape that the matrix forms with the interrelationship matrix, which resembles a roof. The customer specifications are each weighted to depict how important each attribute is to the customer. Then each specification’s impact on the design parameter is assessed and is scored. Subsequently, each design parameter’s impact of the other design parameters is also judged in the interrelationship matrix. [23]

The QFD matrix can be found in Figure 4.14.

Method: Product cost breakdown
Purpose: Cost estimation of final product
Desired result: An estimation of the preliminary costs upon ramp-up

In an effort to keep the production costs at a minimum, the design of the final product was founded on common standardised building parts found at mass production steel manufacturers and vendors. This allowed for SAF to purchase parts at an economy of scale and then work with machining to customise parts to fit the product specification. By achieving an economy of scale in the production, the costs per product unit decreases and often the quality increases [21]. The cost estimation was achieved by gathering price quotes from appropriate vendors and calculating the sum of producing a single module and an entire cultivation plant (the cost estimate for the pisciculture project).

The full cost breakdown has been excluded from the report by request of SAF. However, the results of the cost estimation can be reviewed in Chapter 4.

4

Results

The following chapter contains the results of the methods used, that were explained in the previous chapter, from data collection to the final concept design.

4.1 Results Gathered from the Data Collection Methods

The data collected in the pre-study of the project served as information input into the development methods. The results of the research are presented here below.

4.1.1 SAF's Existing Product Description

The existing cultivation module was constructed in 2015 as a “one-off” product for the company to be able to cultivate algae for test purposes. The module consisted of five 1100 x 800 x 100 mm trays with water circulation outlets in the bottom of the trays leading to the tray underneath. A water container was allocated at the bottom of the module with a pump that moved the water from the container to the top tray. The module was placed in a small greenhouse in a courtyard at the Botanical Garden facility. During the harvest process, the pump was turned off and trays were drained. The trays were then scraped to remove the biomass and collected for analysis. Depictions of the module can be seen in Figure 4.1 below.

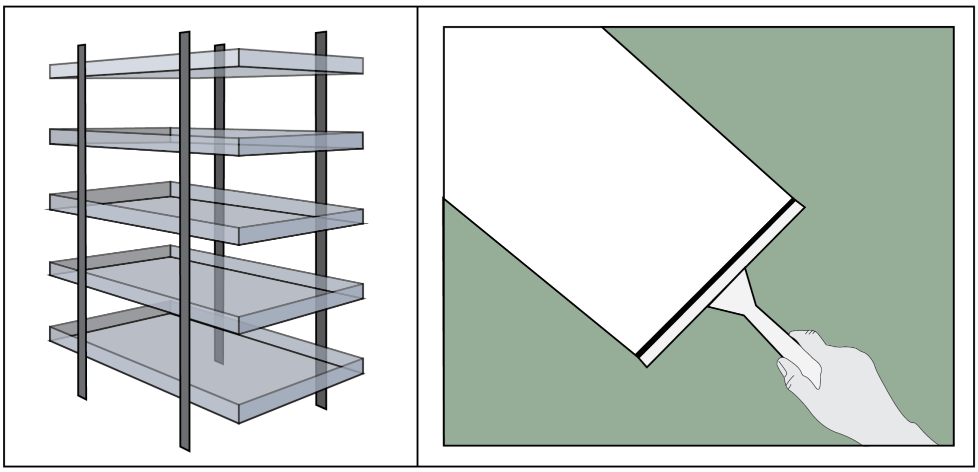

Figure 4.1: Illustration of the existing cultivation module.

4.1.2 Understanding the Function of the Product

The function analysis shown in the figure below depicts the inputs and outputs of the system along with the internal sub functions that transform them.

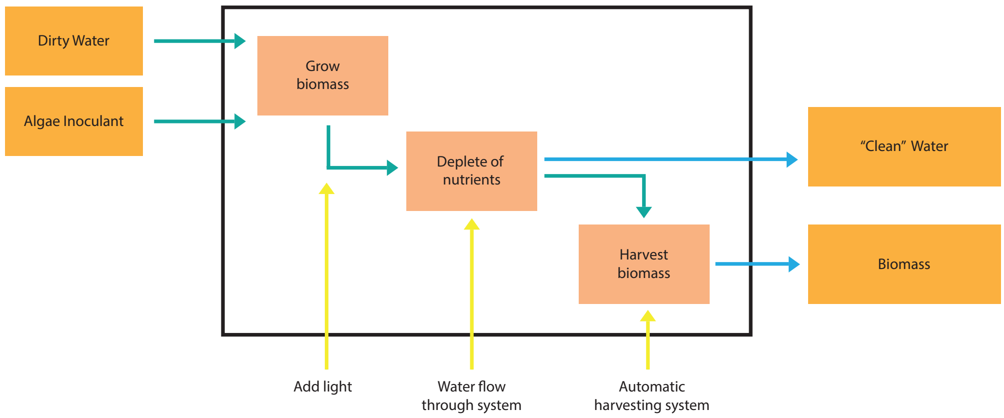

Figure 4.2: Functional analysis of product.

The analysis shows the inputs as waste water and algae inoculation which ultimately become the outputs, biomass and "clean"* water. Through the process of growing the biomass, the water depletes of nutrients which becomes the output of "clean" water. After extracting the output of "clean" water the process moves on to a harvest process which then becomes the output of biomass.

**The water can not be guaranteed to be clean, in this annotation it is interpreted as cleaner or depleted of nitrate, ammonia, phosphorus and certain trace metals.*

4.1.3 Identified Customer Needs and Target Specifications

The customer needs depicted in Table 4.1 below are based off of the customer needs statements from the interviews (these can be found in Figures A.1 and A.2 in the Appendix) and additional information gathered.

Table 4.1: Customer Needs List

No.		**Need**	**Weight**	**Owner**
1	The module	promotes fast growth	5	SAF
2	The module	is easy to use	5	SAF
3	The module	maximises the use of natural light	5	SAF
4	The module	is easy to clean	4	SAF
5	The module	keeps a stable temperature	4	SAF
6	The module	keeps a steady water flow	4	SAF
7	The module	fulfils the maximum height requirement	3	Rena Hav AB
8	The module	fulfils the maximum weight requirement	3	Rena Hav AB
9	The module	can be used to promote the company	3	SAF
10	The module	is cost efficient	3	SAF
11	The module	is enabled for an automatic harvest	3	SAF
12	The module	fits in a 40ft shipping container	3	SAF
13	The module	allows for upgrades	3	SAF
14	The module	allows for manual handling	3	SAF
15	The module	has a modular design	2	SAF and Rena Hav AB
16	The module	handles a specified amount of water per day	2	SAF and Rena Hav AB
17	The module	uses the space efficiently	2	Rena Hav AB
18	The module	continuously purifies water of pollutants	1	Rena Hav AB
19	The module	continuously purifies water of N	1	Rena Hav AB

Based off of the customer needs and both the project and case descriptions, preliminary target specifications were put together. These specifications can be seen in table 4.2 below. They served as the base on which the concept generation was built and aimed to fulfil. This list was continuously updated as the development project advanced to ultimately become the final product specifications that can be seen in Figure A.7 in the Appendix.

Table 4.2: Target Product Specification

Metric No.	**Need No.**	**Metric**	**Imp.**	**Marginal Value**	**Ideal Value**	**Unit**
1	2,4	Ease of use	5	4	5	subj.
2	10	Cost efficient	3	<10	5	MSEK
3	1	Promotes fast growth	5	-	-	g/m^2/day
4	10,11	Automatic harvest energy output	3	450	250	kW
5	15	Modular design	2	4	5	subj.
6	18	Continuous water purification - P	1	-	-	mg/L
7	19	Continuous water purification - N	1	-	-	mg/L
8	3	Maximises natural light	5	2	4	subj.
9	12	Fits in 40ft shipping container	3	<12x2	<11,8x2	m
10	13,14,8	Strength of structure	3	250	400	MPa
11	16,17,6	Handles specified amount of water per day	2	>500	1500	m^3/day
12	7	Maximum height requirement	4	3	2	m
13	8	Maximum weight requirement	3	700	300	kg/m^2
14	14,4	Area around module	3	1	0,7	m
15	17	Space utilisation	2	<3075	2900	m^2
16	5	Temperature	4	10	13	°C
17	6	Water flow rate	4	0,2	0,4	L/s
18	10	Product life	4	4	10	Years
19	9	Instills pride	3	3	5	subj

4.1.4 Assessment of the Final Product's Place in the Market

The research study on existing algal cultivation systems established that there are two main methods of cultivating algae, open pond and photobioreactors. Open pond

systems entail large shallow ponds built on a large flat surface. The ponds are often extremely large and thereby commonly referred to as “raceways”. A mechanical circulation mechanism is frequently implemented to keep the algae in motion. [3]
The company Sapphire Energy is building the first commercial demonstration open pond algae farm that is intended to be fully completed in 2017. At full capacity the farm will produce 1600 tonnes biomass per year to be used for either biofuels or nutrients for the algae. [17]

A photobioreactor is a closed system growing method that cultivates algae in transparent containers, often in the form of tubes, panels or plastic bags. The algae is grown in suspension with a constant water pressure that circulates the algae. The closed system minimises the risk of contamination and allows to carefully control parameters such as the nutrient supply. [4]
An example of such a production method is the one used by the Swedish company Simris Alg AB. They cultivate algae in long glass tubular photobioreactors that they then manufacture health products with. [19]

As the specific algae that SAF work with grows in a biofilm that attaches to surfaces in a shallow body of water, none of the existing commercial cultivation systems were applicable as they both cater to algae that grow in suspension. Due to this, a benchmarking analysis comparing industrial algae cultivation solutions was made difficult. However, one potential future competitor was found, the ALGADISK project currently being developed in Spain. The project is still in the development phase and according to their latest update on their website, they built a prototype on an industrial scale in 2015. The purpose of the project is to find an industrial algae biolfilm cultivation system to compete with open ponds and photobioreactors. Very much like SAF’s development project. Their product entails disks on which the biofilm is formed that rotate in a semi shaded water tank.[2]
As the project has not been commercialised, complete specific information on their product was not able to be found only the general idea of the product has been published. A benchmarking analysis was conducted comparing this product to SAF’s existing product as no other comparative products could be found.

Table 4.3: Benchmarking Analysis

No.	Need	Imp.	SAF existing product	ALGADISK
1	promotes fast growth	5	+ + +	+ +
2	is easy to use	5	+ + +	+ +
3	maximises the use of natural light	5	+ + +	+ +
4	is easy to clean	4	+ + +	+
5	keeps a stable temperature	4	+ +	+ +
6	keeps a steady water flow	4	+ +	+ + +
7	fulfils the maximum height requirement	3	+ + + +	+ + + +
8	fulfils the maximum weight requirement	3	+ + + +	+ + + +
9	can be used to promote the company	3	+ + +	+ +
10	is cost efficient	3	+ + + +	?
11	is enabled for an automatic harvest	3	+	+ + +
12	fits in a 40ft shipping container	3	+ + + +	+ + + +
13	allows for upgrades	3	+ + +	+
14	allows for manual handling	3	+ + +	+ +
15	has a modular design	2	+ + +	+ + +
16	handles a specified amount of water per day	2	+ +	+ + +
17	uses the space efficiently	2	+ + +	+ +
18	continuously purifies water of P and N	1	+ +	+ +

The evaluation was done on how well it was perceived that the products performed in conformance to the customer needs stated. SAF had the opportunity to test the ALGADISK with their algae as a prototype of the product had been lent to the Marine Biology Department at The University of Gothenburg. The test was unsucessful as the algae was too heavy to remain on the rotating discs. Thus, the product would not be applicable for use for SAF. On a purely innovative note, the design of the ALGADISK is quite impressive and could definitely be a potential competitor upon commercial launch.

4.2 Initial Generated Product Concept

The initial concept was presented at the end of the first half of the master thesis project in August of 2015. The results of the development methods below are the basis for the concept design.

4.2.1 Results of the Concept Generation Methods

The concept generation phase took the information gathered in the research phase into viable concepts to be considered and evaluated.

4.2.1.1 Identifying Functions and Means

The function-means tree was used to break down the system into smaller parts that could easier be analysed. For each function, means that could fulfil the function were identified, which created a large amount of potential sub functions. The ideas generated from this method was used in the next stage of idea generation. Due to the size, a fully legible function-means tree can be found as Figure A.3 in the Appendix and a smaller depiction can be seen in the Figure 4.3.

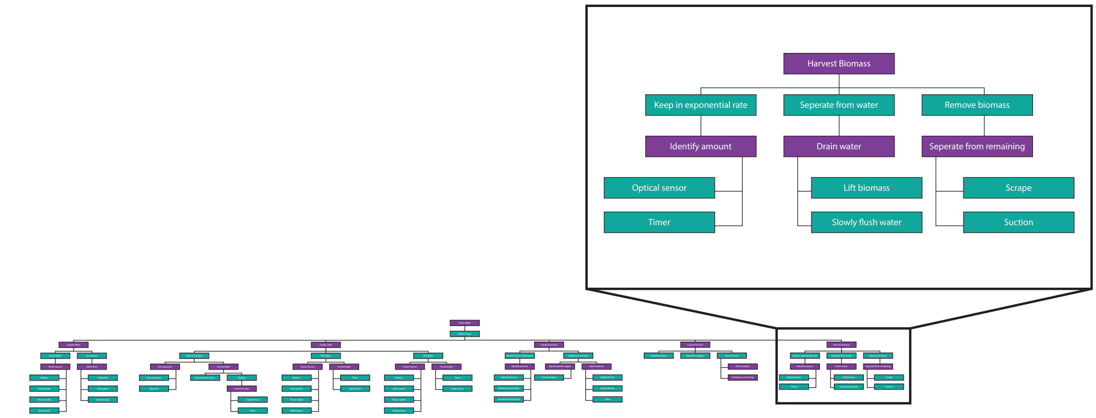

Figure 4.3: Depiction of the Function-Means Tree.

4.2.1.2 Putting Pen to Paper: Idea Generation Sketches

To generate solutions to sub functions for the full concept, sketches were made in idea generation sessions. The Figure 4.4 below shows an example of the sketches made to document the ideas generated. The sketches helped to form ideas and visualise them to be able to communicate them to other parties involved in the project and further the development process.

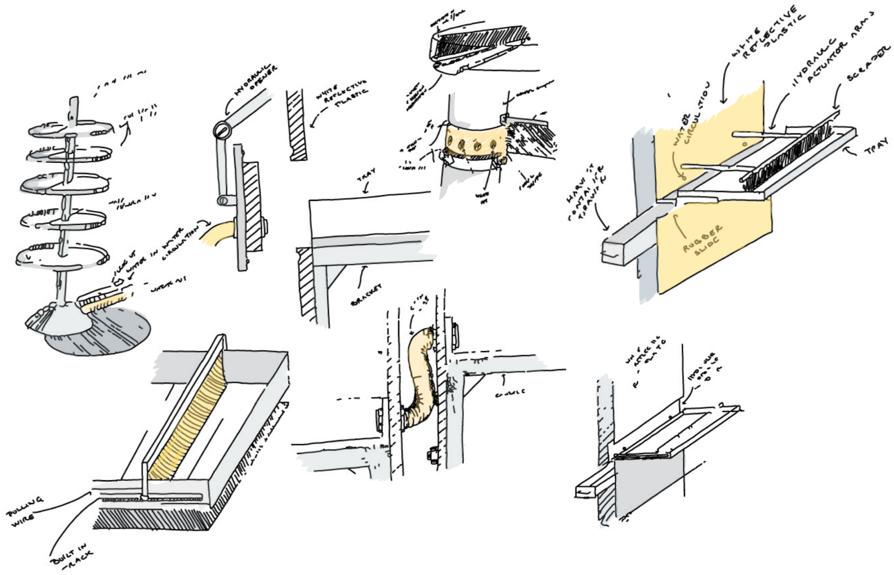

Figure 4.4: Collection of sketches.

4.2.1.3 Systematically Creating Possible Concepts

With all the gathered information from both the research and the idea generation methods, a morphological matrix was created. A large amount of sub solutions were identified and put into the rows of the matrix. Small sketches were created for each sub solution to clearly demonstrate the solutions function, as can be seen in the Figure 4.5 below.

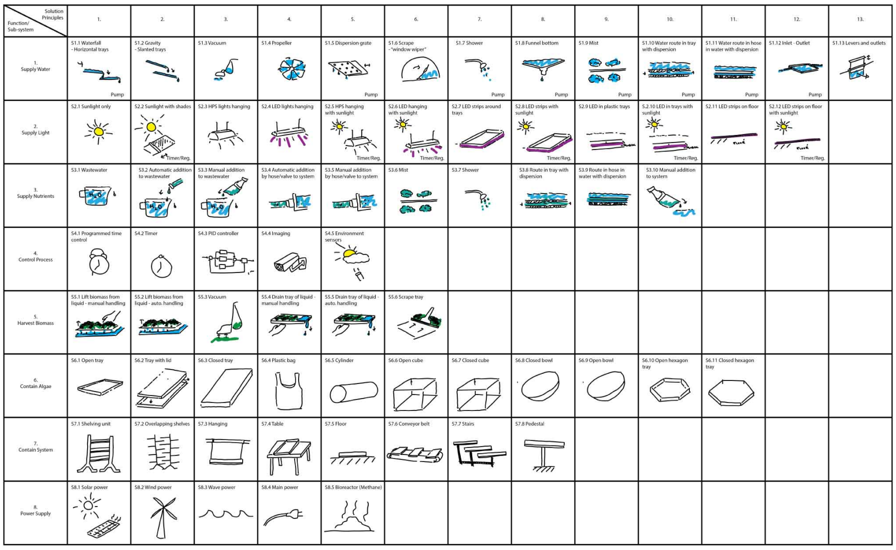

Figure 4.5: Morphological Matrix.

Upon completion of the matrix, when all sub functions had a good amount of solutions, complete concepts were put together in the revised morphological concept combination matrix. A total of 25 concepts were put together in the matrix. Each of the concepts were given a name and number to keep track of them as the development progressed. A depiction of the concept combination matrix can be seen in Figure 4.6 below. A larger copy of the morphological matrix and the concept combination matrix can be found in Figures A.4 and A.5 in the Appendix.

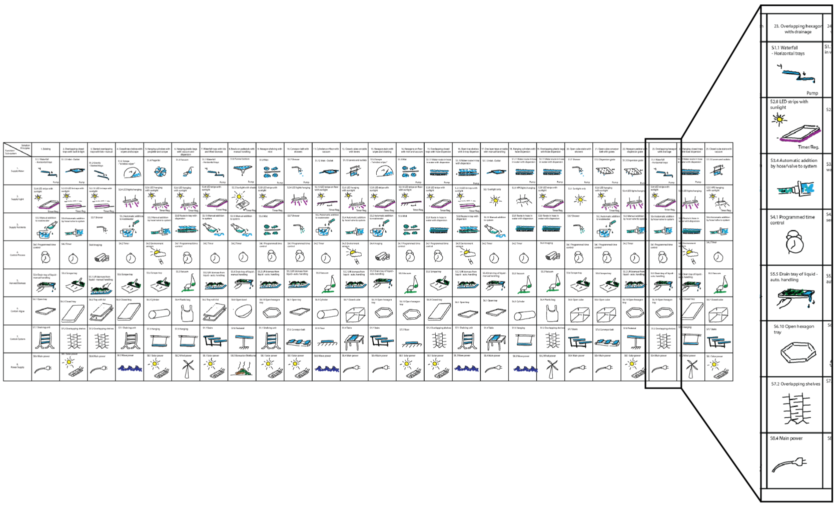

Figure 4.6: Combined Concepts Matrix.

