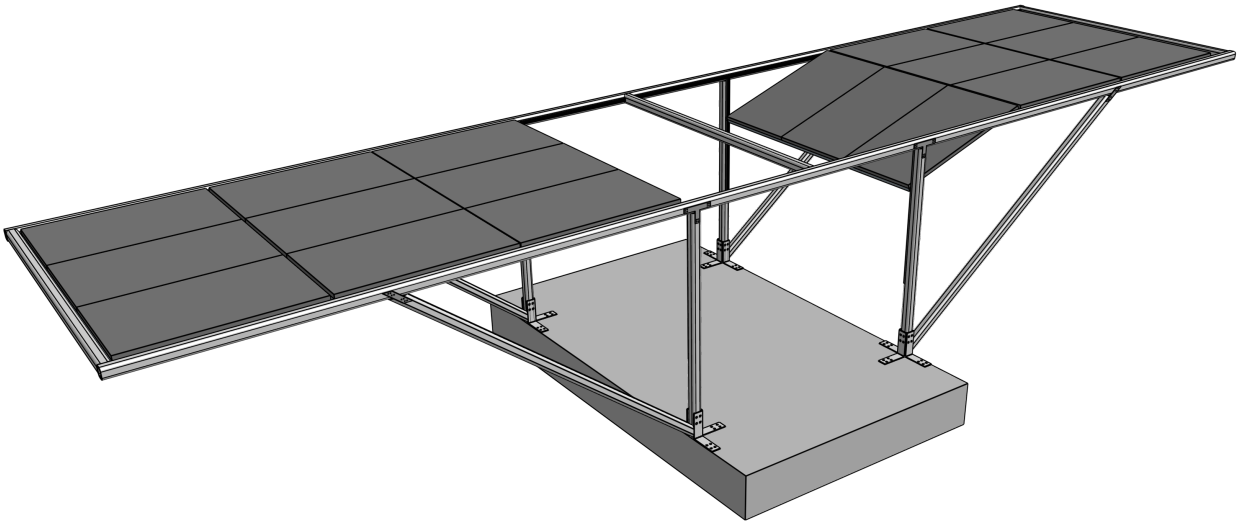

Research and Development of a Solar Wharf Garage

Collaboration between Chalmers, Penn State & Volvo Penta

Bachelor's thesis MMSX20-20-05

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Cover: CAD model of the final concept of the Solar Wharf Garage designed in OnShape (2020) by Gustaf Malmsjö.

Gothenburg, Sweden 2020

Abstract

The growing electrification of leisure boats has engendered the need for accessible marine charging stations. Since many marinas lack the infrastructure necessary to accommodate large numbers of electric boats, local charging solutions are required. This project was to feature the iterative design of an electric boat charging structure with photovoltaic systems, in this project called Solar Wharf Garage, that could be implemented into existing marinas. The overall objective was to generate a creative and feasible solar wharf garage design supported by objective engineering analysis. This required extensive research of electric boats, photovoltaic systems, wharf design, and material selection.

Initially, the most important customer needs were gathered from the client Volvo Penta, including boat power requirements, modularity expectations, and environmental resilience. To begin research, site visits were conducted to marinas and solar energy system providers, that gathered information on marina layouts and commercial solar systems. Thereafter, functional requirements were generated followed by a list of 12 engineering specifications based on the customer needs and literature review. In the concept generation phase, the team iteratively created 30 concepts to address each functional requirement and evaluated these concepts to understand their limitations and explore possible solutions. The performance of each concept was ranked in a Pugh matrix relative to a standard Swedish boathouse and later a generated concept. The highest scored concepts were then evaluated in a Kesselring Matrix relative to an ideal performance for each functional requirement. With only one remaining concept, the work continued in focus groups to develop the different subsystems of the final design.

The expected solar panel efficiency was simulated using the System Advisor Model (SAM) software in order to find the energy output capabilities of the system as well as the photovoltaics' financial feasibility. A thorough mechanical analysis of the design was also completed to calculate the expected applied stress on the garage structure with the chosen aluminum alloy 6061-T6 AA. Lastly, evaluation were done regarding the expected success of the final concept in satisfying the original 12 engineering specifications. The resulting design is a two-boat-garage that generates sufficient electric energy for weekly outings - approximately 5.074 kWh annually. The photovoltaic system design uses two 9-panel strings, mounted flat, with each string of panels wired in series to one grid-tied inverter. The solar panels of the system can be retracted towards the dock for maintenance, removal, or off-season storage. Any excess electricity is fed back into the grid in exchange for credits, which reduce future electricity payments. The payback period of the photovoltaic system is approximately 13 years, which is roughly half of its estimated product lifespan.

Sammandrag

Den växande elektrifieringen av fritidsbåtar har skapat ett ökat behov av laddningsmöjlighter i småbåtshamnar. Eftersom många marinor saknar den infrastruktur som krävs för att tillgodose laddningsbehovet hos ett större antal elektriska båtar krävs mer lokala lösningar. Denna rapport beskriver en iterativ utvecklingsprocess för att ta fram ett solcellsladdat båtgarage, benämnt som the Solar Wharf Garage, som ska kunna implementeras i marinor. Det övergripande syftet med projektet var att skapa ett kreativt och genomförbart Solar Wharf Garage koncept med stöd av en objektiv teknisk analys. Detta krävde bakgrundsundersökning kring elektriskt drivna båtar, solenergisystem, marinor och korrosionsbeständiga material.

De viktigaste kundbehoven gavs av uppdragsgivaren Volvo Penta, och innefattade strömkrav, modularitetsförväntningar och hållbarhet ur olika aspekter. Studiebesök till småbåtshamnar samt leverantörer av solenergisystem genomfördes för att samla information om marina layouter och kommersiella system för solenergi. Därefter fastställdes funktionskrav och en lista med 12 tekniska specifikationer baserade på behoven efter utförd undersökning. I konceptgenereringsfasen skapades iterativt 30 koncept för att med olika metoder uppfylla samtliga funktionskrav. Dessa utvärderades för att synliggöra begränsningar och utforska realiserbara lösningar. Prestandan för varje koncept rankades i Pugh-matriser i förhållande till ett svenskt traditionellt båthus och senare ett av de mer framstående framtagna koncepten. De högst rankade koncepten evaluerades sedan i en Kesselring-matris. Där utväderades de relativt en ideal prestanda för varje funktionskrav. När ett vinnande koncept identifierats, delades projektet in i fokusgrupper för att utveckla delsystemen av den slutgiltiga designen.

Solenergisystemet simulerades med hjälp av programvaran System Advisor Model (SAM) för att utvärdera modulernas totala elproduktion och systemets ekonomiska genomförbarhet. En mekanisk analys av konstruktionen genomfördes för att beräkna den förväntade påkänningen på garagestrukturen med den valda aluminiumlegeringen 6061-T6 AA. Slutligen utvärderades det slutliga konceptet med avseende på kravspecifikationerna. Designen är ett tvåbåtsgarage som genererar cirka 5 074 kWh årligen. Solenergisystemet är monterat i två strängar (en per båtplats) med nio paneler envar. Varje sträng av paneler är seriekopplat till en elnätsuppkopplad växelriktare dit även båtens batteri kopplas. Systemets solpaneler kan dras tillbaka till bryggan för underhåll eller säsongsförvaring. Återbetalningsperioden för systemet är ungefär 13 år, vilket är drygt hälften av dess beräknade produktlivslängd på 25 år.

Acknowledgments

Throughout the project, the team has had help from several additional sources. We would like to thank everybody involved in this thesis. Thanks to Herbert and Karin Jacobssons Foundation, for giving the team an opportunity to meet in the United States, for which we are very grateful. Thanks to Seth Larsson at Gothia Solenergi and the people working at Öckerö Marina for giving us of their time and providing their knowledge and experience.

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Gothenburg, May 2020
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1 Introduction

With the present environmental crisis and growing pollution, a reduction in CO_2 levels is needed to mitigate environmental problems connected to the greenhouse effect. New, more sustainable, innovations are essential to achieve this mitigation while maintaining a progressive society. The electrification of the marine industry has already started to compete with the traditional internal combustion powertrain for ships and ferries. In recent years, the market of electrical leisure boats has increased and can now be found in different segments. While these boats offer a way to more sustainably enjoy the sea, they present new challenges for boat owners and marinas regarding the increased power demand.

This project was aimed to provide a concept of supplying an electric leisure boat with sufficient power through implementing a solar wharf design in the marina. To what degree the electric boat is more environmentally friendly than a conventional one is essentially due to how sustainable the power source is. Solar power is easily harnessed using solar panels in the marina and in this project the panels are also aimed to provide beneficial climatic protection for a boat.

The project group consisted of students from both Chalmers University of Technology and Penn State University (PSU). In the Chalmers team there were three Mechanical Engineering students and one Automation & Mechatronics Engineering student, whereas the four Penn State students represented majors of Mechanical Engineering and Energy Engineering. The students have worked closely together to develop a solar wharf garage. Volvo Penta has been the project client, and will potentially proceed with further development. During the project, the students from Chalmers and Penn State generated numerous concepts and performed an objective elimination process.

1.1 Background

Batteries in electrical boats can either be charged by a power source on the vessel, which usually has a relatively low power rating, or by a power source in the marina. So far, boats are yet to draw advantage of an effective way to regenerate power during propulsion. Therefore they have limited possibilities to charge their batteries during usage. This puts a big strain on the marinas to provide a large proportion of the required power for boats' electrical need.

The transition from internal combustion engines to electric motors needs to be convenient for today's boat owners to effectively allow continued development towards sustainable boating. Most marinas offer electrical charging from three-phase (400 V) outlets, however, this may not be sustainable in the future for a fully electric boat segment unless the generated electricity is renewable. To enable development of electrical marine vessels, innovative and cost-effective solutions are needed. The coast provides great opportunities for collecting solar energy, with large open spaces and a heightened efficiency due to the reflective abilities of water. Using this potent power source and at the same time preserving the coast environment provides challenges in aesthetics and construction.

The financial cost for photovoltaic power is today less expensive than any fossil-fuels option, even without financial assistance (IRENA, 2019). If properly installed and given the proper maintenance a lifespan of 25-30 years can be expected (energysage, 2019). Many sailboats already use solar panels for supporting the battery charging. Their combustion engines are rarely used and therefore do not provide the required charging to the battery. Energy from these solar panels can also be used to support appliances.

Modern boats are well equipped with corrosion retardant technology such as anodes and coating. However, rain, wind, sunlight and pollution particles can in a relatively short period of time wear on textiles and other materials exposed. Minimization of exposure to these wearing environmental circumstances will expand the life length of various relevant components.

1.2 Purpose and Objectives

The development of the marine industry can be considered an important milestone towards a sustainable future. Majority of the boats active today use combustion engines which not only have low efficiency compared to electric propulsion but also delays the electrification of the marine segment.

1.2.1 Purpose

This project aims to generate a creative and feasible solar wharf design, supported by objective engineering analysis, for the client Volvo Penta (2020). The Solar Wharf Garage should protect the boat from the deleterious effects of the weather and also provide power to the boat using energy gathered by photovoltaic solar panels.

1.2.2 Objective

The objective is to improve the marine lifestyle towards the environment without hurting its interests, which hopefully provides an end effect of increased utilization of electric boats. By conducting thorough research, the team aims to develop a solar wharf garage that satisfies many different customers and markets.

1.3 Problem statement

The main purpose of this project was to develop a system that can harvest solar energy to charge electric boats and shelter docked boats from external damage caused by various weather conditions. Figure 1.1 illustrates a function box which includes the inputs for the system as well as the outputs. Each of these elements have been researched to effectively achieve desired outputs through developing the Solar Wharf Garage.

Figure 1.1: *Function box for the Solar Wharf Garage*

The main issue included:

1. Study the challenges in how to design a marine graded garage with solar panels in a standard slip for small and medium-sized boats.
2. Study how other companies have designed their respective technologies.
3. Collect and analyze data regarding power needs for a normal leisure boat.
4. Calculate the quantity of solar panels and the solar panel size needed to sustain weekly boating.
5. Study which materials can be used in the specific area regarding mechanical stress and material properties.
6. Make cost calculations of the Solar Wharf Garage.
7. Generate ideas for how to use abundance of generated power when the battery is full.
8. Provide design sketches and simplified CAD-models of the Solar Wharf Garage.
9. Build a down-scaled prototype of the Solar Wharf Garage.
10. Practice to work and communicate in a global product development team.

1.4 Demarcation

The project had various limitations regarding the system design; dock size, solar panel specifications, inclement weather, feasible materials, length and frequency of boat trips. Presented below is a list of demarcations which framed the project:

- The restricted time available limited the results of the project. Difficulties regarding long term tests for different solutions were experienced and the solution therefore mainly depends upon theoretical research.
- The project was not supposed to provide a finished product but rather a well drawn sketch, function describing CAD-model and a prototype.
- By request from Volvo Penta small to medium sized boats were treated, where a medium sized boat is no more than 11 meters from bow to stern. The power consumption of the boat-motor was further given to lay between 37-45 kW (50-60 HP). Sailboats were not included in the project.
- The Solar Wharf Garage had to accomplish a fully charged battery with nothing but solar power in less than one week. Derived from the previous demarcation, the specific energy demand was specified to 4.36 kWh per day, see Section 2.4.
- Component and structural costs used in the project had to create an affordable solution for either private customers or entire marinas.
- Ability to function through all seasons and weather conditions in Gothenburg was a requirement.
- The project mainly treated the Solar Wharf Garage design and does not cover structural specifications regarding the existing wharf.

1.5 Risk analysis

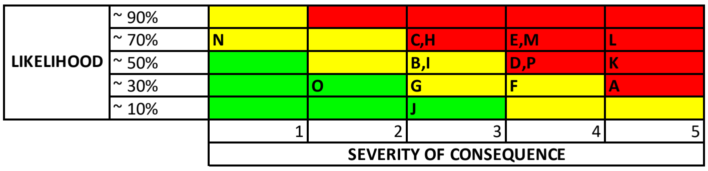
Over the course of this project, the following list of considerable risks was generated with the goal to assess and proactively avoid each one. Additionally, the risks were subgrouped into four primary categories: Performance, Schedule, Success of Deliverables, and Interpersonal Relations. These risks were altered and updated as further progress was made. Four risks were added because of the Covid-19 outbreak that caused widespread disruptions of education, travel, and project expectations.

A. If the system does not meet power requirements, it could limit how often owners could use their boats.
B. If proper safety and industry standards are not followed, the final design may be unfeasible for further development by Volvo Penta.
C. Online team meetings may lead to miscommunications that result in poorly completed tasks, slowing team progress.
D. If a meeting between Chalmers and Penn State gets cancelled, progress could be delayed by 1 week.
E. If the team does not routinely check the Gantt chart, important milestones may be neglected and due dates may be missed.
F. If significant time is not spent on concept generation, the final result could be a suboptimal design.
G. If academic due dates are not respected, team members could receive poor grades from evaluations.
H. As class timelines were disrupted by the switch to online instruction, progress could be slowed, leading to missed deadlines.
I. Home internet access could be poor, which could lead to team members being absent for important meetings or work sessions.
J. If financial status of the project is not carefully tracked, sufficient funds may not be available to present a feasible and qualitative design on time.
K. If project specifications and customer needs are not effectively communicated between Chalmers and Penn State, conflicting elements may be developed for the final design.
L. If customer needs/expectations are not clarified, the delivered product design may not be viable.
M. If research is not conducted, time could be wasted attempting to solve a problem that is not fully understood.
N. Without access to campus resources and in-person teamwork, construction of a physical model will be difficult. This may lead to a crude or unprofessional model being created.
O. If there is not respect between team members as engineers and creative thinkers, resentment may build and team morale could plummet.
P. If the requested deliverables are not delivered with satisfactory quality, the relationship between Penn State, Chalmers, and Volvo Penta could be damaged.

Performance: A, B, C
Schedule: D, E, F, G, H, I
Success of Deliverables: J, K, L, M, N, F
Interpersonal Relations: O, P

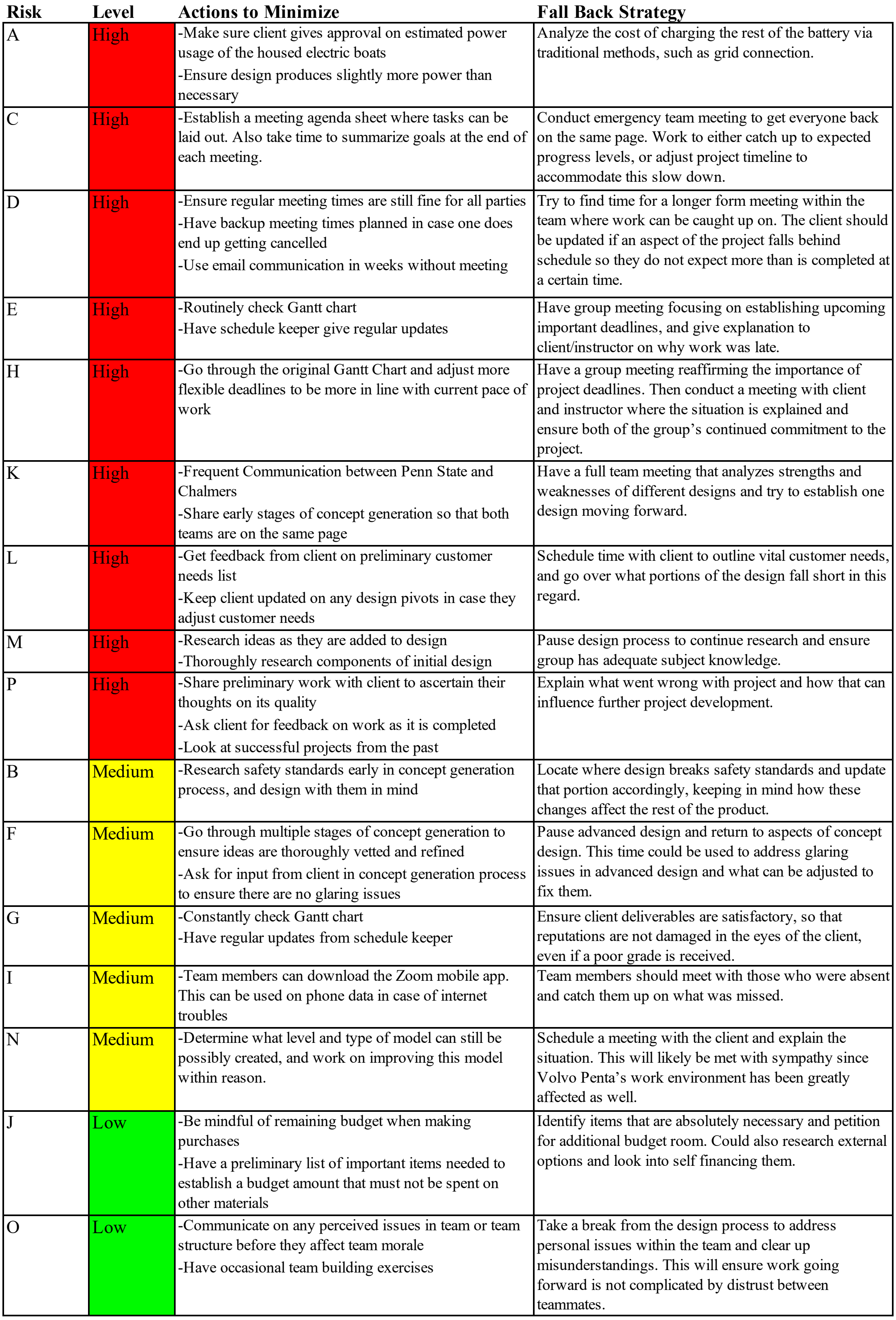
Table 1.2 shows these risks with predetermined responses. These responses were planned with the goal of mitigating negative effects if a risk came to fruition. Each risk has been assigned a level of high, medium or, low. This level is determined as a factor of consequence versus likelihood. Table 1.1 shows how these levels were assigned.

Table 1.1: Risk level chart. Green = low, yellow = medium, red = high combination of likelihood of occurrence and severity of consequence, 1 = lowest and 5 = highest.



LIKELIHOOD	~ 90%	🟨	🟥	🟥	🟥	🟥
	~ 70%	🟨 **N**	🟨	🟥 **C,H**	🟥 **E,M**	🟥 **L**
	~ 50%	🟩	🟨	🟨 **B,I**	🟥 **D,P**	🟥 **K**
	~ 30%	🟩	🟩 **O**	🟨 **G**	🟨 **F**	🟥 **A**
	~ 10%	🟩	🟩	🟩 **J**	🟨	🟨
		1	2	3	4	5
		SEVERITY OF CONSEQUENCE				

Table 1.2: Risk management strategy



Risk	Level	Actions to Minimize	Fall Back Strategy
A	High	-Make sure client gives approval on estimated power usage of the housed electric boats -Ensure design produces slightly more power than necessary	Analyze the cost of charging the rest of the battery via traditional methods, such as grid connection.
C	High	-Establish a meeting agenda sheet where tasks can be laid out. Also take time to summarize goals at the end of each meeting.	Conduct emergency team meeting to get everyone back on the same page. Work to either catch up to expected progress levels, or adjust project timeline to accommodate this slow down.
D	High	-Ensure regular meeting times are still fine for all parties -Have backup meeting times planned in case one does end up getting cancelled -Use email communication in weeks without meeting	Try to find time for a longer form meeting within the team where work can be caught up on. The client should be updated if an aspect of the project falls behind schedule so they do not expect more than is completed at a certain time.
E	High	-Routinely check Gantt chart -Have schedule keeper give regular updates	Have group meeting focusing on establishing upcoming important deadlines, and give explanation to client/instructor on why work was late.
H	High	-Go through the original Gantt Chart and adjust more flexible deadlines to be more in line with current pace of work	Have a group meeting reaffirming the importance of project deadlines. Then conduct a meeting with client and instructor where the situation is explained and ensure both of the group's continued commitment to the project.
K	High	-Frequent Communication between Penn State and Chalmers -Share early stages of concept generation so that both teams are on the same page	Have a full team meeting that analyzes strengths and weaknesses of different designs and try to establish one design moving forward.
L	High	-Get feedback from client on preliminary customer needs list -Keep client updated on any design pivots in case they adjust customer needs	Schedule time with client to outline vital customer needs, and go over what portions of the design fall short in this regard.
M	High	-Research ideas as they are added to design -Thoroughly research components of initial design	Pause design process to continue research and ensure group has adequate subject knowledge.
P	High	-Share preliminary work with client to ascertain their thoughts on its quality -Ask client for feedback on work as it is completed -Look at successful projects from the past	Explain what went wrong with project and how that can influence further project development.
B	Medium	-Research safety standards early in concept generation process, and design with them in mind	Locate where design breaks safety standards and update that portion accordingly, keeping in mind how these changes affect the rest of the product.
F	Medium	-Go through multiple stages of concept generation to ensure ideas are thoroughly vetted and refined -Ask for input from client in concept generation process to ensure there are no glaring issues	Pause advanced design and return to aspects of concept design. This time could be used to address glaring issues in advanced design and what can be adjusted to fix them.
G	Medium	-Constantly check Gantt chart -Have regular updates from schedule keeper	Ensure client deliverables are satisfactory, so that reputations are not damaged in the eyes of the client, even if a poor grade is received.
I	Medium	-Team members can download the Zoom mobile app. This can be used on phone data in case of internet troubles	Team members should meet with those who were absent and catch them up on what was missed.
N	Medium	-Determine what level and type of model can still be possibly created, and work on improving this model within reason.	Schedule a meeting with the client and explain the situation. This will likely be met with sympathy since Volvo Penta's work environment has been greatly affected as well.
J	Low	-Be mindful of remaining budget when making purchases -Have a preliminary list of important items needed to establish a budget amount that must not be spent on other materials	Identify items that are absolutely necessary and petition for additional budget room. Could also research external options and look into self financing them.
O	Low	-Communicate on any perceived issues in team or team structure before they affect team morale -Have occasional team building exercises	Take a break from the design process to address personal issues within the team and clear up misunderstandings. This will ensure work going forward is not complicated by distrust between teammates.

1.6 Outline of the report

The report covers the entire development process and is written in chronological order to create a clear description of the work made and accomplishments that followed. The idea is to let the reader understand and be able to discuss the project's structure and approach.

Much of the project requires some knowledge about the scientific areas it involves and the following chapter will provide information that is considered valuable for a greater understanding. Descriptions of how and why certain methods were used and chosen will be primarily focused to chapter three and four. The ending chapters will cover both the result accomplished by the project group but also some aspects that may be of interest for continued work and recommendations for further development.

Some parts of this project contain figures and larger documents that do not contribute enough to the readers understanding to be shown in the main structure of this report, these objects will always be referred to in the appendix as suggestions for deeper dive into the details of this particular project.

2 Background Research

The development of the Solar Wharf Garage required knowledge from several different disciplines. Below, initial research considering important subjects have been gathered from various sources to create a fitting knowledge base.

2.1 Solar cells and irradiation

Solar cells are divided into two main groups; Crystalline silicon cells and Thin-film cells. There are also other various solar cells being experimented with but not yet in commercial use. Crystalline silicon cells are the most commonly used and they are a first generation solar cell. They have relatively high efficiency of 16-20% (Gothia Solenergi, 2020) and since their primary ingredient is silicon, which is a common element in the earth's crust, it is advantageous with regard to the natural resources. However, the efficiency is mirrored in a heightened cost and the production process demands plenty of energy. Also the efficiency is significantly lowered when used in heated conditions (Nohrstedt, 2017). Furthermore, Nohrstedt describes thin-film cells as the second generation of solar cells, that have a lower material cost and also work better in cloudy weather conditions compared to its precursor. Therefore these second generation cells provide a more reliable energy production even though the efficiency during good weather conditions is slightly lower compared to crystalline silicon cells.

For solar cells, the power varies almost all the time depending on the weather and the position of the sun. However, what is meant when specifying the number of kW for a photovoltaic system is the power that the system can produce under almost ideal conditions. A more accurate term for this is the kilowatt peak, kWp. In southern Sweden the energy collected per kWp installed is 1000 kWh/year. Provided that the panels are tilted around 30 degrees towards the south and are not regularly shaded by their environment (Sherman, 2018).

2.2 Solar power system technology

To maintain best use and maximize the harvest of solar energy, solar charge controllers are implemented in direct connection to solar panel systems. Two types of technologies are used for this; Pulse Width Modulation (PWM) and Maximum Power Point Tracker (MPPT) where the last one is more expensive but also most suitable for achieving an efficient charging system.

To supply the boat battery with electricity from the solar panels, it is needed to convert the generated DC power so that it is suitable for the battery. It is important to provide protection from both too low voltage and too high voltage. Preventing that currents from the battery back to the panel occurs during nighttime when the sun is down as well as preventing overcharging of the battery is also required. It is preferred to provide uninterrupted current since the PV-cells are degrading when pulsed current is consumed out of them. Therefore a DC/DC converter is connected between solar panels and the battery.

If a solar panel system is connected to the grid it requires conversion of direct current to alternating current which is done through an inverter. Modern inverters generally have a very high transmission efficiency of 98% in medium powers and its main functions is to regulate the output voltage, perform wave-shaping and to make sure operation is near peak power point (Scarabelot et al, 2018). The performance of the inverter can be affected by the efficiency of the solar panels, frequency, harmonic distortion, and the MPPT. When the PV modules are partly or entirely shaded from the sun, the output current decreases significantly which causes the output power to drop. This affects the performance of the inverter, since an inverter operates at its maximum efficiency when the input power is between 30-50% of its rated capacity (Kalogirou, 2014).

Grid-connected solar systems gain the possibility of extra income when selling excess electricity. The grid can also serve as a "battery bank," where power is figuratively saved so that it can be used later. In Sweden and Norway, solar energy producers can also be rewarded through the Electricity Certificate System, in which one certificate is awarded per MWh of electricity produced annually. These certificates can be sold for extra revenue in the free market and bought by energy suppliers who must meet a quota of certificates in proportion to their own energy sales. This means electricity customers across the two countries are helping to fund the production of renewable energy (Energimyndigheten, 2017).

The Swedish part of the team did a study visit to Gothia Solenergi in February. Solar panels were displayed both in their facilities and mounted in different set-ups on their roof. The team received valuable information regarding solar power history and implementation in Sweden as well as an introduction to solar calculations. Knowledge about the requirements for connecting to the grid in terms of voltage level was presented to the group, where the top level of the grid at 325 V was pointed out as minimum.

2.3 Electric vessels

Inspirational advancements in the area of solar powered marine vessels include the Monaco Solar & Energy Boat Challenge and the world's largest solar powered boat, MS Tûranor PlanetSolar. The Boat Challenge in Monaco is unique in the world and has been organised since 2014. It provides a real technological challenge for engineering teams and boat manufacturers with the goal to develop alternative propulsion using only green energy (MCSEBC, 2020). The MS Tûranor, with a length of 31 meter and weight of 89 ton, was conceptualised in 2007 by a Swiss explorer named Raphaël Domjan. With a total panel area of 537 m^2 it can propel the boat at a maximum velocity of 9 knots (nautical mile per hour) with a peak power of 120 kW. The total battery weight of 12 ton creates autonomy for 3 days without sunshine (planetSolar, 2019). Their vision building MS Tûranor was to showcase the possibilities of coping with climate change through more sustainable solutions, and executed the first solar-powered Round the World tour between the years 2010-2012.

