Ocean Wave Energy Converter

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Preface

The bachelor thesis “Ocean wave energy converter” is written by three Mechanical engineer students at the Department of Mechanical and Marine Engineering (IMM) at Western Norway University of Applied Science (WNUAS). The project is written with the help and collaboration of Dr. Saeed Bikass at WNUAS.

When producing a prototype for the project, the group used the Machine lab at WNUAS. At the lab, the group has been receiving guidance and help with machining parts from Kjetil Gravelsaeter and Frode Wessel Jansen. We would also like to thank Solund Verft AS for providing reasonable aluminium prices for the prototype.

The group was given the task of “designing and testing an electricity generator from the wave loads” by the Western Norway University of Applied Science. The end criteria for the task are to achieve knowledge about the wave energy in general, available potentials, and design techniques as well as experimental data.

Abstract

The report documents the process of developing a concept that utilizes wave motion to create energy. It enlightens the reader on existing technology and concepts while giving an insight into how ocean waves work and different types of wave energy. There is a range of different existing technologies that seek to solve this matter, but unlike wind energy, there is not a main design for harvesting wave energy. The fact that capturing ocean wave energy is such a difficult task, makes this project extremely exciting and relevant for the onwards battle for creating a more sustainable future.

The group started the project by ideating an array of different designs without looking at already existing technology. By this, the creativity would not get disturbed by concepts from the internet. In addition to this, the group used a “random word” technique for challenging the imagination and coming up with non-existing concepts. After every group member had made six different designs each, an idea screening process was used to pick the best idea that was to be produced.

Further, the thesis documents the engineering of the prototype which gives the reader an insight into the different stages of producing a concept. The group faced some budget problems due to increased commodity prices, but with the help from Solund Verft AS that provided material, and smart solutions the group solved the problem.

The last part describes the results when testing the prototype and the final design. The testing is aimed to prove if the design works on a small scale and would give documentation that could be beneficial for making the design in full scale. For the final design, the project is optimized and gives an insight into what could be improved when making a better version of the concept.

Sammendrag

Rapporten dokumenterer prosessen med å utvikle et konsept som utnytter bølgebevegelse til å skape energi. Den opplyser leseren om eksisterende teknologi og konsepter, samtidig som den gir et innblikk i hvordan havbølger fungerer og ulike typer bølgeenergi. Det finnes en rekke forskjellige eksisterende teknologier som søker å løse denne saken, men i motsetning til vindenergi er det ikke et hoveddesign for høsting av bølgeenergi. Det faktum at å fange havbølgeenergi er en så vanskelig oppgave, gjør dette prosjektet ekstremt spennende og relevant for den videre kampen for å skape en mer bærekraftig fremtid.

Gruppen startet prosjektet med å tenke på en rekke forskjellige design uten å se på eksisterende teknologi, slik at kreativiteten ikke ble forstyrret av konsepter fra internett. I tillegg til dette brukte gruppen en "tilfeldig ord"-teknikk for å utfordre fantasien og komme opp med ikke-eksisterende konsepter. Etter at hvert gruppemedlem hadde laget seks forskjellige design hver, ble en idéscreeningsprosess brukt for å velge den beste ideen som skulle produseres.

Videre dokumenterer oppgaven konstruksjonen av prototypen som gir leseren et innblikk i de ulike stadiene i å produsere et konsept. Gruppen fikk noen budsjettproblemer på grunn av økte råvarepriser, men med hjelp fra Solund Verft AS som leverte materiell, og smarte løsninger klarte gruppen å løse problemet.

Den siste delen beskriver resultatene ved testing av prototypen og det endelige designet. Testingen er rettet mot å bevise om designet fungerer i liten skala og vil gi dokumentasjon som kan være gunstig for å gjøre designet i full skala. For den endelige utformingen er prosjektet optimalisert og gir et innblikk i hva som kan forbedres ved å lage en bedre versjon av konseptet.

Table of contents

1. Introduction

The thesis “Ocean wave energy converter” (OWEC) explores the possibilities of harvesting energy from the ocean. Wave energy converters are devices that convert the kinetic and potential energy related to a moving ocean wave into useful mechanical or electrical energy. The converters can provide clean energy to power the electrical grid and several different applications such as fish farms or pumping for seawater desalination. The project is aimed at studying available ideas to help get an understanding of potential improvements to then to be used for developing a prototype.

1.1 Motivation

Ocean waves hold an endless supply of energy, waiting to be harvested. Several companies have tried to find a design robust enough to withstand the forces from the waves, while at the same time being cost-efficient. The design will also need to withstand being placed in a harsh environment with the possibility of being corrosion resistant due to salty water. This has led to expensive designs and made wave energy non profitable. There are different designs for harvesting wave energy, not only one like you see for wind energy. A company in Sweden called CorPower Ocean says they have designed a way to harvest 5 times more energy for a third of the cost compared to other wave energy companies [1].