4.2.2 Results of the Concept Selection Methods

One often speaks of the product development funnel were the widest part of the funnel allows a large amount of ideas to pass through, then begins to taper resulting in the sole dominant concept being able to pass [23]. This is the point where the funnel begins to taper.

4.2.2.1 Weeding through the Generated Concepts

The 25 generated concepts from the previous product development phase were put into the concept screening matrix to be evaluated. Each concept was scored on how well they fulfilled the criteria of solving the main problem, fulfilling demands, safety, realisability, reasonable cost and modularity. After scoring each concept they were evaluated if they were fit to continue on in the development process or to be discarded. Upon completion of the matrix and reflection of the results, 6 concepts passed the screening, 3 full concepts and 3 that were synthesised from 6 concepts. The elimination matrix can be seen in Table 4.4 below.

Table 4.4: Elimination Matrix

2* Date: 12/08/2015	2* Criteria Fulfilment:	(+) Yes	(?) Info Needed	2*Decision:		(+) Continue	(?) Info Needed	2*Elimination Matrix for: SAF algae cultivation module	
		(-) No	(!) Check Spec.			(-) Remove	(!) Check Spec.		
Solution Number	***Solution Name***	***Solves the main problem***	***Fulfils demands***	***Safe***	***Realisable***	***Reasonable cost***	***Modularity***	***Comment***	***Decision***
2	Overlapping closed trays with built in light	+	+	+	+	+	+		+
3	Slanted overlapping trays with lids - manual	+	+	+	+	+	+		+
4	Closed tray shelves with wipers and scrape	+	+	+	?	?	+	Integrating automated wipers inside closed container is possibly very complicated andexpensive	?
5	Hanging cylinders with propeller and scrape	+	-	+	?	+	-	Hanging cylinders appropriate for only large scale plants - not modular	-
6	Hanging plastic bags with vacuum and dispersion	+	-	+	-	+	-	Hanging bags appropriate for only large scale plants - not modular	-
7	Waterfall trays with lids and lifted biomass	+	+	+	+	+	+		+
8	Bowls on pedestals with manual handling	+	-	+	+	+	-	Hanging bags appropriate for only large scale plants - not modular	-
9	Hexagon shelving with mist	+	+	-	-	?	+	Mist of nutrients could be unsafe and not effective	-
10	Conveyor belt with showers	+	-	?	?	?	-	Conveyor belt not modular	-
11	Cylinders on floor with vacuum	+	?	+	+	+	-	Cylinder pipes not modular	-
12	Closed cubes on tables with levers	+	-	+	+	+	+	Only one layer - not efficient	-
13	Hexagon stairs with wipes and draining	+	+	+	+	+	+	Combine with 23	+
14	Hexagons on floor with mist and vacuum	+	+	-	-	+	+	Mist of nutrients could be unsafe and not effective	-
15	Overlapping closed trays with hose dispersion	+	+	+	+	+	+		+
16	Open tray shelves with in tray dispersion	+	+	+	+	+	+		+
17	One layer trays on table with manual handling	+	-	+	+	+	+	Only one layer - not efficient	-
18	Hanging cylinders with hose dispersion	+	+	+	?	+	-	Hanging cylinders appropriate for only large scale plants - not modular	-
19	Overlapping plastic bags with hose dispersion	+	?	+	+	+	+	Need more info on sedimentation in plastic bags	?
20	Open cube stairs with showers	+	?	+	+	+	+	Cube size and growth rate needs more info	?
21	Open cube conveyor belt with grates	+	-	+	?	?	-	Conveyor belt not modular	-
22	Hexagon pedestal with dispersion grate	+	?	+	?	+	-	Single unit growing - not modular	-
23	Overlapping hexagon with drainage	+	+	+	+	+	+	Combine with 13	+
24	Hanging closed trays with hose dispersion	+	+	+	+	+	?	Efficiency of hanging units needs more info	?
25	Closed cube stairs with vacuum	+	?	+	+	+	+	Cube size and growth rate needs more info	?

4.2.2.2 Concepts Generated and Screened

The concepts generated from the morphological matrix that passed the concept screening matrix are presented here below. These were presented to a group of interested parties at a Pugh matrix screening session. *Note that all of the concept depictions include a water dispensing container with a water inlet and a nutrition addition valve. This is a manifestation of the process that would be collective for the entire cultivation plant.*

2 - Overlapping Closed trays

This design encompasses overlapping trays in the sense of overlapping between modules that entails a vertical displacement of trays between the left and right side of the module. LED light strips are encapsulated into the bottom of the tray to give a uniform light dispersion both under the algae and over the algae in the next tray. The trays are completely closed with only in and outlets for water circulation and algae harvest collection. A harvesting system entails an internal mechanism that scrapes the trays and collects the biomass in a container that is connected to the outside of the tray. See the Figure 4.7 below.

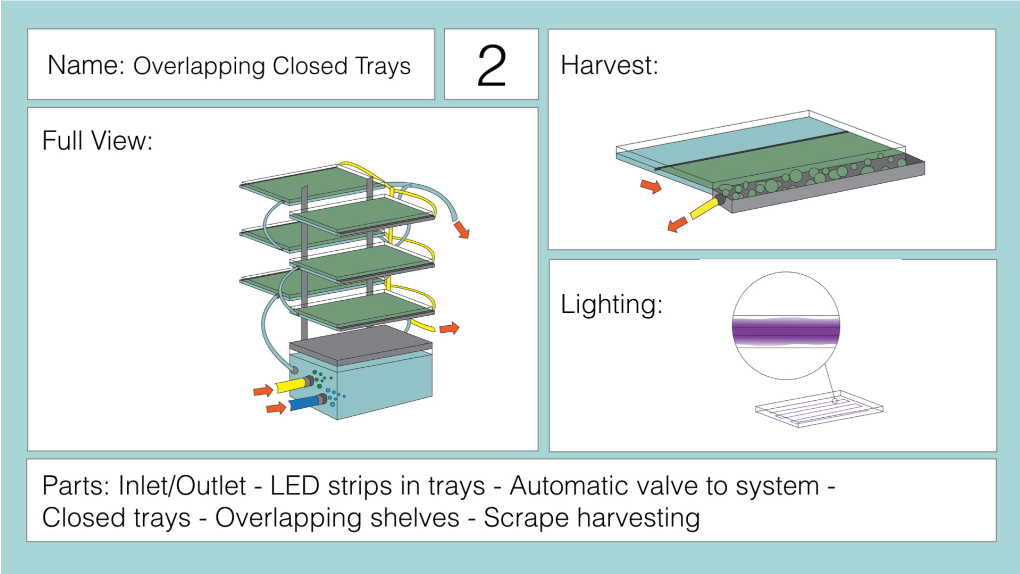

Figure 4.7: Concept 2 - *Overlapping trays*

3 - Slanted trays

The design of this module is similar to the existing lab module. The trays have a vertical displacement as with the previous concept, they are also slanted to aid the water circulation. The trays are equipped with lids that are connected to a perforated plate on which the algae grows. Upon harvest, the lids are lifted together with the plate and removed to collect the biomass. Additional lighting is supplemented through LED light strips encapsulated into the bottom of the trays. See the Figure 4.8 below.

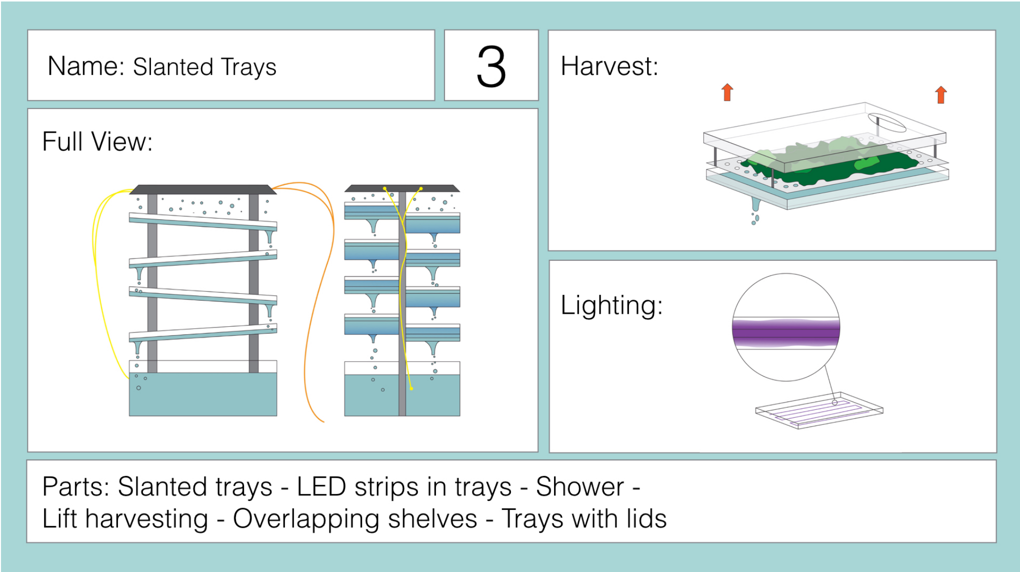

Figure 4.8: Concept 3 - *Slanted trays*

7a - Waterfall trays

The trays in this design are installed on stilt-like legs and arranged in a descending stairs formation. The primary water inlet is placed in the top level of the trays and an outlet dispenses the water to the subsequent tray. LED light strips are attached along the sides of the trays. As with the previous concept, the trays are equipped with lids connected to a harvesting plate, and the harvested biomass is collected manually. See the Figure 4.9 below.

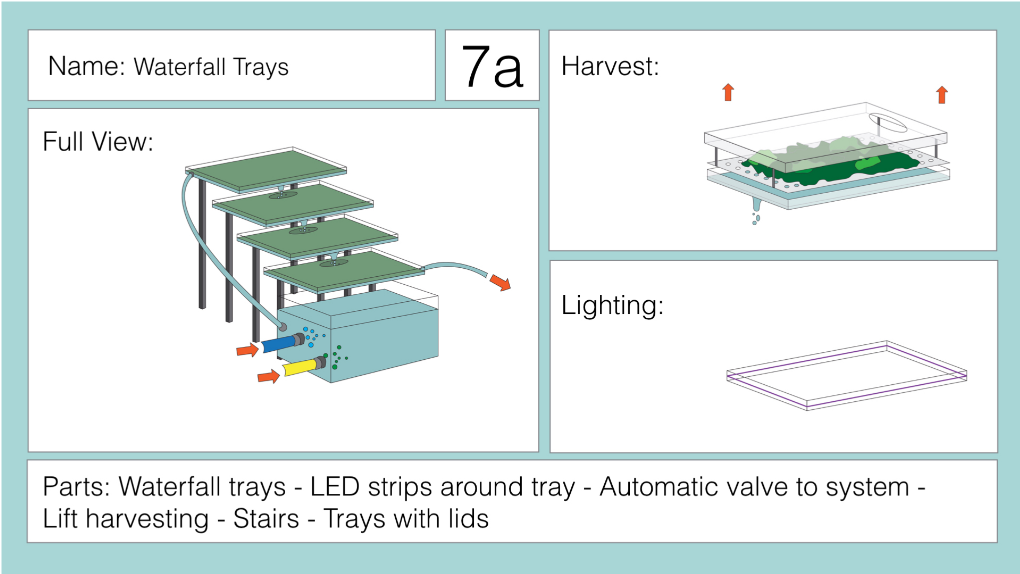

Figure 4.9: Concept 7a - *Waterfall trays*

13a - Hexagon Stairs

Similar to the previous design, the trays are arranged in a descending stairs formation. In this design the trays have a hexagon shape. The bottoms of the trays have a "trap door" that opens when it is time to harvest to expose a collection chamber connected to a vacuum that sucks the biomass to a central sediment tank. For additional light, LED light strips are attached around the sides of the trays. See the Figure 4.10 below.

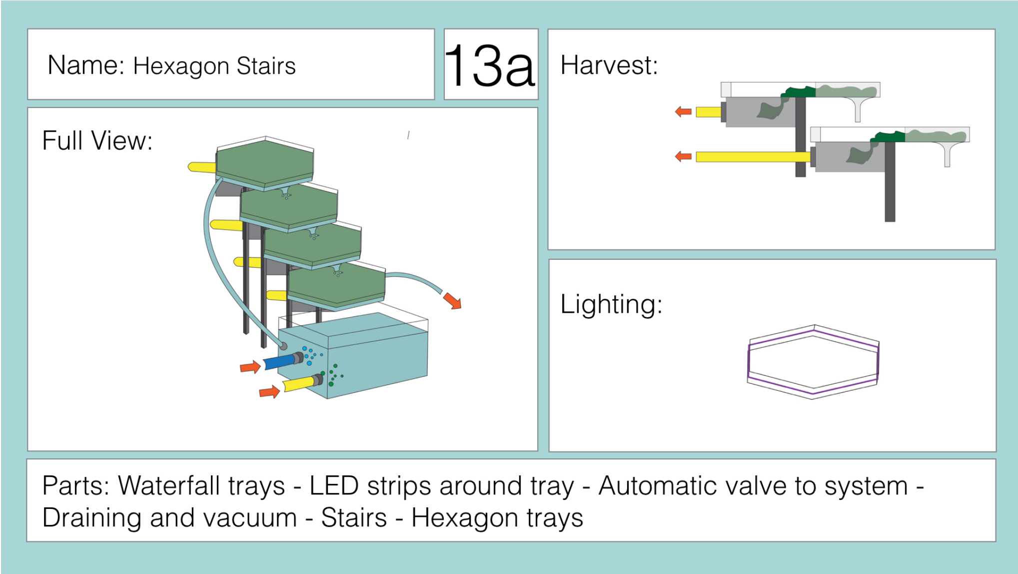

Figure 4.10: Concept 13a - *Hexagon Stairs*

15 - Hose Distribution

This design is a variation of the "overlapping closed trays" concept. The trays are arranged in a vertical displacement and the trays are completely closed except for water in- and outlets as well as harvesting collection opening. The scrape harvesting mechanism is built into the trays with an external harvest collection container attachment. The additional lighting is supplemented through external LED light strips along the outer sides of the trays. In the trays, water and nutrient hoses are placed to allow for an even dispersion throughout the trays. See the Figure 4.11 below.

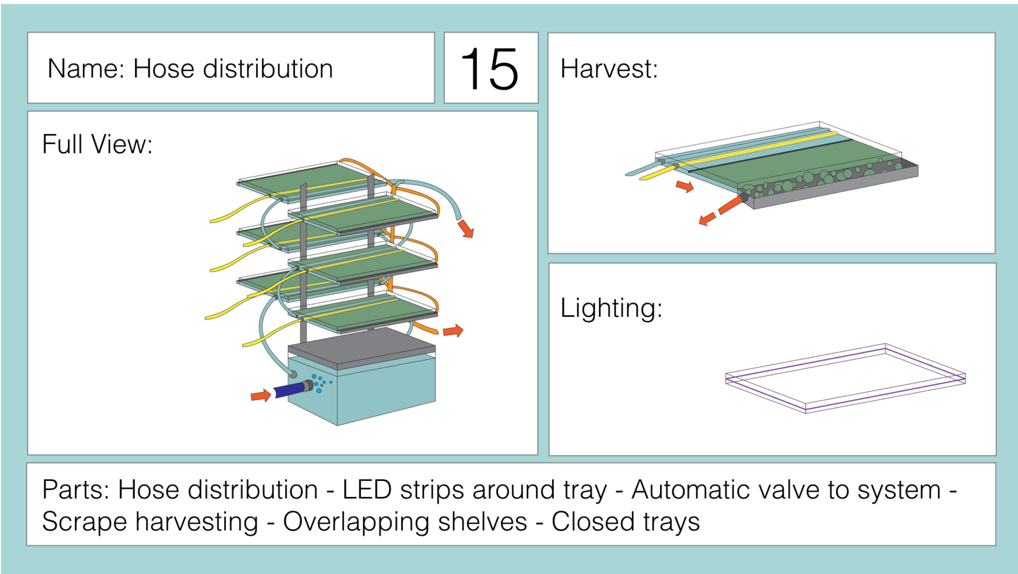

Figure 4.11: Concept 15 - *Hose Distribution*

16A - In-tray Distribution

The final selected concept is named after the water and nutrient distribution construction of the trays. Internal canals are integrated into the trays to allow for a water and nutrient passage to create an even distribution throughout the tray. Additional lighting is also encapsulated in the tray to allow for an even light dispersion. The trays are equipped with lids that are attached to a perforated harvesting plate that are lifted during the harvesting process to remove the biomass from the trays. See the Figure 4.12 below.

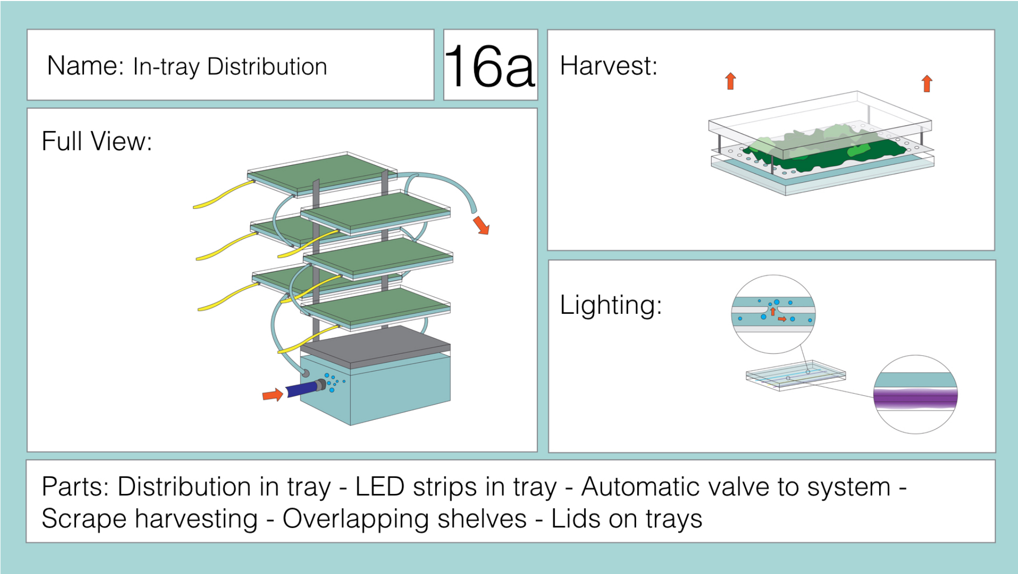

Figure 4.12: Concept 16a - *In-tray Distribution*

4.2.2.3 Results of the Concept Screening by Pugh Matrix

The Pugh matrix was used as a method of screening the six aforementioned concepts in a group meeting of interested parties. The existing cultivation was used as the reference for which the other concepts were compared against. The concepts were scored on their relative performance on a list of criteria taken from the customer needs list. The completed Pugh matrix can be found as Figure A.6 in the Appendix.