An identification of the current market for electrical leisure boats was introduced through attending the Swedish boat fair in Gothenburg in February 2020 (Båtmässan, 2020). Information regarding the diversity of boats and the already, or near future, developed technology were collected. The electric power boat market is expanding at a high pace, and their power needs are of a wide range. Some more reasonably sized boats at the fair were of interest, with a significantly lower power need and prize. Some particularly interesting companies met were:

1. Starcut - Starcut 2.0 is a cruising boat which is custom made with electric propulsion. The boat has a low propulsion resistance and is built for private use and four persons with an engine of 20 kW, top speed of 18 knots and a battery capacity of 20 kWh. The range is 15 NM (1 nautical mile is equal to 1852 m) at a cruise speed of 15 knots, 20 NM at a speed of 8 knots and approximately 50 NM at a low speed of 3 knots (Strom Engineering AB, 2020).

2. X Shore - Swedish powerboats designed and produced on the east coast with engines of 225 kW and lithium ION batteries of 120 kWh. With top speeds of 40 knots, the X Shore boats could start to compare with combustion driven boats and can even reach 100 NM in lower speeds. A good example on how capable the electric boat market can be with the right investors (X Shore, 2020).

3. Candela - Innovative company that designs foiling boats to reduce energy consumption and therefore expand the range of electrical boats. Their advanced control systems give new opportunities to the boat industry. The Candela has a 40 kWh Lithium Ion battery and a motor of 55 kW. The range of the Candela speed boat is up to 55 NM at the speed of 22 knots due to its foiling capabilities (Candela, 2020).

4. Bjurtech - Visionary concept design with the aim of 100% self sufficient solar powered boat. Main purpose to be used in developing countries as a fishing boat. At cruising speed of 5.5 knots, the range is 33 NM. When interviewed, the founder of Bjurtech explained future plans on developing leisure vessels (Bjurtech AB, 2020).

5. Aquawatt - Established Austrian manufacturer of electrical outboard and inboard engines from 4.3 kW to 50 kW. Their outboard engine, Green Thruster, has a power output of 22 kW and uses a battery between 12.8 kWh to 48 kWh (Aquawatt, 2020).

6. Torqeedo - Offers powerful electric outboard engines in the Travel and Cruise series with up to 80 HP. Their Deep Blue 25 RL with a 30.5 kWh battery is comparable to a 40 HP petrol outboard motor. The range of the battery is 24-78 NM in 5 knots, and 12 NM in 10 knots (Torqeedo, 2020).

2.4 Energy demand

It is predicted that boats will be used once a week, thus requiring a charge once a week. The boat power requirements received from the projects' industrial partner was, as earlier mentioned in Section 1.4, given to lay between 37-45 kW (50-60 HP). Based on the listed electric vessels, a common electric leisure boat with that power is equipped with batteries of capacities between 12.8 and 48 kWh. Therefore, an estimated battery size of 30.5 kWh was chosen to simplify further investigation in dimension of the garage electricity components. If these values are assumed to be the weekly allotment, it could then be assumed that the boat requires 4.36 kWh of energy to be collected per day.

2.5 Marina

Researching the different mooring possibilities in Swedish marinas shows four typical alternatives below in Figure 2.1 (POLY, 2020). They have different characteristics and the choice depends on boat size and marina layout. The configuration of the different mooring possibilities gave an insight of how a solar wharf garage could be attached to the dock.

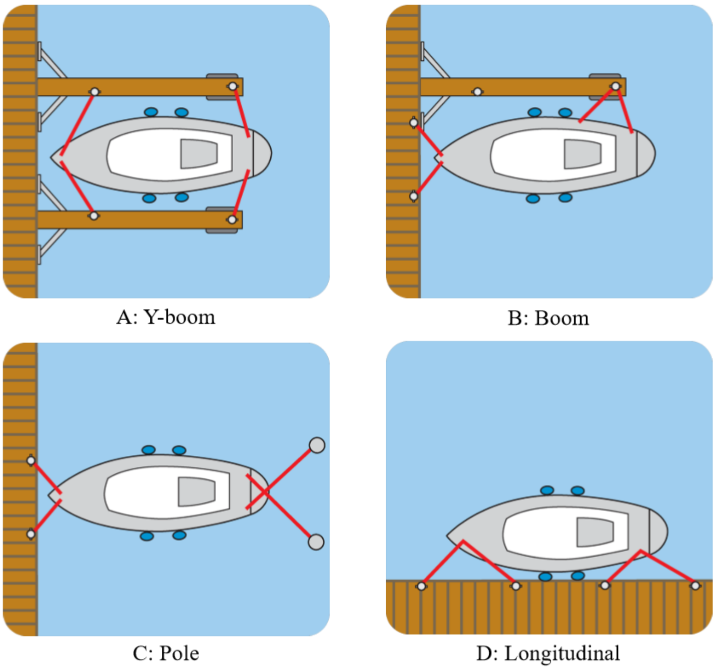
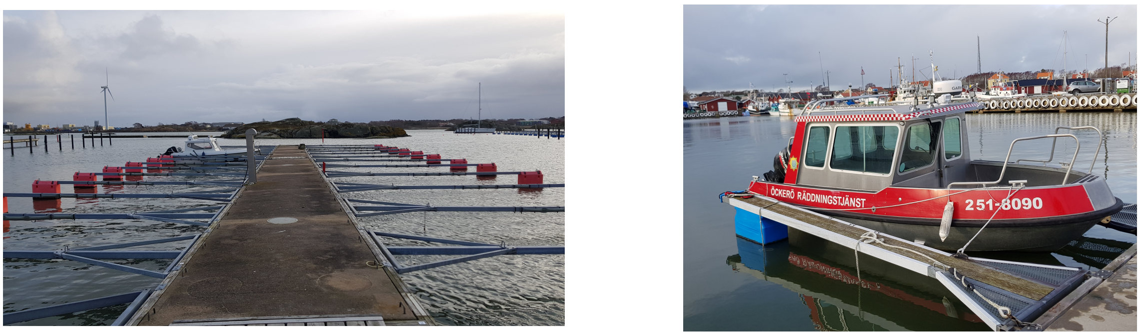

A: Y-boom
B: Boom
C: Pole
D: Longitudinal

Figure 2.1: *Different mooring possibilities*

In order to gather information about marinas in and around Gothenburg, a study visit to the marina Öckerö Hamn at Öckerö, located in the northern parts of the Gothenburg archipelago, was carried out (Öckerö Hamn, 2020). The harbor has already started their work towards transitioning to renewable energy and has put up crystalline solar panels on many of the premises' roofs. Furthermore, they see an increase in electric vessels. The idea of the Solar Wharf Garage was introduced to the harbor manager, the vice-president of the boat club and the maintenance manager as a possible investment for the future. The response was overall positive and opened ideas for designs and implementations but also mentioned possible concerns regarding building permits. Another input was that wharfs will often be at different stages of their lifetimes, and some may not be fit for the system. Pictures from the visit are seen below in Figure 2.2.



(a) *Leisure boat wharf with Y-booms.* (b) *Docked boat.*

Figure 2.2: *Pictures from Öckerö Hamn, 2020.*

Given the study visit, typical dimensions of a boat slip were also investigated at Öckerö Hamn, see Table 2.1. The dimensions of the slips when using Y-booms are given in the following table and were of help for the following dimensioning of the system.

Table 2.1: Usual boat slip dimensions in Gothenburg

Width	Length
2.6 m	6 m
3.26 m	8 m
3.6 m	9 m

2.6 Materials

In a corrosive environment, like the marine environment of harbors, a suitable material choice is of importance. A wide range of materials are already in use in marine applications with documented material properties over the years of use. These materials are also commercially available in a range of dimensions. This section of the report will cover the potential corrosive effects on materials exposed to marine environments and the marine-graded materials that are currently available.

2.6.1 Corrosion

Several different types of corrosion occur frequently in marine environments. These corrosive effects can be accelerated by higher chloride concentrations, such as that of seawater, or by moving water. Corrosion rates can occur nearly seven times as rapidly in moving waters than in stagnant waters (Cicek, 2014).

Literature studies on why corrosive attacks occur are used to work out preventative measures in the design that could extend the final products lifespan by multiple years. Overall, the cleaner a structure is, the less likely it is to corrode. The team further addresses this concern through the regular rinsing procedure in a maintenance plan. The corrosion types that are identified as most problematic regarding the circumstances are listed and described below.

2.6.1.1 Atmospheric corrosion

When the critical humidity is reached a thin film of electrolyte forms onto a metallic surface. Primarily this corrosion type is caused by moisture and oxygen but is amplified by contaminants like sulfur compounds, sodium chloride and salt spray. The corrosion of steel is shown to dramatically accelerate with a shortened distance to the seacoast. In one study, steel located 25 meters from the shore corroded 12 times faster than if placed 250 meters away (Substructure, 2020).

2.6.1.2 Galvanic corrosion

Galvanic corrosion occurs when dissimilar materials are coupled in an electrolyte. One of the metals, with the lower potential, will act as anode and corrode with greater speed than it would by itself. The opposite effect will be present at the other metal that will act as cathode (NACE International, 2020).

2.6.1.3 Fretting

Repeated relative surface motion abrades the protective film on metal surfaces and exposes active metal. These areas will be victims to corrosive actions of the atmosphere. Pits, grooves and oxide debris are common consequences for this type of corrosion which compromises the mechanical properties of the design (Substructure, 2020).

2.6.1.4 Stress-corrosion cracking

This type of corrosion occurs when the material is exposed to tension, compression or vibrations while being corroded. It can be difficult to notice this kind of corrosion since it does not occur at the surface of the metal. The material keeps its shape but loses strength. The team had concerns about the possibility of stress-corrosion cracking in the structure due to the cyclic stresses from waves in the harbor, considering the design could be used in a variety of locations and wave patterns (Mattson, 2012).

2.6.2 Material options

Three notable marine-grade materials are investigated for the garage structure: Aluminum, Stainless Steel, and Galvanized Steel. These materials are detailed below.

2.6.2.1 Aluminum

Aluminum, particularly 6061-T6 and 2024-T3, are industry standard for most structural marine applications because it is lightweight, cheap, and has high strength capabilities. Generally, this material is considered to be corrosion resistant, but in the particular case of seawater applications, the corrosion of aluminium is accelerated considerably by the galvanic contact. If this material is used, contact with other metal materials for joints or fasteners should be minimized, (Bardal, 2004). 6061-T6 is notably more corrosion resistant in these saline solutions than 2024-T3, which is a significant factor in the material decision and could outweigh the benefits of 2024-T3's superior fatigue strength (Clinton Aluminum, 2017).

2.6.2.2 Stainless steel

Stainless steel, particularly austenitic stainless steels like 304 and 316, is commonly used for marine fittings, marine fasteners, and marine structures. 304 stainless steel is cheaper and very formable, but not as corrosion resistant as 316, so it is best used for parts on which corrosive elements will be frequently washed away by water. 316 is better used above the water line, because it is less prone to crevice corrosion than 304 (ASSDA, 1996).

2.6.2.3 Galvanized steel

Galvanized steel is well suited for marine environments because the magnesium and calcium ions protect the steel from the zinc corrosion that would typically occur in seawater with high chromium levels (Duran III, 2012).

2.7 Customer needs

The design is intended to be attached to the wharf located in the marina, who is considered the primary customer. The design will therefore be a possible long-term investment that does not only provide the marina with sufficient electrical infrastructure to enable electrical boating but also for positive economic purposes when selling excess harvested energy.

The customer needs were primarily gathered through meetings with the client and through the background research. Volvo Penta outlined and thoroughly explained the customer needs that they typically prioritize for a developmental project. The following list illustrates the customer needs that is considered for this report:

1. Sufficient power must be generated
    (a) Charged within the time between boat use, allowing for weekly boating
    (b) Electric system can be connected to local grid to sell excess energy and buy when needed
2. System cost to user should be comparable to other charging options
    (a) Considering subsidiaries and long-term outcomes
3. Safety
    (a) The system is safe to use in a variety of weather conditions
    (b) User and surrounding equipment should be safe when interfacing with electrical components using normal electricity installation standards
4. User friendly
    (a) The design should be possible to install by limited personnel
    (b) The design should be accessible in the case of required maintenance
    (c) Modules of design should be easily replaced in the case of irreparable failure
    (d) Intuitive design interface for conveying information to the customer
    (e) The garage should be accessible to customers and convenient to enter
    (f) The garage should fit small to medium boats
5. Design is constructed in a sustainable manner
    (a) Regarding manufacturing and material choices
    (b) Considering ethical aspects and environmental impact
6. Durable design
    (a) The system can be maintained/serviced for the duration of boat ownership
    (b) The design should be corrosion-resistant
    (c) The design should withstand physical strain of sea forces
7. Flexible design to accommodate for environmental changes
    (a) The design should be possible to be adjusted quickly in case of a storm by limited personnel

2.8 Target specifications

From the customer needs, twelve target specifications were formed, see Table 2.2. They were considered to outline the expectations of the final design with regards to the structure, life cycle, power generation and distribution, modularity, material selection, and cost. Specifications have been established using the needs outlined by the point of contact from Volvo Penta and based on the data collected through the initial research.

Table 2.2: Target specifications for the Solar Wharf Garage

Specification No.	Specification	Importance (1=not very, 5=very)	Threshold Value (1)	Objective Value (2)	Units
1	Garage length	5	6	9	m
2	Garage width	5	2,6	3,6	m
3	Physical accommodation	3	1	≥1	boats
4	Electricity generation	4	30	80	kWh/week
5	Power distribution	3	1	≥1	boats
6	Charging time	4	7	1	days
7	Solar cell area	3	10	20.5	m^2
8	Operation Personnel Required	3	2	1	people
9	Disassembly Personnel Required	3	2	1	people
10	Disassembly Time	2	120	45	minutes
11	Ambient Operating Temperature	5	-25 to 35	-30 to 50	°C
12	Life Cycle with Maintenance	4	10	20	years

The *length* and *width* dimensions of the Solar Wharf Garage were taken from the boat slips in Öckerö Marina. These dimensions further gave the *solar cell area.* Since it was not stated how much solar cell area was needed yet, 70% of the maximum garage roof area was stated as the objective value.

Based on the batteries in the electrical boats from the boat fair as well as commercial leisure boats, *electricity generation* need was determined to be over 30 kWh/week. For managing to charge larger batteries, or enabling several charges, the threshold value was set to 80 kWh/week. Based on the allowance for weekly boating, the *charging time* was set to a maximum of 7 days, preferably less.

The *physical accommodation* and *power distribution* were set for one boat, but with an objective value of several boats since this might be a possibility.

In the target specification the design will ideally be able to be quickly disassembled in the case of particularly harsh weather or to prepare the dock for the winter months. Because small marina owners may only have one or a few staff members, the system will preferably be *disassemblabled* by only 1 to 2 personnel. The *disassembly time* is therefore also short, 120 min preferably less, since the staff of the marinas should be able to disassemble many garages in one day. When the *operation* *personnel* is using the Solar Wharf Garage it is required that two people should be needed to use it, however, this has an objective at one person since boat owners sometimes are out with the boat alone.

The *temperature* requirements were set to withstand harsh winter climate as well as strong sunlight in the summers. The *life cycle* of the Solar Wharf Garage was set to at least manage 10 years, but with the life cycle of solar cells (>20 years) in mind, the threshold value was set to 20 years (Engineering, 2014).

The conducted research presented in the chapter covered different solutions for solar cells, solar technology and the marine segment. The marine segment includes investigation of electric vessels, energy demand, and infrastructure of the marinas. For the design structure being in a harsh environment, different materials was compared with the focus on their corrosive properties. With a formulated target specification based upon the customer needs and research, the project had guidelines of what to consider for the development of the Solar Wharf Garage. Idea- and concept generation were thereby initiated, which is described in the upcoming chapter.

3 Concept Generation

In order to generate well developed solutions and analyze different aspects, it was important to spend ample time on a combination of idea and concept generation. By dividing the system into subsystems, a thorough functional analysis of the Solar Wharf Garage could be completed. This was used to frame where new solutions were necessary or advantageous. These solutions were combined and reused during an iterative process to maintain a variety of different possibilities.

After each iteration of evaluation using Pugh matrices, valuable functions to reuse were identified and implemented in other concepts. By doing this in between iterations the risk of valuable ideas and solutions being eliminated were reduced. The elimination process has been inspired from The Value Model (Lindstedt and Burenius, 2017).

3.1 Function analysis

The following section discusses the functionality of the system. The design will be described in terms of its purpose and functional requirements. According to the project definition, the final concept must effectively house, charge and protect an electric boat. The concept must be resilient to the deleterious effects of harsh weather. Specifically, the structure must maintain its integrity in extremely adverse marine weather while simultaneously absorbing and converting sunlight irradiation for electrical charging of the boat.

In order to first gain an understanding of the functional requirements and design considerations that must be addressed by the design, a function analysis was made from a customer's needs interpretation. The requirements were divided into Mechanical and Solar categories. As shown Figure 3.1, these two primary categories were further divided into specific items. Although the items are inherently related, they also stand alone as unique design considerations. Each item must be addressed by the design, in some manner, and be subject to objective engineering analysis. Attached to each of these subdivisions are blue bubbles containing further elaboration.

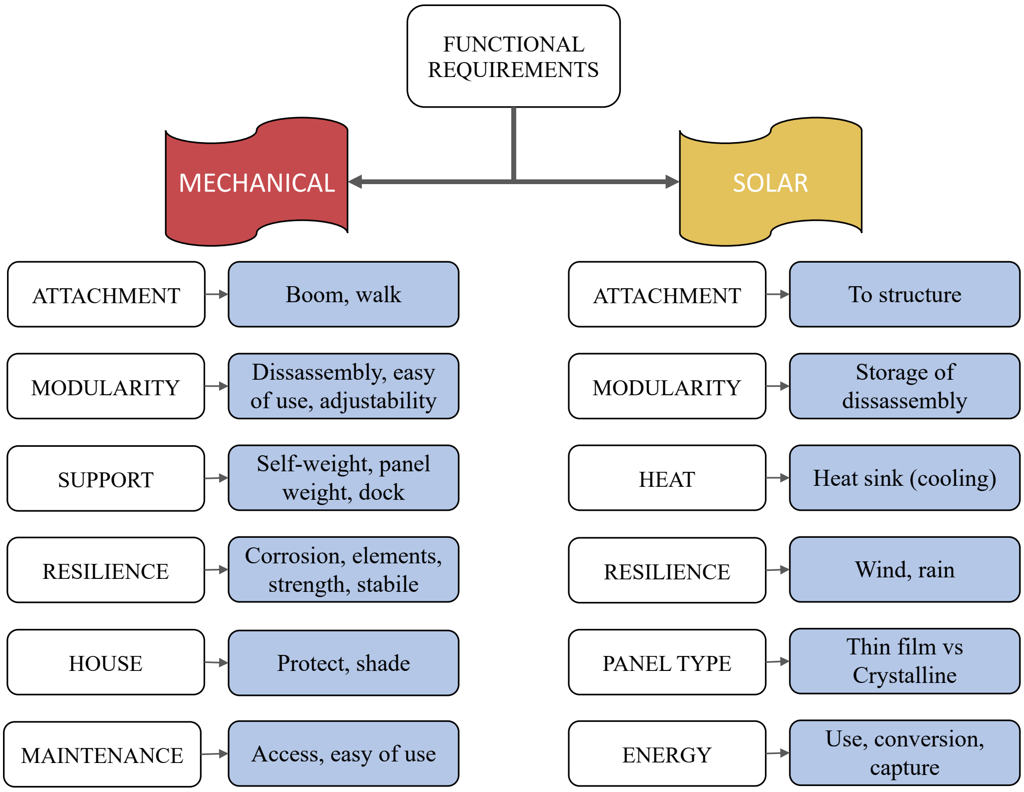


Figure 3.1: *Functional requirements*

Many functional requirements were self-imposed in order to further constrain the design. This provided a useful, and more realistic, context for implementation. These functional requirements had to be addressed in the final concept and forced a generation of detailed designs. Each concept generated had to address one or more of these functional requirements, which include modularity, structural resistance, boat protection, panel resilience, energy handling, panel cooling, and assembly of panels. These functional requirements became guidelines for the following idea generation.

3.2 Idea generation

In order to find different solutions to the functional requirements, the team took a few different approaches for the idea generation phase. By brainstorming and brainwriting, the team generated several different solutions to address each requirement which were later combined into concepts. The intention of this approach was to ensure that each requirement was accounted for and to later combine the best aspects of each concept after the idea generation phase. Some of the preliminary sketches are illustrated in Figure 3.2.

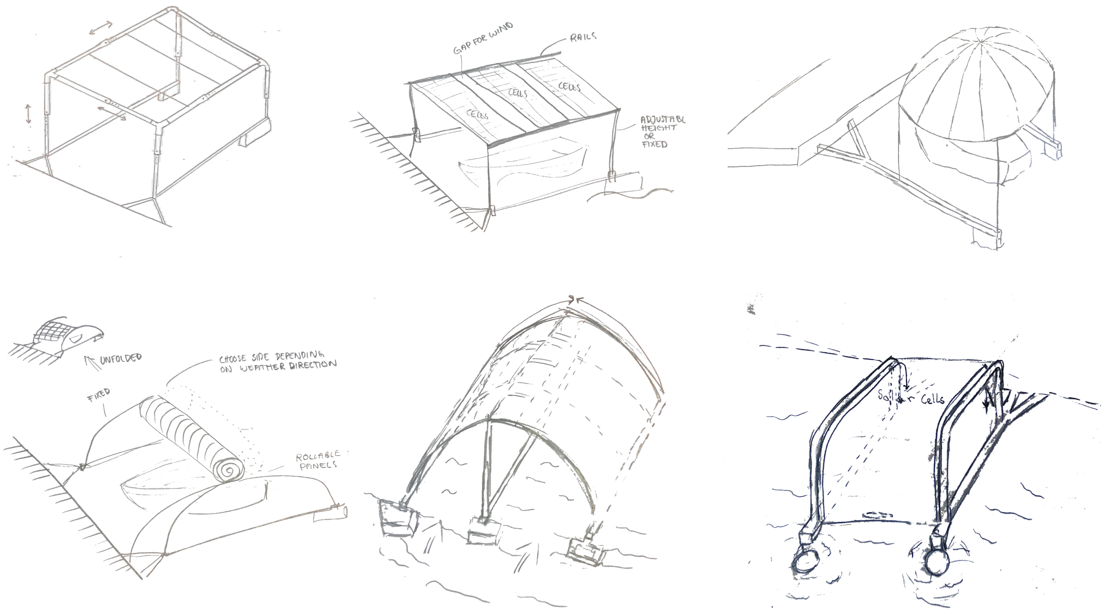


Figure 3.2: *Sketches of early concepts*

To further enlarge the variety of possible concepts, PSU and Chalmers students executed idea generations separately and later combined the products. By dividing the team into two working groups it was expected to decrease the influence of favouring group dynamics and provide a fair evaluation.

As each group progressed in the idea generation phase, they began to utilize virtual sketches as a method of sharing concepts to discuss between the groups. These virtual sketches have been compiled in a concept catalogue to describe and visualize each generated concept. The catalogue entries include the sketch, some key features of the design, and considerations that may have led to its deselection. The Concept catalogue can be found in Appendix A.

These first system solutions enabled evaluation and elimination methods to be used for further development towards a final design. This was the early stage of the idea generation, however, it was also an ongoing process throughout the project to prevent early lock-in and consider new inputs.

3.3 Evaluation and elimination

To evaluate and compare the concepts, two Pugh matrices and one Kesselring matrix were used with inspiration taken from The Value Model (Lindstedt and Burenius, 2017). Since the team was divided by distance between two universities, the elimination using Pugh matrices were also made separately. Between the iterated Pugh matrices, there were discussions about the results with the entire team.

In parallel with evaluation of the existing concepts, development of new ones were generated by combining good features from eliminated concepts with partly fresh ideas but also implemented with existing ones. By doing this in an iterative manner it reduced the risk of valuable ideas and solutions to certain problems to not be taken into consideration while evaluating the final concept.

3.3.1 Elimination using the Pugh matrix

To systematically eliminate concepts, Pugh matrices were used, which is an elimination matrix method. It is an effective and clear method to analyze concepts. Specific criteria that compare the concepts to a reference are established from the target specification and customer needs. The reference is a concept chosen by the team to compare and analyze the differences between the concepts. The reference is changed between the two iterations of Pugh matrices to ensure stability of the results. The concepts were examined through different aspects; Customer value, Geometry, Manufacturing, Costs, Durability, Risks, Protect and Functions. The team decided that some of the aspects deserved a higher weight based on their importance to the customer. Weighted values were assigned to each subsection in the matrix and are briefly explained below.

- **Customer value:** The importance of this evaluating point was considered to be high in order to create a desirable design towards the customer, whose values should be nurtured. These specific criteria were discovered during interviews with customers.

- **Geometry:** Many different aspects were connected to the shape and structure of the design and were therefore considered a more highly valued evaluation point.

- **Manufacturing:** Limited time was used for investigating manufacturing methods, the majority of materials and profiles were expected to be of standard. Therefore a low percentage was assigned to this evaluation point.

- **Cost:** The client mentioned early in the project that the cost was not the most important factor in the process. Therefore the value of the evaluation point was low.

- **Durability:** The lifespan of different parts of the design should be relatively even to drastically reduce the time needed for maintenance and service costs. It should also match the lifespan of a wharf to reduce the difficulties in replacement of major parts of the system or the wharf.

- **Risks:** The risks connected to the different concepts were believed to be comparable. It was not expected to have a considerable impact on which concepts would be eliminated. The weight in the Pugh matrix was therefore decided to be low.

- **Protect:** The main function of the Solar Wharf Garage is to charge electrical boats battery and protection was therefore of lower priority. Anyhow, protection of the abrasive effects of weather were desirable to benefit the customers transition towards electrical powered boating.

- **Functions:** This aspect helped to provide heightened usefulness, different designs had different possibilities in implementing functions that could improve the design.

When the concepts are compared with the reference they receive a score of 1, 0 or -1. The concept gets 1 if it is considered to perform better than the reference in that specific criteria, 0 if they perform the same and -1 if the concept perform worse. When all the concepts have been compared to the reference concept, their values are multiplied with the weighted percentage and then summed for a total score. The concepts with the lowest scores are potentially eliminated.

3.3.1.1 First Pugh matrix

The reference for the first Pugh matrices was chosen to be the traditional Swedish wooden boathouse (Concept 10), which is commonly seen in Sweden. Chalmers' first Pugh matrix is seen in Table 3.1 and PSU's first in Table 3.2. More information about the concepts can be found in the Concept catalogue, Appendix A.

At this stage, specifics of the concepts were not yet fully determined and the refinement level was low. Instead, a wide variety of solutions was covered and evaluated in order to iterate the development towards a rising degree of refinement. The concepts in the Chalmers' first Pugh matrix are shown in Figure 3.3 and the concepts in PSU's first are shown in Figure 3.4.

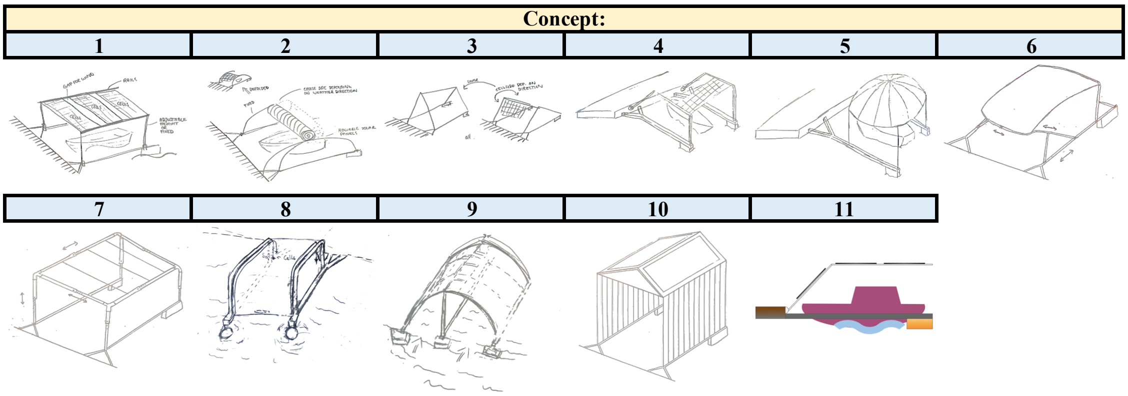


Figure 3.3: *Illustrations of the concepts in Chalmers' first Pugh matrix*

Table 3.1: Chalmers' first Pugh matrix

			Concept:										
		Weight	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Customer value	Solar cell area	35%	0	1	1	0	1	0	0	1	1	Reference	0
	Sight during mooring		1	1	1	1	1	1	1	1	1		1
	Easy mooring		1	1	-1	1	1	1	1	1	1		1
	Give support		-1	-1	-1	-1	-1	-1	-1	-1	-1		-1
	User friendly		0	-1	0	0	0	0	0	-1	0		0
		0,35	0,35	0,35	0	0,35	0,7	0,35	0,35	0,35	0,7		0,35
Geometry	Complexity	15%	1	-1	0	-1	-1	-1	0	-1	-1		0
	Flexibility		1	1	0	0	0	1	1	1	0		0
	Estetic		0	0	0	0	0	0	0	0	0		0
	Stability		-1	-1	-1	-1	-1	-1	-1	-1	-1		-1
		0,15	0,15	-0,15	-0,15	-0,3	-0,3	-0,15	0	-0,15	-0,3		-0,15
Manufacturing	Time	4%	1	1	1	1	1	1	1	1	1		1
	Complexity		1	-1	1	1	-1	-1	-1	-1	1		1
		0,04	0,08	0	0,08	0,08	0	0	0	0	0,08		0,08
Cost	Purchase price	2%	1	-1	1	1	-1	0	1	-1	1		1
	Manufacturing cost		1	-1	1	1	-1	0	1	-1	1		1
		0,02	0,04	-0,04	0,04	0,04	-0,04	0	0,04	-0,04	0,04		0,04
Durability	Corrosion resistance	20%	-1	-1	0	0	0	-1	-1	-1	-1		0
	Strength		-1	-1	-1	-1	-1	-1	-1	-1	-1		-1
	Recyclability		0	0	0	0	0	0	0	0	0		0
	Reusability		1	1	1	1	1	1	1	1	1		1
	Maintenance		1	1	1	1	1	1	1	1	1		1
		0,2	0	0	0,2	0,2	0,2	0	0	0	0		0,2
Risks	Technical	4%	-1	-1	-1	-1	-1	-1	-1	-1	-1		-1
	Personal danger		0	-1	0	0	0	-1	-1	-1	0		0
		0,04	-0,04	-0,08	-0,04	-0,04	-0,04	-0,08	-0,08	-0,08	-0,04		-0,04
Protect	Rain	5%	-1	-1	0	-1	-1	-1	-1	-1	0		-1
	Wind		1	1	1	1	-1	1	1	1	1		1
	Dirt		-1	-1	0	-1	-1	-1	-1	-1	0		-1
	Snow		-1	1	1	-1	0	1	0	1	1		-1
		0,05	-0,1	0	0,1	-0,1	-0,15	0	-0,05	0	0,1		-0,1
Functions	Foldability	15%	0	1	0	0	0	1	0	1	0		0
	Thermal management		1	1	1	1	1	1	1	1	1		1
	Assemblability		1	1	1	1	1	1	1	1	1		1
		0,15	0,3	0,45	0,3	0,3	0,3	0,45	0,3	0,45	0,3		0,3
	SUM	**1**	**0,78**	**0,53**	**0,53**	**0,53**	**0,67**	**0,57**	**0,56**	**0,53**	**0,88**		**0,68**

As can be seen in Table 3.1 all concepts final scores were positive. This suggested that the reference was least preferable with the evaluation points and weights considered in this Pugh matrix. Conclusions regarding potential of the concepts were difficult to draw from this, however, it gave a good implication that they were addressing plenty of the value points brought up by the early customer research on which the evaluation points were based upon. None of the concepts included in the Chalmers' first Pugh matrix were discarded before the second iteration, because of similarity in the scores among the concepts.

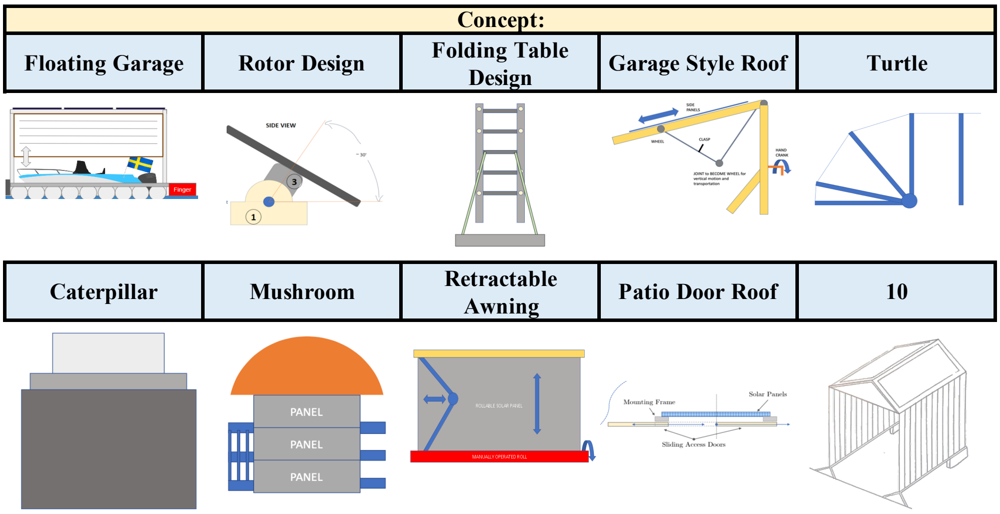
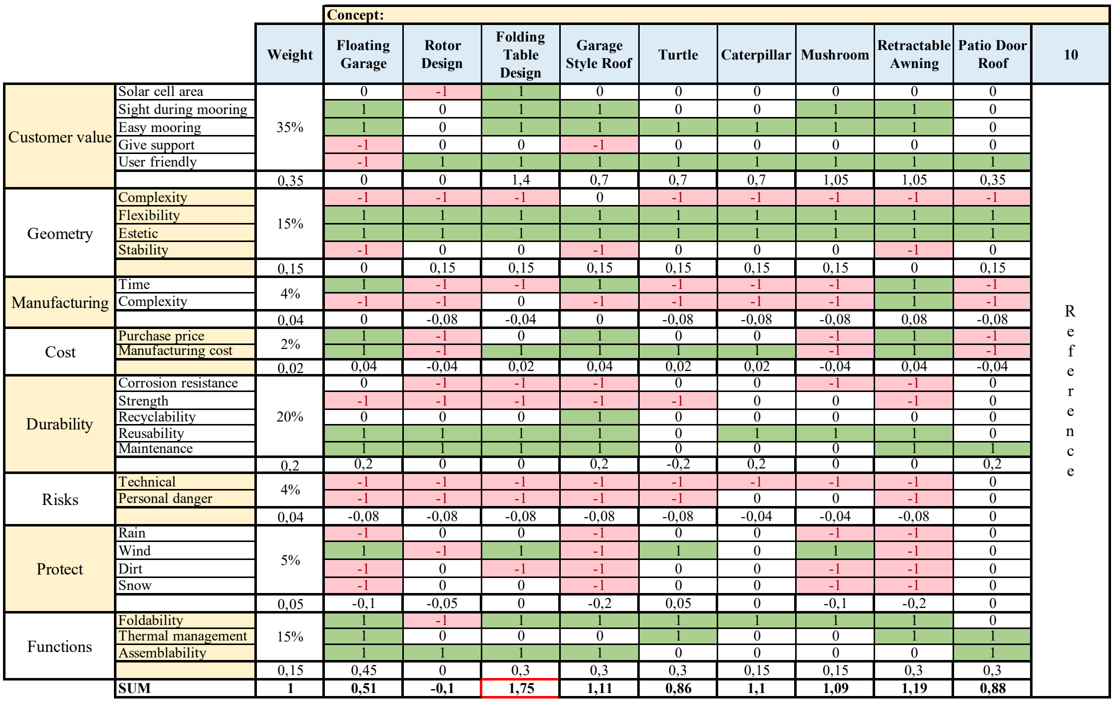


Figure 3.4: *Illustrations of the concepts in PSU's first Pugh matrix*

Table 3.2: PSU's first Pugh matrix



			Concept:									
		Weight	Floating Garage	Rotor Design	Folding Table Design	Garage Style Roof	Turtle	Caterpillar	Mushroom	Retractable Awning	Patio Door Roof	10
Customer value	Solar cell area	35%	0	-1	1	0	0	0	0	0	0	Reference
	Sight during mooring		1	0	1	1	0	0	1	1	0	
	Easy mooring		1	0	1	1	1	1	1	1	0	
	Give support		-1	0	0	-1	0	0	0	0	0	
	User friendly		-1	1	1	1	1	1	1	1	1	
		0,35	0	0	1,4	0,7	0,7	0,7	1,05	1,05	0,35	
Geometry	Complexity	15%	-1	-1	-1	0	-1	-1	-1	-1	-1	
	Flexibility		1	1	1	1	1	1	1	1	1	
	Estetic		1	1	1	1	1	1	1	1	1	
	Stability		-1	0	0	-1	0	0	0	-1	0	
		0,15	0	0,15	0,15	0,15	0,15	0,15	0,15	0	0,15	
Manufacturing	Time	4%	1	-1	-1	1	-1	-1	-1	1	-1	
	Complexity		-1	-1	0	-1	-1	-1	-1	1	-1	
		0,04	0	-0,08	-0,04	0	-0,08	-0,08	-0,08	0,08	-0,08	
Cost	Purchase price	2%	1	-1	0	1	0	0	-1	1	-1	
	Manufacturing cost		1	-1	1	1	1	1	-1	1	-1	
		0,02	0,04	-0,04	0,02	0,04	0,02	0,02	-0,04	0,04	-0,04	
Durability	Corrosion resistance	20%	0	-1	-1	-1	0	0	-1	-1	0	
	Strength		-1	-1	-1	-1	-1	0	0	-1	0	
	Recyclability		0	0	0	1	0	0	0	0	0	
	Reusability		1	1	1	1	0	1	1	1	0	
	Maintenance		1	1	1	1	0	0	0	1	1	
		0,2	0,2	0	0	0,2	-0,2	0,2	0	0	0,2	
Risks	Technical	4%	-1	-1	-1	-1	-1	-1	-1	-1	0	
	Personal danger		-1	-1	-1	-1	-1	0	0	-1	0	
		0,04	-0,08	-0,08	-0,08	-0,08	-0,08	-0,04	-0,04	-0,08	0	
Protect	Rain	5%	-1	0	0	-1	0	0	-1	-1	0	
	Wind		1	-1	1	-1	1	0	1	-1	0	
	Dirt		-1	0	-1	-1	0	0	-1	-1	0	
	Snow		-1	0	0	-1	0	0	-1	-1	0	
		0,05	-0,1	-0,05	0	-0,2	0,05	0	-0,1	-0,2	0	
Functions	Foldability	15%	1	-1	1	1	1	1	1	1	0	
	Thermal management		1	0	0	0	1	0	0	1	1	
	Assemblability		1	1	1	1	0	0	0	0	1	
		0,15	0,45	0	0,3	0,3	0,3	0,15	0,15	0,3	0,3	
	SUM	**1**	**0,51**	**-0,1**	**1,75**	**1,11**	**0,86**	**1,1**	**1,09**	**1,19**	**0,88**	

In the Penn State university's first iteration Pugh matrix the majority of concepts were valued higher than the reference. It was also chosen to eliminate three of the lowest scored concepts.

- Floating garage: This concept was primarily eliminated because of low scores in the Customer value and Geometry sections. Since these evaluation points were highly weighted and this particular concept did not provide sufficient ways to address these, it was discarded.

- Rotor design: Rotor design was a highly complex design which would be difficult to manufacture, even though some good features regarding aesthetics and stability. This concept was the only one to receive a negative score compared towards the chosen reference and was therefore eliminated.

- Patio door roof: While this concept had a high score in the Pugh matrix, it was eliminated due to compatibility issues. This was a concept for a roof rather than a full structure. The roof itself performed well in the matrix, it was decided that this design would be difficult to implement onto the other structure designs.

After the first evaluation with the Pugh matrices, new concepts were developed through cross combination. Additional research was also made during this period to provide a more detailed overview and explanation to the concepts.

In this first iteration of the Pugh matrices many concepts with thin film panel solutions received a lower score in the high weighted categories, especially in geometry and durability. The reason was the more complex structure required to effectively make use of their advantages, for example retractable solar panel solutions. Elimination of the more complex structures would leave a much smaller variety of concepts. To keep the potent function of rollable/foldable solar cells, this function was implemented together with other concepts in the next iteration.

Eliminated functions were kept to make sure certain aspects of designs that showed potential were not errantly discarded. For example, when noticed that one function scored well in one category, it could be used in another design to make the end score higher. In general, the scores went up after performing this change, which indicated that most of the designs performed well in some areas.

3.3.1.2 Second Pugh matrix

For the second Pugh matrices nine new concepts were developed and added, six in the Chalmers' matrix and three in the PSU's matrix. These were mainly flexible types of the previous concepts, to withstand the wave dynamics and be user friendly. The references were also changed to the highest-scored concepts from the first Pugh matrices. For the Chalmers' Pugh matrix the new reference was Concept 9 and for PSU's, the new reference was the Folding Table Solution. By using a generated concept as a reference, the stability of the result can be improved and the outcome becomes more trustworthy. The result from the second Pugh matrices are found in Table 3.3 and Table 3.4 below. The concepts in the Chalmers' second Pugh matrix are shown in Figure 3.5 and the concepts in PSU's second are seen in Figure 3.6.

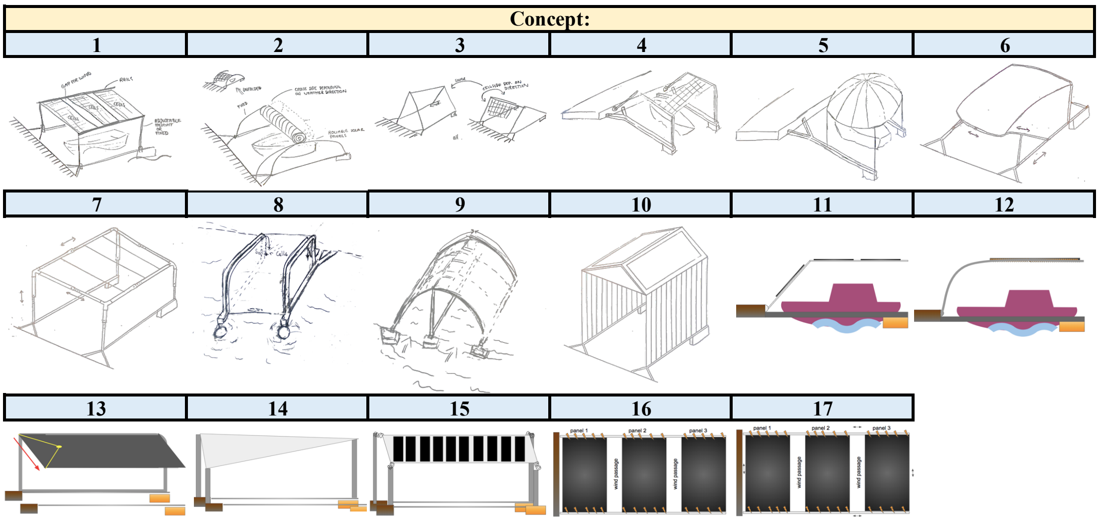
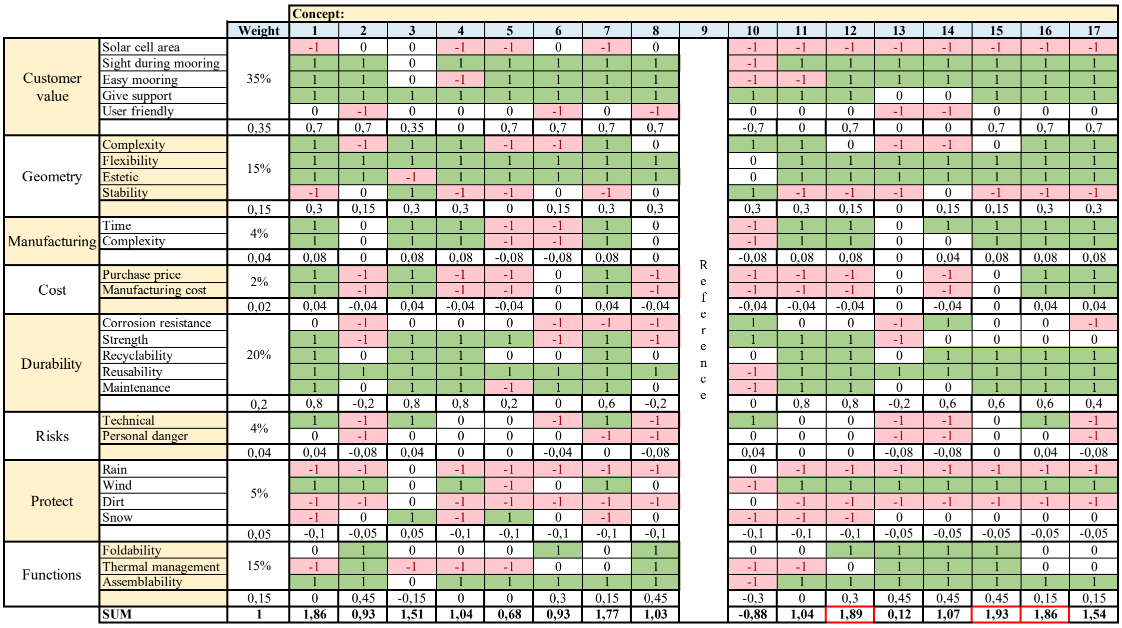


Figure 3.5: *Illustrations of the concepts in Chalmers' second Pugh matrix*

Table 3.3: Chalmers' second Pugh matrix



			Concept:																
		Weight	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
Customer value	Solar cell area	35%	-1	0	0	-1	-1	0	-1	0	Reference	-1	-1	-1	-1	-1	-1	-1	-1
	Sight during mooring		1	1	0	1	1	1	1	1		-1	1	1	1	1	1	1	1
	Easy mooring		1	1	0	-1	1	1	1	1		-1	-1	1	1	1	1	1	1
	Give support		1	1	1	1	1	1	1	1		1	1	1	0	0	1	1	1
	User friendly		0	-1	0	0	0	-1	0	-1		0	0	0	-1	-1	0	0	0
		0,35	0,7	0,7	0,35	0	0,7	0,7	0,7	0,7		-0,7	0	0,7	0	0	0,7	0,7	0,7
Geometry	Complexity	15%	1	-1	1	1	-1	-1	1	0		1	1	0	-1	-1	0	1	1
	Flexibility		1	1	1	1	1	1	1	1		0	1	1	1	1	1	1	1
	Estetic		1	1	-1	1	1	1	1	1		0	1	1	1	1	1	1	1
	Stability		-1	0	1	-1	-1	0	-1	0		1	-1	-1	-1	0	-1	-1	-1
		0,15	0,3	0,15	0,3	0,3	0	0,15	0,3	0,3		0,3	0,3	0,15	0	0,15	0,15	0,3	0,3
Manufacturing	Time	4%	1	0	1	1	-1	-1	1	0		-1	1	1	0	1	1	1	1
	Complexity		1	0	1	1	-1	-1	1	0		-1	1	1	0	0	1	1	1
		0,04	0,08	0	0,08	0,08	-0,08	-0,08	0,08	0		-0,08	0,08	0,08	0	0,04	0,08	0,08	0,08
Cost	Purchase price	2%	1	-1	1	-1	-1	0	1	-1		-1	-1	-1	0	-1	0	1	1
	Manufacturing cost		1	-1	1	-1	-1	0	1	-1		-1	-1	-1	0	-1	0	1	1
		0,02	0,04	-0,04	0,04	-0,04	-0,04	0	0,04	-0,04		-0,04	-0,04	-0,04	0	-0,04	0	0,04	0,04
Durability	Corrosion resistance	20%	0	-1	0	0	0	-1	-1	-1		1	0	0	-1	1	0	0	-1
	Strength		1	-1	1	1	1	-1	1	-1		1	1	1	-1	0	0	0	0
	Recyclability		1	0	1	1	0	0	1	0		0	1	1	0	1	1	1	1
	Reusability		1	1	1	1	1	1	1	1		-1	1	1	1	1	1	1	1
	Maintenance		1	0	1	1	-1	1	1	0		-1	1	1	0	0	1	1	1
		0,2	0,8	-0,2	0,8	0,8	0,2	0	0,6	-0,2		0	0,8	0,8	-0,2	0,6	0,6	0,6	0,4
Risks	Technical	4%	1	-1	1	0	0	-1	1	-1		1	0	0	-1	-1	0	1	-1
	Personal danger		0	-1	0	0	0	0	-1	-1		0	0	0	-1	-1	0	0	-1
		0,04	0,04	-0,08	0,04	0	0	-0,04	0	-0,08		0,04	0	0	-0,08	-0,08	0	0,04	-0,08
Protect	Rain	5%	-1	-1	0	-1	-1	-1	-1	-1		0	-1	-1	-1	-1	-1	-1	-1
	Wind		1	1	0	1	-1	0	1	0		-1	1	1	1	1	1	1	1
	Dirt		-1	-1	0	-1	-1	-1	-1	-1		0	-1	-1	-1	-1	-1	-1	-1
	Snow		-1	0	1	-1	1	0	-1	0		-1	-1	-1	0	0	0	0	0
		0,05	-0,1	-0,05	0,05	-0,1	-0,1	-0,1	-0,1	-0,1		-0,1	-0,1	-0,1	-0,05	-0,05	-0,05	-0,05	-0,05
Functions	Foldability	15%	0	1	0	0	0	1	0	1		0	0	1	1	1	1	0	0
	Thermal management		-1	1	-1	-1	-1	0	0	1		-1	-1	0	1	1	1	0	0
	Assemblability		1	1	0	1	1	1	1	1		-1	1	1	1	1	1	1	1
		0,15	0	0,45	-0,15	0	0	0,3	0,15	0,45		-0,3	0	0,3	0,45	0,45	0,45	0,15	0,15
	SUM	**1**	**1,86**	**0,93**	**1,51**	**1,04**	**0,68**	**0,93**	**1,77**	**1,03**		**-0,88**	**1,04**	**1,89**	**0,12**	**1,07**	**1,93**	**1,86**	**1,54**

The second iteration aimed to achieve a larger amount of eliminated concepts. Eight concepts were decided to be further investigated, which have been highlighted with a red outlining in Table 3.3 and Table 3.4. All the eliminated concepts are examined to which categories they did not perform as expected. As in previous iterations, valuable subfunctions would still be considered if they could be incorporated into remaining concepts.

Concept 8 and 11 did not perform as well as expected, however, they were combined to a new concept, Concept 18, which was later evaluated in the Kesselring matrix as one of the highest scored concepts. The reason why the team valued these concepts is to maintain a variety of solutions to the solar system.

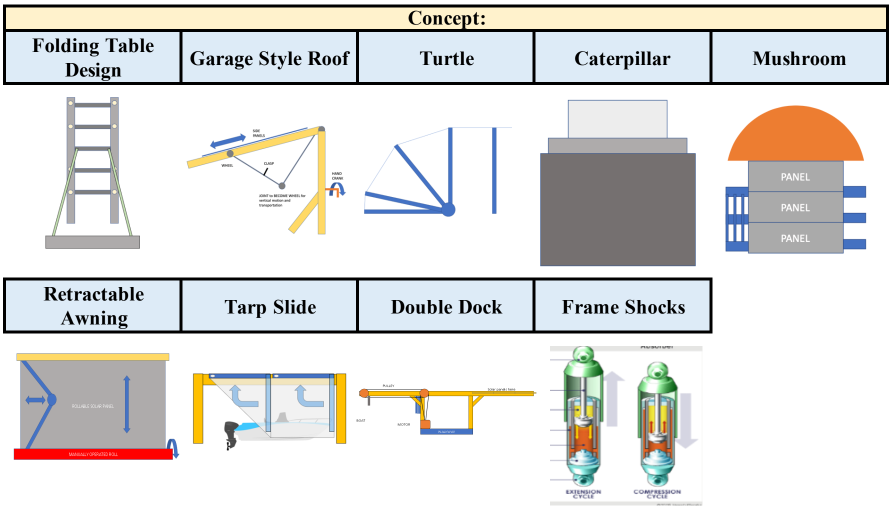
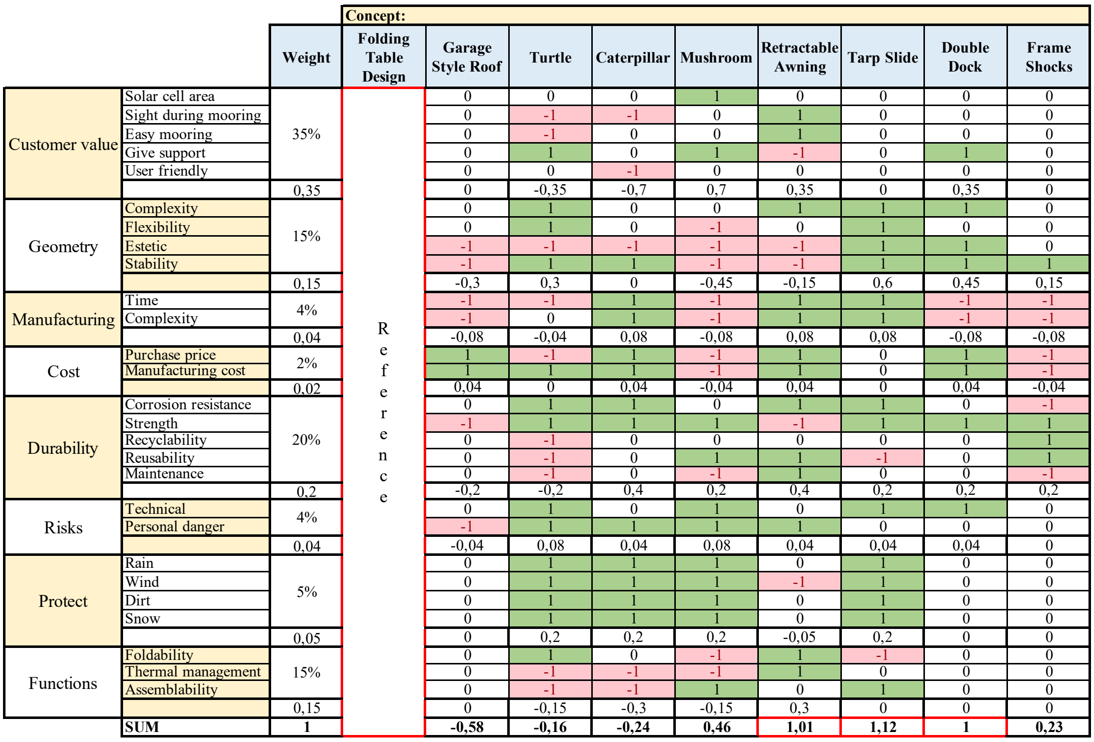


Figure 3.6: *Illustrations of the concepts in PSU's second Pugh matrix*

Table 3.4: PSU's second Pugh matrix



			Concept:								
		Weight	**Folding Table Design**	**Garage Style Roof**	**Turtle**	**Caterpillar**	**Mushroom**	**Retractable Awning**	**Tarp Slide**	**Double Dock**	**Frame Shocks**
Customer value	Solar cell area	35%	Reference	0	0	0	1	0	0	0	0
	Sight during mooring			0	-1	-1	0	1	0	0	0
	Easy mooring			0	-1	0	0	1	0	0	0
	Give support			0	1	0	1	-1	0	1	0
	User friendly			0	0	-1	0	0	0	0	0
		0,35		0	-0,35	-0,7	0,7	0,35	0	0,35	0
Geometry	Complexity	15%		0	1	0	0	1	1	1	0
	Flexibility			0	1	0	-1	0	1	0	0
	Estetic			-1	-1	-1	-1	-1	1	1	0
	Stability			-1	1	1	-1	-1	1	1	1
		0,15		-0,3	0,3	0	-0,45	-0,15	0,6	0,45	0,15
Manufacturing	Time	4%		-1	-1	1	-1	1	1	-1	-1
	Complexity			-1	0	1	-1	1	1	-1	-1
		0,04		-0,08	-0,04	0,08	-0,08	0,08	0,08	-0,08	-0,08
Cost	Purchase price	2%		1	-1	1	-1	1	0	1	-1
	Manufacturing cost			1	1	1	-1	1	0	1	-1
		0,02		0,04	0	0,04	-0,04	0,04	0	0,04	-0,04
Durability	Corrosion resistance	20%		0	1	1	0	1	1	0	-1
	Strength			-1	1	1	1	-1	1	1	1
	Recyclability			0	-1	0	0	0	0	0	1
	Reusability			0	-1	0	1	1	-1	0	1
	Maintenance			0	-1	0	-1	1	0	0	-1
		0,2		-0,2	-0,2	0,4	0,2	0,4	0,2	0,2	0,2
Risks	Technical	4%		0	1	0	1	0	1	1	0
	Personal danger			-1	1	1	1	1	0	0	0
		0,04		-0,04	0,08	0,04	0,08	0,04	0,04	0,04	0
Protect	Rain	5%		0	1	1	1	0	1	0	0
	Wind			0	1	1	1	-1	1	0	0
	Dirt			0	1	1	1	0	1	0	0
	Snow			0	1	1	1	0	1	0	0
		0,05		0	0,2	0,2	0,2	-0,05	0,2	0	0
Functions	Foldability	15%		0	1	0	-1	1	-1	0	0
	Thermal management			0	-1	-1	-1	1	0	0	0
	Assemblability			0	-1	-1	1	0	1	0	0
		0,15		0	-0,15	-0,3	-0,15	0,3	0	0	0
	SUM	**1**		**-0,58**	**-0,16**	**-0,24**	**0,46**	**1,01**	**1,12**	**1**	**0,23**

3.3.2 Elimination using Kesselring matrix

The four highest scoring concepts from each teams' second Pugh matrix were further examined in a Kesselring matrix. However, from the Chalmers' second Pugh matrix, only three concepts were later examined in the Kesselring matrix. The fourth concept was a cross combination from the second Pugh matrix (Concept 8 and Concept 11).

The Kesselring matrix is a decision matrix method similar to Pugh matrices and brings further information on how the concepts perform in different aspects. Unlike the Pugh matrices, the Kesselring matrix evaluates the concepts against an ideal score, rather than a concept-reference. Also, as can be seen in Table 3.7, this method takes the number of weak points into consideration. A weak point is a low score, a 1 or 2, in one of the evaluation points, which can reveal potential difficulties in further developing the concept in question.

Since a separate concept generation was conducted in this project, which included the Pugh matrices, it was of importance to evaluate the remaining concepts towards each other fairly. The understanding of certain concepts might differ between the parts of the team who developed them, therefore a grading base was designed to address this by clarifying the grading standards. Seven evaluation points which were considered more important were brought up and designed to give a greater understanding, see Table 3.5. Some of the categories used in the Pugh matrix were not providing the desired comparison between the concepts. A full row where all the concepts perform better or worse than a certain reference does not provide sufficient information to effectively evaluate the concepts, though these have given information on how the project in itself has weaknesses.

Some of the categories were discovered to slightly overlap, for example, the Geometry aspect was closely related to both how well the garage protected the boat from different weathers and mounting complexity. Also all the evaluation points under the aspect Functions were chosen to be discarded since the possibilities in further developing which functions are compatible with each concept were hard to investigate at this stage in the project.