During the meeting and the review of the concepts, it became apparent that there was no clear winner or dominant design. There was much discussion on the validity of the complete concepts and the function of the sub solutions. Therefore, the Pugh matrix served as a formidable foundation for discussion and debate on different solutions. Many new ideas and reflections came to the surface during the meeting. The result of the meeting was in sorts a screening of concepts where no concepts passed and instead a synthesis of different presented solutions and new ideas occurred. All statements were noted during the meeting and the input, in conformance with target specifications, was used in a new concept design that was presented at a later group meeting.

4.2.2.4 Concept Selected to be Refined

As mentioned, the concept that was moved into the detailed design phase of the project was generated from an array of development practices and input from the stakeholders. The concept depiction can be viewed in Figure 4.13 below.

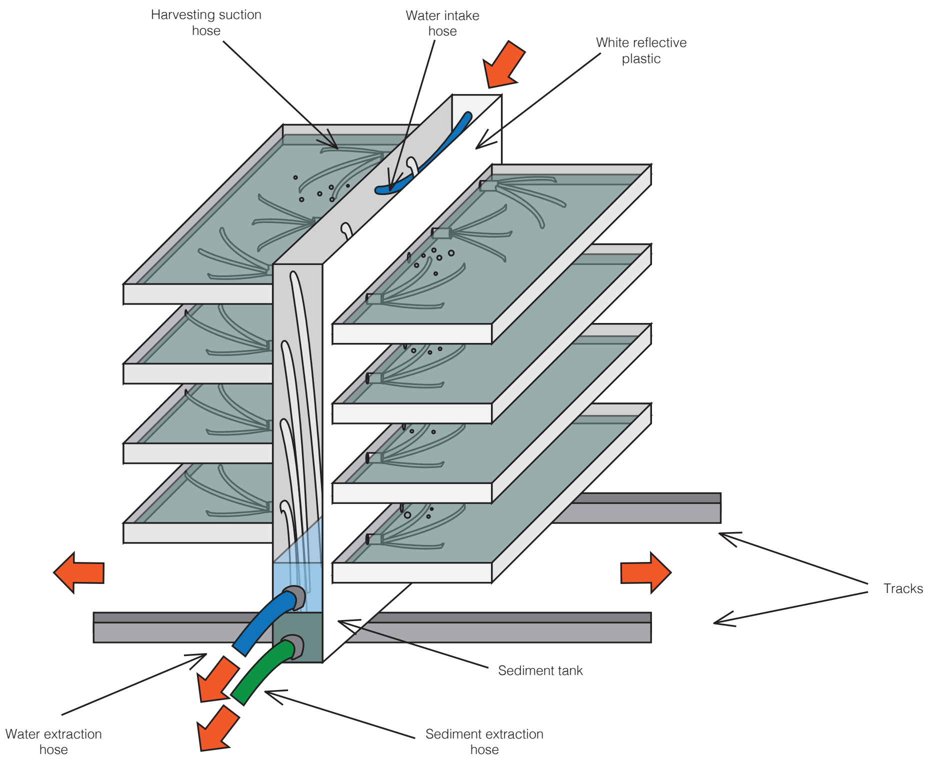

Figure 4.13: Final concept selection before detailed design

The concept consists of trays mounted on an internal structure with a vertical displacement between sides. The internal structure that holds the entire module is covered by a white reflective sheet of plastic to maximise the light by reflecting it back into the trays. The structure is placed on tracks that allow the modules to be moved closer and further apart from each other to work with shading and space utilisation. The water circulation is done through in and outlet connections in the trays through the reflective plastic sheet. Thin catheters are used to suck the biomass from the trays to a sedimentation tank when it is time for harvest.

4.2.3 Concept Refinement: Paving the Way to the Final Concept

After the selected concept was presented in August of 2015, there was a hiatus in the project until the middle of January of 2016. It was during this time that it was decided that the detail design of the automated harvesting system would be outsourced to an automation specialist company. Therefore, the design of the harvesting system in the project would be solely a concept design going forward. As there was still some uncertainty on the selected concept, further concept refinement was conducted before the detailed design phase commenced. During the concept refinement, changes were made to the concept when it became apparent that certain details of solutions were not optimal or could be improved upon. For example, the design of additional lighting in the form of LED strips, was removed from the product design as this is something that would need to be modelled and tested in a separate project. This decision was taken as there is little lighting data that could be used and specific testing would have to be conducted.

4.2.3.1 Mapping the Impact on Quality

In the following “house of quality”, a few alterations have been made to the classic format of the method. Instead of using the symbols “+” and “-“ to depict the relationships, numbers were used to allow for a summation of each parameter. This enabled a clearer portrayal of which parameters had either a negative or positive impact on the product as a whole. The QFD can be seen in the Figure 4.14 below.

House of Quality

	Importance (%)	Moveable system on tracks	Tray offset placement	Capillary suction hoses harvesting	3D structure in water	White reflective plastic middle	Open trays	Built-in sedimentation tank	Sum	Sum x Weight
Promotes Fast Regernation	21	0	0	-2	2	0	0	0	0	0
Maximises Natural Light	19	1	2	-1	-1	1	1	0	3	57
Ease of use	18	2	2	-2	0	0	2	-1	3	54
Cost Efficient	13	-2	0	-2	-1	-1	1	-2	-7	-91
Automatic Harvest	9	-1	-1	-2	-1	0	1	0	-4	-36
Modular Design	8	-1	2	1	0	0	1	1	4	32
Light Weight	5	-2	0	1	0	-1	1	-2	-3	-15
Continuous Water Purification	4	0	0	0	1	0	0	0	1	4
Max Height 2m	3	-1	-1	0	0	0	1	-2	-3	-9
Sum	100	-4	4	-7	0	-1	8	-6		

Interrelationship

	Moveable system on tracks	Tray offset placement	Capillary suction hoses harvesting	3D structure in water	White reflective plastic middle	Open trays	Built-in sedimentation tank	Sum
Moveable system on tracks		1	0	0	-1	-1	-1	-2
Tray offset placement	1		0	0	0	1	-1	1
Capillary suction hoses harvesting	0	0		-1	0	1	0	0
3D structure in water	0	0	-1		0	1	0	0
White reflective plastic middle	-1	0	0	0		0	0	-1
Open trays	-1	1	1	1	0		0	2
Built-in sedimentation tank	-1	-1	0	0	0	0		-2

Figure 4.14: QFD "House of Quality".

The result of the “house of quality” shows that the lowest score in accordance to the criteria was the "Capillary suction harvesting system". It scored negatively due to the high risk of internal blockage in the tubes. The design parameters “Moveable system on tracks”, "White reflective plastic" and “Built in sedimentation tank” have the highest negative impacts on the system both in terms of the customer specifications and relationships with other design parameters. With these overall negative scores, a cancellation of these design parameters is called for. The moveable system on tracks scored poorly because of the additional weight and space required to execute this parameter as well as an increased need of stabilisation is required. Accordingly, the built in sedimentation tank had similar reasoning behind the scoring as the increased weight of the tank would not comply with the light weight customer specification. Upon further investigation on the white reflective plastic, there is a high likelihood that it would do more harm than good. As minimal or no additional directed lighting will be used the plastic could shade the trays more than it maximises the light.

4.2.3.2 Testing Design Aspects

The intent of the experiment was to evaluate the effectiveness of two different designs of cultivation trays as well as a simulation of the harvesting technique. The experiment took place at the facilities at the Botanical Garden Campus during a period of five weeks with periodical harvests and controls.

The experiment was founded on the results of a study conducted in the United States. The study showed that implementing varying surfaces in the algae growing container more than doubled the production rate of the algae [1]. As a further development of this experiment, surface treatments were implemented into the cultivation container it self. In addition to examining the speed of regeneration of the algae population it was also an investigation into a way of keeping a certain percent of algae in the cultivation tray after the harvesting process. The experiment examined two different surface treatments of the bottoms of the cultivation trays. These designs will be sealed and kept confidential by request of the company and will simply be denoted as tray A (control tray), tray B and tray C. The trays' water circulation system was connected in parallel and not serial so that each tray had the same nutrient supply. The data collected from the experiment can be seen in Figures 4.15 and 4.16 below. The specific values of the data points have been removed to not divulge any productivity information in the report.

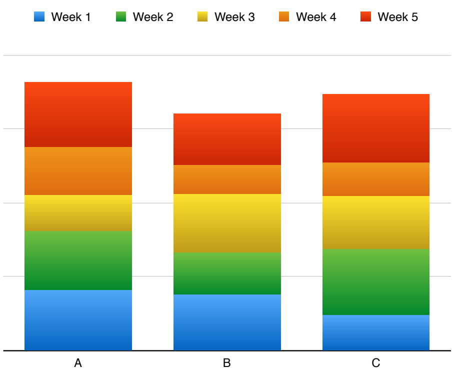

Figure 4.15: Total amount of harvested weight.

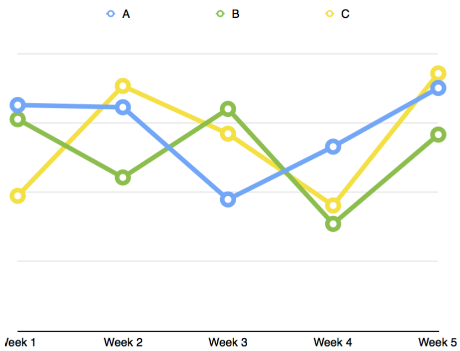

Figure 4.16: Graph of harvested weight per week.

The harvest collected after the fourth week in the trays B and C is substantially lower than in tray A, the control. This is due to a malfunction that occurred during the weekend, where tray B was completely restricted from water and the tray C had a very low water circulation rate. The cause of the malfunction is unknown, but most likely it was due to a regulation error of the water flow. This drastically affected the results of the experiment as it would take a longer time for the affected trays to recover than was permitted. Therefore, control tray A has a higher total amount of harvested algae compared to the other two trays depicted in Figure 4.15. One could draw the conclusion that tray A had the dominant design from this data. However, if one looks closer at the graph in Figure 4.16, tray C kept a relatively stable growth rate, except for the impact of the malfunction during week 4. It was able to recover very quickly and even increase the amount of algal growth during week 5. It is therefore deemed that tray C had the dominant design in this experiment.

An additional result from the experiment was a design choice made upon physical usage of the harvesting method. The initial harvesting method was to scrape the rubber scraper along the bottom, over the edge of the tray where a side, or door, had been removed. This was deemed to be more difficult than expected and it was much easier to lift the scrape with the algae resting on the side by pulling it against a wall of the tray and then collecting the biomass. Due to this experience, the application of having a removeable side of the trays was removed from the concept.

4.2.3.3 Anticipating Possible Failures

The Failure Mode and Effects Analysis reviewed the final concept to evaluate any potential risks of failure that could occur in the future. The analysis shows that there are a number of possible failures that could happen with the current design that need to be tested before an industrial implementation. Certain design aspects were identified that had a high level of insecurity and changes were made in the final design. For example the design of the console connection to the bearing structure had a high potential of failure. The connection was designed as a hook that connected to a slot in the bearing structure. Any minimal gaps or manufacturing discrepancies could cause the tray to fall, slip or leak. As the trays are filled with water it is important that the trays are kept level. To minimise this risk, the design of the connection was changed from a hook and slot to a nut and bolt connection. The biggest result of the analysis is the need for the company to build a full scale prototype of the product to be able to validate the design choices made. The FMEA has been checked by an algae researcher and the process engineer employed at SAF to check the validity of the potential risks and if there were any that had been missed. The FMEA can be found in Figures A.8 and A.9 in the Appendix.

4.3 The Final Concept

To facilitate the scale-up process, the concept was designed as a product platform with two planned generational updates. This allows SAF to grow into the different designs while keeping a high level of flexibility. The first generation, or product platform, is fully designed and scaled for this project. The harvesting system in the second generation is a developed concept and not a full automated design. The third generation is solely a concept proposal and not fully realised. The purpose of demonstrating the two extra generations is to show how the product platform can be utilised in future updates.

4.3.1 Product Platform

The Figure 4.17 depicts a render of the cultivation module platform design. The platform consists of five trays resting on consoles attached to either side of the support beams. The total of ten trays are estimated to amount to an algae cultivation area of ca. 23 [m^2] and holds a volume of 1,74 [m^3] of water on a ground surface area of 4,8 [m^2].

Figure 4.17: Product Platform.

As the support structure is internal it minimises the amount of support structures needed to maximise the algal growth area while keeping both the amount of parts and weight to a minimum. The structure is designed after a classic industrial storage shelving system. This design allows for an easy upscale as one can simply just add on supports and consoles on the end of the previous system and connect the trays. A serial installation of modules creating a cultivation system can be seen in Figure 4.18. The parts used in the design of the structure are common standardised parts that have been machined to fit the design as to keep the costs down.

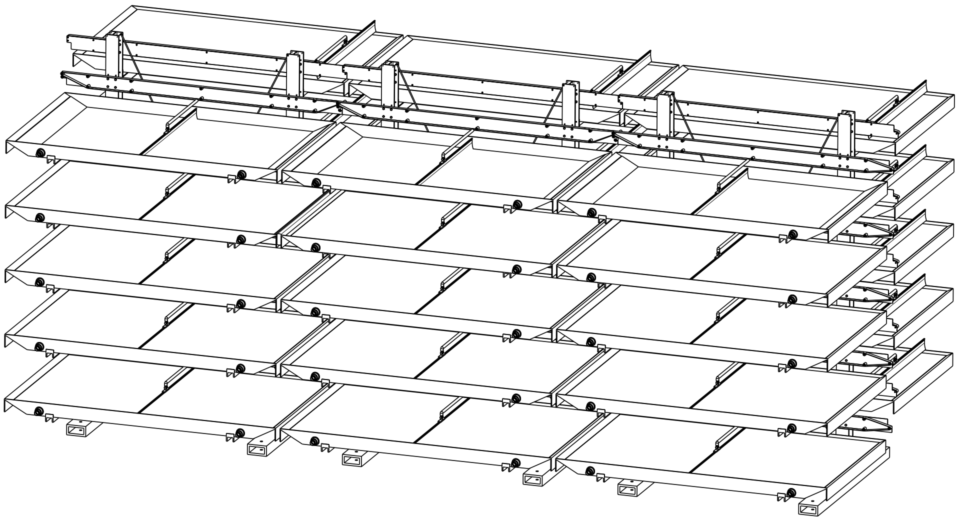

Figure 4.18: Drawing of a serial connection of modules.

The full product specification list can be found as Figure A.7 in the Appendix. Certain aspects have been blocked out of the list to comply with the confidentiality agreement with SAF.

4.3.1.1 Support Beam

The structure is based on the design of the HEA 100 track support beam. The HEA-100 track beam is an industrial standardised part made out of zinc coated galvanised steel. The material was chosen for galvanised steel with a zinc coating is much more cost efficient than stainless steel while still being strong enough to carry the consoles and is not corrosive when in contact with salt water [7]. The hole patterns are located to be as versatile as possible. The lower four holes are designed to carry a console, above this pattern is another set of four screw holes that accommodate the harvesting attachment. Directly above the harvesting attachment hole pattern is another set of holes. These are to attach an additional tray level instead of the harvesting attachment.The console would then connect to the two additional top holes and the bottom two holes of the harvest attachment connection pattern. Please view Figure 4.19. This would allow the module to carry 20 trays in total instead of 10. Se Figures 4.20 and 4.21. The hole patterns have a vertical displacement compared to the other side as to enable the trays to be mounted with an offset. This is to minimise complete shading of the lower trays and to allow for modules to be placed closer together with an overlap between trays if the customer so desires.

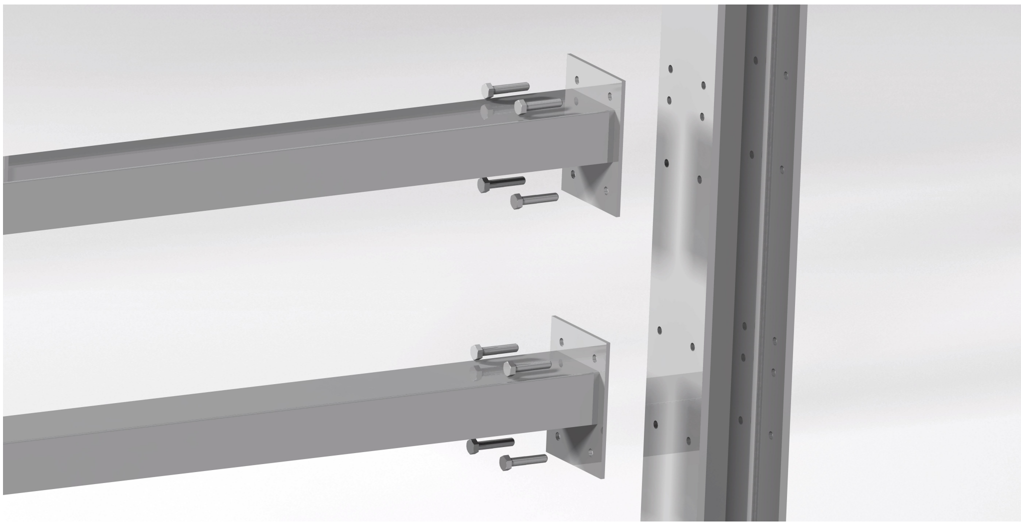

Figure 4.19: Installation of additional level.