Table 3.5: Evaluation points for the Kesselring matrix

Protection of boat	
Number of proteced sides	Value
1/2 side	1
1 side	2
2 side	3
3 side	4
>4 side	5

Solar cell area	
Coverage	Value
Very small	1
Small	2
Medium	3
Large	4
Very large	5

User friendly	
User friendly	Value
Bad	1
Less bad	2
Intermediate	3
Decent	4
Good	5

Design strength	
Rigidity	Value
Bad	1
Less bad	2
Intermediate	3
Decent	4
Good	5

Waves damping	
Ability to withstand waves	Value
Bad	1
Less bad	2
Intermediate	3
Decent	4
Good	5

Mounting complexity	
Procedure	Value
Difficult	1
Less difficult	2
Intermediate	3
Decent	4
Simple	5

Wind handling	
Wind break	Value
High	1
Less high	2
Intermediate	3
Little	4
Low	5

While removing the evaluating points that were superfluous, the remaining percentages were distributed between the rest of the weightings. The evaluation weights now advocated the importance of each point with greater precision and were therefore expected to give a more reliable elimination process, see Table 3.6 below.

Table 3.6: Evaluation weights

Evaluation weigths	
Solar cell area	24%
Waves damping	18%
Design strength	16%
User friendly	12,5%
Protection of boat	12,5%
Wind handling	10%
Mounting complexity	7%

When the concepts are evaluated in the Kesselring matrix a value (v) for each criteria is set for each concept. The value is then multiplied with the weighted value (w) for the specific criteria which gives a total value (t). When all values are given, the total value (t) for each concept is summed up to a total weighted value (T). The total weighted value is the final comparison between the concepts and the ones with low scores are objects for elimination. The concept with the highest total weighted value is the remaining concept from the Kesselring matrix. However, as mentioned above, the weak points should also be in consideration when the remaining concept is established. The result of the Kesselring matrix is seen below in Table 3.7. In Figure 3.7 an illustration of the concepts in the Kesselring matrix is presented, for more information about them see the Concept catalogue in Appendix A.

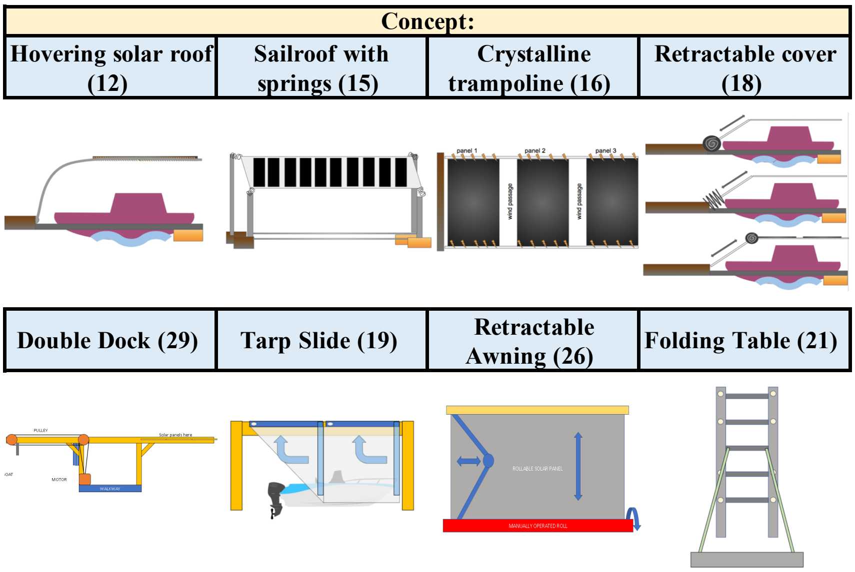


Figure 3.7: *Illustrations of the concepts in the Kesselring matrix*

Table 3.7: Kesselring matrix

		Kesselringmatrix:																	
Criteria		**Alternative**																	
		Ideal		**Hovering solar roof (12)**		**Sailroof with springs (15)**		**Crystalline trampoline (16)**		**Retractable cover (18)**		**Double Dock (29)**		**Tarp Slide (19)**		**Retractable Awning (26)**		**Folding Table (21)**	
Name	w	v	t	v	t	v	t	v	t	v	t	v	t	v	t	v	t	v	t
Solar cell area	0,24	5	1,2	3	0,72	4	0,96	4	0,96	5	1,2	5	1,2	5	1,2	3	0,72	4	0,96
Waves damping	0,18	5	0,9	5	0,9	4	0,72	4	0,72	5	0,9	5	0,9	4	0,72	5	0,9	5	0,9
Design strength	0,16	5	0,8	3	0,48	4	0,64	4	0,64	3	0,48	4	0,64	4	0,64	2	0,32	3	0,48
User friendly	0,125	5	0,625	5	0,625	5	0,625	5	0,625	4	0,5	5	0,625	5	0,625	4	0,5	4	0,5
Protection of boat	0,125	5	0,625	2	0,25	2	0,25	2	0,25	3	0,375	2	0,25	4	0,5	2	0,25	2	0,25
Wind handling	0,1	5	0,5	3	0,3	2	0,2	4	0,4	3	0,3	4	0,4	2	0,2	3	0,3	3	0,3
Mounting complexity	0,07	5	0,35	2	0,14	4	0,28	2	0,14	2	0,14	3	0,21	4	0,28	4	0,28	4	0,28
T (Total weighted value)		5		3,415		3,675		3,735		3,895		4,225		4,165		3,270		3,670	
T / T ideal		1,00		0,68		0,74		0,75		0,78		0,85		0,83		0,65		0,73	
Average		5,00	0,71	3,29	0,49	3,57	0,53	3,57	0,53	3,57	0,56	4,00	0,60	4,00	0,60	3,29	0,47	3,57	0,52
Std-deviation		0,00	0,22	0,98	0,22	0,90	0,24	0,90	0,23	0,94	0,28	0,86	0,27	0,57	0,23	0,90	0,21	0,78	0,23
Median		5,00	0,63	3,00	0,48	4,00	0,63	4,00	0,63	3,00	0,48	4,00	0,63	4,00	0,63	3,00	0,32	4,00	0,48
Number of weak points				2		2		2		1		1		1		2		1	
Ranking				7		5		4		3		1		2		8		6	
Decision		Choose alternative "Double Dock" concidered it got the highest T/T ideal-value																	

The result from the Kesselring matrix shows that the Double Dock concept came out as the highest scoring and remaining concept. The concept stood out because of the high solar cell area, design strength, user friendliness and the addressing of problematic wave dynamics. Furthermore, it has only one week point which also is the best outcome in this Kesselring matrix.

To investigate the robustness of the evaluation the weighting values were slightly alternated. If the weightings stay at the same place but the values differ the Double Dock is still the concept with the highest score. However, if the evaluation weights switch places it is not ensured that the Double Dock is the one with the highest score. The result of having the Double Dock as the remaining concept is for this reason slightly unstable and depends on the priorities decided in early stages of the project.

The chapter Concept Generation included both the methodologies regarding generation of concepts but also the evaluation and elimination. This particular part of the project was considered extra important since usage of solar energy in marine infrastructure is sparse. By using several iterative elimination-matrices, the robustness of the evaluation process was improved and led into further development of the remaining concept, the Double Dock, which is covered in Chapter 4.

4 Further Development of the Final Concept

Many aspects of the Double Dock design had not been fully considered or optimized during idea evaluation and required further development. This section will describe the continued development of the remaining concept.

The remaining concept, the Double Dock, can be attached to an existing concrete walkway at a marina. Figure 4.1 displays the initial illustration of the Double Dock concept and the system components that were intended to be created. The cantilever beam was initially added in an attempt to provide stability to the supports housing the panels without the need for an attachment that protrudes into the water. However, a two-sided structure offers the additional benefits of housing more than one boat and allowing slips to share certain electrical features. The system was also created with intentions of including a pulley system to simplify the removal of the solar panels.

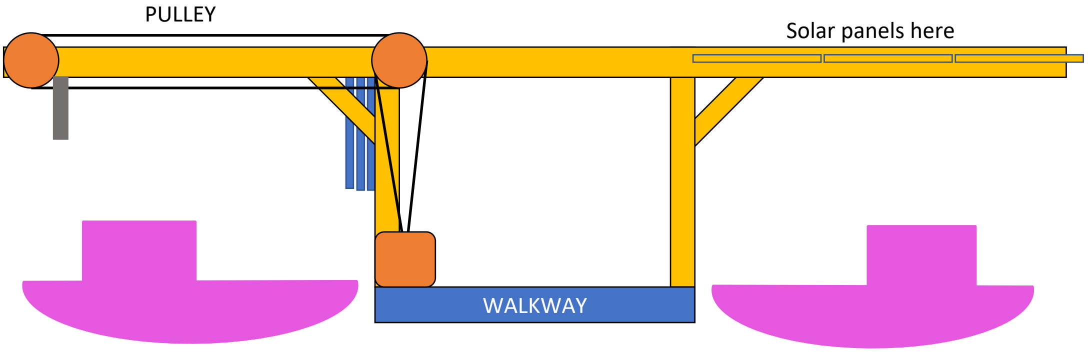


Figure 4.1: *Initial Illustration of the Double Dock Concept*

4.1 Subsystems

The overall system has to perform certain fundamental tasks. These tasks, although often independent of one another, are paramount to the efficacy of the system as a whole. In order to address these essential tasks, the system was broken down into the following subsystems; Panels & Electric, Panel Retraction, Wheels & Hinges, Rail System and lastly Posts & Beams. These subsystems are shown below in Figure 4.2. This added detail to the further development of the Double Dock system.

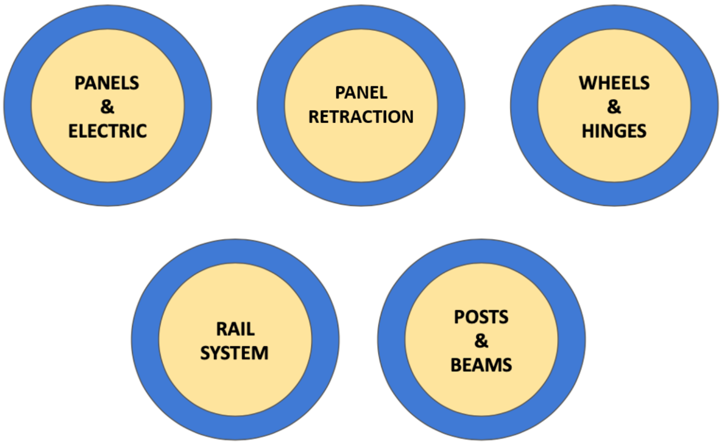


Figure 4.2: *Distribution of the Subsystems*

The primary objective of dividing the concept into subsystems was to determine what tasks these subsystems should mechanically accomplish. The specifics of materials, dimensions, and structural integrity were unknown at this point in the team's concept development. Considerations and necessary components to accomplish these tasks are discussed below.

4.1.1 Panels & Electrical system

The panels and electrical components are responsible for absorbing and converting solar irradiation into electrical energy and delivering it to the grid to offset the energy drawn to charge the boats. It consists of a maximum power point tracker, conversions between AC and DC, cabling, on-board boat battery, the solar panels and additional AC load including lights and power sockets. All of the electric cabling must be marine-graded for harsh outdoor environments, and the placement and protection of these cables needs to be compatible with other subsystems such as the rail system.

At this point in the design process, the solar panel type was undecided between solid crystalline or rollable thin-film panels. Because the design is structurally sound and has ample flat surfaces to support the solar panel arrays, it was most likely that crystalline panels would be used.

4.1.2 Panel retraction system

To accommodate the retraction of panels, the original design incorporated a pulley and motor system, consisting of electric or hand-actuated motors. This would enable the user to bring the solar panels out for use as well as retract them when their function is not required, such as during winter months or anytime the dock is not being utilized.

It was decided that a pulley and motor were not necessary in this design. While they might ease the process of recalling and removing the solar panels, they would create a level of technical complexity which could inhibit the overall function of the design. For this design, it was instead decided that manually pulling the panels along the rail system would be more mechanically feasible and durable. This also eliminated the significant costs that would be associated with the addition of two electric motors into the design.

4.1.3 Wheels & Hinges

It was originally intended that the wheels and hinges would support the pulley and motor system in enabling the panels to be put out for use and retracted when their function is not required. Even after the deselection of the former, the wheels and hinges would still be used but with manual power to assist in panel movement, allowing the panels to be brought in towards the center of the design. Furthermore, this subsystem enables the user to completely remove the panels from the structure.

The team investigated a simpler subsystem consisting of wheels, hinges, joints, bearings, and clasps. Even after the simplification, this is still the most intricate of the subsystems, as well as the most susceptible to damage. It could include many varied movement mechanisms ranging from spinning wheels to folding hinges, which may have difficulty in marine environments if not properly protected from the elements.

4.1.4 Rail system

The rail system offers the wheels a guide for movement, and it consists of a metallic or plastic C-Rail that is attached to the metal cantilever. To properly support the panels for both horizontal and vertical hanging, the C-rail must be made of a high-strength material with strong corrosion resistance, should any environmental elements be exposed to or get trapped within the rail.

4.1.5 Posts & Beams

The structural components of the design must provide the necessary strength to support their own weight as well as the weight of all other subsystems. This subsystem consists of high strength supportive and cantilever bodies. The material used must provide strength and corrosion-resistance while remaining slightly flexible, due to the high winds associated with the marina environment.

This component of the system would be most exposed to the wave-patterns and the corrosive elements in seawater.

4.1.6 Development of subsystems

Development of the five subsystems occurred in focus groups that gathered information on the specific constraints relating to each subsystem, in order to create possible solutions and share the results with the team. The final decisions could therefore be made with a consensus between the members of this project. By focusing each group's research on a certain part of the design, a more detailed description of each subsystem was accomplished.

4.2 Stress analysis

In order to see if the structure would meet the strength requirements, a comprehensive strength analysis of the design was performed. Using an Excel spreadsheet, online resources such as ASME standards (The Engineering ToolBox, 2001), and relevant strength of material textbooks (Dowling, 2013; Hibbeler, 2016), requirements of the design were computed. Although this analysis was comprehensive and helped to guide material selection, necessary component quantity, and specimen dimension/limitation, it did not supplant the value of a formal finite-element analysis or other computational tool.

4.2.1 Constraints

The analysis model depended on the strength and material characteristics of the Double Dock's structural framework as well as the wharf it is being attached to. In order to constrain the design, a provisional wharf was selected. The selected wharf was a concrete pontoon with a three meter wide walkway. The material and dimensions chosen for the uprights, cantilevers, crossbeams, bolts and braces still needed to be determined. The aforementioned stress analyses model aided in this.

4.2.2 Structural analysis

This structural analysis process is presented to orient the reader with the proposed analysis methods. The results of this analysis were to be collected and presented with the final concept. Initial estimations on photovoltaic panel mass and cantilever extension were used to construct the analysis model. A side view of the system design was used to define certain features such as the left and right uprights, cantilevers, and T-Plates. Side supports were implemented to support the load of the solar panels. Furthermore, this side view was used as a measure to illustrate load distribution, see Figure 4.3. This information gave insight into sections of high stress.

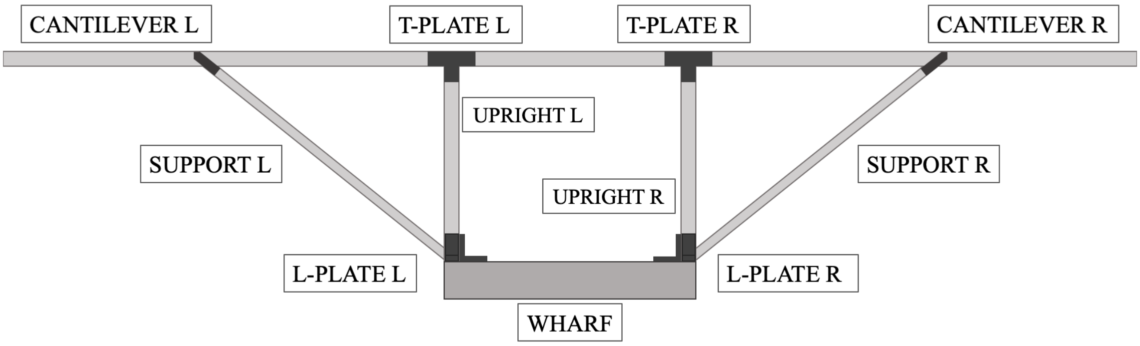


Figure 4.3: *Structure Features (side view)*

To develop an understanding of material performance, four distinct materials with different cross sections were selected for analysis. Two hollow square members and two hollow circular members of distinct steels and aluminum alloys were used. This provided 16 single-material framework resolutions. The materials and cross sections are shown below in Table 4.1. Although different sections of the design could be constructed with different materials, a single material design was preferred because of corrosion considerations.

Table 4.1: Material cross sections

Cross Sections	**Dimensions**		**Material 1**	**Material 2**	**Material 3**	**Material 4**
	[inch]	**[mm]**				
Hollow square	**6 x 6 x 0.5**	**152.4 x 152.4 x 12.7**	High Strength Steel	Galvanized Steel Grade 33	6061-T6	2024-T3
Hollow square	**4 x 4 x 0.5**	**101.6 x 101.6 x 12.7**	High Strength Steel	Galvanized Steel Grade 33	6061-T6	2024-T3
Hollow circular	**6 x 0.5**	**152.4 x 12.7**	High Strength Steel	Galvanized Steel Grade 33	6061-T6	2024-T3
Hollow circular	**4.5 x 0.375**	**114.3 x 9.525**	High Strength Steel	Galvanized Steel Grade 33	6061-T6	2024-T3

The analysis was divided into five primary areas of interest - cantilevers, uprights, plates, bolts and dock. The cantilevers and uprights required shear and bending stress analysis; the plates, including T-Plates and L-Plates, required bearing stress analysis; the bolts required, in varying instances, shear, axial and bearing stress analyses; the concrete required a bearing stress analysis (The National Concrete Masonry Association, 2013). Additionally, the cantilevers required a deflection analysis and the uprights required a buckling analysis.

4.3 CAD

To gain a perspective of the final concept, a 3D CAD-model was constructed in the online tool OnShape (2014). The CAD-work helped the dimensioning of the system as well as visualizing the functions with applied animations and constrains. From the CAD-work, drawings of the Solar Wharf Garage could be generated and the model is presented in Section 5.

4.4 Strength simulations

As a complement to the stress analysis, simulations were made in SimScale (2013) using a cantilever beam from the OnShape CAD-model. This more formal analysis was performed to validate the theoretical stress analysis discussed in Section 4.2. Furthermore, it provided the team with more precise measurements of stress and deflection.

Since the solar panels could be rearranged in the middle, the cantilever was divided into four subsections, the inner and outer left cantilever and the inner and outer right cantilever. The organization of the panels fundamentally alters the location of load application. This is best shown in Figure 4.4.

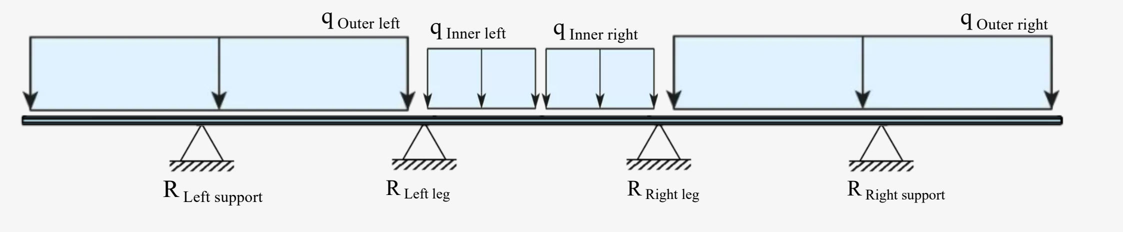
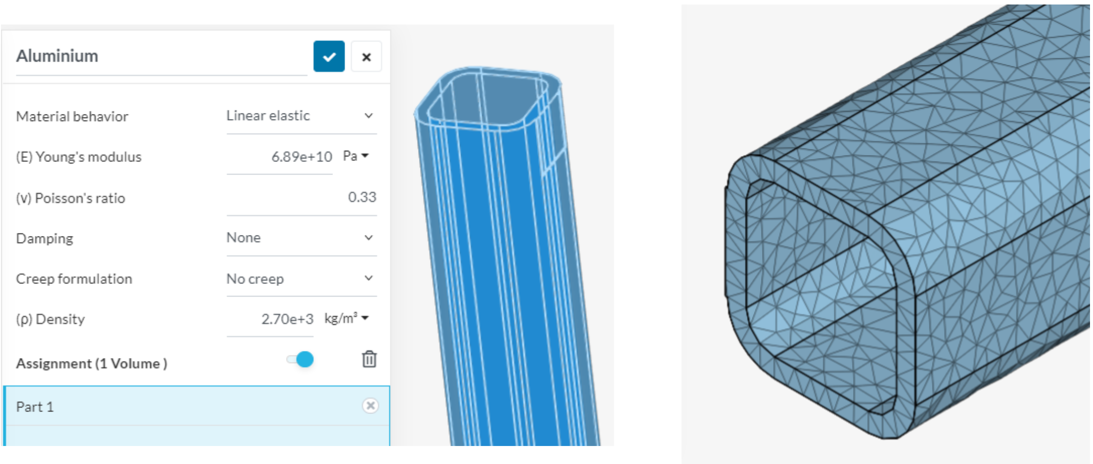


Figure 4.4: *Loads and Supports*

For the simulations in SimScale, material was chosen and data for the 6061-T6 Aluminum Alloy inserted, see Figure 4.5a. The model was then divided into small finite elements resulting in a mesh for which displacement and stress could be calculated, Figure 4.5b.



Aluminium

Material behavior: Linear elastic

(E) Young's modulus: 6.89e+10 Pa

(v) Poisson's ratio: 0.33

Damping: None

Creep formulation: No creep

(ρ) Density: 2.70e+3 kg/m³

Assignment (1 Volume)

Part 1

(a) *Material selection*

(b) *Mesh generation*

Figure 4.5: *SimScale simulation setup*

The simulation could analyze the material choice and structural strength, and was a helpful tool for deciding and verifying that the material selection and the geometry was adequate.

Development of the Double Dock concept was made through each subsystem, followed by how these interacted with each other to fulfill the requirements of the Solar Wharf Garage. Illustrative figures widened the understanding of the strength and weaknesses in the design. The main purpose of this part was to ensure an advantageous usage of the entire system both regarding its location and the targeted users. With the research and development conducted in this chapter, a final design was formed and is further described throughout the rest of the report.

5 Results and illustrations of the Solar Wharf Garage

The further development has given more detail to the Double Dock concept, and this section presents specifications regarding the concept. Description of the concept, the final subsystem components, the modeling, manufacturing and maintenance, accompanied with the various calculations used to analyze the system, concludes the Solar Wharf Garage development.

5.1 Final concept

The final concept was the Double Dock which is illustrated in Figure 5.1. The concept is a two-boat-garage for boats opposite to each other and made up of an aluminum square hollow beam structure attached to an existing concrete wharf. The garage consists of 18 crystalline solar panels with 9 over each boat slip. The solar panels are arranged in modules of three and slides on the inside of the cantilevers in a rail-system.

This section illustrates the development of the concept and revisits the five subsystems described earlier in Section 4.1. Each subsystem is described in its final form below, to provide a complete overview of the final design. The most significant features of the design have stayed constant, including its four-point attachment to the dock, the long overhead beam which will support the panels, and a user-friendly removal system for the panels. However, each of these components have now been thoroughly discussed and detailed, with all of the considerations mentioned in mind.

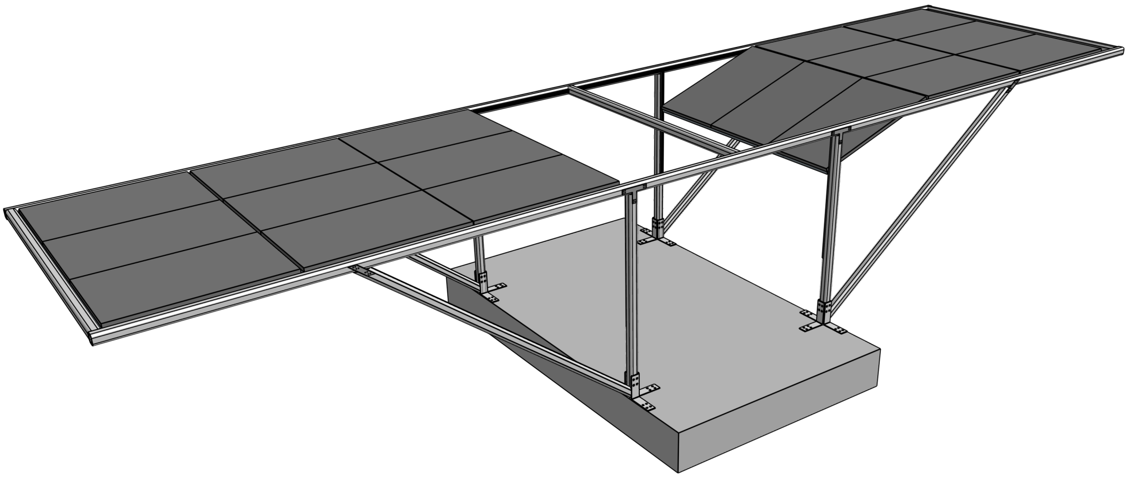


Figure 5.1: *Final CAD rendering of Double Dock*

5.1.1 Final Panels & Electrical system

Because of the limited available surface area constrained by the slip dimension, relative to most photovoltaic systems that are attached on roofs, the solar panel chosen for this project was the high-end 60-cell monocrystalline panel from LG named LG370Q1C-V5 (LG, 2020). This high-performance model comes at an above average price tag, but ensures that the panel system would meet functional requirements. It has a maximum power output of 370 W at Standard Test Conditions (meaning irradiance 1000 W/m^2, cell temperature 25° C and AM 1.5), a high efficiency of 20.8% and the module is guaranteed to produce at least 90.8% of its labeled power output. A protection degree IP68 with 3 bypass diodes ensures optimized conditions in the current environment. The panel weight is 17.5 kg and the dimensions of each module is 1700 x 1016 x 40 mm^3 which then allows for 9 panels to be attached above each slip, making it a total of 18 panels for the final Double Dock design.

This subsystem will be grid-connected to double as a passive income generator and potential battery bank. Most of the annual electricity production will be excess, and while the system is overproducing electricity, it sells to the grid. When the production is low, and there is an energy need, the marina can instead purchase electricity from the grid, with the grid functioning as a "virtual battery". From a sustainable aspect, this is beneficial since most of the energy is otherwise wasted.

To enable conversion from the panels or from the grid to the battery, and to supply additional appliances and feedback into the grid, a Multi Port Converter will be implemented in the system to manage the required transformations. Due to the combinations of different inverters within this system, there are multiple electrical constraints, see Section 5.5, that must be accommodated since the power levels are diverse for the different inputs/outputs. This conversion could instead have been solved by always feeding the produced solar power to the grid and extracting what is necessary for the battery directly from the grid as well. Which is the more conventional solution since the presented converter is not available on the market today, but then the battery would never be directly fed by the produced solar power from the garage.

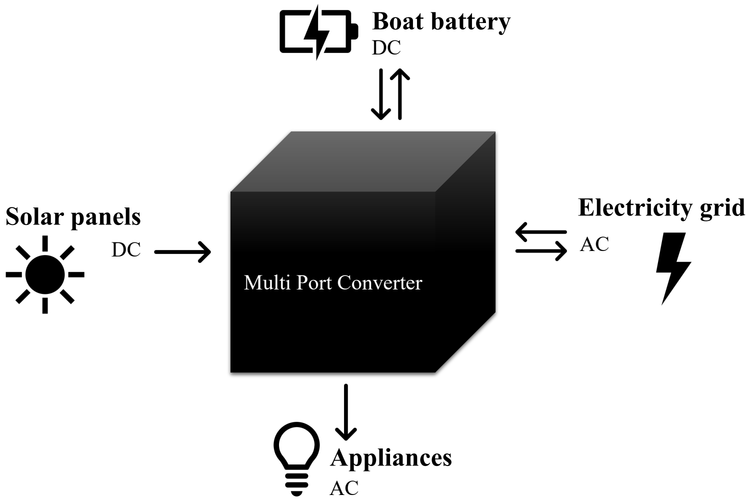


Figure 5.2: *The Multi Port Converter will have 4 inputs/outputs; one DC input for solar, one DC input/output for the boat battery, one AC input/output for the grid and one AC output for additional loads (appliances).*

The Multi Port Converter will need to withstand harsh conditions including rain, humidity, heat and dirt, while at the same time generating and delivering power. The use of a high quality inverter to uphold a sufficient lifetime is therefore required - this will raise the final cost of the product. The device's installment position depends on the characteristics of the wharf but will likely be located on the end of the wharf or attached to one of the supports. The necessary cabling is to be ordered by professionals to ensure sufficient safety standards in accordance with the Swedish Electricity Safety Agency (Elsäkerhetsverket, 2019). IP65 classification is recommended, which describes the degree of protection of enclosures. It is suitable for most outdoor enclosures that will not encounter extreme weather such as flooding (NoWire, 2019).

5.1.2 Final Panel retraction system

Manual power will be used to pull the solar panels towards the dock. Each row of solar panels will be connected with steel cabling and will be kept more tight than the inter-beam electrical wiring, wherein one beam is defined as one row of solar panels. This ensures tension will not be put on the electric wiring between paneling, but the steel cabling instead as the panels are retracted. The panel modules slide through the rail-system on the inside of the cantilevers and down the uprights, as shown in Figure 5.3. The panels can then be detached from each other, and either hung in the middle or taken down by letting the back wheel slide down the upright. The rails and wheels are further described in the following sections.

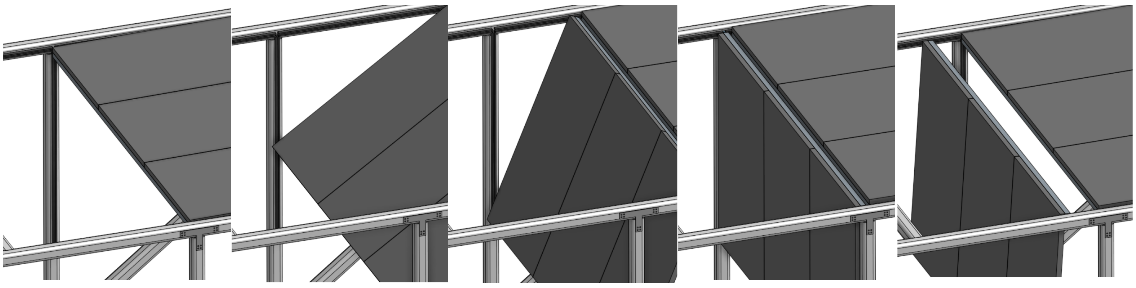


Figure 5.3: *Illustration of solar panels being retracted*

5.1.3 Final Wheels & Hinges

Each solar module will be connected to a wheel system similar to those seen on sliding doors, shown in Figure 5.4. These will allow the panels to shift freely as they are moved. Locks on the wheels will prevent the panels from moving while they are in use. This is the most intricate of the subsystems, and the most susceptible to damage. Because of this, the final design includes a plastic cover over the wheels and railings. This will help keep moisture out of the wheel system, increasing its lifespan, and preventing premature system failure. This product will also use standard hinges and clasps. These pieces will be responsible for connecting each of the subsystems to each other.

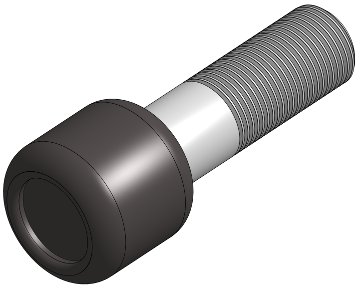
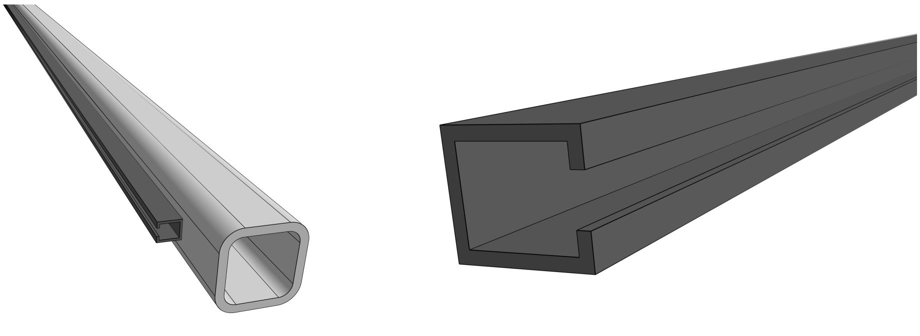


Figure 5.4: *Type of wheel used for panel retraction*

5.1.4 Final Rail system

The wheels are an integral part of the aluminum C-rail system, seen in Figure 5.5. This rail will be attached to the metal cantilevers and the length of the slip. This will allow for easy movement of panels to shift them towards the dock for maintenance or removal. Once a solar beam is slid towards the dock, the wheels will follow the rail as it curves vertically downward. The beams could then be hung over top of the dock or shifted out over the water. The panels can be fully lifted off of the rail at this position in order to remove them from the system. The removal of panels from one side of the Double Dock does not require removal from the alternate side, meaning that both, one, or neither slips could be utilized at any time.



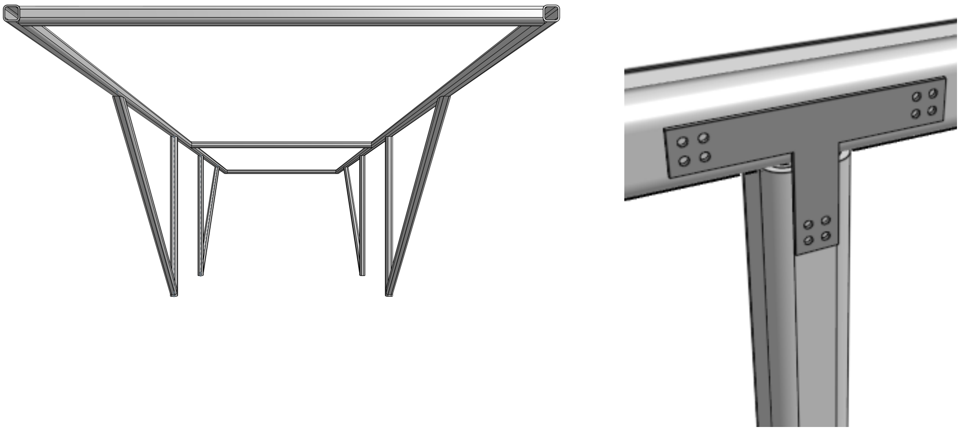
(a) *Attached C-rail* (b) *C-rail*

Figure 5.5: *C-rail system*

5.1.5 Final Posts & Beams

The most significant decision made about the posts and beams was the material selection. The team selected 6061-T6 AA for all structural and supportive members, which is motivated in Section 5.2. The decision to move forward with a single-material design reduces the risk of corrosion.

The structure consists of two 152.4 x 152.4 x 12.7 mm (6 x 6 x 0.5") hollow square cross-section cantilevers that span over both boat slips and the dock at a total of 13.5 meters, see Figure 5.6a. These beams are supported by four vertical posts, each fastened to the dock with anchorage L-plates and bolts. The two cantilevers are also connected with a series of three horizontal beams, specifically a single horizontal beam at the end of both cantilevers and one in the middle of the structure over the walkway. These beams resist horizontal displacement of the cantilevers and excess torsional strain in the uprights due to lateral forces such as wind. Hollow square cross-sections were selected because of their high performance under bending and torsion. Furthermore, these hollow square cross-sections enabled simple T-Plates to connect orthogonal members, see Figure 5.6b, which also avoided welding and thereby enabled flexibility. To enhance the structural integrity of the system and ensure it can withstand the load of the solar panels, an angled side brace was attached between each post and beam.



(a) *Square hollow beam structure* (b) *T-plate*

Figure 5.6: *Post & Beams*

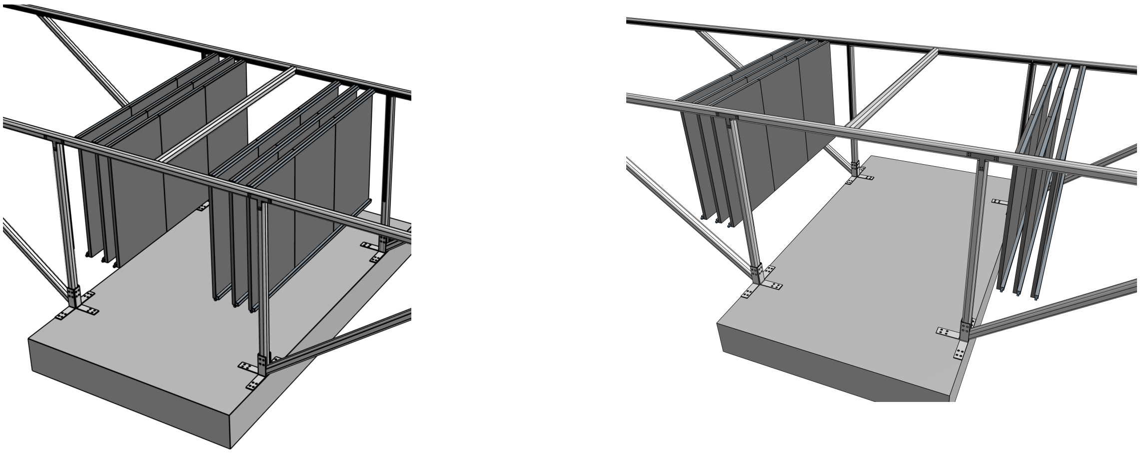
5.2 Materials

When deciding on the structure's material, the team considered two of the materials discussed earlier; aluminum and stainless steel. Galvanized steel was disregarded because of the superior qualities of the other two material types. Both aluminum and stainless steel provide adequate strength, fatigue behavior, and corrosion resistance, but aluminum comes at a significantly lower price than stainless steel although more material is necessary to carry the same load. To prioritize customer needs at an appropriate cost, the team decided it was reasonable to proceed with aluminum, even though stainless steel provides slightly more strength and corrosion resistance. Furthermore, the team chose aluminum alloy 6061-T6 over the aluminum alloy 2024-T3 because of superior corrosion resistance of the 6061-T6 variety. As demonstrated in Section 5.4, 6061-T6 aluminum is shown to satisfy and exceed the structural safety requirements of the system.

The team has also considered a variety of materials for side coverage or additional overhead coverage where the structure may not fully protect the boat. Possible materials include a carbon-fiber sail material, agricultural tarping material using reinforced polyethylene, and nylon materials. Each of these coverage materials makes the system more susceptible to the wind, so there is a need for the material to be extremely flexible and lightweight.

5.3 CAD and Drawings

The CAD-work resulted in a 3D-model of the Solar Wharf Garage attached to a concrete pontoon wharf, see Figure 5.1. Through animation software in OnShape, functions were further tested and verified, and the main function of the rail-system turned out successful. As can be seen in Figure 5.7a and 5.7b, the functions of the rail system enables the panels to either hang over the wharf or over the boat slip to make room on the wharf. Attached in the Appendix C is a Drawing of the square hollow beam structure with measurements.



(a) *Retracted panels hanging over the dock* (b) *Retracted panels hanging over boat slip*

Figure 5.7: *Retracted panels*

5.4 Structure calculations and simulations

After a thorough analysis of material combination with respect to cantilevers, uprights, bolts and plates, a formal recommendation is here defined in Tables 5.1, 5.2, and 5.3.

Table 5.1: Total framework material, dimension and number results per product

FRAMEWORK		**Cantilever Beams**		**Upright Beams**	
Material		6061-T6		6061-T6	
Dimension		152.4 x 152.4 x 12.7 mm	13.5 m	152.4 x 152.4 x 12.7 mm	2.4 m
Cross Section	Length				
Number		2		4	

Table 5.2: Total plate material, dimension and number results per upright

PLATES	**T-Plate**	**Anchorage Bolt L-Plate**	**Upright L-Plate**
Material	6061-T6	6061-T6	6061-T6
Dimension	No requirement	9” base (minimum)	No requirement
Number	2 per Upright	1 per Upright	2 per Upright

Table 5.3: Total bolt material, dimension and number results per upright

BOLTS	**T-Plate**	**Anchorage**	**Upright L-Plate**
Material	6061-T6	6061-T6	6061-T6
Dimension (Major Diameter/head Diameter)	3/8”	1-3/4”	3/8”
	No head requirement	1-7/8”	No head requirement
Number	12 per Upright*	2 per Upright	6-8 per Upright

*12 T-Plate bolts per Upright if the bolts extend through the cantilever. Otherwise 24 bolts would be required per upright - in order that the both T-Plates are fixed on either side.

Extractions from the Excel spreadsheet that was used for calculations are provided in Appendix D. The spreadsheet computations were made without side supports and shows a beam deflection of 17 mm. Calculations show the stress of bolts with varying thickness for anchorage, baseplate, and sleeve bolts, motivating the recommended choice. The upright buckling analysis shows a great safety factor as well as the bending stress analysis. The final design showcases 152.4 x 152.4 x 12.7 mm (6 x 6 x 0.5”) square hollow 6061-T6 supporting members. It performs under extreme loading conditions and utilizes a material that has performed well historically in marine environments, AA 6061-T6. The design was analyzed in perfectly symmetric as well as asymmetric loading schemes. This ensured the design was robust even in the most improper circumstances. It must be noted that yield strengths were taken as 75% of their minimum literature values and von-Mises effective stresses were used in analysis. Furthermore, safety factors were set at a minimum of 10 for all materials and components, including the concrete. Concrete masonry standards for anchorage bolts under tensile loads were utilized.

In summary, the design is robust and safe and of a singular material. The design is corrosion-resistant, strong, fatigue-resistant, lightweight, and economical. A side view of the final design is shown below, see Figure 5.8.

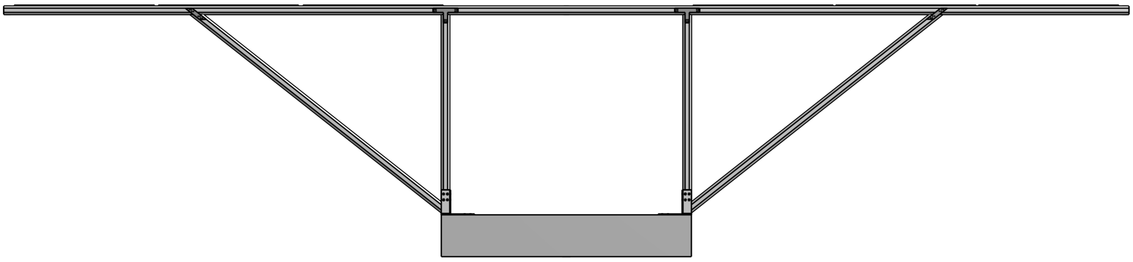


Figure 5.8: *Double Dock side view*

In addition to the structure calculations, the results from the simulations in SimScale show the displacement of the different configurations of solar panels, as stated in Section 4.4, implemented with side supports. The simulations were made with an overdimensioned load of 10 panels of 18 kg, resulting in a force of 1766 N, on each side.

The configuration with the solar panel load on the sides, see Figure 5.9, show results in a displacement of 2.4 mm which is not more than 0.1% of the total height of 2400 mm in deflection. The result was sufficient and as seen in the figure.

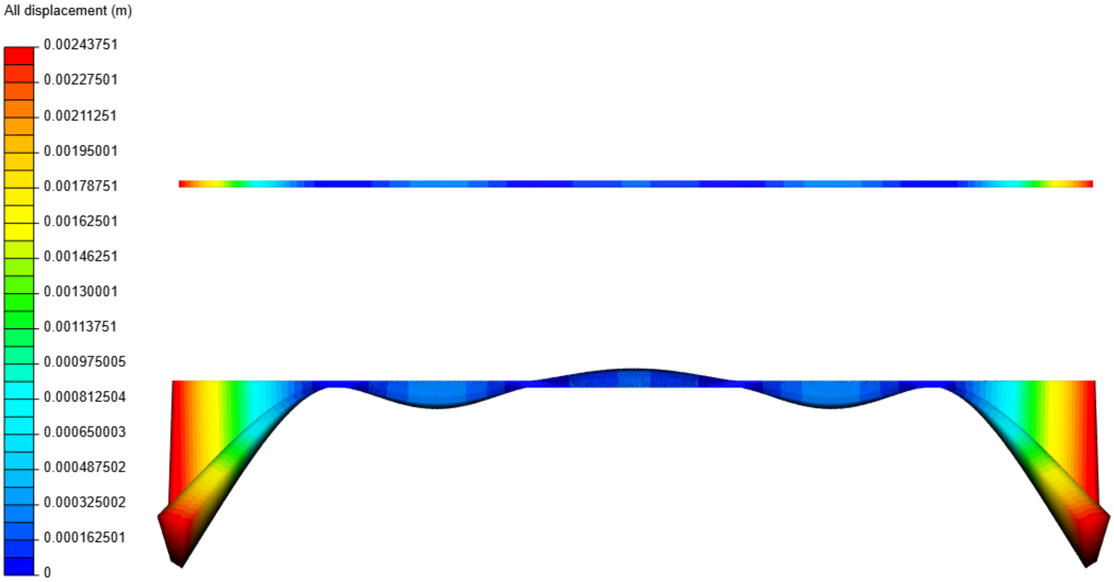


Figure 5.9: *Displacement & enlarged deformation of side panel load*

The configuration with solar panel load in the middle, see Figure 5.10, results in a displacement of 1.9 mm which is not more than 0.08% of the total height of 2400 mm in deflection. The simulation of the mid-load cantilever, as well as the side-load, results in an acceptable deflection.

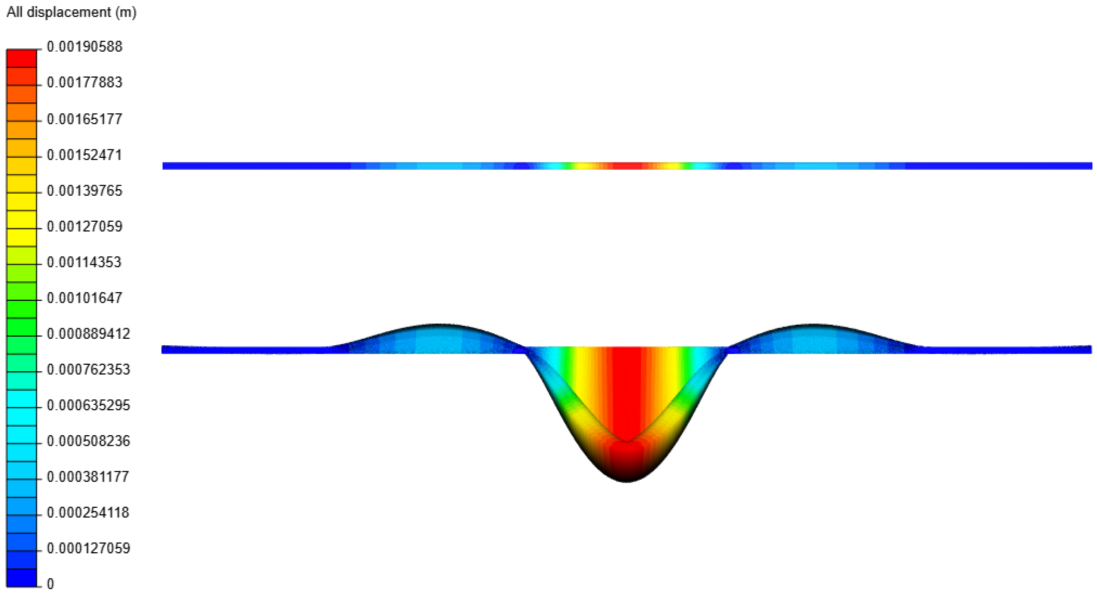


Figure 5.10: *Displacement & enlarged deformation of centralized panel load*

Analysis of the von Mises stress resulted in stress levels under the yield point of 241 MPa for the 6061-T6 AA (The Engineering ToolBox, 2001). The side load gives a safety magnitude of eight, with 28 MPa stress, and the mid load a safety magnitude of two, with 116 MPa stress.

The simulations and calculations proves the selection is suitable for the application and will not be any danger or expense due to failure.

5.5 Electrical calculations and simulations

The electrical system was designed to accommodate charging of the boat batteries once every week. This was assessed using a battery size of 30.5 kWh, which was determined from the research done on electric boats. This constraint required the generation of approximately 135 kWh each month per boat.

Solar simulations were done using the System Advisor Model (SAM) provided by NREL (2017). SAM was configured to model the system in a simplified manner, analyzing the net system performance, rather than considering each internal component. The program estimates solar performance on an hourly basis using location, panel type, system layout parameters, among others. The parameters used within this simulation was; 2 parallel subarrays with 9 panels in each connected in series per array (total area of 30.1 m^2) and 1 inverter with a ratio of 1.32 from DC to AC. The string V_{OC} at reference conditions was simulated to be 385.2 V and the V_{mp} to be 333 V. A fixed orientation with 0° tilt and no tracking was used. This gave a resulting nameplated DC capacity of 6.667 kW and a total AC capacity of 5.05 kW along with a maximum DC voltage of 480 V. Further parameters from the simulation are viewable in Appendix B.

Figure 5.11 shows the expected energy generation (kWh) from a single garage structure for each month. As shown, the system meets energy requirements each month that it is expected to be in operation (March-October). In the summer months, when boating is likely to occur more than once per week, the system accommodates for a higher number of charges. At the height of energy production rates in July, the system is expected to fully charge the battery every two-three days.

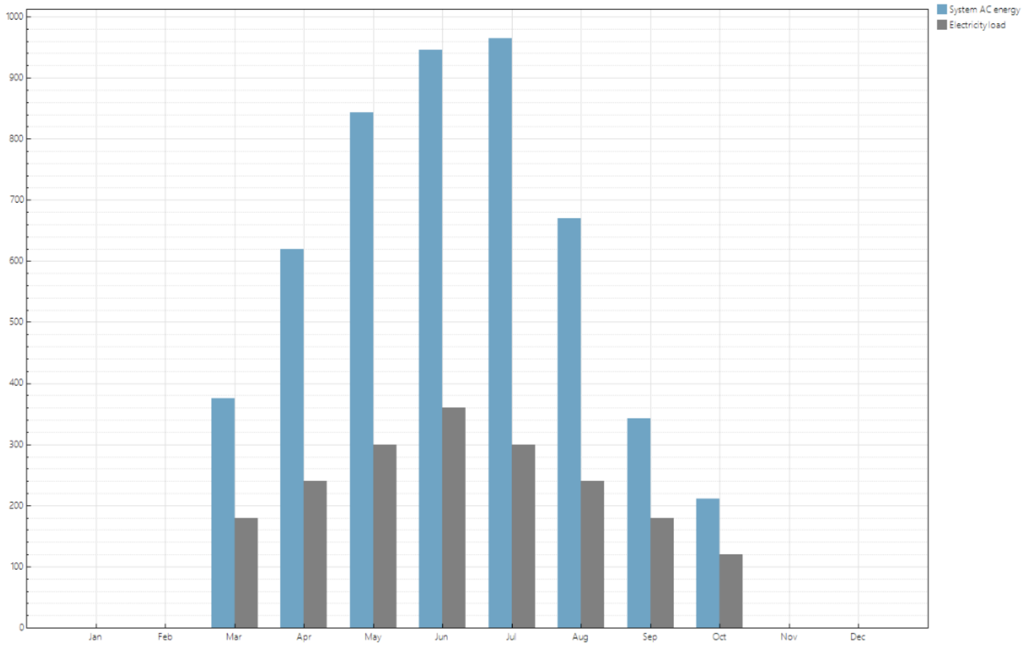


Figure 5.11: *Expected monthly Electricity load (grey) and System AC energy (blue)(kWh) from SAM (2020).*

The total monthly energy production shown in Figure 5.11 can further be broken down to show the average energy produced at each hour of the day during a specified month. This more detailed breakdown, shown in Figure 5.12, can be helpful to visually understand at what times of day the system can be expected to produce electrical energy.

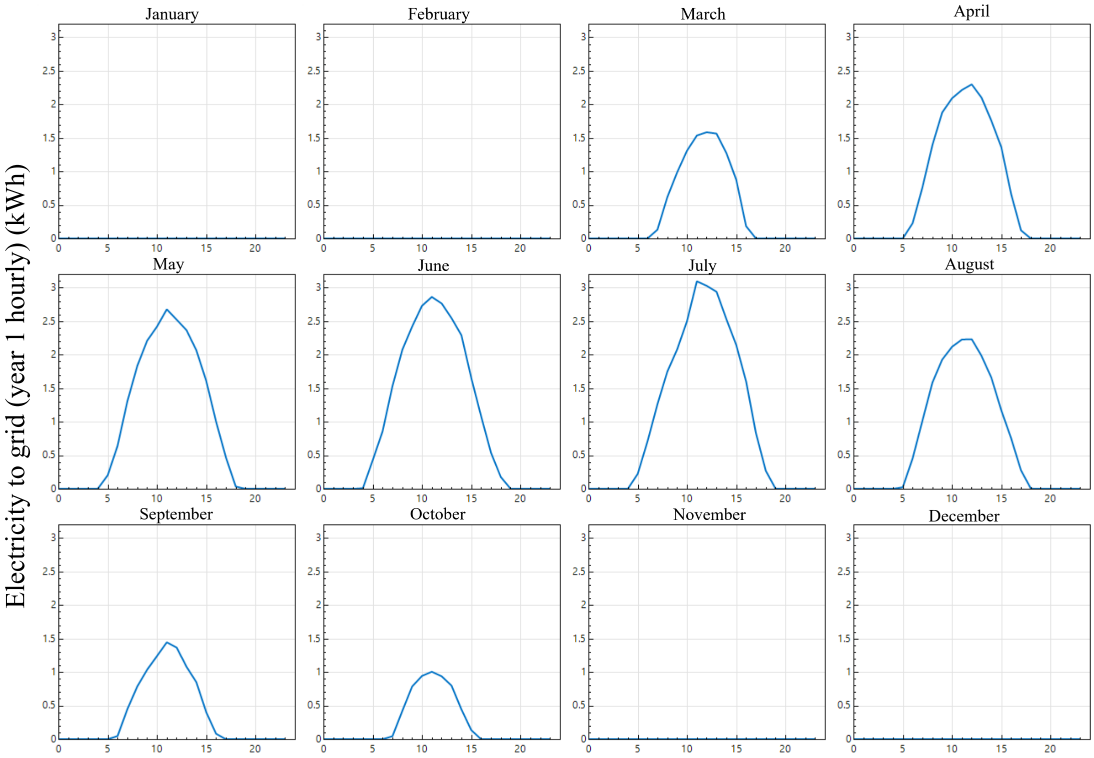


Figure 5.12: *Average energy produced at each hour of the day in a given month (SAM, 2020)*

Because the panels need to provide a higher voltage than the top voltage of the grid to the inverter, it was necessary that each slip connect all of its 9 solar panels as a single string, wired together in series, to reach that voltage. The inverter for the boat battery requires to endure the upper power constraint that the battery can receive which for this system is estimated to be 50 kW for a marine battery Akasystem 15 OEM PRC of 33 kWh from Akasol (Akasol, 2020).

For the customer to be able to use further appliances at the slip, the installation of a common 10 A 230 V (2.3 kW) socket by the wharf is considered in the design. Lastly, the Multi Port Converter part handling the grid will be dimensioned by the highest of either the battery or the panels.

5.6 Cost calculations

As a result of the Double Dock's intended uses, likely install locations, and targeted customers, project materials costs deviate from that of more typical solar photovoltaic projects. Where most photovoltaic systems are designed to utilize pre-existing structures to physically mount to (limiting costs strictly to the solar array's system components), implantation of the Double Dock's unique photovoltaic system also requires the construction of the structure for the Double Dock itself, adding additional elements to the photovoltaic system's costs.

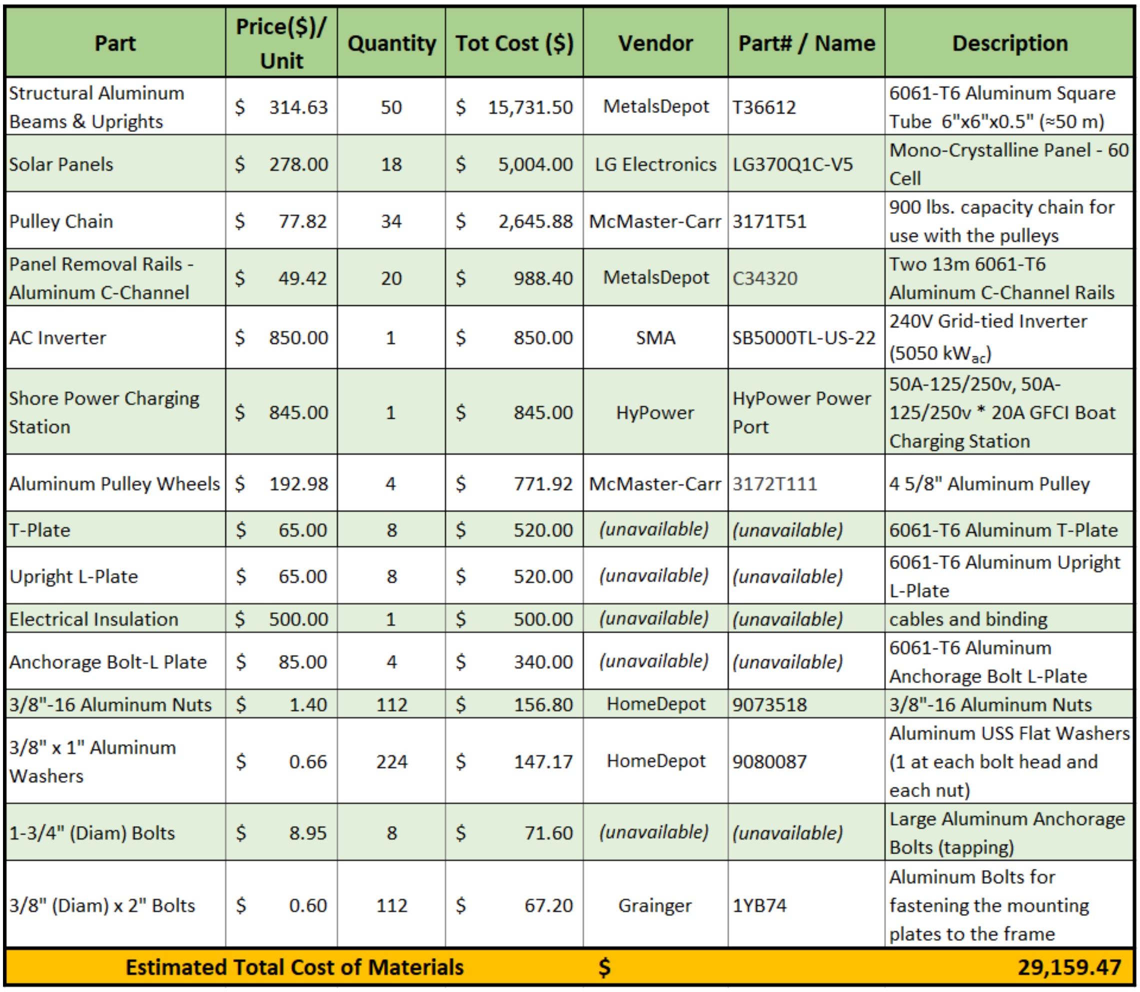
Though this addition does significantly increase the total materials cost of the system (by roughly 325%), it is important to keep in mind that, as of the time of finalizing this design, there is no other product on the market that serves the same purposes as the Double Dock, so there is no way of directly comparing prices. The total cost of materials for the Double Dock, as it is presented within this document, comes to $29,160 – or $14,580 per boat stored beneath the Double Dock's protection.