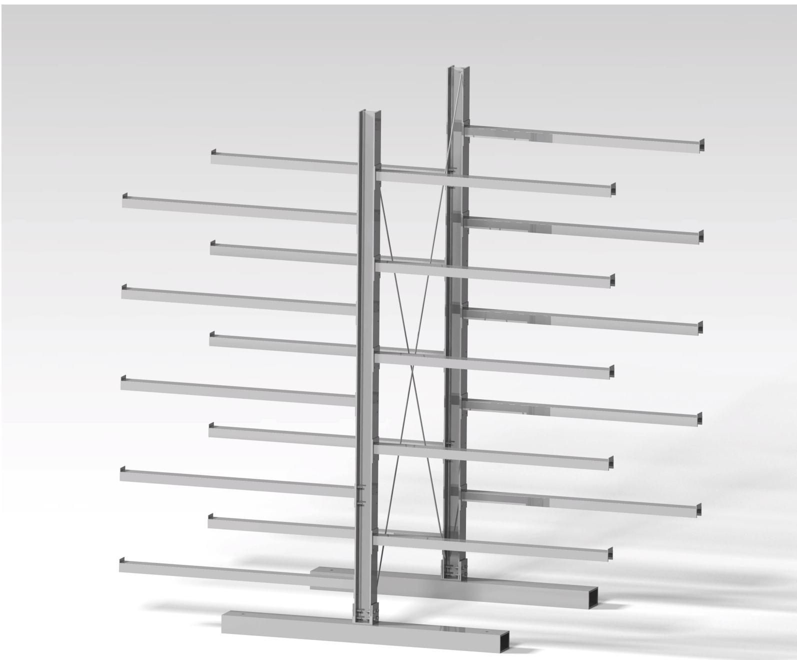

Figure 4.20: Structure with 10 levels

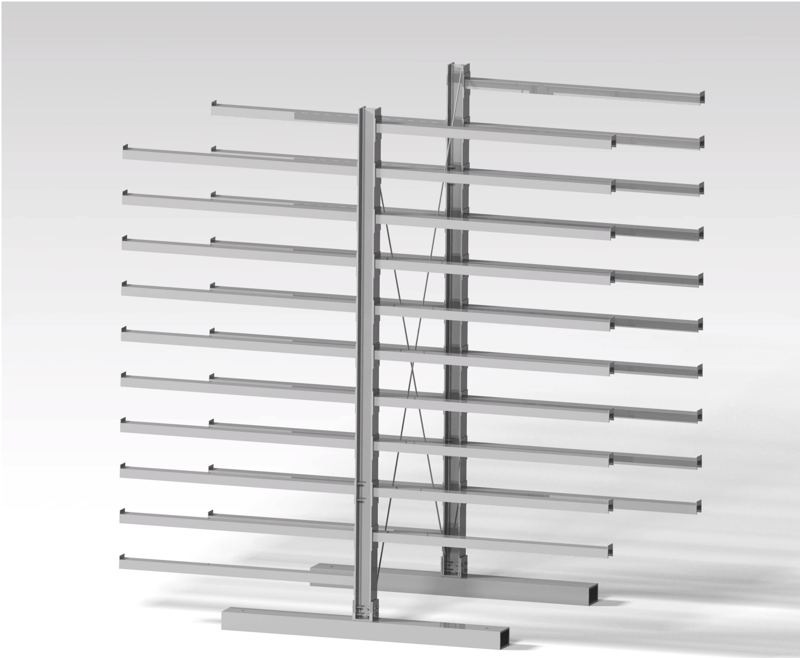

Figure 4.21: Structure with 20 levels

4.3.1.2 Console

The console's function is to carry the trays and keep them level. The console is attached to the support beam by M8 stainless steel screws. The installation of the console can be seen in Figure 4.22 below. The console is constructed out of zinc coated galvanised steel just like the support beam. A UPE 80 beam comprises the main structure of the console with some machining manipulations. The end of the console is equipped with a "stop" to secure that the trays do not fall off the consoles. The U-shaped beam is welded to a rectangular metal sheet that supports the console and allows it to be connected to the support beam.

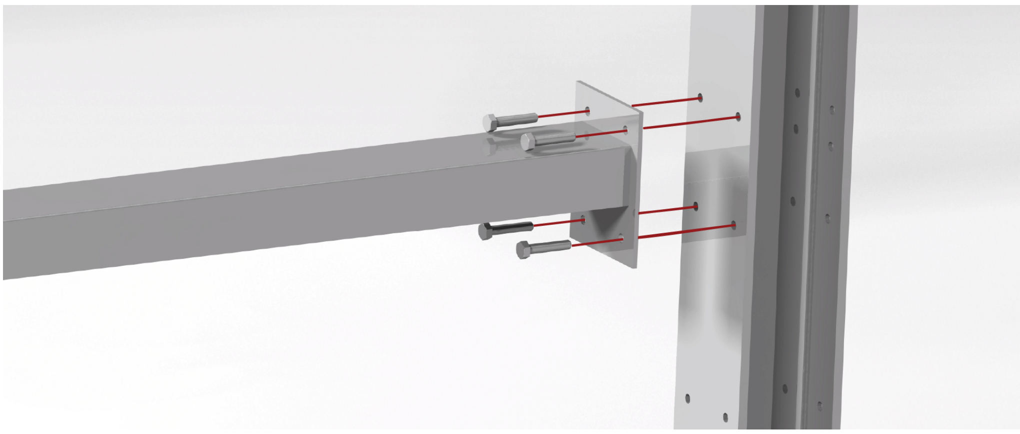

Figure 4.22: Console installation

For the console structure to be an effective design choice, it is imperative that it can carry the trays without the risk of collapse. The design must be robust enough to handle the weight of the trays, the algae, the water, the harvesting process and a cleaning process. A FEA was conducted on the console to ensure the validity of the design by simulating the distributed force on the console. The analysis was done in the CAD software CATIA V5. A visualisation of the impact study can be seen in Figures 4.25 and 4.26 below. The distributed load (Q) was calculated with the following calculations [12].

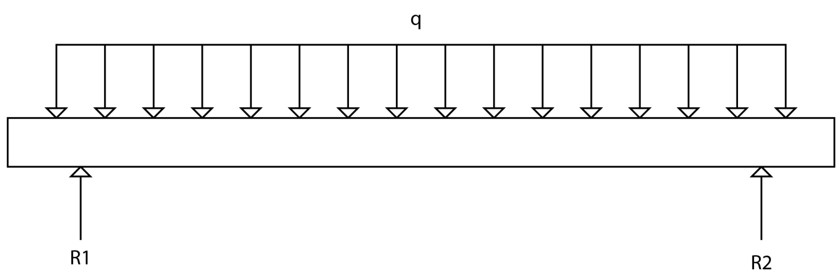

Figure 4.23: Analysis of the forces the consoles are exposed to

m = 200 [kg] (mass of water and tray)
g = 9,82 [m/s^2]$(acceleration of gravity)$

$$q = m * g[N] \tag{4.1}$$

$$R = R1 = R2 = q/2[N] \tag{4.2}$$

$$R = 982[N] \tag{4.3}$$

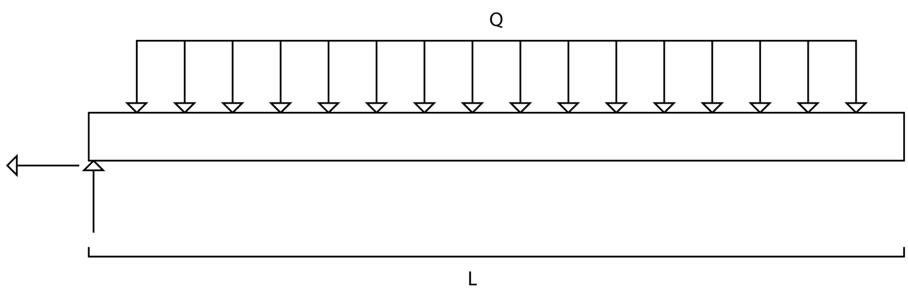

Figure 4.24: Analysis of the distributed force the console is exposed to

L = 1,35 [m] (length of distributed load on console)

$$Q = R/L[N/m] \tag{4.4}$$

$$Q = 727,41[N/m] \tag{4.5}$$

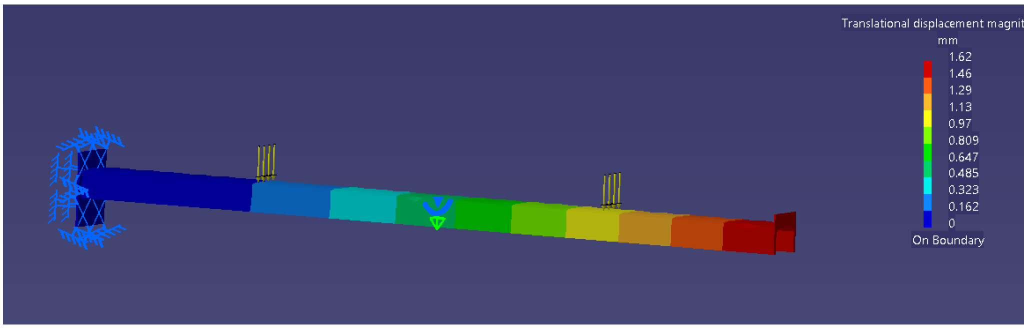

Figure 4.25: Material displacement analysis on Console

The Figure 4.25 shows that the maximum material displacement, caused by the distributed force Q, is 1,62 mm at the very end of the console. The displacement causes a strain on the material underneath the reinforcement structure of the console. This stress analysis is called the Von Mises analysis and is portrayed in Figure 4.26.

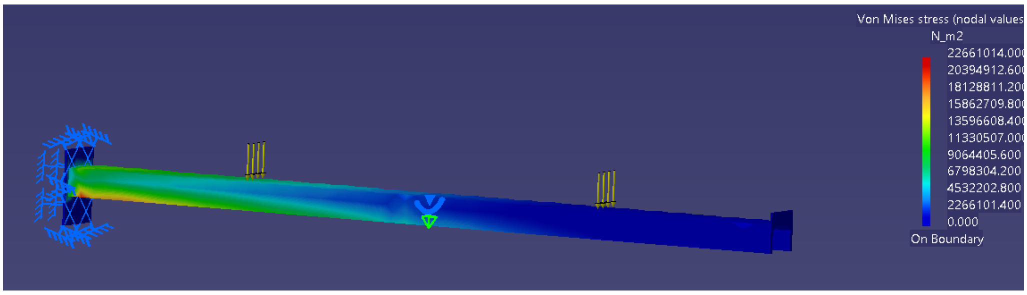

Figure 4.26: Von Mises analysis on Console

The maximum stress is estimated to be 22,6 MPa which is well below the yield strength (elastic limit) of the material which is between 250-395 MPa and the fracture toughness of 41-82 MPa [7]. The displacement caused from the distributed force is deemed to be within acceptable limits of the product specification and will not have a negative effect on the cultivation of the algae. From this analysis it is concluded that the design of the consoles are appropriate for their function. However a stress test on a physical prototype to ensure validity of these calculations must be conducted before ramp-up.

4.3.1.3 Structure Foot

The support beam is connected to a structure foot that rests on the ground that can be seen in Figure 4.27 below. The structure foot is made out of two parts, a connection to the support beam and a heavy duty rectangular beam that distributes the load on the ground and stabilises the structure. The support beam connection is a square U-shaped piece of zinc coated galvanised steel that stabilises the support beam with four M10 stainless steel nuts and bolts. The piece is manufactured by bending a sheet of thick steel and then welded to the top of the rectangular beam.

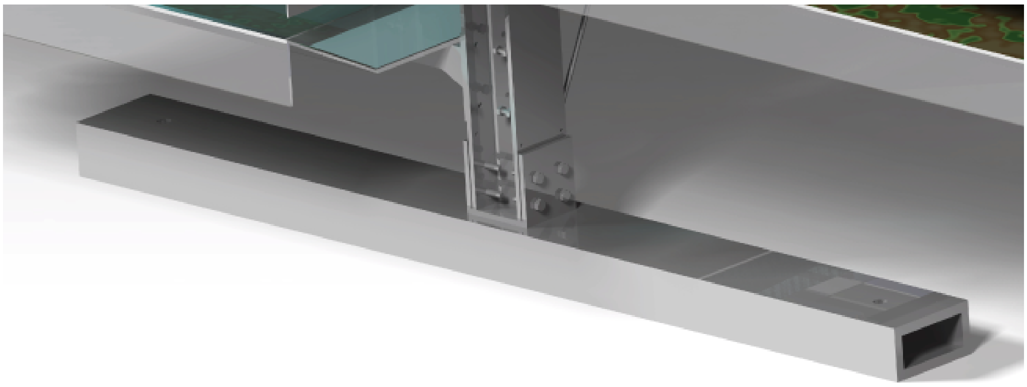

Figure 4.27: Structure Foot.

The foot has two drilled holes close to the end of the rectangular beam. The function of these are to be able to attach a standardised stabilisation footing structure or to secure the system to the ground.

4.3.1.4 Support Rods

Two thin support rods connect the support beams to each other. The rods are attached to the top of the first beam and then the bottom of the subsequent beam in both directions forming an X shape. The function of the rods are to ensure the stability of the beams in the Y-axis, so to speak, to minimise any lateral movement. The rods are connected with two M5 bolts.

4.3.1.5 Cultivation Trays

The trays are designed to maximise the algal growth area while using standardised parts that are available for a reasonable price. The trays are made out 5 mm thick polymethylmethacrylic plastic (PMMA) also known as plexiglas. The material was chosen for its optical quality transparency, UV resistance, durability and salt water and organic solvent resistance [7]. The largest standardised 5 mm PMMA sheet is 2050 x 3050 mm. These standardised dimensions had a huge impact on the design of the trays. Upon consultation with several experts in the field of both plastics and plastic forming, there is no way to join sheets of PMMA on a horizontal field that could resist the force of the water over a longer period of time. The joint would crack very easily and the costs would be very high to both manufacture and repair such trays. Therefore the design was created to utilise the standardised part and instead of creating long trays, several trays are connected in serial. The tray has almost a trough like shape as the shorter sides are bent to an angle. This design choice was done to minimise the amount of 90 degree corners (it is hard to clean any algae caught in the sharp corner), reinforce the structure and to allow a continuous harvesting process across the entire length of the tray. The resulting dominant design generated from the design experiment will be implemented into the internal bottom of the tray. As this design has been requested to be excluded from the printed report no images or further information will be provided on the subject. The design of the tray can be seen in the figures below.

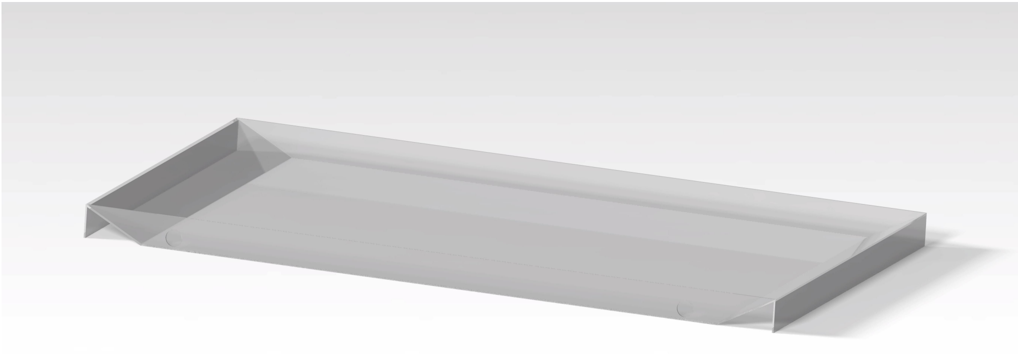

Figure 4.28: Design of Cultivation Tray

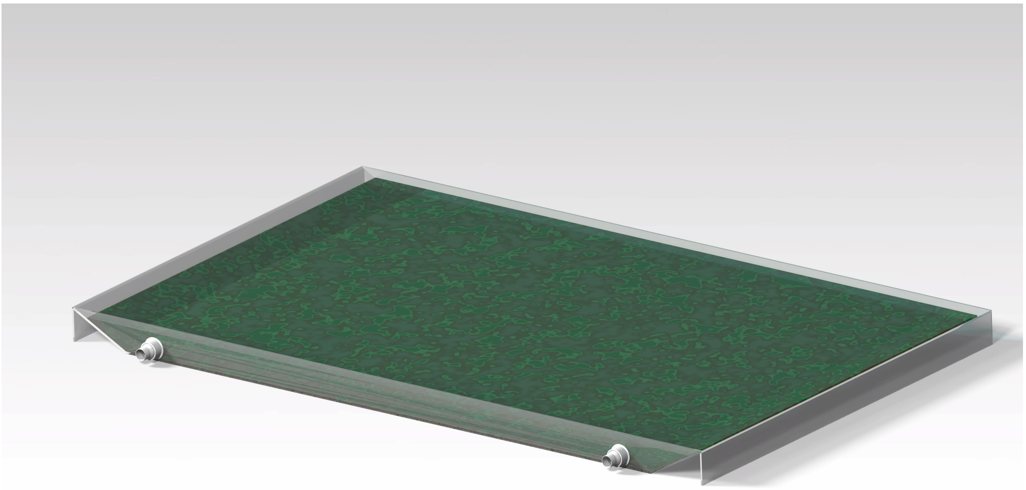

Figure 4.29: Cultivation Tray with water and algae

A similar analysis as done on the console was conducted on the tray in the program CATIA V5. The simulation analyses the material displacement and stress that the distributed force of the water and the algae have on the tray. The results of the analysis can be seen in the figures below.

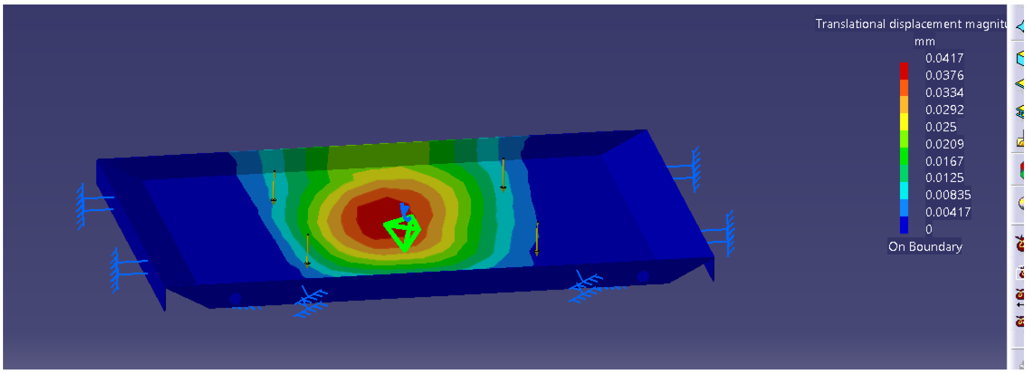

Figure 4.30: Material displacement analysis on Tray

The analysis shows that the load will have a maximum of translational displacement of 0,04 mm in the center of the tray. The displacement will cause a stress of 0,168 MPa on the material which is below the estimated yield strength of the PMMA which is between 57,6-63,7 MPa and fracture strength of 0,7-1,6 MPa [7]. The results of the Von Mises analysis can be seen in Figure 4.31

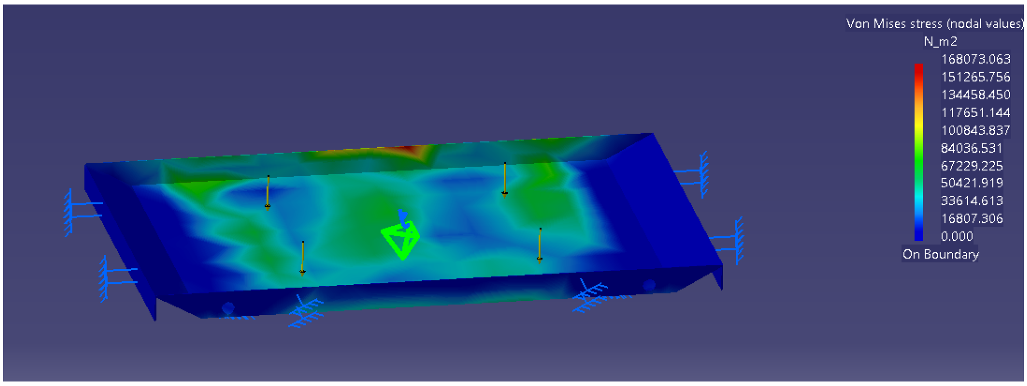

Figure 4.31: Von Mises analysis on Tray.