5.6.1 Total Double Dock material costs

Originally, stainless steel was the intended material of choice to make up the Double Dock's large frame, considering its corrosion resistance and high strength. Though stainless steel's physical properties make it an excellent structure material choice, it is a relatively expensive material, as mentioned in section 5.2. The price for square tube 304 stainless steel is about $1,150 per meter for 6x6x3/8" (MetalsDepot, 2020).

For comparison, the cost of the similarly performing 152.4 x 152.4 x 12.7 mm (6x6x0.5") square tube of 6061-T6 aluminum used in the Double Dock's design is substantially less at $315 per meter, see Table 5.4. It may be important to note that given the project's physical size and total combined length of aluminum required for construction, it may be possible to negotiate with the material supplier for a lower "bulk" price. However, at this time, the potential bulk cost remains an undetermined design variable, so the calculations below all use the aforementioned pricing.
Of the Double Dock's total cost of materials, about 71% of the cumulative total is attributed to by just two components: the aluminum structure and the solar panels, see Figure 5.13. Construction of the Double Dock's structure will require about 50 meters of aluminum, costing a total of $15,700 in structure materials, not including mounting hardware, as shown in Table 5.4. As displayed graphically in Figure 5.13, it can easily be seen that the cost of the aluminum structure material is the single largest contributor to the Double Dock's total materials cost, accounting for 54% of the total.

Table 5.4: Total bill of materials



Part	Price($)/ Unit	Quantity	Tot Cost ($)	Vendor	Part# / Name	Description
Structural Aluminum Beams & Uprights	$ 314.63	50	$ 15,731.50	MetalsDepot	T36612	6061-T6 Aluminum Square Tube 6"x6"x0.5" (≈50 m)
Solar Panels	$ 278.00	18	$ 5,004.00	LG Electronics	LG370Q1C-V5	Mono-Crystalline Panel - 60 Cell
Pulley Chain	$ 77.82	34	$ 2,645.88	McMaster-Carr	3171T51	900 lbs. capacity chain for use with the pulleys
Panel Removal Rails - Aluminum C-Channel	$ 49.42	20	$ 988.40	MetalsDepot	C34320	Two 13m 6061-T6 Aluminum C-Channel Rails
AC Inverter	$ 850.00	1	$ 850.00	SMA	SB5000TL-US-22	240V Grid-tied Inverter (5050 kW_{ac})
Shore Power Charging Station	$ 845.00	1	$ 845.00	HyPower	HyPower Power Port	50A-125/250v, 50A-125/250v * 20A GFCI Boat Charging Station
Aluminum Pulley Wheels	$ 192.98	4	$ 771.92	McMaster-Carr	3172T111	4 5/8" Aluminum Pulley
T-Plate	$ 65.00	8	$ 520.00	*(unavailable)*	*(unavailable)*	6061-T6 Aluminum T-Plate
Upright L-Plate	$ 65.00	8	$ 520.00	*(unavailable)*	*(unavailable)*	6061-T6 Aluminum Upright L-Plate
Electrical Insulation	$ 500.00	1	$ 500.00	*(unavailable)*	*(unavailable)*	cables and binding
Anchorage Bolt-L Plate	$ 85.00	4	$ 340.00	*(unavailable)*	*(unavailable)*	6061-T6 Aluminum Anchorage Bolt L-Plate
3/8"-16 Aluminum Nuts	$ 1.40	112	$ 156.80	HomeDepot	9073518	3/8"-16 Aluminum Nuts
3/8" x 1" Aluminum Washers	$ 0.66	224	$ 147.17	HomeDepot	9080087	Aluminum USS Flat Washers (1 at each bolt head and each nut)
1-3/4" (Diam) Bolts	$ 8.95	8	$ 71.60	*(unavailable)*	*(unavailable)*	Large Aluminum Anchorage Bolts (tapping)
3/8" (Diam) x 2" Bolts	$ 0.60	112	$ 67.20	Grainger	1YB74	Aluminum Bolts for fastening the mounting plates to the frame
Estimated Total Cost of Materials				**$**		**29,159.47**

The next most significant component cost is the solar panels. At an industry average price for the specific panel chosen of $278 per panel, the combined cost for 18 solar panels per Double Dock sums to just over $5,000, contributing 17% to the project's total materials cost.

5.6.2 Cost analysis of photovoltaic system

Separate from the system's total materials costs is a financial analysis of the Double Dock's photovoltatic system. Most of these financial calculations were done using the previously mentioned simulation software, SAM. The simulation takes into account things like material costs as well installation and labor costs, electricity buy and sell rates varying by utility determined Time of Use (TOU) periods, flat rate utility charges, inflation, component depreciation, government sponsored investment and energy production incentives, and more. An example of system cost parameters used within SAM can be found in Appendix B.

From the simulation results in SAM, Table 5.5 compares the annual electricity bill from two boats that would be expected by a marina without the Double Dock's photovoltaic system installed to an expected electricity bill with the Double Dock's photovoltaic system installed. From this comparison, it is straight forward to see that with the system installed, the first year savings on electricity costs is expected to be $495. Without the system installed, electricity would cost the marina around $280, but with the Double Dock's PV system installed, the electric utility would instead be paying the marina nearly $215 at the end of each year.

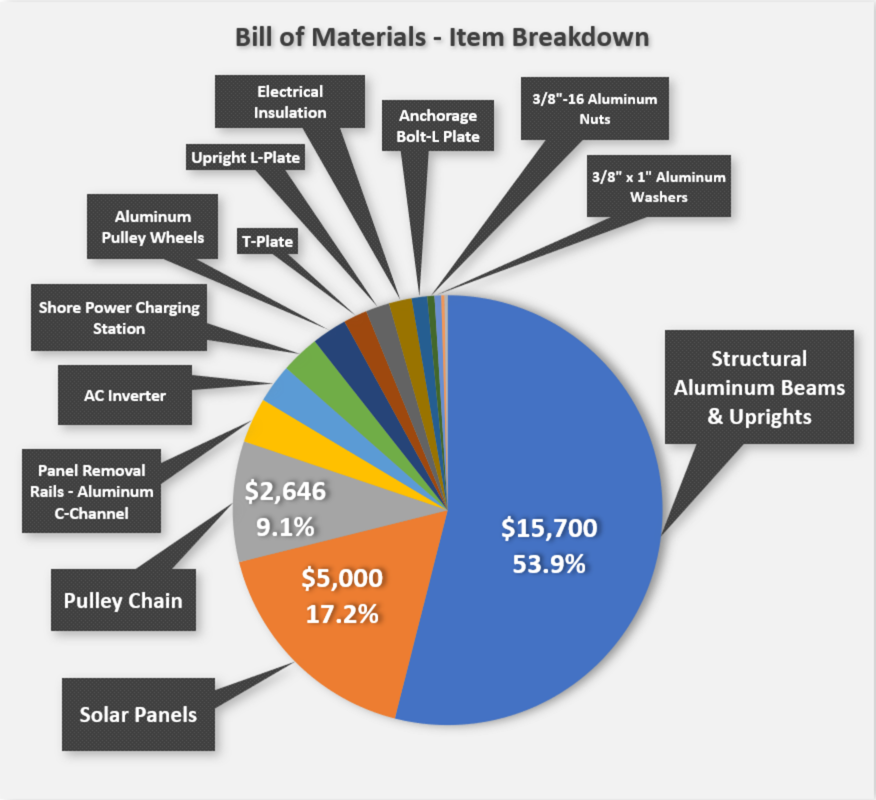


Figure 5.13: *Material cost distribution*

Table 5.5: Total electricity bill the first year

Charge	***Without* PV System**	***With* PV System**
Energy	$192.46	$0.00
Fixed	$89.28	$89.28
Year end net metering credit	$0.00	-$302.56
Total Bill	**$281.74**	-**$213.28**
Savings compared to no system	$0.00	$495.02

When considering the costs and savings of a project over its lifespan (like this system's 25 year period), project financial analysis metrics such present value and net present value (NPV) are considered. Table 5.6 shows the project's present value of the costs incurred by the addition of the system as well as the final NPV of the project. Figure 5.14 shows the photovoltaic system's cumulative annual payback cash flow, indicating a payback period of around 12-13 years.

Table 5.6: Present value of annual costs and net present value

Present Value	***Without* PV System**	***With* PV System**
Electricity bill	$4,025.50	-$2,304.27
Income tax increase due to bill savings	$0.00	$1,326.09
System costs after tax	$0.00	$2,243.82
Battery replacement cost	$0.00	$0.00
Total Cost	**$0.00**	**$1,265.64**
NPV of project with bill savings	$0.00	$2,759.86

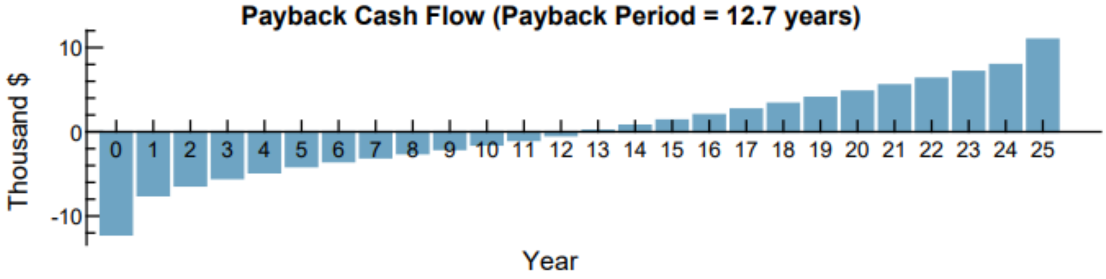


Figure 5.14: *Cumulative annual payback (after expenses)*

5.7 Maintenance plans and reliability

The structure strength of the Double Dock system and the technical lifetime of the solar cells results in an expected durability and lifetime of 25 years. This expectation is with minimal needs for maintenance, however, the team considered the best methods of maintenance with an emphasis on corrosion prevention.

Worst-case conditions (using the typical conditions of the North Sea) are wave speeds around 10 knots and a chlorine concentration of 19.3 ppm (Weather 2, 2020), which correspond to a corrosion rate of 0.089 mm/year (Cicek, 2014). Because the load-bearing supports will be 2-4 orders of magnitude greater in size than the material loss over the product's lifetime, assumptions could be made that the effects of corrosion will not significantly change the integrity of the system at any point of its life-cycle (Alcan Marine, 2020).

There are still some reliability concerns about the longevity of the rail system, should debris or corrosion start to affect its functionality. This is especially a concern because above the sea surface, where the seawater cannot wet metallic structures, there is a possibility for a high corrosion rate due to a humid atmosphere having high salt contents. At the sea surface, metal surfaces are cyclically rinsed and dried due to waves and tides, meaning reactants of corrosion could be sitting on the surface as it dries. The team plans to take preventative measures to extend the life of the design, including rinsing all surfaces of the design as part of a monthly maintenance program. Solar panels are manufactured with the expectation of regular cleanings of this nature, and this cleaning is of greater importance in applications near seawater, due to the high salt content.

The warranty and exact parameters of performance for panels depend on the manufacturer. The true performance can be monitored through energy output or physical checks of the panels. The individual panel performance could be measured electronically using thermal imaging, but this equipment is costly so in small applications, such as this, a physical check of the panel's well-being is more appropriate. The panels themselves require little maintenance and should not have any considerable efficiency losses within the first 25 years of the product's life, so the team does not need to include any panel maintenance beyond monthly rinsing and visual checks (Ecomark solar, 2016).

5.8 Manufacturing plans

There are no current plans for the manufacturing of the system or for the long-term mass production of it, however, manufacturability and assemblability are still important aspects for the team to consider. Most importantly, the marine environment presents unique challenges to the physical installment of the Double Dock system, so the more assemblable it is, the easier it will be for those who construct it on the dock. Ideally, the majority of the structure could be assembled offsite, and then transported to the marina for installment.

As discussed in design, the functionality of the design does not depend on precise manufacturing techniques, so the team does not need to invest in complex methods or custom tooling. The design will still require slightly more specialization of stock materials, however, it is important to have sufficient surface finish at joints so as to not provide recesses where crevice corrosion could become more likely. Upright supports and support attachment points on the cantilever beam will require higher quality surface finish than the rest of the material. Additionally, inner corners, such as those in the cantilever beam and in the railing, should have a large radius so that moisture is less likely to get trapped and harm the design through corrosion (Alcan Marine, 2020).

In terms of assemblability, this design features parts that can be centrally manufactured and shipped to the intended marina. Here, the railing system can be attached to the frame, the frame can be attached to the dock, the electrical wiring can be attached to the panels, and then panels can be slotted into the railing system. This allows for easy assembly in environments not typically suited for construction work.

The final design fulfills the requirements that were formed in early stages of the project. However, many aspects of this design could be further investigated and refined if more time and resources were available. Therefore the following chapters will provide some recommendations for potential continued work as well as a further discussion about the results.

6 Discussion

This section includes discussion regarding the results and what aspects that might differ to current circumstances. Some things might not be considered by the reader, but are nonetheless of value to enlarge the perspective of the project. The discussion covers aspects of the Double Dock system's specifications to its expected capabilities, the ethics of the design, and the overall impact of the COVID-19 pandemic.

6.1 Design analysis

It is important to consider how the design fulfills each of the parameters used during concept evaluation. The team included this discussion in hopes of comparing the final capabilities of the system with the initial metrics. This ensures that the final concept is not only fully developed in an engineering sense, but also measurably satisfactory in that it meets all intended specifications. The following nine aspects encompass the customer needs and the 12 engineering specifications, which will each be discussed within their respective parameters. The full table of target specifications can be found in Section 2.8.

6.1.1 Customer value

The most heavily weighted function was the system's value to its customer. It must improve the boating experience in a meaningful way beyond the typical marina experience, through modularity, accessibility, and user-friendly features. As a solar powered garage for electric boats, this design's main objective is ensuring adequate power is supplied to the boat. It accomplishes this by providing a monthly average of 83 kWh/week per boat for two docked boats, exceeding the target specifications #4-6.

For most dock mounted structures, weight placement, such as the solar panels, can be a challenge. The distance that the top surface can span over the water is limited, as well as how much weight can be placed on it. The Double Dock design solves this by spanning over the water in opposite directions, having the center of gravity over the wharf. In this way, the system is self-balancing, and can handle more weight further out over the water, creating an excellent amount of available surface area for solar cells. Since the roof is a flat surface, the orientation of the design will not affect the amount of solar energy that can be harvested.

Customer value is also manifested through the boat owners' experiences, such as the ease of docking a boat into this garage and driver sight during this procedure. As a largely open structure, the Double Dock performs much like an open slip during mooring, but with the additional benefit of overhead protection. The design also features stable handholds through the side supports to aid in entrance and exit from the boat. During further development, tension cords could also be strung along the cantilever to provide balance and safety to the user.

Though not functionally important, structural aesthetics of the system were also considered. It was assumed that customers would prefer a product that enhanced and did not interfere with the natural beauty of the waterfront environment. Since the Double Dock does not feature sides, it allows for uninterrupted views from the dock or shoreline.

6.1.2 Structural durability

Structural durability was the next highest priority during evaluation. With conducted research and simulations the lifespan expectancy is at least 25 years, in both the structural and solar system components. This lifetime ensures that the system meets engineering specification #12, which requires a lifetime of at least 10 years. Additionally, this lifetime accounts for exposure to lower temperatures and environmental elements, satisfying engineering specification #11 of operating temperature.

In terms of resistance to corrosion, the Double Dock is manufactured using marine-grade materials with high corrosion resistance and the system will utilize regular maintenance procedures, further preventing corrosive damage, as discussed in Sections 5.7 and 5.8. Overall, the panel lifetime is expected to be more of a limiting factor than the structural durability on the product's lifetime.

The residential graded solar panels used in the design are able to resist harsh weather and retain the bulk of manufactured efficiency well into their lifetimes. Panels can be removed from the structure for winter or inclement weather, which will further increase their lifetimes. Once panels are removed, the centrally mounted structure is robust enough to survive harsh winter conditions without failure.

Structural calculations and simulations shows that the design is capable of carrying 18 solar panels and that there are marginals for the rail-system, cabling, and other potential features. The side supports also show a great increase in structural strength. However, it is recommended that the structural analysis, in addition to the calculations and simulations, also includes a fatigue and cyclic loading consideration.

6.1.3 Structure geometry

The complexity, flexibility, and structural strength were the main pieces analyzed for this function. The pulley system adds a layer of complexity to its design. However, the omission of side walls and a main garage door significantly reduces the design's complexity.

Overall, the design is relatively simple and reasonable for a typical marine environment. Since this structure is not connected to floating Y-booms, structural flexibility in response to wave and tidal patterns is not as important. It is connected to the dock at four points as well, rendering the garage stable.

6.1.4 Functional adaptability

The design is modular in that it allows for disassembly of the panel system. One weakness of the Double Dock design is that it does not offer means of the structure folding away when charging is not needed. However, it does allow for panels and other electrical components to be removed when not needed. The assembly and disassembly of the panel system will be easily achievable with the railing system, wherein disassembly is defined as the physical removal of panels from the structure while the structure remains in place. It is expected that both disassembly and assembly of the solar panels could be possible by two people in under 30 minutes, satisfying target specifications #8-10. Furthermore, it is possible for one person to retract the panels towards the dock themselves, but two people will be required to physically remove them from the structure in terms of ergonomics due to the panels' weight.

Once assembled and operational, the design needs to account for thermal management of the solar panels. If ignored, heat accumulation will cause panel efficiency to decrease. The Double Dock omits the need for additional roofing material by providing full overhead coverage using just panels. This allows the panels to release heat into open air through convection.

6.1.5 Boat protection

Regarding the boat protection and the housing ability, an analysis was made for protection from four elements prevalent in Gothenburg: rain, wind, dirt, and snow. Protection could be considered the Double Dock's weakness because this design lacks side walls, which would shield boats from elements like rain and snow, especially if wind is blowing precipitation at an angle that goes around the roof in place. However, due to the open structure design, the wind break and risk of the structure blowing away is low. The boat is further on well protected from incoming projectiles, such as hail and bird feces. It also gives a good protection from frost and the sun's deleterious effects on the boat-materials. This system has been designed to be implemented onto existing open docks. Because of this, people will not inherently be sacrificing boat protection with this design, but rather gaining the benefit of it. Any methods already in place to protect the boat, such as tarps or canvas covers, can continue to be used in conjunction with the Double Dock design. Sides which attaches to, for example, Y-booms could also be further developed.

The overhead protection does insure that the design meets target specifications #1-3 of length, width, and physical accommodation by housing two small-medium boats. The system does not protrude into the water and thereby does not limit boat size. If multiple systems were to be implemented at the same marina, the marina owner would have the ability to choose how much space to allow between the docks. The ample overhead surface area also ensures that the dock satisfies target specification #7, with an overall surface area of 15.5 m^2 per boat.

6.1.6 System cost

System costs were one low-weight function considered due to the open task from Volvo Penta. The overall task was to design new charging stations for marinas that lack the infrastructure to charge these boats from the grid. Because of this, and because there is no industry standard, cost is not strictly being compared against the cost of charging the boat from the grid. With this being said, the Double Dock design performs well in cost analysis compared to other concepts, since it allows two slips to share electrical components, and uses limited physical material per-slip compared to other generated concepts.

Development of the Solar Wharf Garage has as mentioned been aimed towards the marina as primary customer. The total cost of the system may therefore not be as attractive to private or other potential buyers. In further development this might be an aspect worth considering to open up several customer bases.

6.1.7 Manufacturing

The design is favorable for manufacturing for a few reasons. The system can be partially assembled before reaching the dock, easing the overall manufacturing process. The structure is then assembled by screw joints and plates, avoiding welding and thereby enabling disassembly. The function of the system does not depend on precise manufacturing techniques, meaning no need to invest in complex manufacturing methods or custom tooling. Additionally, manufacturing becomes simpler since the overhead design uses few overall materials, and the two slips can share structural supports.

6.1.8 Risks

Risks are always present in mechanical systems, and designs must consider how they can be avoided. The main risks of the Solar Wharf Garage is regarding the moving rail-system which enables panel retraction. This system consists of wheels with bearings and other moving parts which can wear, especially in harsh weather. To avoid or delay the wear on the rail-system, sealings or plastic covers could be implemented which spans over the entire rail-system and are attached to the top of the cantilevers. Other structural risks of the Solar Wharf Garage, like corrosion, strength, and solar panel durability, would be similar to other generated concepts with the same materials.

Regarding the solar and electrical system, the breakage of the cabling and wires is a risk. Each row of solar panels must therefore be connected with steel cabling so that the solar wires does not stretch when panels are retracted.

6.1.9 Electrical system

The decision of making the design's electrical system tied to the grid is to ensure that continuous use is possible and provide a long term solution which fulfills its purposes even in cloudy conditions. The possibility of selling excess electricity will contribute to a more economically attractive design, as well as adding to the renewable energy sources share of the grid. However, this does make the Double Dock difficult to implement in smaller marinas where the electrical infrastructure might not be as developed.

6.2 Result discussion

It may be discussed whether the final concept can be defined as a garage or not, since it lacks side protection. However, with some simple solutions, the sides could be covered with side tarpings, see Figure 6.1, and that way protect the boat more like a garage. This solution has, however, not been examined after the Double Dock concept was further developed. It still needs more investigation on the lower attachment and further consideration would depend on the interests of the marina owner.

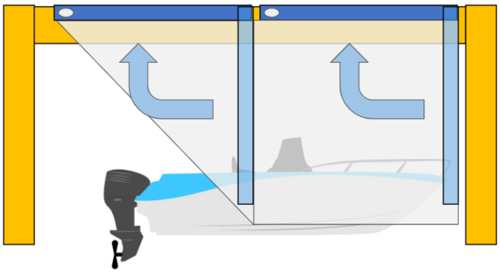


Figure 6.1: *Side tarping*

The system is alternatively used with merely connection to the boats' battery, if so only supplied when the boat is present, or with an external battery bank attached directly by the wharf so that energy can be harnessed and stored even when not connected to grid or to the boat battery. With grid-connection or extra battery, power can be guaranteed to the customer. The alternatives of not having a grid connection or extra batteries to the system are interesting aspects to assess, but could interfere with the system users' expectations of access to energy.

The project has not considered the wharves and if they manage to carry the Double Dock or not. It may be an important study to see if the design is useful for the marinas. If only one Double Dock can be installed on one wharf it loses some of its purpose. The meaning is to have many Double Docks side by side on the wharf, but then the wharf has to have a structure strong enough. Some of the conducted research show, however, that a concrete pontoon of 10-22 m length and 2.4-5 m width can carry up to 500 kg/m^2 which should be sufficient for the Solar Wharf Garage of approximately 950 kg (Svenska pontonhamnar, 2020). Whether or not building permits for marine infrastructure allows for the construction of the Solar Wharf Garage has not yet been investigated.

6.3 Ethics

The project has contributed to the stride of a more sustainable leisure boating life, and the resulting concept may function as beneficial support to achieve political goals about reducing the use of fossil fuels. For the electrical boat market to grow and reach into several customer segments, additional alternatives for generating power to the boats are required. Since solar panels are available all around the world in several price classes, it serves as a good complement to charging batteries in marinas for the benefit of both boat owners' finances and the environment. The annual electricity production from this garage is to be excess when the boats' energy demand has been satisfied, which then further emphasizes the benefits of connecting the system to the grid so that contributions to the renewable energy share of the grid will not be wasted.

Since the system does not include an extra battery beyond that of the boat, the project has not investigated further into the field of unethical mining activity that may be involved when extracting battery material. However, ethical extraction of material for the panels and remaining components of the design are considered important but not as critical since silicon is the second most abundant material in the earth's crust and therefore easy to get hold of.

The resulting design does however, result in an enlarged shaded area in marinas, where the water is shallow and a diverse flora is residing. This marine wildlife could get affected by the reduced amount of light reaching them. One of the most affected plants in such environments is eelgrass, which have been reduced by 42-64% in recent years (Eriander et al, 2017).

6.4 COVID-19

The team experienced some logistical complexities due to the COVID-19 outbreak and following regulations. Both Penn State and Chalmers transitioned to online learning in late March, making it infeasible to meet as a group. Additionally at the same time, Volvo Penta suspended company work for 6 weeks, making it impossible for the client to support team efforts. Because the team had already been communicating through Skype, it was a simple transition to fully virtual meetings on Zoom. However, the Chalmers students were unable to visit Penn State and the team was unable to create a physical model using university resources as planned. Overall, it can be said that the impact of the pandemic was unforeseen and the team was able to compensate for the loss of the functional model through alternative deliverables, including the virtual rendering of the design and a short video.

In Section 1.3 it was stated that a prototype was planned as one of final deliverables of the project. However, the COVID-19 outbreak made it difficult to access the equipment needed for this task. Building a prototype can instead be considered an important part of further development.

7 Conclusion

Throughout the total span of the project, the team has successfully developed a boat-garage that protects boats from the elements, generates electrical power using photovoltaic panels and charges docked boats. Additionally, the objectives were exceeded by ensuring that excess power can be fed back into the grid. The research gathered and work presented allows the client to further develop the design to create a unique and marketable Solar Wharf Garage with an expected payback period of 13 years for the PV system. This projected payback period only considers costs related to the PV system and the electric bill over its 25 year lifespan. It does not include the garage structure investment cost, property taxes with/without the structure, or the structure's end-of-life salvage value. The structure and photovoltaic system costs are basically considered separate from each other due to “value” quantifications over each component's lifespan. - i.e. the PV system can pay for itself after 50% of its lifetime whereas the garage structure cannot directly pay for itself but may last long be used for two or more different PV systems' lifespans.

With the knowledge and expertise gained through this project, the team has compiled the following list of suggestions for future work on the concept. The team recommends that Volvo Penta consider:

- Attaching a solar roof to the boat, so that access to energy is available everywhere the boat goes.
- Creating a modular attachment mechanism so versions of the design are attachable to different types of docks.
- Including more functions within the garage, such as light or infrared heating.
- Developing a version of the concept that would not use grid connection. This would allow the structure to be attached to freestanding docks.
- Adding siding to the design, to gain more protection for the boat.
- Analyzing a battery bank as opposed to having an inverter and grid connection.
- Verifying that the structure of the wharf is compatible for carrying many garages.
- Building a down-scaled prototype of the Solar Wharf Garage.
- Including a fatigue and cyclic loading calculation.

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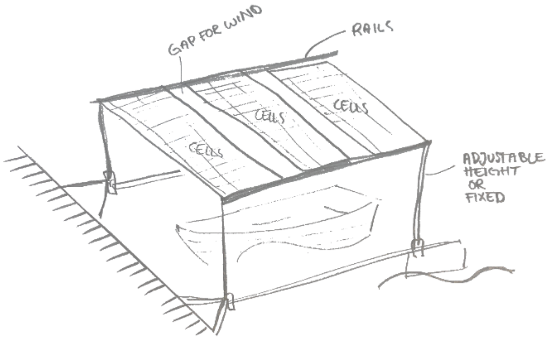
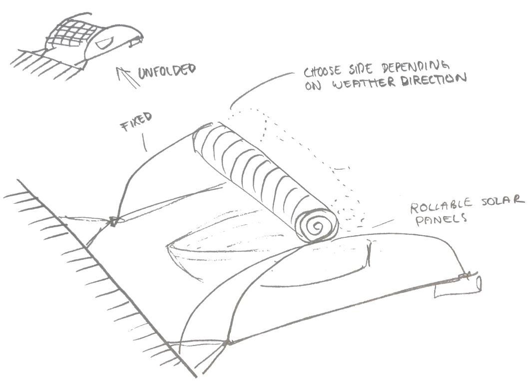
Appendix A - Concept catalogue

Concept 1:
This concept was designed with simplicity in mind. Fixed steel bars with adjustable height on the Y-booms would hold the rectangular structure with rails for the solar panels. The crystalline solar panels would be separated for wind passage and attached so that they are easy to demount when the season is at its end. Movement from the waves could provide a problem for this structure since the booms move differently.



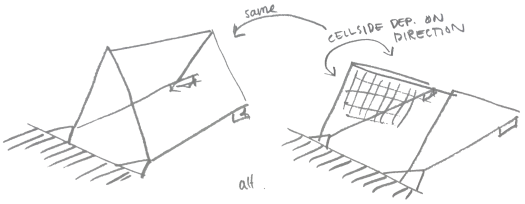
Concept 2:

This concept was generated to provide flexibility. The bent bars on the Y-booms would hold a roll of rollable thin-film solar panel, so that the structure could be kept at a low height but still be accessible. Then the roll could be attached to cover either the front or the back half of the boat, dependent on the slips angle towards the south. Movement from the waves could provide a problem for this structure since the booms move differently.



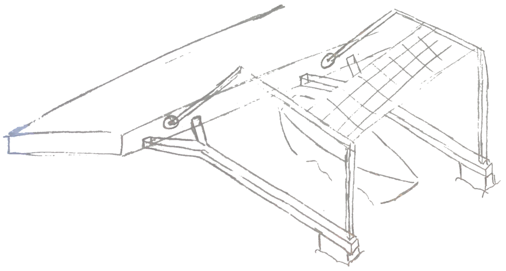
Concept 3:

This concept was inspired by a triangular tent. This structure provides plenty of protection in regards to sun and wind. Also this design is simple and therefore not so costly. The solar panels are crystalline and could be mounted on either side of the structure depending on direction towards the south.



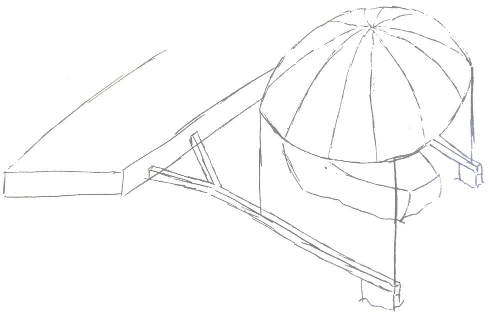
Concept 4:

This concept was generated to investigate different attaching-methods to the wharf. Steel bars are connected on the wharf and have support from the Y-booms. As a roof it has crystalline solar panels.



Concept 5:

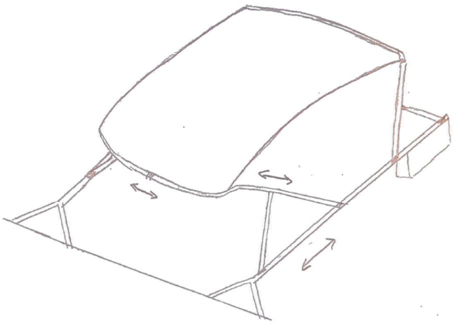
Coupole roof attached on the Y-booms. This concept is thought to provide exceptional weather protection to the boat. With sloping surfaces it allows both dirt and snow to slide off.



Concept 6:

This concept is similar to a traditional sun canopy for boat cockpits. The idéa is to have a flexible and collapsible system.

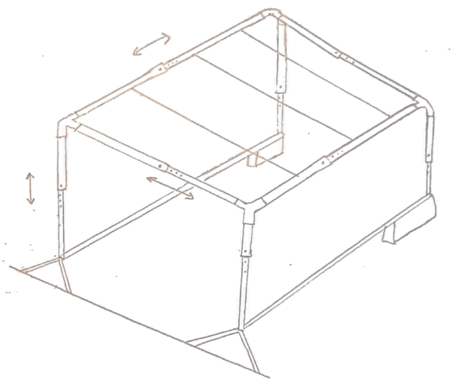
It consists of thin solar panels which are tightened up by bent steel bars. These are fixed on slides on the Y-boom.



Concept 7:

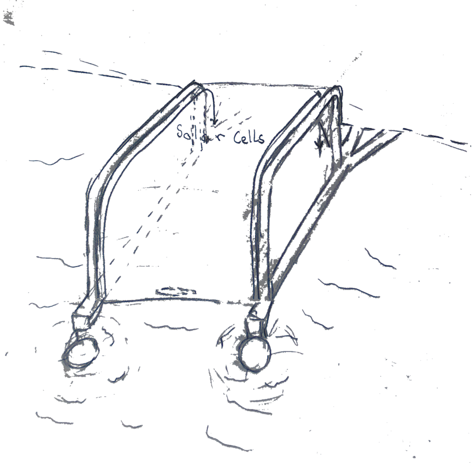
This concept is a flexible steel bar structure with a "telescope" function to change the length of the bars.

The idea is similar to a crutch where one bar slips into the other bar with a lock mechanism. This enables flexibility and choice of roof angle for the crystalline solar panels.



Concept 8:

Concept 8 provides a flexible roof with an appealing design. By allowing removal of the covering surface the user is enabled to freely use the space as he/she wishes.

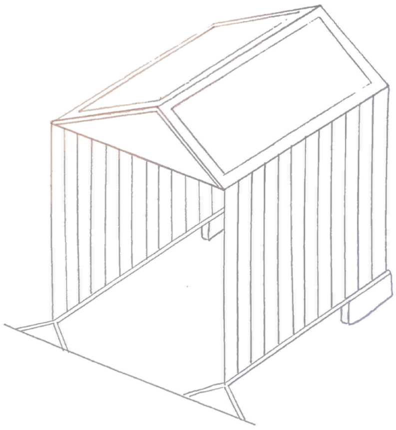


Concept 9:

This concept houses two boats simultaneously with flexible solar panels. Enables easier sharing of electricity and also reduces the amount of components needed per boat slip.

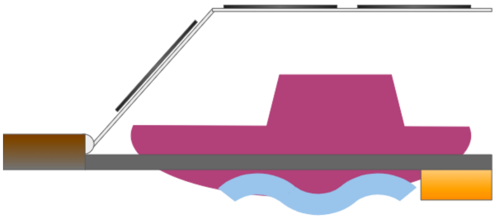
Concept 10:

This concept symbolises the “traditional” Swedish boat house of wood with a gable roof. Built on the Y-booms with crystalline solar panels on the roof.



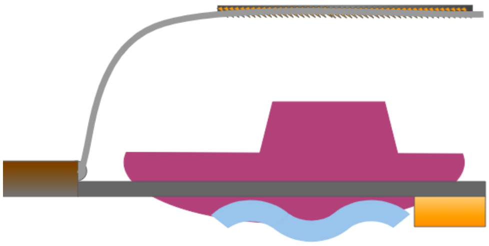
Concept 11:

Steel bars connected from the wharf with crystalline solar panels. Since the concept is not attached to the boomes it is not as affected from the waves as the previous ones.



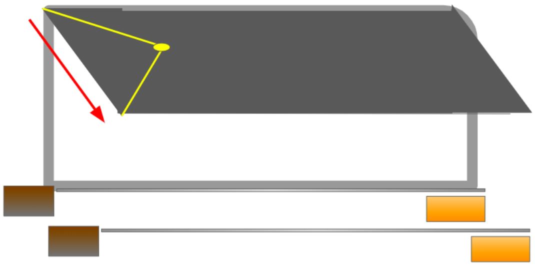
Concept 12: Hovering solar roof

Steel bars connected from the wharf. Crystalline solar panels are attached to the bars with springs. The springs allow movement in the bars without giving an impact on the solar panels.



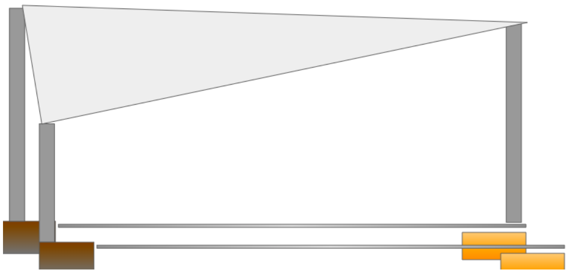
Concept 13:

This concept is a retractable awning made up rollable solar panels. Either a motor or user operated hand crank would allow for deployment and retraction. Concerns were raised due to limitations of rollable solar panels and usable surface area. Also, the torque created of the awning hanging out was problematic.



Concept 14:

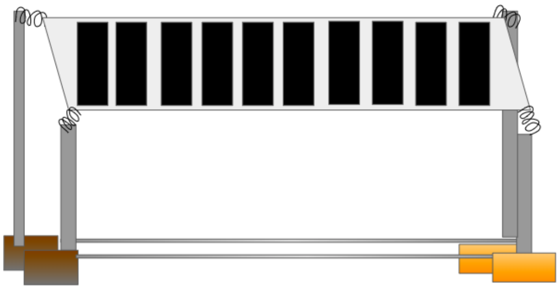
This concept is made up with inspiration from sail-roofs for outdoor dinings etc. Here, solar panels are attached to the sail which is tightened up to three poles on the Y-booms.



Concept 15: Sailroof with springs

Thin film panels would be attached through runners onto a soft sail fabric roof connected to 4 steel rods with springs to allow movement in different axes.

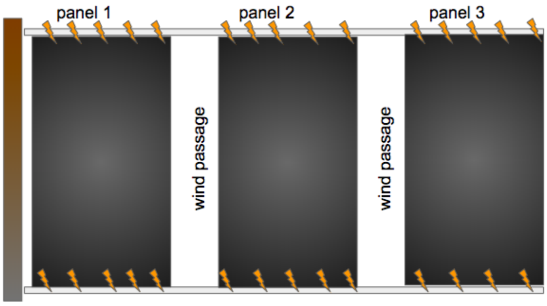
The sail roof could then be easily unhooked in the ends and folded.



Concept 16: Crystalline trampoline

Similar to Concept 1, however the springs from concept 12 have been implemented.

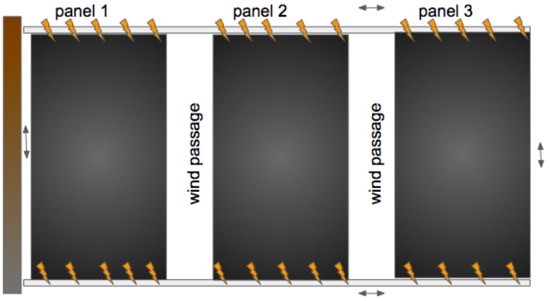
The springs allow movement in the bars without giving an impact on the solar panels.



Concept 17:

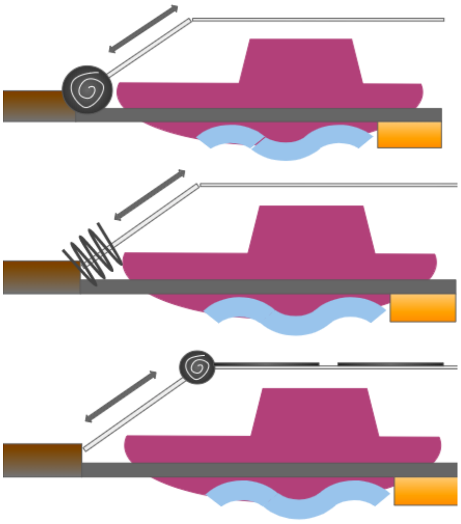
Similar to Concept 7, however the springs from concept 12 have been implemented.

Steel bars connected from the wharf. Crystalline solar panels are attached to the bars with springs. The springs allow movement in the bars without giving an impact on the solar panels.



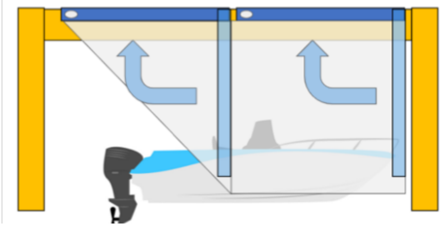
Concept 18: Retractable cover

Retractable cover is directly attached to the wharf, divided into two different sections on the roof combined with a joint. The solar panels are thin-film panels which may be retracted towards the wharfside in different manners by using rails implemented into the roof-bars.



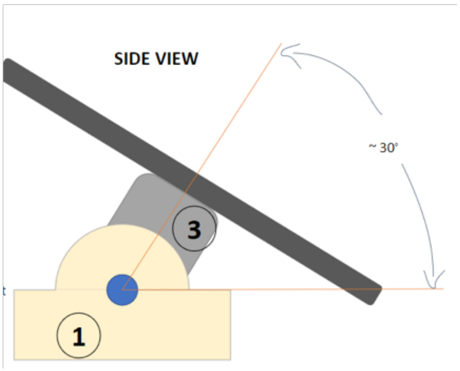
Concept 19: Tarp Slide

This concept is free-standing and includes a panel system that allows a user to slide panels into their position along the x-axis then pivot up to snap into the horizontal position, with side tarping attached to the panels, which will deploy as the panels are positioned. This concept focuses on protection of the boat, surface area for charging, and deployability of solar panels. However, this concept has considerable limitations of wind susceptibility and structural rigidity.



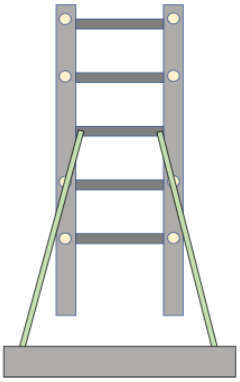
Concept 20: Rotor

This concept was inspired by helicopter rotors and fidget spinners. This design addresses the problem of modularity through panel ease-of-access and compactness. It provides the unique opportunity to access all panels from one single point and optimizes panel placement, but has a considerable amount of technical complexity and does not provide much structural support for the panels.



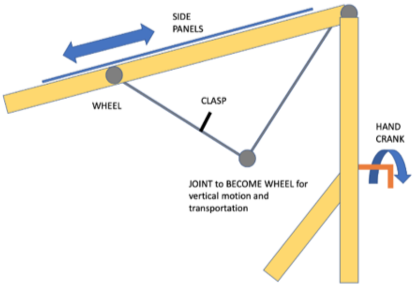
Concept 21: Folding Table Concept

This concept was inspired by space-saving foldable furniture. It addresses surface area, flexibility, and ease-of-access. The aesthetics of this design especially made it a good contender, but it has a considerable amount of technical/manufacturing complexity, may not be structurally feasible, and would need room for elevation in the unfolded (disassembly) position.



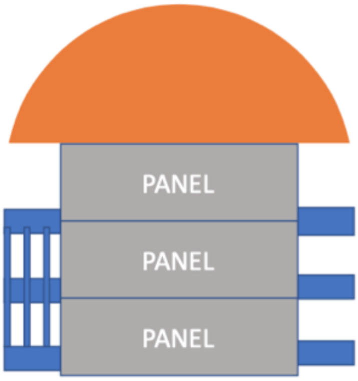
Concept 22: Garage Style Design

This concept features a garage-style mechanism to bring the solar panels into and out of use. This makes this particular design grealty modular. However, there are some technical risks associated with this design. Most notably, all the movement mechanisms have a high susceptibility to fail with the marine environment.



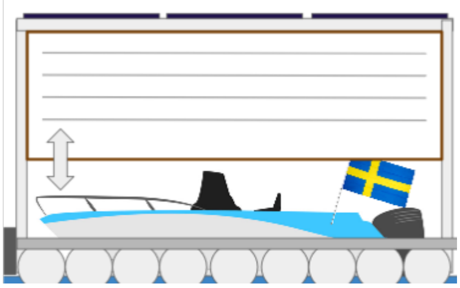
Concept 23: Mushroom

This interesting concept features a thick industrial plastic head to guard the front of the boat, moveable blinds to protect the side of the boat and provide shade, and a firm structure to which the panels can be attached. This design had many positive aspects, however, the blinds were susceptible to the harsh marine environment and the many different materials potentially raise the cost too much.



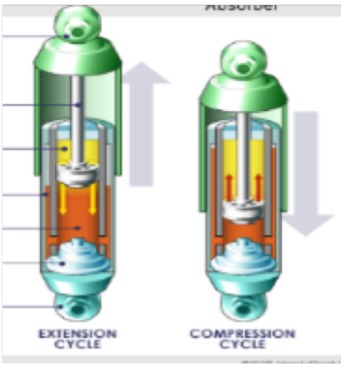
Concept 24: Floating Garage

This concept features a garage that floats on the water as opposed to attaching to the dock. This allows for free movement with waves and tidal patterns, reducing stress on the structure's joints from flexing. The biggest weaknesses of this concept were its lack of security and lack of stability.



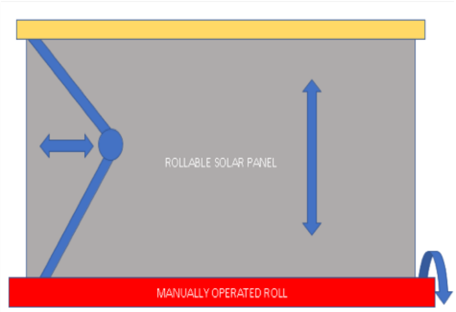
Concept 25: Frame Shock Absorbers

This concept describes shock absorbers that can be connected to a garage's vertical frame pieces. These will lessen the impact of tidal and wave movements on the garage structure. However, it also introduces additional complexity and an additional instrument that would require maintenance.



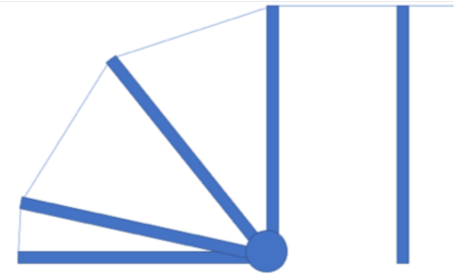
Concept 26: Solar Awning

This concept is a retractable awning made up rollable solar panels. Either a motor or user operated hand crank would allow for deployment and retraction. Concerns were raised due to limitations of rollable solar panels and usable surface area.



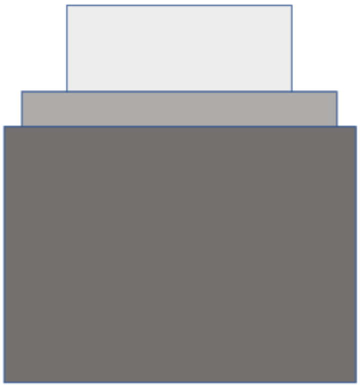
Concept 27: Turtle Shell Garage

This concept is a collapsable, tunnel-like structure inspired by hitting turtles seen in baseball. It features a semicircle back that can be folded outwards to 90 degrees and then further extended. This concept's biggest weaknesses were its complex frame and challenges arising from collapsing areas being used for solar cells.



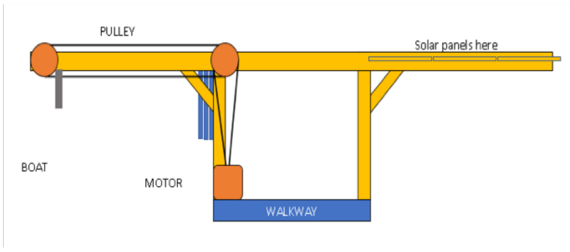
Concept 28: Caterpillar Garage

This concept is a rectangular, collapsible structure. It allows for the garage to be scaled down when not in use, easing storage constraints when removed from the water. One challenge with this design was maintenance of solar panels. When the garage is in use, they are over the water and hard to access. When collapsed, they are covered by other segments of the design.



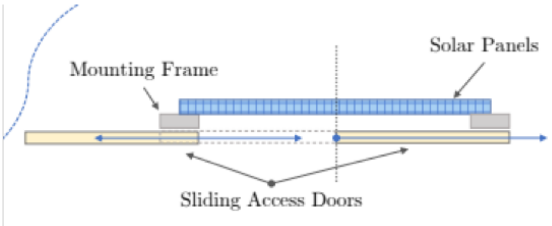
Concept 29: Double Dock

This concept, our final concept, can house and charge two boats on opposite sides of a docked walkway using two long overhead supports to hold the panels. The panels are attached into a railing so that they can slide over and be removed, without disassembly of the structure. The advantages and disadvantages of this design are thoroughly discussed in the final report.



Concept 30: Patio Door Roof

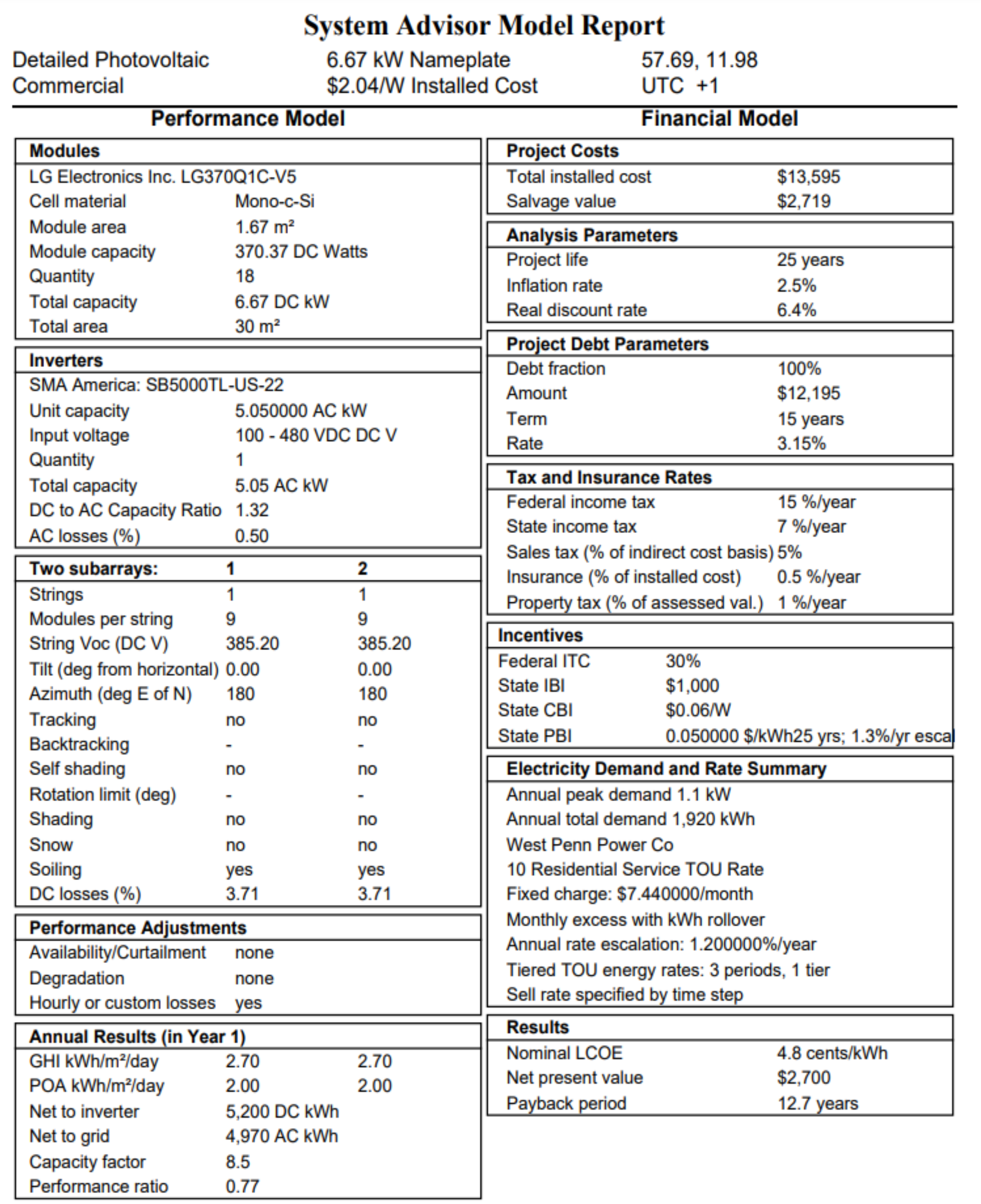
This is a sub-function concept to specifically address panel housing and maintenance. Support material beneath the panels provides a sliding door feature, so that boat or marina owners could access the panels while in the boat below for easier maintenance or removal. This concept is a bit mechanically complex and would require extra support material and subassemblies.



Appendix B - SAM Simulations

SAM Report – Photovoltaic System Results

SAM Report (page 1 of 3) – PV System Performance and Financial Model Results Summary



System Advisor Model Report

Detailed Photovoltaic	6.67 kW Nameplate	57.69, 11.98
Commercial	$2.04/W Installed Cost	UTC +1

Performance Model

Modules	
LG Electronics Inc. LG370Q1C-V5	
Cell material	Mono-c-Si
Module area	1.67 m²
Module capacity	370.37 DC Watts
Quantity	18
Total capacity	6.67 DC kW
Total area	30 m²

Inverters	
SMA America: SB5000TL-US-22	
Unit capacity	5.050000 AC kW
Input voltage	100 - 480 VDC DC V
Quantity	1
Total capacity	5.05 AC kW
DC to AC Capacity Ratio	1.32
AC losses (%)	0.50

Two subarrays:	**1**	**2**
Strings	1	1
Modules per string	9	9
String Voc (DC V)	385.20	385.20
Tilt (deg from horizontal)	0.00	0.00
Azimuth (deg E of N)	180	180
Tracking	no	no
Backtracking	-	-
Self shading	no	no
Rotation limit (deg)	-	-
Shading	no	no
Snow	no	no
Soiling	yes	yes
DC losses (%)	3.71	3.71

Performance Adjustments	
Availability/Curtailment	none
Degradation	none
Hourly or custom losses	yes

Annual Results (in Year 1)		
GHI kWh/m²/day	2.70	2.70
POA kWh/m²/day	2.00	2.00
Net to inverter	5,200 DC kWh	
Net to grid	4,970 AC kWh	
Capacity factor	8.5	
Performance ratio	0.77	

Financial Model

Project Costs	
Total installed cost	$13,595
Salvage value	$2,719

Analysis Parameters	
Project life	25 years
Inflation rate	2.5%
Real discount rate	6.4%

Project Debt Parameters	
Debt fraction	100%
Amount	$12,195
Term	15 years
Rate	3.15%

Tax and Insurance Rates	
Federal income tax	15 %/year
State income tax	7 %/year
Sales tax (% of indirect cost basis)	5%
Insurance (% of installed cost)	0.5 %/year
Property tax (% of assessed val.)	1 %/year

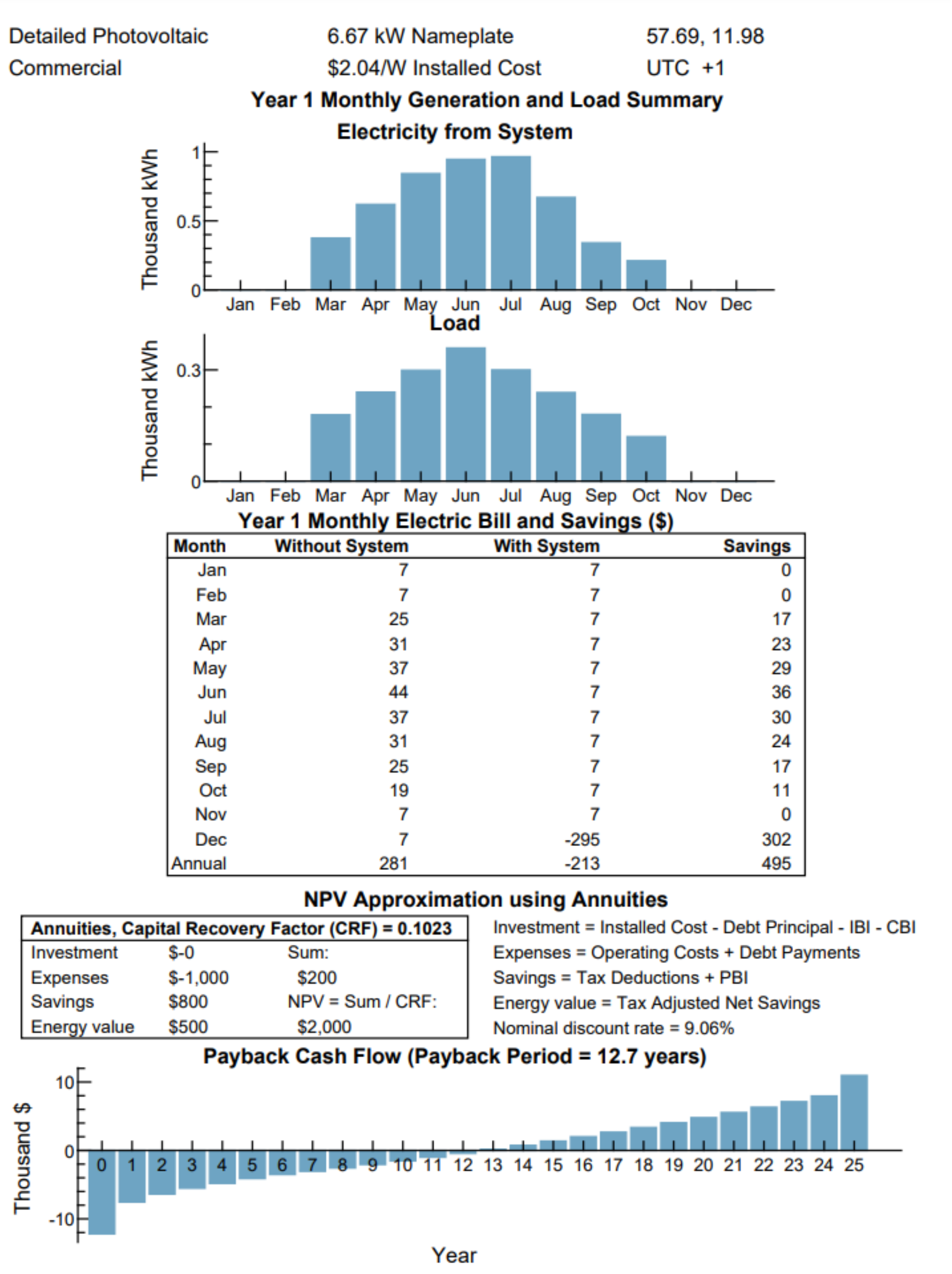
Incentives	
Federal ITC	30%
State IBI	$1,000
State CBI	$0.06/W
State PBI	0.050000 $/kWh25 yrs; 1.3%/yr esca

Electricity Demand and Rate Summary

Annual peak demand 1.1 kW
Annual total demand 1,920 kWh
West Penn Power Co
10 Residential Service TOU Rate
Fixed charge: $7.440000/month
Monthly excess with kWh rollover
Annual rate escalation: 1.200000%/year
Tiered TOU energy rates: 3 periods, 1 tier
Sell rate specified by time step

Results	
Nominal LCOE	4.8 cents/kWh
Net present value	$2,700
Payback period	12.7 years

SAM Report (page 2 of 3) – Project Financial Analysis' Monthly and Annual Data



Detailed Photovoltaic 6.67 kW Nameplate 57.69, 11.98
Commercial $2.04/W Installed Cost UTC +1

Year 1 Monthly Generation and Load Summary

Year 1 Monthly Electric Bill and Savings ($)

Month	Without System	With System	Savings
Jan	7	7	0
Feb	7	7	0
Mar	25	7	17
Apr	31	7	23
May	37	7	29
Jun	44	7	36
Jul	37	7	30
Aug	31	7	24
Sep	25	7	17
Oct	19	7	11
Nov	7	7	0
Dec	7	-295	302
Annual	281	-213	495