4.3.1.6 Tube Connectors

The connection between the tubes and the trays are done by a standard high pressure hose connector. The connection is connected through several parts that allows it to be mounted from the inside of the tray. The tubes that are to be connected are easy to attach and remove by screwing off the outer part connected to the tube. The tubes must be easily removed without dismantling the entire tray to be able to cleaned. A render of the installation of the tube connection can be seen below.

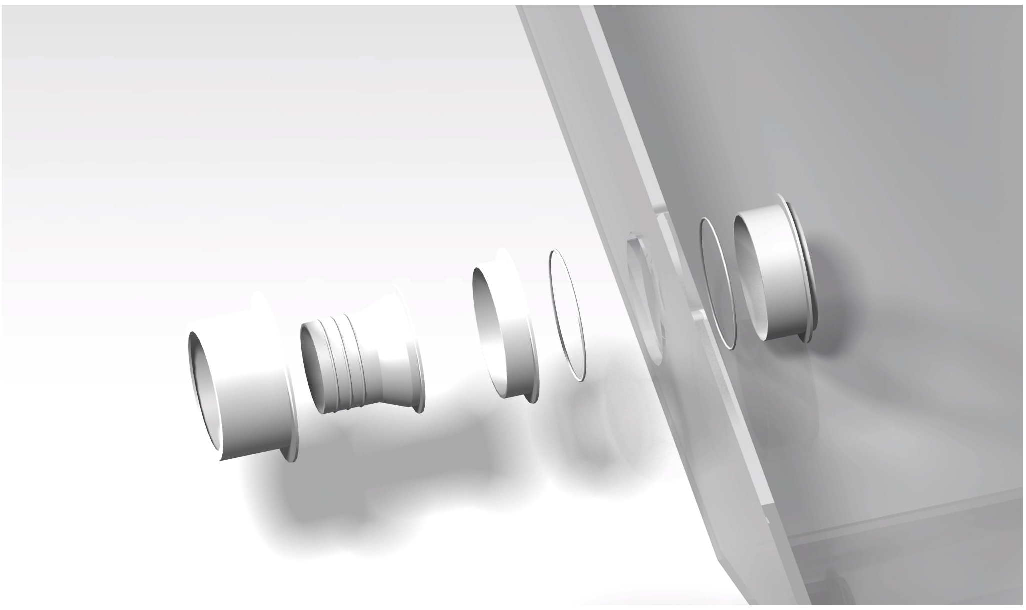

Figure 4.32: Tube connectors.

4.3.1.7 Process

Water Regulation into System
The water that enters the system is dispensed by a pump that is connected to the main water source. Before the water enters the pump, any additional nutrients or additives are pumped into the water inlet so that the water has a homogeneous nutrient content. The pump is then coupled to a pipe distributor that connects the tubes that provides the cultivation trays with water. The sizing of the pump is dependant on the size of the system. For a single module to a smaller system of modules, a pump such as the TP25-50 model from the company Grundfos would be appropriate.

Water Regulation out of System
During the cultivation period, the water flows freely out of the system either back into the water reservoir or to a separate entity depending on the application of the system. Once the cultivation period is completed the inlet pump is turned off and the evacuation pump is turned on. A pump with a low suction inlet (dependant on the size of the system) carefully sucks the superfluous water out of the system to allow the harvested biomass to have as little water content as possible. With this type of water evacuation process it is likely that the biomass collected will have a high water content as the suction must be done very restrictively as not to flush the algae out of the system. This worth noting when designing the after-processing methods.

Water Regulation in the System
When the water is circulating in the system, it flows by the help of the pressure force from the inlet pump as well as the gravitational pull between the levels. The water enters the top level of the trays and then passes on to the next tray through a PVC tube connected to both trays. At the end of the trays on a certain level, a hose is con-

nected to the tray below and the water flows back through the trays in the opposite direction. The same vertical connection between trays is applied when one module is in operation alone. These tube connections can be seen in the Figures 4.33 and 4.34.

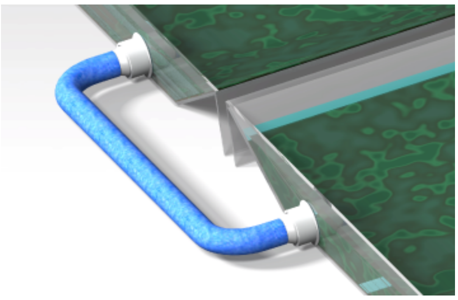

Figure 4.33: Tube between horizontal trays.

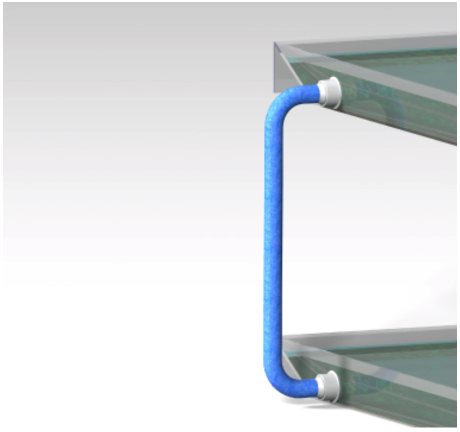

Figure 4.34: Tube between vertical trays.

Sanitation Process

As the trays are to remain fixed in their position in the system, a sanitation process must be flexible. When it comes to sanitise either due to a contamination, or a habitual cleaning routine, the system will first be cleared of any algae and water. Thereby the system will be sprayed with a high pressure water stream followed by a low concentration Hydrogen Peroxide solution to kill any unwanted organisms in the system. To complete, the system is washed once again with water.

4.3.2 Second Generation

The second generation is the first step towards automation of the system. One could imply that it is the semi-automatic generation. The base of the system is the platform with an automatic harvest "attachment". Above each tray there are predrilled holes in the support beam to be able to mount the harvesting system. This allows for an easy gradual update from the first generation to the second. The harvesting system is automated to the point where the plastic scrape removes the biomass from the trays and places it in a collection container.

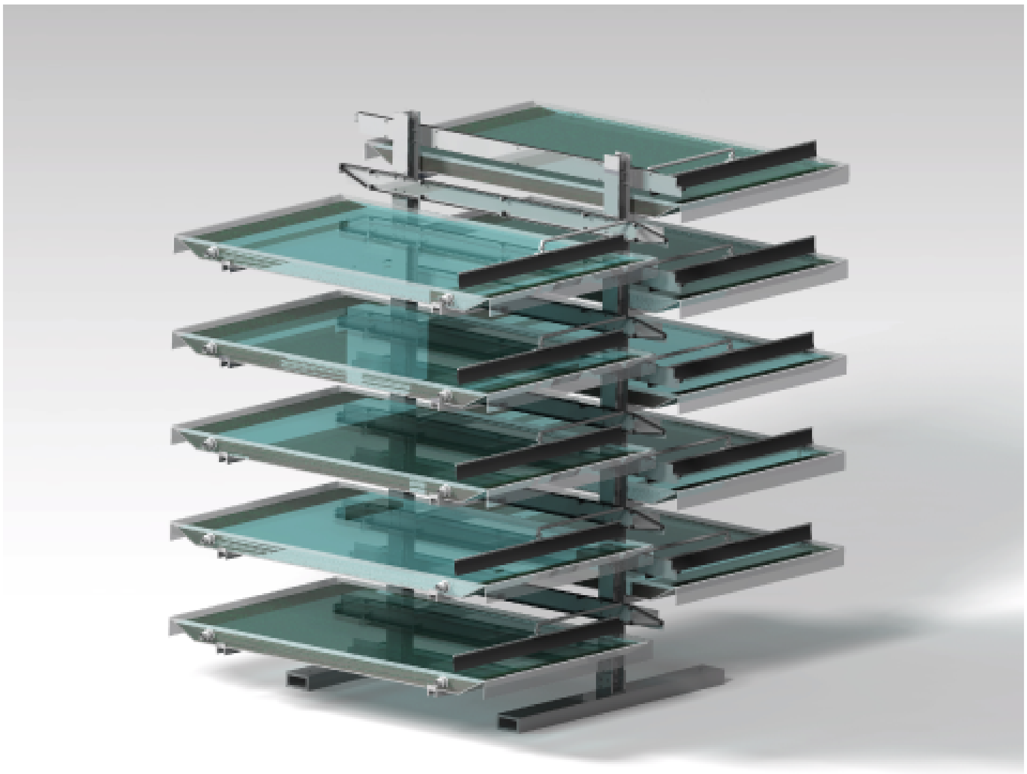

Figure 4.35: Second Generation Module.

4.3.2.1 Harvesting System

Since a complete automated harvesting plan is outside of the scope of this project, the following is purely a proposed concept of an automated harvesting system.

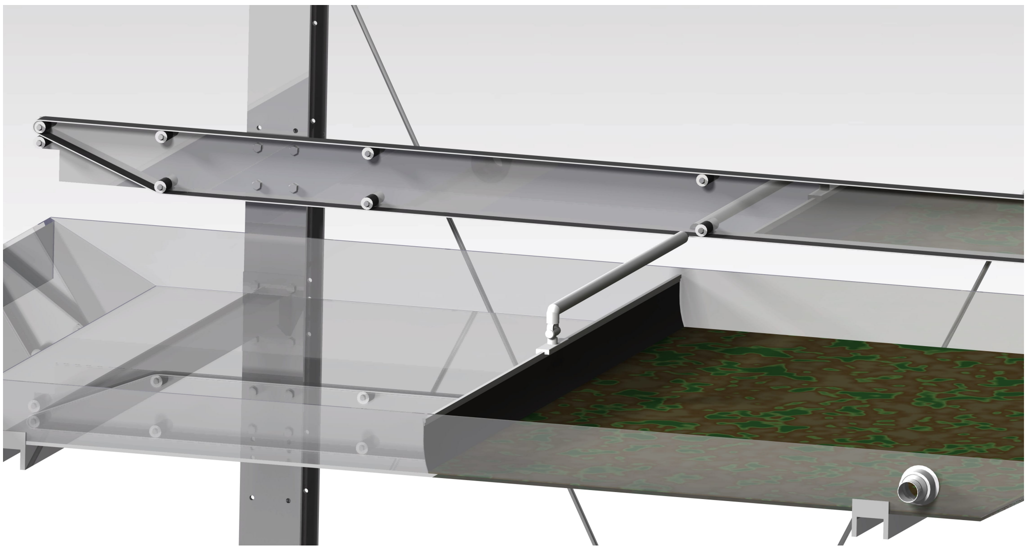

Figure 4.36: Harvesting system in motion.

The principle of the harvesting system is a rubber scrape scraping the bottom of the trays and pushing the collected biomass into a collection container over the edge of the tray. A break-down of the system can be seen in Figure 4.37 below. The scrape is connected to a rotational joint that enables the scrape to follow the form of the tray. The joint is in its turn connected to a guiding arm that is attached to a rubber conveyor belt. The conveyor belt is driven by a DC motor connected to a belt pulley. The motor is intended to drive all of the conveyor belts in the system through a gear mechanism that connects the driven belt pulleys.

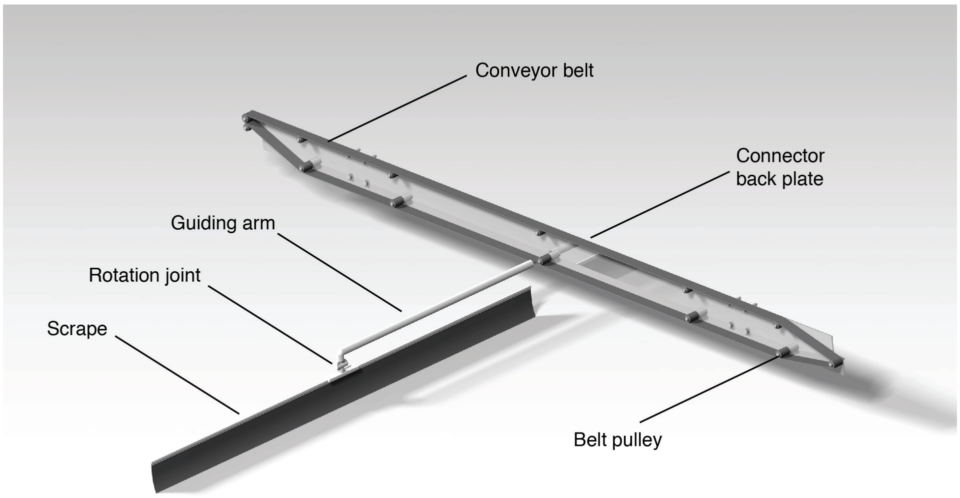

Figure 4.37: Proposed harvesting system.

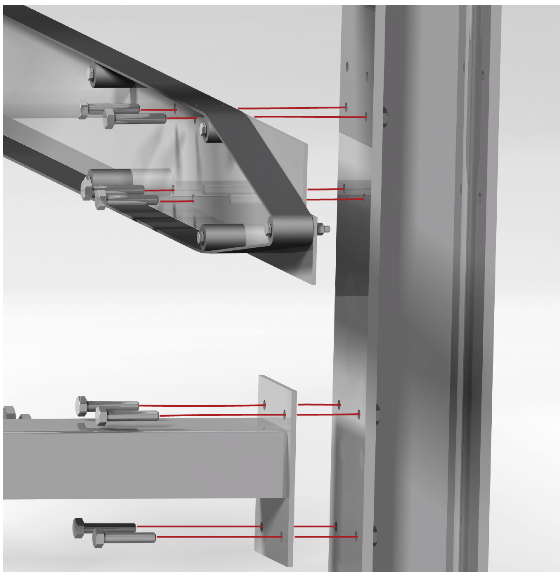

Figure 4.38: Installation of harvesting system

The harvesting system is designed as an optional attachment to the system. The plate that connects the harvesting system to the support beams is easily attached with M8 bolts. The connection can be seen in Figure 4.38 above. If several trays are connected subsequently, the conveyor belt is dimensioned after the size of the system. The plate connected to the support beam is designed to connect with the following system to align the conveyor belt between systems. The either ends of the harvesting system can be seen in the top two figures in Figure 4.40. The bottom figure shows two modules serially connected. The trays are attached to each other with a PVC tray connector that is fitted to the inside of the slanted parts of the trays. The connector creates a seamless transition between trays for the scrape to follow. The red line in the figure shows how a long conveyor belt would be arranged in the system.

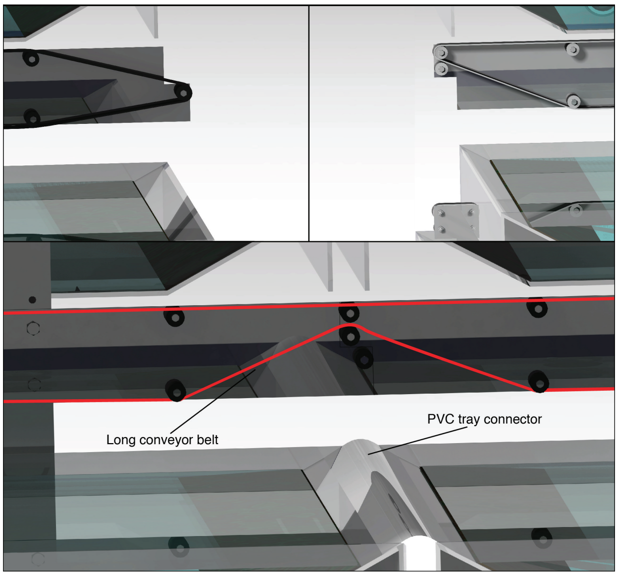

Figure 4.39: Serial connection of harvesting systems.

Biomass Collection

When the harvesting system has scraped the entire system and comes to the end, the biomass is scraped over the edge of the tray into a removable collection container. The container is manually handled and attached by a service operator. The container is moulded out of PVC plastic that can easily be cleaned. The design can be seen in the figure below.

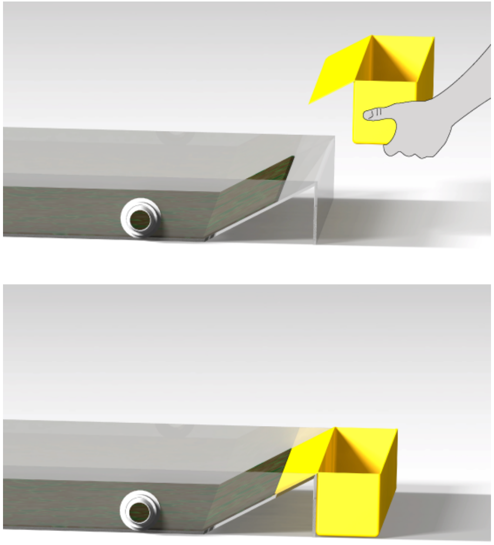

Figure 4.40: Biomass Collection Container.

4.3.3 Third Generation

The third, and final, generation of the concept is a fully automated system. A summation of the upgrade can be seen in the Figure 4.41. Just as with the second generation it is built on the first generation platform with an attached automated harvesting system. A part of the upgrade in this generation is the automated collection system that transports the harvested biomass from the module to a separate collection receptacle so that no human entity has the need to manually operate the system.

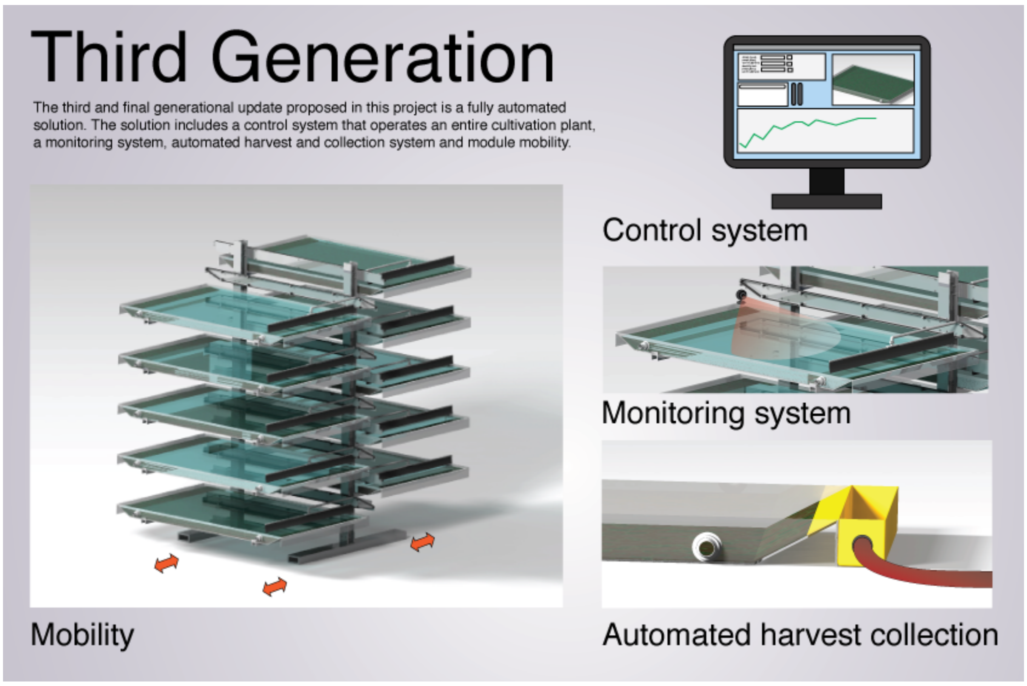

Figure 4.41: Third generational update.