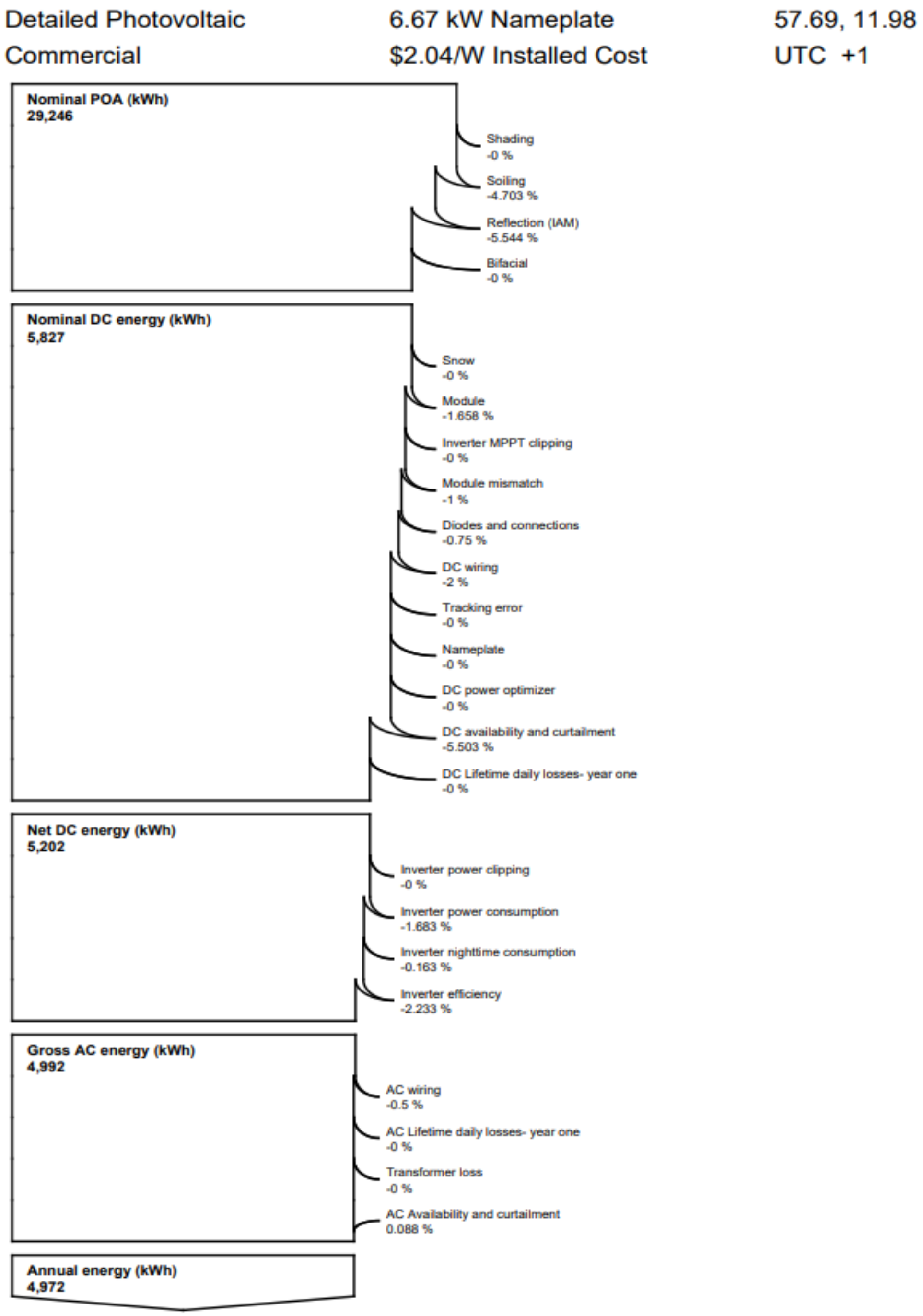
NPV Approximation using Annuities

Annuities, Capital Recovery Factor (CRF) = 0.1023		
Investment	$-0	Sum:
Expenses	$-1,000	$200
Savings	$800	NPV = Sum / CRF:
Energy value	$500	$2,000

Investment = Installed Cost - Debt Principal - IBI - CBI
Expenses = Operating Costs + Debt Payments
Savings = Tax Deductions + PBI
Energy value = Tax Adjusted Net Savings
Nominal discount rate = 9.06%

Payback Cash Flow (Payback Period = 12.7 years)

SAM Report (page 3 of 3) – System Energy Losses



Detailed Photovoltaic
Commercial

6.67 kW Nameplate
$2.04/W Installed Cost

57.69, 11.98
UTC +1

Nominal POA (kWh)
29,246

Shading -0 %
Soiling -4.703 %
Reflection (IAM) -5.544 %
Bifacial -0 %

Nominal DC energy (kWh)
5,827

Snow -0 %
Module -1.658 %
Inverter MPPT clipping -0 %
Module mismatch -1 %
Diodes and connections -0.75 %
DC wiring -2 %
Tracking error -0 %
Nameplate -0 %
DC power optimizer -0 %
DC availability and curtailment -5.503 %
DC Lifetime daily losses- year one -0 %

Net DC energy (kWh)
5,202

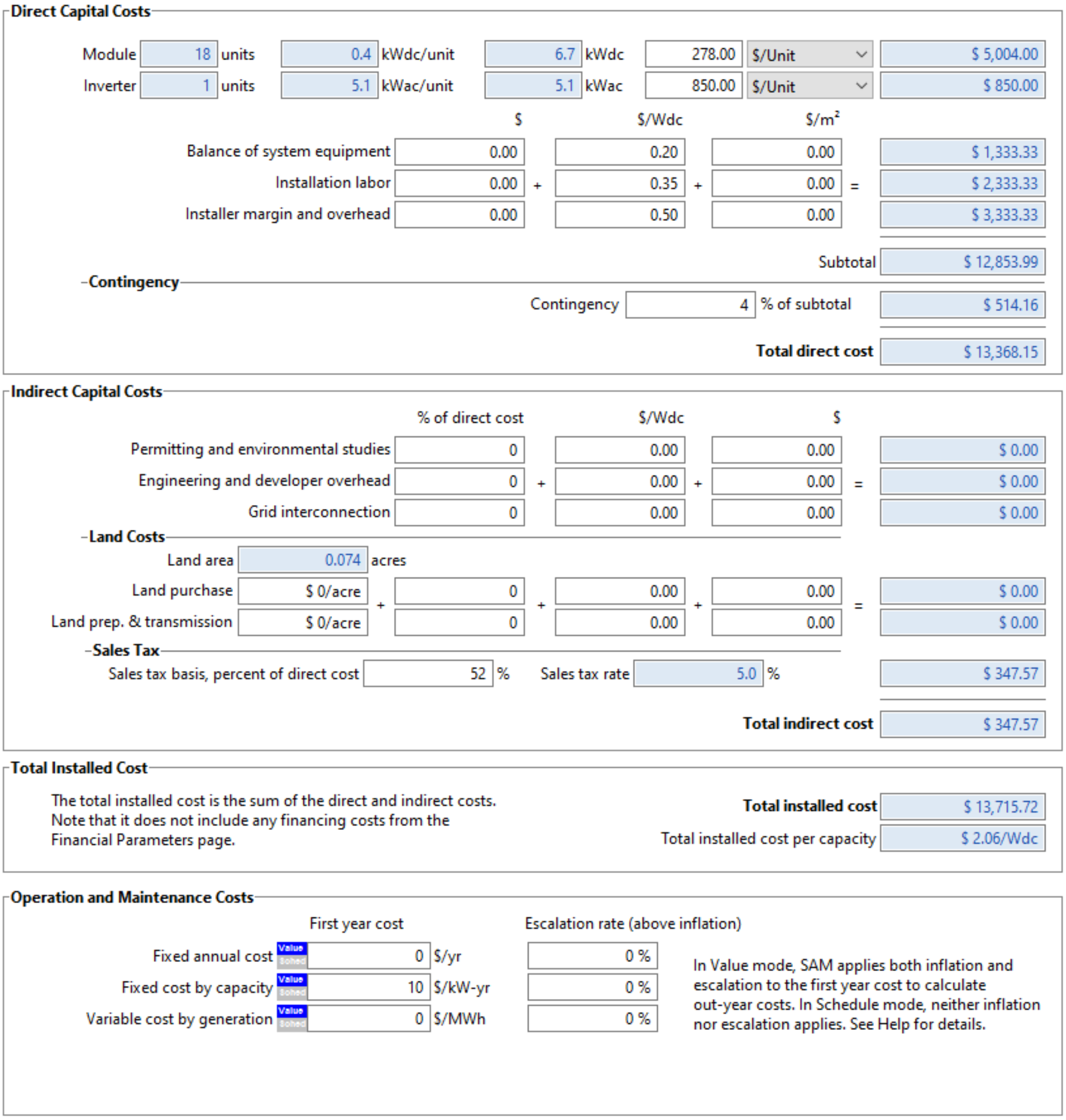
Inverter power clipping -0 %
Inverter power consumption -1.683 %
Inverter nighttime consumption -0.163 %
Inverter efficiency -2.233 %

Gross AC energy (kWh)
4,992

AC wiring -0.5 %
AC Lifetime daily losses- year one -0 %
Transformer loss -0 %
AC Availability and curtailment 0.088 %

Annual energy (kWh)
4,972

SAM Photovoltaic System Cost Parameters



Direct Capital Costs

Module	18 units	0.4 kWdc/unit	6.7 kWdc	278.00 $/Unit	$ 5,004.00
Inverter	1 units	5.1 kWac/unit	5.1 kWac	850.00 $/Unit	$ 850.00

	$	$/Wdc	$/m²	
Balance of system equipment	0.00	0.20	0.00	$ 1,333.33
Installation labor	0.00	0.35	0.00	$ 2,333.33
Installer margin and overhead	0.00	0.50	0.00	$ 3,333.33
Subtotal				$ 12,853.99

Contingency

Contingency	4 % of subtotal	$ 514.16
Total direct cost		$ 13,368.15

Indirect Capital Costs

	% of direct cost	$/Wdc	$	
Permitting and environmental studies	0	0.00	0.00	$ 0.00
Engineering and developer overhead	0	0.00	0.00	$ 0.00
Grid interconnection	0	0.00	0.00	$ 0.00

Land Costs

Land area 0.074 acres

		% of direct cost	$/Wdc	$	
Land purchase	$ 0/acre	0	0.00	0.00	$ 0.00
Land prep. & transmission	$ 0/acre	0	0.00	0.00	$ 0.00

Sales Tax

Sales tax basis, percent of direct cost	52 %	Sales tax rate 5.0 %	$ 347.57
Total indirect cost			$ 347.57

Total Installed Cost

The total installed cost is the sum of the direct and indirect costs. Note that it does not include any financing costs from the Financial Parameters page.

Total installed cost	$ 13,715.72
Total installed cost per capacity	$ 2.06/Wdc

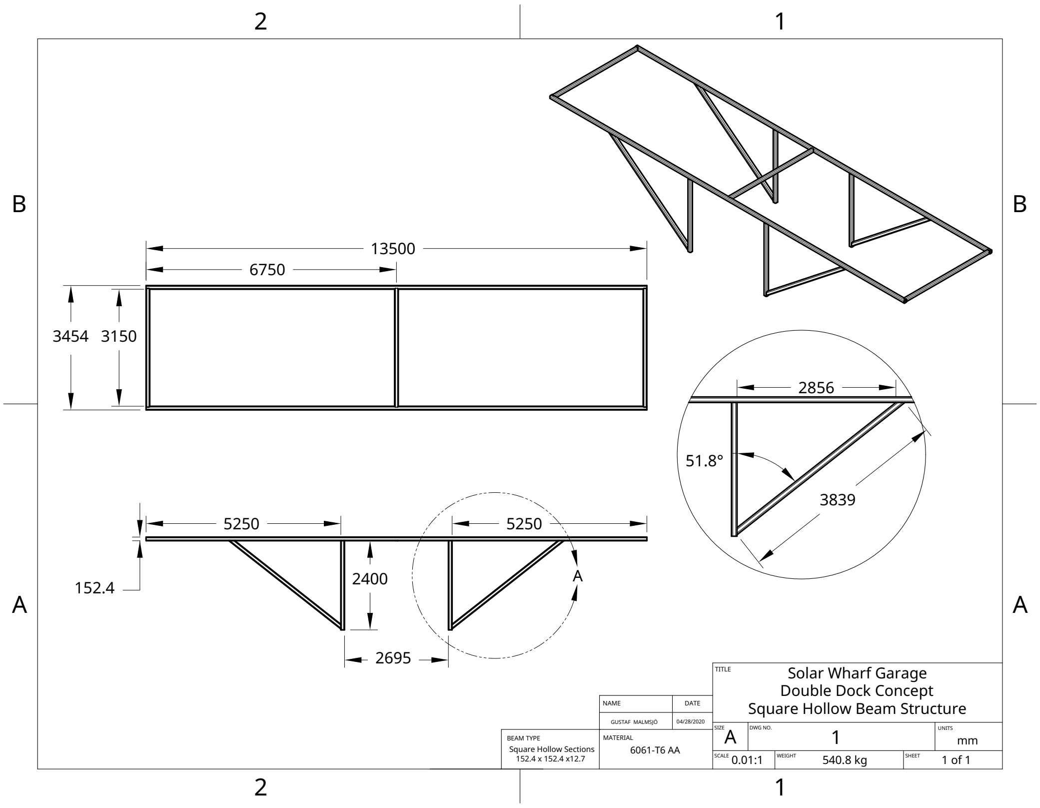
Operation and Maintenance Costs

	First year cost	Escalation rate (above inflation)
Fixed annual cost	0 $/yr	0 %
Fixed cost by capacity	10 $/kW-yr	0 %
Variable cost by generation	0 $/MWh	0 %

In Value mode, SAM applies both inflation and escalation to the first year cost to calculate out-year costs. In Schedule mode, neither inflation nor escalation applies. See Help for details.

Appendix C - Drawings

Square Hollow Beam Structure



TITLE Solar Wharf Garage
Double Dock Concept
Square Hollow Beam Structure

NAME GUSTAF MALMSJÖ
DATE 04/28/2020

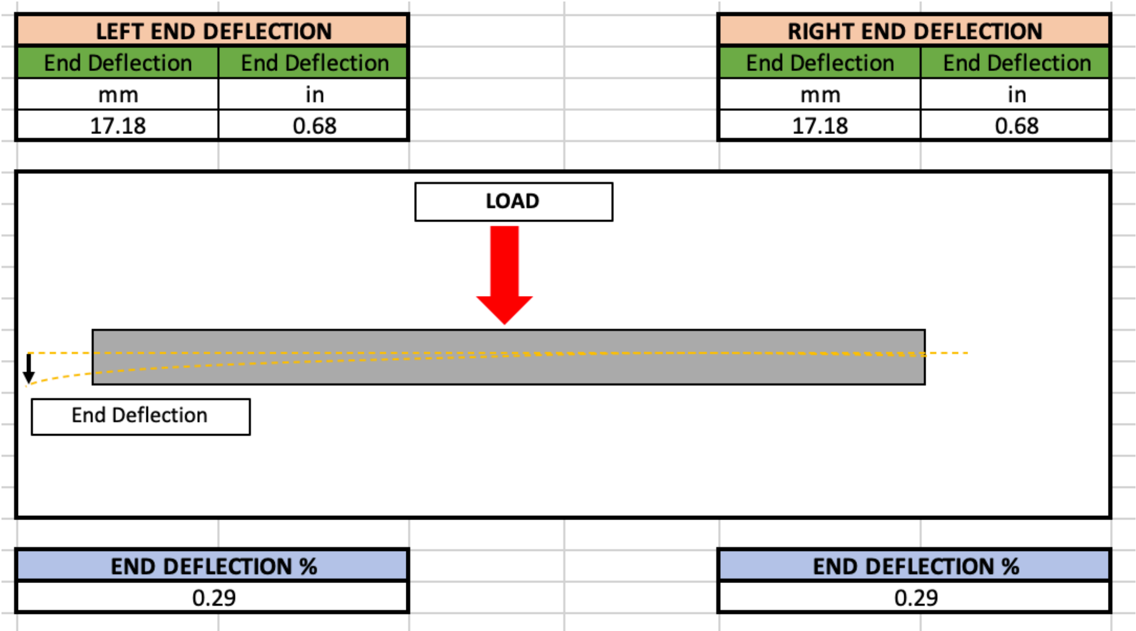
BEAM TYPE Square Hollow Sections
152.4 x 152.4 x12.7

MATERIAL 6061-T6 AA

SIZE A
DWG NO. 1
UNITS mm
SCALE 0.01:1
WEIGHT 540.8 kg
SHEET 1 of 1

Appendix D - Structural analysis

Beam Deflection Analysis



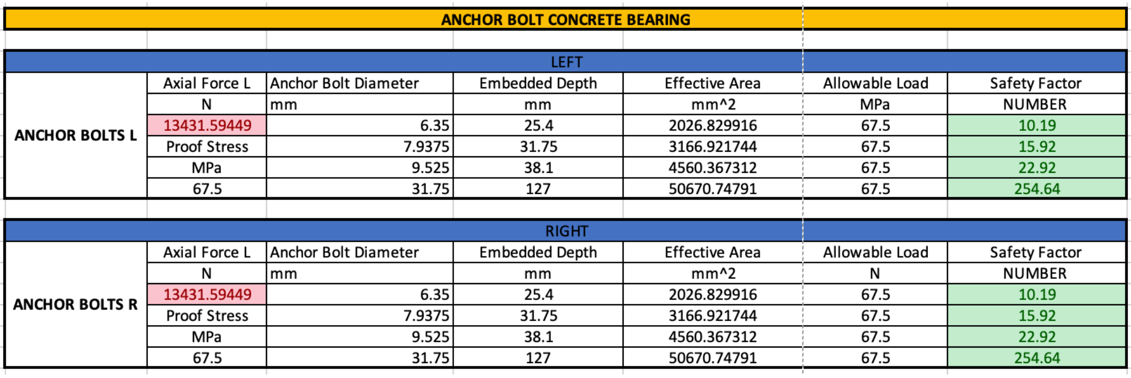
LEFT END DEFLECTION	
End Deflection	End Deflection
mm	in
17.18	0.68

RIGHT END DEFLECTION	
End Deflection	End Deflection
mm	in
17.18	0.68

END DEFLECTION %
0.29

END DEFLECTION %
0.29

Anchor Bolt Stress Analysis with Varying Diameter



ANCHOR BOLT CONCRETE BEARING

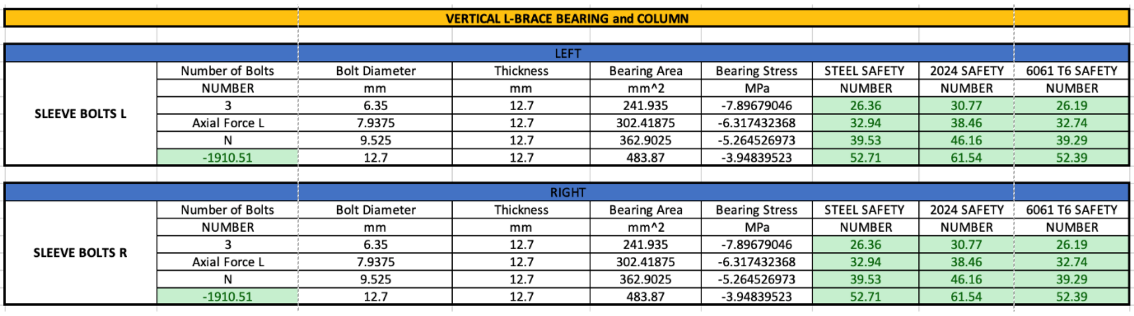
LEFT

	Axial Force L	Anchor Bolt Diameter	Embedded Depth	Effective Area	Allowable Load	Safety Factor
	N	mm	mm	mm^2	MPa	NUMBER
ANCHOR BOLTS L	13431.59449	6.35	25.4	2026.829916	67.5	10.19
	Proof Stress	7.9375	31.75	3166.921744	67.5	15.92
	MPa	9.525	38.1	4560.367312	67.5	22.92
	67.5	31.75	127	50670.74791	67.5	254.64

RIGHT

	Axial Force L	Anchor Bolt Diameter	Embedded Depth	Effective Area	Allowable Load	Safety Factor
	N	mm	mm	mm^2	N	NUMBER
ANCHOR BOLTS R	13431.59449	6.35	25.4	2026.829916	67.5	10.19
	Proof Stress	7.9375	31.75	3166.921744	67.5	15.92
	MPa	9.525	38.1	4560.367312	67.5	22.92
	67.5	31.75	127	50670.74791	67.5	254.64

Sleeve Bolts Stress Analysis with Varying Diameter



VERTICAL L-BRACE BEARING and COLUMN

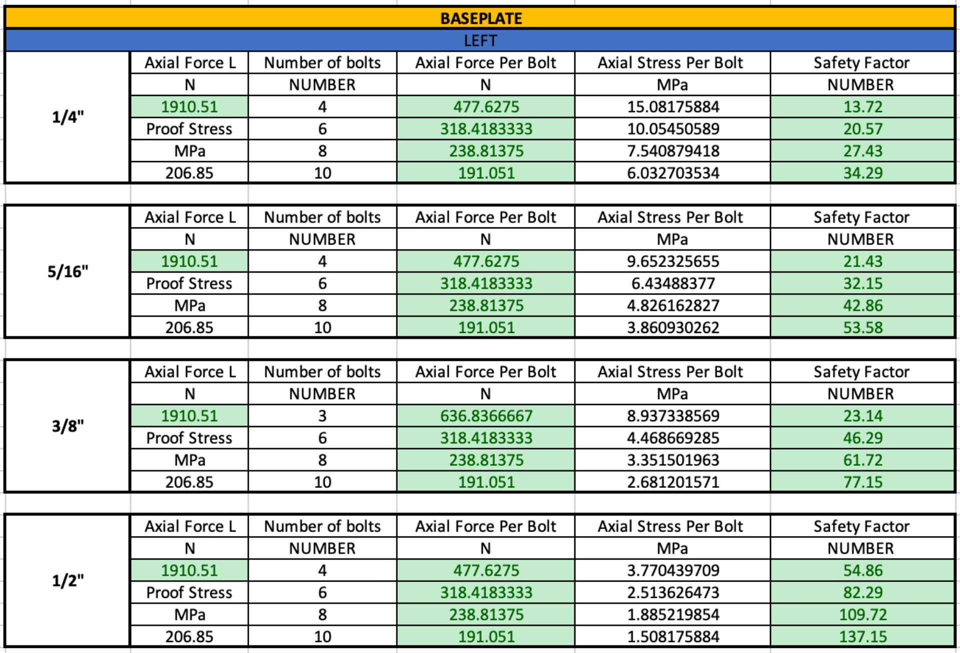
LEFT

	Number of Bolts	Bolt Diameter	Thickness	Bearing Area	Bearing Stress	STEEL SAFETY	2024 SAFETY	6061 T6 SAFETY
	NUMBER	mm	mm	mm^2	MPa	NUMBER	NUMBER	NUMBER
SLEEVE BOLTS L	3	6.35	12.7	241.935	-7.89679046	26.36	30.77	26.19
	Axial Force L	7.9375	12.7	302.41875	-6.317432368	32.94	38.46	32.74
	N	9.525	12.7	362.9025	-5.264526973	39.53	46.16	39.29
	-1910.51	12.7	12.7	483.87	-3.94839523	52.71	61.54	52.39

RIGHT

	Number of Bolts	Bolt Diameter	Thickness	Bearing Area	Bearing Stress	STEEL SAFETY	2024 SAFETY	6061 T6 SAFETY
	NUMBER	mm	mm	mm^2	MPa	NUMBER	NUMBER	NUMBER
SLEEVE BOLTS R	3	6.35	12.7	241.935	-7.89679046	26.36	30.77	26.19
	Axial Force L	7.9375	12.7	302.41875	-6.317432368	32.94	38.46	32.74
	N	9.525	12.7	362.9025	-5.264526973	39.53	46.16	39.29
	-1910.51	12.7	12.7	483.87	-3.94839523	52.71	61.54	52.39

Baseplate Analysis with Varying Thickness and Number of Bolts

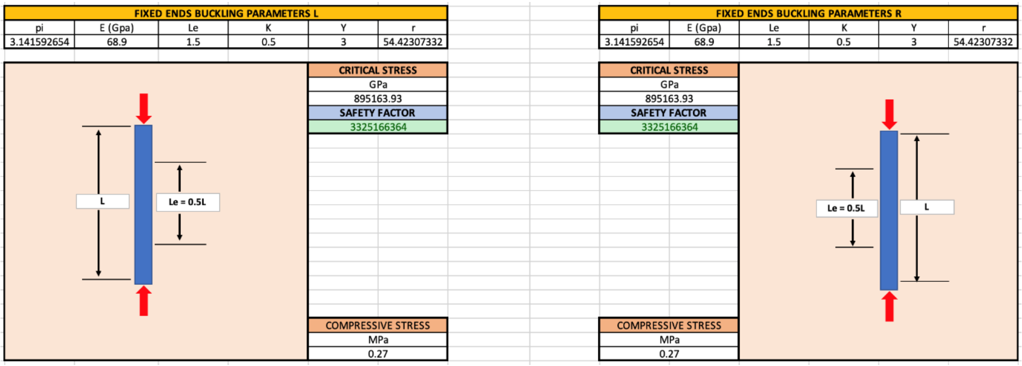


BASEPLATE

LEFT

	Axial Force L	Number of bolts	Axial Force Per Bolt	Axial Stress Per Bolt	Safety Factor
1/4"	N	NUMBER	N	MPa	NUMBER
	1910.51	4	477.6275	15.08175884	13.72
	Proof Stress	6	318.4183333	10.05450589	20.57
	MPa	8	238.81375	7.540879418	27.43
	206.85	10	191.051	6.032703534	34.29
	Axial Force L	Number of bolts	Axial Force Per Bolt	Axial Stress Per Bolt	Safety Factor
5/16"	N	NUMBER	N	MPa	NUMBER
	1910.51	4	477.6275	9.652325655	21.43
	Proof Stress	6	318.4183333	6.43488377	32.15
	MPa	8	238.81375	4.826162827	42.86
	206.85	10	191.051	3.860930262	53.58
	Axial Force L	Number of bolts	Axial Force Per Bolt	Axial Stress Per Bolt	Safety Factor
3/8"	N	NUMBER	N	MPa	NUMBER
	1910.51	3	636.8366667	8.937338569	23.14
	Proof Stress	6	318.4183333	4.468669285	46.29
	MPa	8	238.81375	3.351501963	61.72
	206.85	10	191.051	2.681201571	77.15
	Axial Force L	Number of bolts	Axial Force Per Bolt	Axial Stress Per Bolt	Safety Factor
1/2"	N	NUMBER	N	MPa	NUMBER
	1910.51	4	477.6275	3.770439709	54.86
	Proof Stress	6	318.4183333	2.513626473	82.29
	MPa	8	238.81375	1.885219854	109.72
	206.85	10	191.051	1.508175884	137.15

Buckling Analysis



FIXED ENDS BUCKLING PARAMETERS L

pi	E (Gpa)	Le	K	Y	r
3.141592654	68.9	1.5	0.5	3	54.42307332

CRITICAL STRESS
GPa
895163.93
SAFETY FACTOR
3325166364

COMPRESSIVE STRESS
MPa
0.27

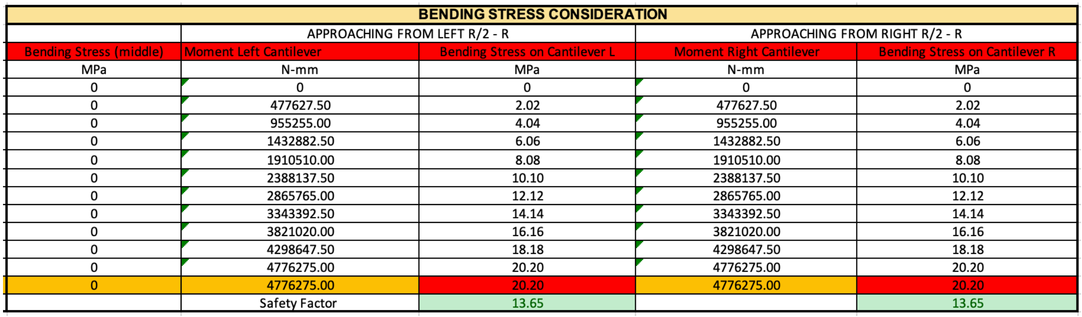
FIXED ENDS BUCKLING PARAMETERS R

pi	E (Gpa)	Le	K	Y	r
3.141592654	68.9	1.5	0.5	3	54.42307332

CRITICAL STRESS
GPa
895163.93
SAFETY FACTOR
3325166364

COMPRESSIVE STRESS
MPa
0.27

Bending Stress Analysis



BENDING STRESS CONSIDERATION

	APPROACHING FROM LEFT R/2 - R		APPROACHING FROM RIGHT R/2 - R	
Bending Stress (middle)	Moment Left Cantilever	Bending Stress on Cantilever L	Moment Right Cantilever	Bending Stress on Cantilever R
MPa	N-mm	MPa	N-mm	MPa
0	0	0	0	0
0	477627.50	2.02	477627.50	2.02
0	955255.00	4.04	955255.00	4.04
0	1432882.50	6.06	1432882.50	6.06
0	1910510.00	8.08	1910510.00	8.08
0	2388137.50	10.10	2388137.50	10.10
0	2865765.00	12.12	2865765.00	12.12
0	3343392.50	14.14	3343392.50	14.14
0	3821020.00	16.16	3821020.00	16.16
0	4298647.50	18.18	4298647.50	18.18
0	4776275.00	20.20	4776275.00	20.20
0	4776275.00	20.20	4776275.00	20.20
	Safety Factor	13.65		13.65