The modules are placed on automated tracks so that the modules can be arranged with a larger overlap between trays. This feature was originally disregarded from the design due to stabilisation and weight requirements. Upon reflection and the possibility of adding updates when required by a system, it was reissued in the final generational upgrade as an optional application. By being able to move the entire system it facilitates any repair work and allows for the owner of the system to work with different shading installations by moving the trays closer together at certain parts of the day for example. Please see Figure 4.42 below. The upgrade also has monitoring cameras and reflective sensors to indicate when the tray is ready for harvest and monitor any contaminations or malfunctions. This enables the use of an external computer control program.

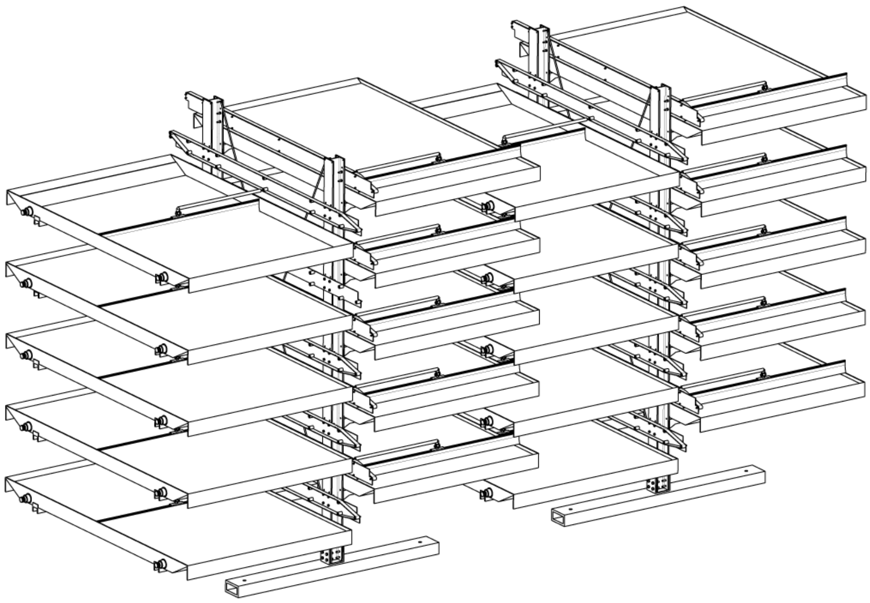

Figure 4.42: Close parallell spacing between modules.

4.3.4 Manufacturing and Installation

The parts that make up the support structure are to be purchased as standardised parts from a large steel manufacturer that are able to customise the parts on in their warehouse before delivery. Thus, all the cutting to size and drilling hole patterns will be completed upon arrival. The parts that are to be welded together will be sent to a manufacturing company that will finish the parts. The complete structure will then be transported to the cultivation plant site and installed on location. The trays are to be manufactured by heat bending, cutting and gluing by a plastic processing manufacturer. Upon completion, the trays will be delivered to the cultivation site and installed in the structure. All additional parts such as tubes and tube connectors are standard parts and will be purchased from appropriate retailers.

A full parts list and manufacturing plan has been provided to SAF. These documents have been excluded from the report by request of the company.

4.3.5 Cost Estimation

The cost estimation of manufacturing the product was based off the quotes that were provided by several different vendors. Two cost estimations were made, one calculating the cost of producing a single module (the cost of building an initial prototype) and the other estimating the cost of an entire cultivation plant. The Figure 4.43 depicts the cost drivers of the product. The size of the circles are relative to their investment cost. The larger the circle, the higher estimated investment cost.

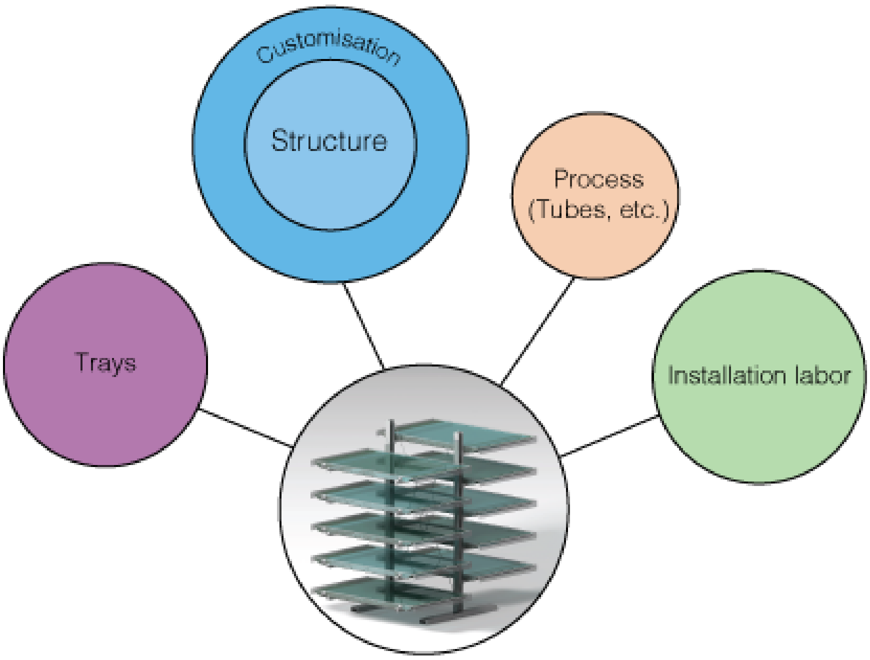

Figure 4.43: Visual representation of the cost drivers.

The largest investment is the manufacturing and purchase of the support structure. Even though each part is made out of standardised parts, they all need to be customised to fit the product. This machining work is a major investment cost that impacts the final cost estimation. This is due to the large amount and the customised design. The trays are another large investment. A thorough study of plastic manufacturers and suppliers was conducted to find the best price to accommodate the low cost requirement. However, the recommended plastics manufacturer provides a good price for the ramp-up. Following, the installation of the product is deemed to be the third largest cost driver. This driver has the biggest impact when it comes to scaling up the product. The cost is calculated by an hourly rate, therefore the longer installation time, the more costly the installation will become.

The least expensive parts are the tubes and tube connectors that are to be bought "off the shelf" and there is no need for customisation.

As this is a new potential product on the market it is hard to gage where the estimated cost of the module is on the expense scale. The module includes a large amount of parts that are interchangeable and upgradeable which drives the cost. To justify the initial cost, certain benefits where identified that make the product profitable during a period of 10 years (the product is most likely to be profitable beyond a ten year period, this was period was used in this evaluation in compliance with the product specification). The design of new module increases the algal growth area by 522 % compared to the lab scale module. In comparison to the utilised ground surface area of 4,8 $[m^2]$ that the module utilises, it generates an increase of 479 % of algal growth area. This increase of algal growth area per ground surface area allows the company to maximise the amount of algae cultivated on a relatively small area. The estimated increase of algae growth will benefit the company by increasing the yield of the algae that could be sold and processed into value products.

5
Rena Hav AB Project Proposal

The cultivation module was, in part, designed to accommodate the Rena Hav AB pisciculture project's specifications. The following is a proposal of an execution plan to achieve the goals of the project.

The proposed full scale plant includes 22 algae cultivation systems containing 20 algae cultivation modules each. A scaled layout depiction can be seen in Figure 5.1. A group of 11 systems are installed parallel to the long side of the building with a center row between them and the next group of 11 systems. This partition is to allow for access to the harvesting collection, tube gathering or general space for operational practices. There is a 70 cm space between the lengths of the systems. This allows the operators to access each tray in the system for either cleaning, repairs or inspection. The entire cultivation plant is encapsulated by a greenhouse to keep a constant temperature and shield from harsh weather conditions. The greenhouse design is outside of the scope of this project and is therefore not dimensioned at this stage.

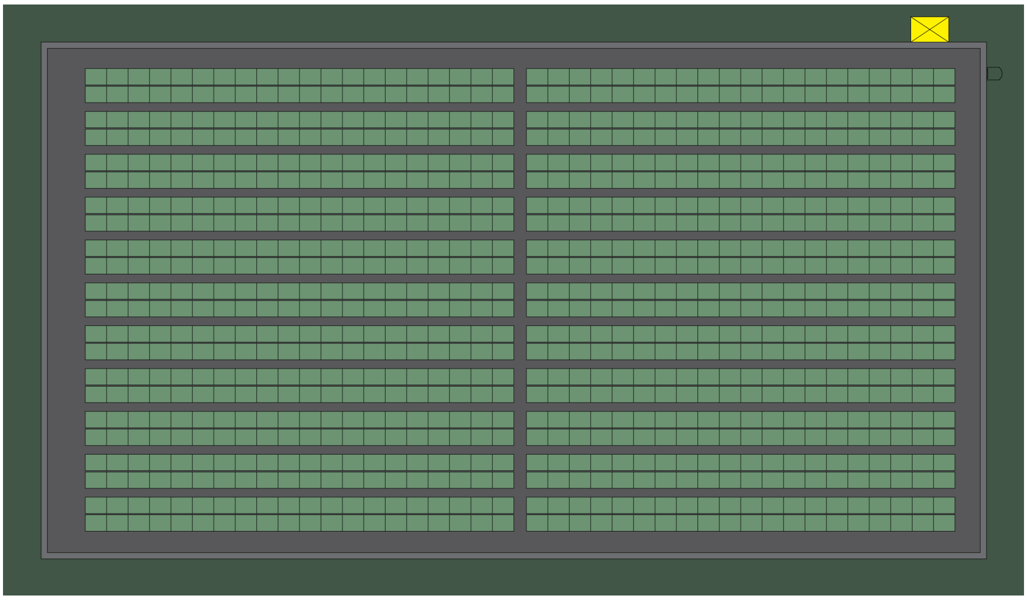

Figure 5.1: Rena Hav AB algae cultivation plant layout.

The water from the pisciculture is pumped from the ground level of the building to the roof with a CRN-150 model pump from the company Grundfos, which is a high pressure centrifugal pump. This specific pump was not only chosen as it fulfilled the required specifications of the project but also that the other pumps that are to be used in the pisciculture are from the same manufacturer. The pump is connected to the outlet of the particle separator or directly to the fish tanks and connected to a high pressure pipe that leads to the roof. An illustration of the connecting process between the fish tanks and the algae cultivation system can be viewed in Figure 5.2. On the roof, the pipe is connected to a water distributor pipe that connects 11 tubes. These tubes are then connected to a double tube separator resulting in 22 water inlet tubes that connect to the systems. The water outlet tubes are handled in the same fashion, through a set of tubes connecting to a pipe distributor and descending pipe back down to the ground floor.

By executing this plan, the following results are estimated to be achieved.

Table 5.1: Rena Hav AB Cultivation Plant Specification

Modules per system	20
Total amount of systems	22
Total amount of cultivation area	10181 [m^2]
Water in full cultivation plant	765 [m^3]
Water flow into system	144 [m^3/h]
Pump Model	CRN 150-1-1 A-F-G-E-HQQE

Each system can be equipped with the aforementioned harvesting system method by simply scaling the conveyor belt and motor after the size of the system. The resulting harvesting system would entail a collection of 220 rows of cultivation trays. The harvest is collected by a service operator. To keep an even nutrient depletion rate, the harvesting of the systems occurs in a rotational scheduled pattern to keep enough algae growing in the cultivation plant at all times. By request of SAF, no algae production rates are to be published in this report and therefore the resulting water nutrient depletion is not specified.

It is requested that the algae cultivation plant is built in stages, beginning with a single prototype module to ensure that the design accomplishes the needs of the product and can be installed and operated safely. As the plant is located on a roof there are certain safety restrictions that need to be adhered to. Upon validation of the prototype, a gradual or full ramp-up can be completed.

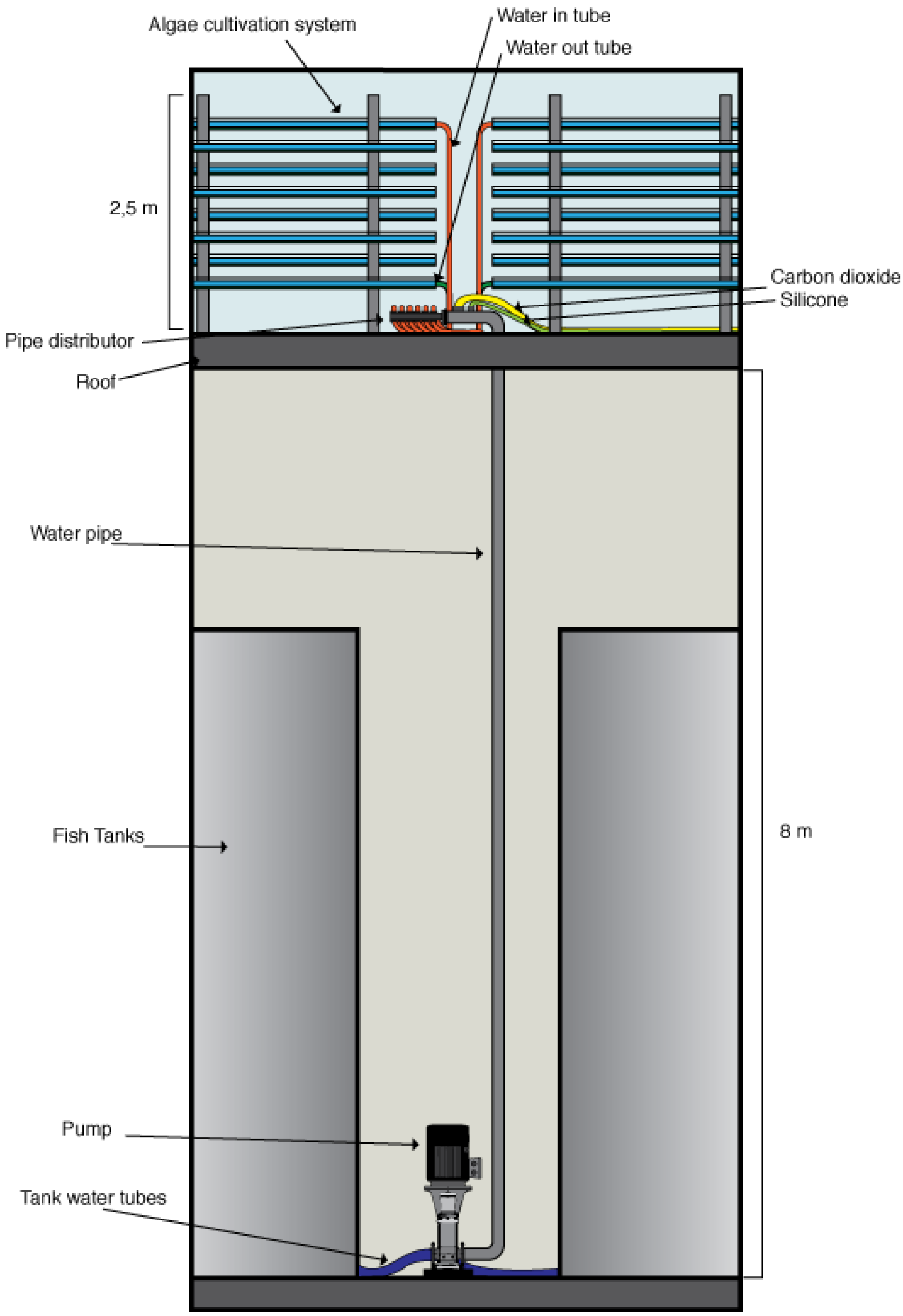

Figure 5.2: Rena Hav AB pisciculture connection depiction.

6
Discussion

Upon completion of the project, there are a couple of instances that are worth reflection.

6.1 Impact of the Maturity of the Company

As SAF is a relatively new company, there was limited long term data on the growth cycles and conditions of the specific algae and cultivation method that were applicable to this development project. Micro algae is a very complex product to work with as it is hard to pinpoint exact truths to either the algae or its growing conditions due to its size. Some of the data used in this project were estimations made by the algae researchers. Therefore there is a high likelihood that the calculations made during this project could vary when implemented in a physical product. Another attributing factor due to the maturity of the company is the need for flexibility in the product. As of yet, the company is still investigating all possible markets that could be interested customers of their product. This means that the system must be flexible to be able to cater to all possible end-users. Thus, certain design choices were attributed to this factor which could fault the final concept from being the most optimal design.

6.2 The Design Experiment

When it comes to the design experiment or prototype, there were a couple of inconsistencies in the handling of the subject matter which could have an attributing effect on the results. The harvesting was done by pulling a scrape along the bottom surface and collecting the biomass. The scrape was lifted along the back wall of the tray and tipped into a 50 ml centrifuge tube. It was difficult to collect all of the sample into the small tube without spilling. Therefore there could be some differences in the data collected and the actual growth. However, the spillage was minor and was deemed not to have had an impact on the comparative results between the trays. Unfortunately, during the weekend before the fourth harvest there was as problem with the water circulation in two of the trays. This caused one tray to dry out and one had a very low water flow rate, thus the algae ceased growing during that period. This impacted the data from that week tremendously. Therefore, it was decided to continue the experiment an additional week. There is a possibility that the failure caused unrepairable damage to the algae and the subsequent data collection had an impact.

During the usage of the prototype implemented in the experiment, a design choice of not having removable “doors” was made. This was a subjective judgement made while handling the trays during the harvest after the first and second harvest. There is no justifiable data to support this decision as the change was made permanent after the second harvest. Thus, this design choice could be subject to improvements. Finally, the experiment was only conducted during a period of five weeks. To achieve undeniable evidence from this type of experiment, it would need to continue over a longer period of time.

6.3 Design of the Final Product

During the concept refinement period, the concept that was being developed entailed implementing extremely long trays that would minimise the amount of modules needed in an entire system. This deemed to be difficult to validate the mechanics due to the stress factor of the weight of the water. Several plastic manufacturers and retailers were contacted to estimate a price for the construction. The unanimous response was that there is no way to construct trays with those dimensions. The standardised parts of PMMA that they work with are 2050 x 3050 mm so the only way to achieve a large tray would be to join the parts with adhesive. The joints would not be stable and the likelihood of fractures would be extremely high not to mention that the work and material would be extremely costly. Due to this feedback design changes were made to accommodate the manufacturing process and low cost requirement. In retrospect, the manufacturers and material experts should have been involved in the design process much earlier to ensure that the design was plausible to manufacture.

The vertical displacement on the edge of the console beam could possibly be seen as somewhat high and could cause an uneven water level. However, it should be noted that the calculation simulates a distributed force along the entire beam that displaces vertically along with the material. The trays that are the actual physical loads that the consoles will be exposed to are rigid bodies and will not follow the descent. Again, this is an imperative factor to test the in a prototype situation. If it is deemed that the vertical displacement causes an unsatisfactory cultivation environment, it is recommended that the UPE 80 be switched to a UPE 100 beam.

The target product specification was created in the beginning of the project and was set as an outline of the wished performance of the final product. The final product specification is a reflection of the actual performance of the final product. As expected, the target and final product specification differ on some points. The height of the product was targeted to be around 2 m, this was exceeded in the final product design to maximise the amount of algal growth area while allowing for harvesting upgrades. If this increase in height becomes a larger problem than is estimated at this point in the project, it can easily be altered by reducing the height of the H-beam and incorporating 8 trays instead of 10.

6.4 Automation Upgrades

A complete design of an automated harvesting system was initially part of the scope of the project but was then removed. Due to the large amount of uncertainties of the project, the design of the harvesting system was decided to be outsourced to automation professionals. The current harvesting system in the design is solely a proposed concept and not a complete design with validations and a control program. During discussions about the harvesting technique throughout the master thesis project, it was deemed that most appropriate method would be to scrape the trays and collect the biomass. Therefore the design of both the final concept and the design experiment was chosen from that information. This design needs to be validated in the future and possibly compared to other methods of harvesting.

7 Conclusion

This report has summarised the work done in a master thesis project for the company SAF. The following chapter will present the conclusions drawn during the project.

7.1 Concluding Remarks

The purpose of the product development project was to develop an industrial scale algae cultivation module that could be implemented in a commercial algae cultivation plant based on the existing lab scale module and customer needs. SAF are working on commercialising their company to be introduced on the industrial market. As SAF are still in the process of exploring their commercial market opportunities their final product must be able to cater to several different types of endeavours.

A pisciculture plant project that SAF entered into together with the company Rena Hav AB and the municipality of Sotenäs was used as a case study to give the project actual reference figures to help the design process. SAF's part in the project was to build an algae water treatment plant on the roof of the fish farm to purify the water from the nitrate, phosphorus and carbon dioxide created by the fish. Only a small portion of the entire amount of pollutants can be "cleaned" by the algae. However, the portion that is reduced by the algae will put less strain on the other denitrification processes. The project will also be able to serve as a demonstration plant for SAF to show potential investors and customers.

Initially, an automated harvesting system was part of the project but when further investigation was done, it was concluded together with the company that due to the enormity of the project, this would be outsourced to an external automation company. With the added level of uncertainty of the project, it was necessary for the product to be flexible and adaptable to all forms of automation solutions generated in the future. This had a large impact on the final design.

The redesign of the existing module to be applicable on an industrial scale took the form of a product platform. This was to be able to accommodate the various number of potential customers and end users of the product, along with an unknown harvesting system design. By building the system on a platform design it allowed for continual upgrades of the system and the initial product life time to be much longer. The basic platform consisted of an internal shelving structure with two load bearing support beams, a ground stabilisation connection and attachable consoles.

The cultivation trays were to be placed on the consoles and connected through PVC tubes for water circulation. The final module design creates an algae growing area of 23 m^2 on a ground surface area of 4,8 m^2 and holds up to 1,74 m^3 of water. All parts in the module were designed from industrial standardised parts to keep the cost as low as possible.

An experiment was conducted during the project to investigate different surface designs that promote the regeneration of algae after a harvesting process as well as boosting the total algal growth. The experiment also served as an opportunity to simulate a proposed harvest system method of scraping the trays in a control manor. The resulting dominant design will be implemented in the cultivation trays upon manufacturing.

On completion of the project, SAF have been provided with detailed drawings of the design, a manufacturing plan with proposed partnering companies, a complete cost analysis, the results of the experiment and an execution plan for the project together with Rena Hav AB.

7.2 Further Work

A great deal of knowledge was created during the project but for the project to be fully dimensioned, the following further work needs to be completed.

- Prototype - A full scale prototype needs to be built to ensure the validity of the designs and mechanical calculations.
- Automation of the harvesting system - The system design that was presented in this project was merely a concept design. The scrape method was tested in the experiment and validated to be effective. However, there was never any comparative data to be able to establish the best harvesting technique. If the proposed system is to be fully designed the following must be dimensioned.
  - Motor size
  - Mechanical gear system
  - Power supply
  - Automated collection system
- Monitoring and control system - For very large systems, a control and monitoring system will most likely be required to ensure a stable product.
- Continuation of experiment - The experiment was conducted during a period of five weeks. To be certain of the results the experiment should be carried on for a longer period of time.
- Additional lighting - An investigation into the appropriate lighting should be done to ensure that the right intensities are utilised.
- Greenhouse design - A large greenhouse must encapsulate the cultivation plant. Further dimensioning and design of said greenhouse must be conducted.
- Price negotiations - The cost analysis that was conducted and delivered to SAF did not include price negotiations. More affordable prices could possibly be achieved.

Bibliography

[1] Adey, W. H., (2010),"Algal Turf Scrubber (ATS), Algae to Energy Project: Cleaning Rivers while Producing Biofuels and Agricultural and Health Products", Progress Report to the Lewis Foundation, Smithsonian Institution.

[2] Prediction.algadisk.eu. (2016). Algadisk - Project. [online] Available at: http://prediction.algadisk.eu/project.

[3] Allaboutalgae.com, (2015). Algae Basics - Production Systems of Algae. [online] Available at: http://allaboutalgae.com/open-pond/ [Accessed 3 Jul. 2015].

[4] Allaboutalgae.com, (2015). Algae Basics - Production Systems of Algae. [online] Available at: http://allaboutalgae.com/closed-system/ [Accessed 3 Jul. 2015].

[5] Andreasen, M. M., 1980, Machine design methods based on systematic approach contribution to design theory, Doctoral Thesis, Lund University, Sweden.

[6] Bergman, B. and Klefsjö, B. (2010). Quality. Lund: Studentlitteratur.

[7] CES Edupack. (2015). Cambridge, UK: Granta Design.

[8] Dugdale, T., Dagastine, R., Chiovitti, A. and Wetherbee, R. (2006). Diatom Adhesive Mucilage Contains Distinct Supramolecular Assemblies of a Single Modular Protein. Biophysical Journal, 90(8), pp.2987-2993.

[9] Griffee, D.T. 2005, "Research Tips: Interview Data Collection", Journal of Developmental Education, vol. 28, no. 3, pp. 36-37.

[10] Hedblom, M. (2015). Stakeholder Interview.

[11] Herling, R. W., Weinberger, L. and Harris, L. (2000), “Case Study Research: Defined for Application in the Field of HRD”, St. Paul, University of Minnesota, Human Resource Development Research Centre.

[12] Lundh, H. (2000). Grundläggande hållfasthetslära. Stockholm: Institutionen för hållfasthetslära, Tekniska högsk.

[13] Lupton, E (ed.) 2011, Graphic Design Thinking : Beyond Brainstorming, Princeton Architectural Press, New York, NY, USA. Available from: ProQuest ebrary.

[14] Pahl, G. Beitz, W., (1996) “Engineering Design, a Systematic Approach”, 2nd English Edition, Springer-Verlag, Berlin, Germany

[15] Pugh, S. (1990). Integrated methods for successful product engineering. New Jersey: Addison-Wesley.

[16] Robson, C. (1998). Real World Research: A resource for social scientists and practitioner-researchers. Oxford: Blackwell.

[17] Sapphireenergy.com. (2015). Algae Farm. [online] Available at: http://www.sapphireenergy.com/locations/green-crude-farm.html [Accessed 3 Jul. 2015].

[18] SAF-website, (2015). saf-website. [online] Available at: http://www.swedishalgaefactory.com/!firm/c1n8o [Accessed 15 Jun. 2015].

[19] Simrisalg.se. (2016). What we do | Simris – Algae farmed, grown and harvested in Sweden. [online] Available at: http://simrisalg.se/en/what-we-do/ [Accessed 4 Jul. 2015].

[20] Tripathy, MR 2009, 'Case Methodology in Teaching and Research: A Critical Review', Indian Journal Of Industrial Relations, 44, 4, pp. 660-671, Business Source Premier, EBSCOhost

[21] Ulrich, K. and Eppinger, S. (2012). Product design and development. New York: McGraw-Hill/Irwin.

[22] Wallgren, P. (2014). Qualitative methods: Data collection.

[23] Wheelwright, S. and Clark, K. (1992). Revolutionizing product development. New York: Free Press.

[24] Zwicky, F., (1966) "Entdecken, Erfinden, Forschen im Morphologischen Weltbild" (Explore, Invent, Research in the Morphological Perspective) (in German), Droemer-Knaur, München

A
Appendix

Interpreted Needs	Index	Frequency	Total Frequency
Modulen främjar optimala ljus förhållanden. !!	1	2	9
Modulen är anpassad för reglering av ämnen och tester. !!	2	1	4
Modulen/Anläggning är anpassad för ett flertal industriell tillämpningar. !	3	3	10
Modulen är anpassad för effektiv vatten hantering. !!	4	1	4
Modulen ökar produktionen av alger. !!!	5	2	4
Anläggningen minimerar kontamination. !!	6	1	4
Anläggningen är anpassad för ett övervakning och regleringssystem. !!	7	2	6
Modulen är anpassad för modulär uppskalning. !!!	8	2	3
Modulen främjar produktion av biofilm. !!!	9	3	4
Modulen är utformade för maximal yteffektivitet. !!!	10	2	6
Anläggningen är lätt att sköta. !!	11	2	5
Anläggningen kontrollerar gasutbytet. !!	12	2	3
Modulen är anpassad för en jämn tillförsel av vatten. !!	13	1	1
Anläggningen främjar optimala ljus och temperatur förhållanden. !!	14	1	1
Modulen/Anläggningen är energieffektiv. !!	15	1	1
Modulen främjar en jämn ljusspridning. !!	16	2	2
Anläggningen minimerar avdunstning. !!	17	2	3
Modulen främjar upptag av ämnen. !!	18	1	1
Modulen är anpassad för att hålla algerna i exponentiell tillväxt. !!!	19	1	5
Modulen håller en optimal temperatur. !!	20	1	2
Modulen främjar reglering av parametrar. !!	21	1	2
Modulen främjar en jämn tillförsel av näringsämnen. !!	22	1	1
Modulen är anpassad för maximal användning av naturligt solljus. !!	23	1	1
Modulen är anpassad för *alg namnet.!!*	24	1	7
Anläggningen är anpassad för tillförsel av diverse ämnen vid behov. !	25	1	3
Anläggningen är kostnadseffektivit. !!!	26	1	2
	27	1	2
Modulen är skalad till volymen av vatten tillförseln. !	28	1	2
Skördningen stör inte den expontentiella tillväxt fasen. !!!	29	1	1
Modulen främjar upptag av fosfor. !!	30	1	1
Anläggningen är anpassad för ett effektivt vatten flöde. !!	31	1	1
Anläggningen är tålig för höga halter saltvatten. !!	33	1	1
Anläggningen håller en viss temperatur på vattnet. !!	34	1	1
Anläggningen förser algerna med rätt mängd ljus. !!	36	1	1
Monteringen ska kunnas göras av en tredje part. !	37	1	1
Modulen främjar övervakningssystem och tester. !!	38	0	2
Modulen främjar reglering och tester. !!	39		1
		Sum:	108

Figure A.1: Combined Customer Needs Statements.

	Need	Frequency	Weight
A.	**ANLÄGGNINGEN FRÄMJAR TILLVÄXT AV ALGER OCH UPPTAG AV ÄMNEN. !!!**	**37**	**5**
1	Modulen är anpassad för att hålla algerna i exponentiell tillväxt. !!!	5	5
2	Modulen ökar produktionen av alger. !!!	4	5
3	Modulen främjar produktion av biofilm. !!!	4	5
4	Skördningen stör inte den expontentiella tillväxt fasen. !!!	1	5
5	Anläggningen minimerar kontamination. !!	4	3
6	Anläggningen kontrollerar gasutbytet. !!	3	3
7	Anläggningen är tålig för höga halter saltvatten. !!	1	3
8	Modulen främjar en jämn tillförsel av näringsämnen. !!	1	2
9		2	4
10	Modulen främjar upptag av ämnen. !!	2	4
11	Anläggningen är anpassad för tillförsel av diverse ämnen vid behov. !	3	3
12	Modulen är anpassad för *algen!!*	7	1
B.	**MODULEN HAR EN YTEFFEKTIV MODULÄR DESIGN. !!!**	**19**	**5**
1	Modulen är utformade för maximal yteffektivitet. !!!	6	5
2	Modulen är anpassad för modulär uppskalning. !!!	3	5
3	Modulen/Anläggning är anpassad för ett flertal industriell tillämpningar. !	10	3
C.	**ANLÄGGNINGEN ÄR ANPASSAD FÖR ETT ÖVERVAKNING OCH REGLERINGSSYSTEM. !!**	**15**	**4**
1	Anläggningen är anpassad för ett övervakning och regleringssystem. !!	6	4
2	Modulen är anpassad för reglering av ämnen och tester. !!	9	4
D.	**MODULEN FRÄMJAR OPTIMALA LJUS FÖRHÅLLANDEN. !!**	**14**	**4**
1	Modulen främjar optimala ljus förhållanden. !!	10	4
2	Modulen främjar en jämn ljusspridning. !!	2	3
3	Modulen är anpassad för maximal användning av naturligt solljus. !!	1	3
4	Anläggningen främjar optimala ljus och temperatur förhållanden. !!	1	3
E.	**MODULEN ÄR ANPASSAD FÖR ETT EFFEKTIVT FLÖDE. !!**	**11**	**3**
1	Modulen är anpassad för effektiv vatten hantering. !!	4	4
2	Anläggningen minimerar avdunstning. !!	3	3
3	Anläggningen är anpassad för ett effektivt vatten flöde. !!	1	3
4	Modulen är anpassad för en jämn tillförsel av vatten. !!	1	3
5	Modulen är skalad till volymen av vatten tillförseln. !	2	2
F.	**HANTERINGEN AV ANLÄGGNINGEN ÄR LÄTT ATT SKÖTA. !!**	**5**	**5**
1	Anläggningen är lätt att sköta. !!	5	5
G.	**UPPBYGGNAD AV EN ANLÄGGNING ÄR ENKEL OCH KOSTNADSEFFEKTIVT. !!!**	**4**	**3**
1	Anläggningen är kostnadseffektivit. !!!	2	4
2	Modulen/Anläggningen är energieffektiv. !!	1	3
3	Monteringen ska kunnas göras av en tredje part. !	1	2
H.	**ANLÄGGNINGEN HÅLLER EN OPTIMAL TEMPERATUR. !!**	**3**	**4**
1	Modulen håller en optimal temperatur. !!	2	4
2	Anläggningen håller en viss temperatur på vattnet. !!	1	4

Figure A.2: Categorised Customer Needs Statements.

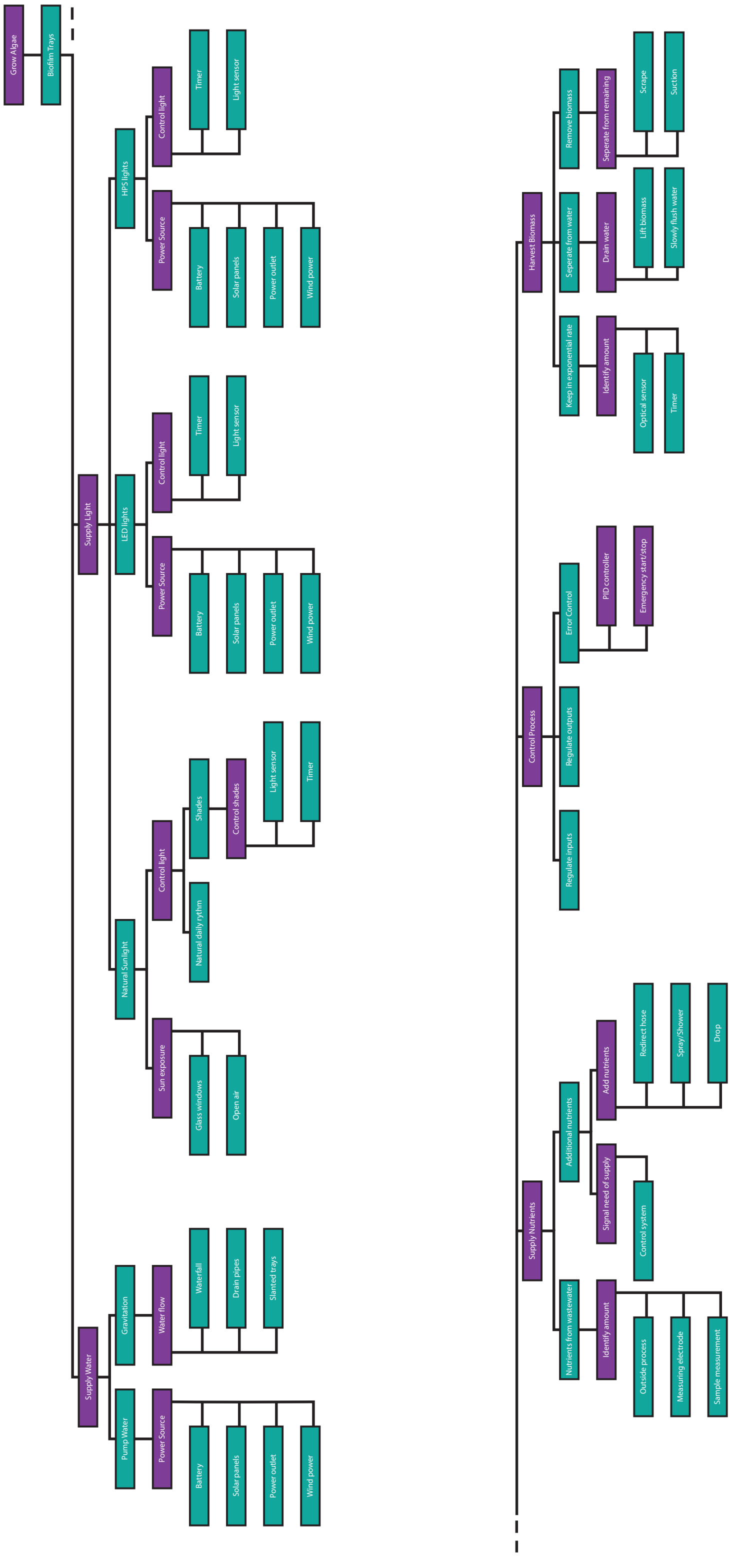

Figure A.3: Function-Means Tree.

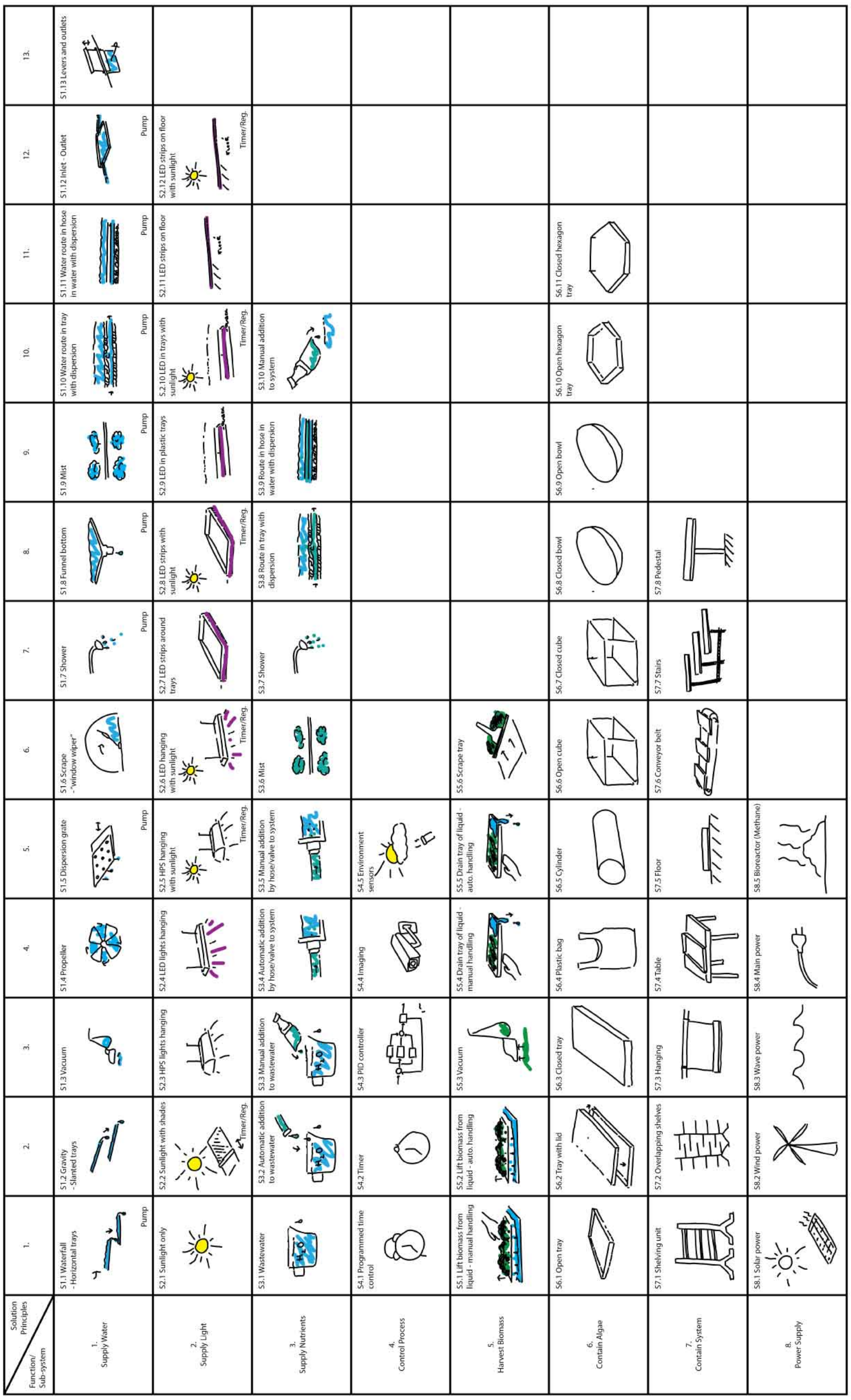

Figure A.4: Morphological Matrix.

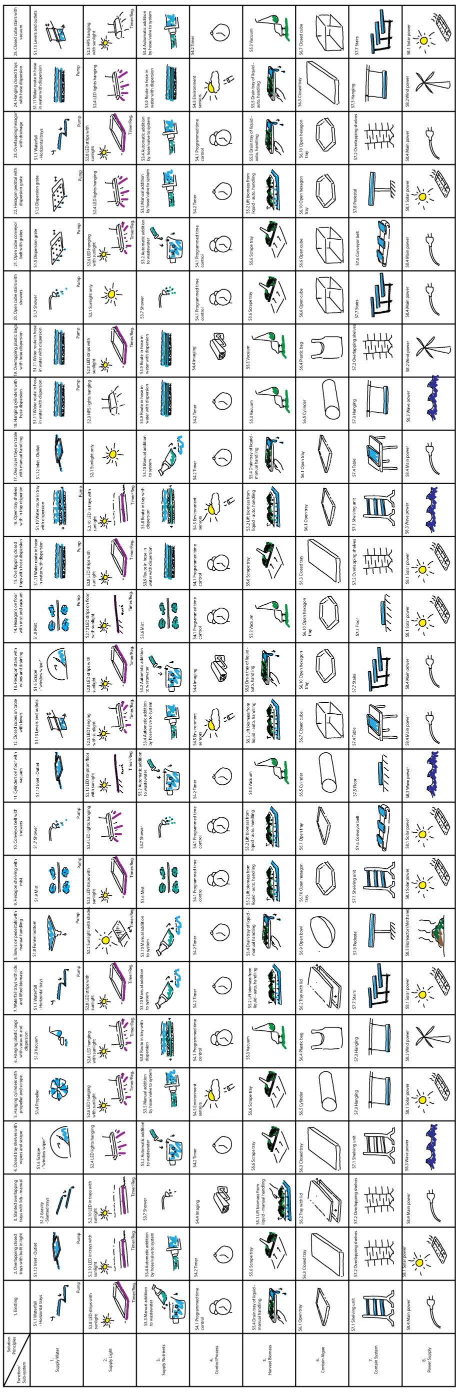

Figure A.5: Morphological Concept Combination Matrix.

Pugh Matrix

#	Criteria	Concepts						
		Existing	Overlapping closed trays	Slanted trays	Waterfall trays	Hexagon stairs	Hose distribution	In-tray distribution
1	Modulen är anpassad för att hålla algerna i exponentiell tillväxt.	0	+	0	0	0	+	+
2	Modulen främjar produktion av biofilm.	0	-	0	0	0	-	+
3	Skördningen stör inte den expontentiella tillväxt fasen.	0	-	0	0	-	-	0
4	Anläggningen minimerar kontamination.	0	+	0	0	0	+	+
5	Modulen främjar en jämn tillförsel av näringsämnen.	0	+	+	+	+	+	+
6	Modulen är utformade för maximal yteffektivitet.	0	0	0	0	0	0	0
7	Modulen är anpassad för modulär uppskalning.	0	0	0	-	-	0	0
8	Modulen/Anläggning är anpassad för ett flertal industriell tillämpningar.	0	+	0	0	0	+	+
9	Anläggningen är anpassad för ett övervakning och regleringssystem.	0	+	+	+	+	+	+
10	Modulen är anpassad för reglering av ämnen och tester.	0	+	+	+	+	+	+
11	Modulen främjar optimala ljus förhållanden.	0	0	-	+	-	0	0
12	Modulen är så lätt som möjligt.	0	0	0	0	0	0	0
13	Modulen är anpassad för maximal användning av naturligt solljus.	0	+	-	+	+	+	+
14	Anläggningen är lätt att sköta.	0	-	0	-	-	-	-
15	Anläggningen är kostnadseffektivit.	0	-	-	-	-	-	-
16	Modulen/Anläggningen är energieffektiv.	0	-	0	0	0	-	-
17	Modulen håller en optimal temperatur.	0	0	0	0	0	0	0
	Sum +'s:	0	7	3	5	4	7	8
	Sum 0's	17	5	11	9	8	5	6
	Sum -'s	0	5	3	3	5	5	3
	Net Score	0	2	0	2	-1	2	5
	Rank	5	2	4	3	6	2	1

Matrix.pdf

Figure A.6: Pugh Matrix.

Final Product Specification

No	Part	Metric	Unit	Value
	Technical			
1	Tray	Length	m	1,78
2		Width	m	1,3
3		Total mass	kg	20,436
4		Material	PMMA	
5		Yield strength	MPa	2,9
6		Maximum water volume	m^3	0,174
7		Maximum Algae growth area	m^2	2,834
8		Maximum material displacement due to load bearing	mm	0,042
9		Maximum material stress due to load bearing	MPa	0,168
10	Construction	Module height	m	2,85
11		Console length	m	1,350
12		Console weight	kg	11,07
13		Support beam weight	kg	44,7
14		Foot weight	kg	9,6
15		Material - Console	Fe 0,1%C with zinc coating	
16		Material - Support Beam	Fe 0,1%C with zinc coating	
17		Material - Foot	Fe 0,1%C with zinc coating	
18		Material - Support Rod	Fe 0,1%C with zinc coating	
19		Material - Nuts and Bolts	Stainless Steel	
20		Console yield strength (Steel)	MPa	300
21		Area module	m^2	4,806
22		Maximum material displacement due to load bearing- Console	mm	0,33
23		Maximum material stress due to load bearing - Console	MPA	3,427
24		Support beam yield strength (Steel)	MPa	300
25		Total mass - structure 10 levels	kg	330
26		Total mass per m^2	kg	68,664
27	Process	Material - Tube	PVC	
28		Water in flow rate	L/h	320
29		Water flow rate - tray	L/h	32
30		Water in tube length	m	> 5
31		Water out tube length	m	> 5
32		Water between trays tube length	m	0,6
33	Whole	Estimated cost of module	SEK	
34		Total mass platform - empty (no harvesting system)	kg	534,36
35		Total mass per m^2 - empty	kg/m^2	111,186
36		Total mass platform - with water and algae (no harvesting system)	kg	2269,86
37		Total mass per m^2 - with water and algae	kg/m^2	472,3
	Operational			
38	Tray	Material resistance to Hydrogen Peroxide	Excellent	
39	Structure	Material resistance to Hydrogen Peroxide	Accepatable	
40	Whole	Product life	Year	10
41		Ease of use	subj.	5
42		Instills pride	subj.	4
43		Room temperature estimation	C	13
	Harvesting Proposal			
44	Harvest system	Maximum weight displacement	kg	
45		Motor output	kW	250
46		Transversal force	N	
47		Harvest time	s	300

Figure A.7: Final Product Specification.

Failure Mode & Effect Analysis - Generation 1 & 2

System	Algae Cultivation and Harvesting System	**Company**	Swedish Algae Factory
Prepared by	Karin Dankis	**Date**	03/03/2016
Approved by	Justin Pearce	**Date**	18/03/2016

Item	Part No	Function or Process	Failure mode	Effect of failure	Cause of failure	Current status				Recommended corrective action	Action by	Action taken	Revised Status			
						OCC	SEV	DET	RPN				OCC	SEV	DET	RPN
1	A1	Cultivation of algae	Crack	Leakage	Manufacturing fault	4	5	3	60	Test trays by filling with water before use	Manufacturer	No	3	5	3	45
2			Deformation	Uneven growth	Material fault	6	3	3	54	Prototype test	SAF	No	4	3	3	36
3			Scratch	Collection of algae	Handeling fault	6	2	4	48	Prototype test	SAF	No	4	2	4	32
4			Crack	Leakage	Handeling fault	4	5	2	40	Prototype test	SAF	No	3	5	2	30
5	A2	Collection of harvest	Crack	Leakage	Handeling fault	3	2	1	6	Prototype test	SAF	No	2	2	1	4
6			Scratch	Collection of algae	Handeling fault	4	2	1	8	Prototype test	SAF	No	2	2	1	4
7			Deformation	Unstable coupling	Material fault	4	4	1	16	Prototype test	SAF	No	2	4	1	8
8	B1	Support/carry trays	Downward Deformation	Uneven growth	Design not robust enough	6	6	3	108	Stress test/Further simulation and dimensioning	Manufacturer	No	2	6	3	36
9			Downward Deformation	Crack in coupling to H-track	Design not robust enough	6	7	3	126	Stress test/Further simulation and dimensioning	Manufacturer	No	2	7	3	42
10			Loose coupling	Uneven growth	Manufacturing fault	7	7	3	147	Design Change	Master Thesis Student	Yes	3	7	3	63
11			Uneven contact surface	Unstable trays/ damage trays	Material fault	6	5	2	60	Silicon covering to stabilise	Master Thesis Student	Yes	2	5	2	20
12	B2	Support/carry consoles	Crack	Coupling gap	Design not robust enough	5	7	3	105	Stress test/Further simulation and dimensioning	Manufacturer	No	3	7	3	63
13			Deformation/Bend in track	Uneven growth	Design not robust enough	2	7	3	42	Stress test/Further simulation and dimensioning	Manufacturer	No	1	7	3	21
14			Deformation	Collapse of module	Design not robust enough	2	8	2	32	Stress test/Further simulation and dimensioning	Manufacturer	No	1	8	2	16
15			Gap in coupling	Unstability	Manufacturing fault	7	7	3	147	Design Change	Master Thesis Student	Yes	3	7	3	63
16	B3	Support/carry track	Gap in coupling	Unstability	Manufacturing fault	4	5	3	60	Prototype test	SAF	No	3	5	3	45
17			Deformation	Uneven growth	Design not robust enough	2	5	3	30	Prototype test	SAF	No	1	5	3	15
18			Deformation	Collapse of module	Design not robust enough	2	8	3	48	Prototype test	SAF	No	1	8	3	24
19	B5	Stabilise Structure	Deformation	Uneven growth	Design not robust enough	4	5	3	60	Prototype test	SAF	No	2	5	3	30
20			Unstable	Uneven growth	Manufacturing fault	5	5	4	100	Prototype test	SAF	No	3	5	4	60
21			Crack	Unstability	Material fault	5	7	3	105	Prototype test	SAF	No	2	7	3	42
22	C1	Remove biomass from trays	Crack	Uneven harvest	Material fault	6	7	4	168	Prototype test	SAF	No	2	7	4	56
23			Deformation	Uneven harvest	Material fault	5	7	4	140	Prototype test	SAF	No	2	7	4	56
24			Crack	Uneven harvest	Handeling fault	3	5	3	45	Prototype test	SAF	No	2	5	3	30
25	C2	Hold Scraper	Crack	Uneven harvest	Material fault	3	5	2	30	Prototype test	SAF	No	2	5	2	20
26			Deformation	Uneven harvest	Material fault	2	5	2	20	Prototype test	SAF	No	1	5	2	10
27	C3	Connect Scraper to arm	Crack	Unstable coupling	Material fault	3	5	2	30	Prototype test	SAF	No	2	5	2	20
28			Crack	Unstable coupling	Design not robust enough	3	4	3	36	Prototype test	SAF	No	2	4	3	24
29	C4	Lower Rotation of Scraper	Stiff joint	Reduced functionalilty	Debris accumultion	6	3	3	54	Prototype test	SAF	No	4	3	3	36
30			Stiff joint	Reduced functionalilty	Manufacturing fault	4	3	3	36	Prototype test	SAF	No	2	3	3	18
31			Stiff joint	Reduced functionalilty	Handeling fault	3	3	1	9	Prototype test	SAF	No	2	3	1	6
32			Crack	Unstability	Material fault	5	5	2	50	Prototype test	SAF	No	4	5	2	40
33			Crack	Unstability	Design not robust enough	4	6	2	48	Prototype test	SAF	No	3	6	2	36
34	C5	Upper Rotation of Scraper	Stiff joint	Reduced functionalilty	Debris accumultion	6	4	3	72	Prototype test - Handeling method	SAF	No	3	4	3	36
35			Stiff joint	Reduced functionalilty	Manufacturing fault	3	3	3	27	Prototype test	SAF	No	1	3	3	9
36			Stiff joint	Reduced functionalilty	Handeling fault	2	3	2	12	Prototype test	SAF	No	1	3	2	6
37			Crack	Unstability	Material fault	4	6	3	72	Prototype test	SAF	No	2	6	3	36
38			Crack	Unstability	Design not robust enough	5	7	3	105	Prototype test	SAF	No	2	7	3	42
39	C8	Guide Scraper	Crack	Unstability	Design not robust enough	4	7	2	56	Prototype test	SAF	No	2	7	2	28
40			Crack	Unstability	Material fault	3	7	2	42	Prototype test	SAF	No	1	7	2	14
41			Gap in coupling	Unstable coupling	Manufacturing fault	4	4	3	48	Prototype test	SAF	No	1	4	3	12
42			Gap in coupling	Unstable coupling	Design not robust enough	3	4	3	36	Prototype test	SAF	No	1	4	3	12
43			Tear	Collapse of system	Design not robust enough	5	8	3	120	Prototype test	SAF	No	2	8	3	48
44			Tear	Collapse of system	Material fault	4	8	3	96	Prototype test	SAF	No	1	8	3	24

Figure A.8: FMEA Part 1.

System	Algae Cultivation and Harvesting System	**Company**	Swedish Algae Factory
Prepared by	Karin Dankis	**Date**	03/03/2016
Approved by	Justin Pearce	**Date**	18/03/2016

Item	Part No	Function or Process	Failure mode	Effect of failure	Cause of failure	Current status				Recommended corrective action	Action by	Action taken	Revised Status			
						OCC	SEV	DET	RPN				OCC	SEV	DET	RPN
45	C10	Drive scraper arm	Tear	Collapse of system	Inaccurate dimensioning	6	8	4	192	Prototype test	SAF	No	2	8	4	64
46			Crack	Reduced functionalilty	Erosion of material	6	8	3	144	Prototype test	SAF	No	3	8	3	72
47			Stuck	Reduced functionalilty	Debris accumultion	7	4	3	84	Prototype test - Handeling method	SAF	No	3	4	3	36
48	C11	Drive conveyor belt	Stuck	Reduced functionalilty	Debris accumultion	7	3	3	63	Prototype test - Handeling method	SAF	No	4	3	3	36
49			Stuck	Reduced functionalilty	Inaccurate dimensioning	5	4	3	60	Prototype test	SAF	No	2	4	3	24
50			Crack	Reduced functionalilty	Design not robust enough	3	5	5	75	Prototype test	SAF	No	2	5	5	50
51	C12	Stabilise conveyor belt	Stuck	Reduced functionalilty	Debris accumultion	6	3	4	72	Prototype test - Handeling method	SAF	No	4	3	4	48
52			Stuck	Reduced functionalilty	Inaccurate dimensioning	6	6	3	108	Prototype test	SAF	No	2	6	3	36
53			Crack	Reduced functionalilty	Design not robust enough	3	5	5	75	Prototype test	SAF	No	1	5	5	25
54	C131,132, 133	Connect Harvest system to structure	Crack	Unstable coupling	Design not robust enough	5	6	4	120	Prototype test	SAF	No	2	6	4	48
55			Crack	Unstable coupling	Manufacturing fault	4	6	4	96	Prototype test	SAF	No	2	6	4	48
56			Deformation	Uneven harvest	Design not robust enough	3	5	3	45	Prototype test	SAF	No	1	5	3	15
57			Deformation	Uneven harvest	Material fault	2	5	3	30	Prototype test	SAF	No	1	5	3	15
58	D1,2,3	Water Process	Clog	Rupture	Debris accumultion	8	7	4	224	Prototype test	SAF	No	5	7	4	140
59			Crack	Leakage	Handeling fault	6	5	3	90	Prototype test	SAF	No	3	5	3	45
60			Crack	Leakage	Material fault	4	5	3	60	Prototype test	SAF	No	2	5	3	30
61	D4	Connect tube to tray	Clog	Reduced functionalilty	Debris accumultion	8	7	3	168	Prototype test	SAF	No	4	7	3	84
62			Clog	Reduced functionalilty	Design not robust enough	5	6	4	120	Prototype test	SAF	No	2	6	4	48
63			Crack	Leakage	Inaccurate dimensioning	4	5	3	60	Prototype test	SAF	No	2	5	3	30
64			Crack	Leakage	Material fault	3	5	3	45	Prototype test	SAF	No	1	5	3	15
									0					0	0	0

Figure A.9: FMEA Part 2.