The goal for this task is to design and create a prototype for a concept that utilizes and harvests energy from waves at sea and captures energy that can be used for different purposes. This involves the transport and capture of energy by ocean surface waves.

Deciding on a final design, the goal is to combine theoretical knowledge of wave dynamics and structural mechanics to provide a functional prototype capable of extracting ocean wave energy. Once the theoretical calculations, using rough sketches are finalized, the design will be 3D modelled. The different parts will be produced using a suitable material for later assembly and testing. A suitable material must be decided upon considering the environment of operation, to prevent failure e.g., seawater or structural failure due to dynamic stress. Once the prototype is produced it will be tested and ideally generate electrical energy capable of being measured. The testing could reveal malfunctions or poor design decisions, leading to revisions of the design. These will then be accounted for and if there is enough time left, a revised prototype will be tested.

Main Objective

Create a feasible prototype capable of generating power from ocean waves.

Objectives

- Understanding and analysing wave dynamics
- Finding different designs for absorbing wave energy
    - Linear motion
    - Non-Linear motion

- Decide on the design
- Designing and producing prototype
    - Sketching
    - 3D Modelling
    - Production
- Testing and measuring output/efficiency

1.2 Requirements and Specifications

An integral part of an offshore ocean wave generator is functionality. A potential customer would prioritise cost and efficiency, however, there are several aspects of the finished project that are requirements and not idealisations. The generator needs to be capable of withstanding the continuous battering from the ocean, causing dynamic stresses throughout the structural segments of the design as seen in Figure 1.

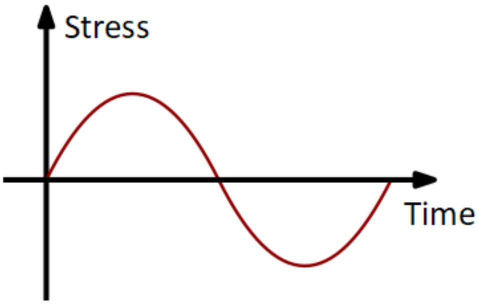


Figure 1 - Stress as a function of Time

Analysing and simulating the energy and stress between joints and welds are of paramount importance as these are often the failure points [2, pp. 285-324]. With the generation of electricity comes electronic systems to regulate voltages and output, as well as other functions of the generator. These systems are vulnerable to seawater, and a leak could result in disaster. The areas such as flanges are particularly vulnerable to any damage from the ocean, and therefore require gaskets and other methods to prevent humidity. Aside from this, the material itself is also at risk of corrosion and needs either surface treatment or be made with specific properties. (e.g., Stainless)

The design needs to follow health safety and environment (HSE) regulations, such that the employees working on the project has a fully adequate working environment. This means the project requires easy instalment and maintenance such that the workers will not sustain any physical or mental injuries because of the employment. The ocean energy harvesting design should generate enough electricity for the customer to receive good value for the investment. It ought to compete with the designs that are already available on the market while delivering good sustainability credentials. For creating an environmentally friendly future the industry requires high demands on green energy, and the group is hoping to achieve a valuable result in the ongoing battle towards this goal. It is preferable that the product is easily accessible and not too far away from the coast. This will reduce cost and time. It also reduces traveling time which is environmentally friendly. Another aspect of maintenance is that the product should be easy to maintain. The cost of the project should not affect the quality of the product. Mainly the financial cost should be enough to finish design requirements, but also not too high.

2. Literature Review

Analysing published articles and literature concerning e.g., wave dynamics and buoyancy leads to a greater understanding of the physics involved in ocean-wave energy extraction. When choosing a concept to design and finalize, there must be a theoretical foundation to build upon. In this chapter, concepts such as ocean wave dynamics and geographical factors affecting the size and shape of ocean waves are discussed.

2.1 Ocean Wave Dynamics

There is an endless amount of energy contained within the sea. Think of the waves pounding on the beaches, or the movement of the tides that makes vast volumes of water rise and fall twice a day. If the energy could be harnessed to power our homes and cities, the world would make a huge step towards a green and environmentally friendly future. What is needed is a way to convert the ocean's kinetic energy into electricity. To do so, one needs to understand wave dynamics and the two main types of energy that can be derived from the ocean: Wave- and tidal energy [3].

Waves are energy passing through the water, causing it to move in a circular motion. When a wave encounters a surface object, the object appears to lurch forward with the wave, but then falls in an orbital rotation as the wave travels onwards. The way of understanding ocean waves is simply the outward manifestation of kinetic energy propagating through seawater. Waves do not move a significant amount of water, they simply transmit energy across the sea [3].

Waves are mostly caused by wind. Ocean surface waves are created by the friction between wind and surface water, making it move in an orbital motion where the water down to the wave's wavelength follows the same movement. As the wind blows across the surface of the ocean, the continual disturbance creates a wave crest. In shallow areas the seabed causes the lower portion of the wave to slow down and compress, forcing the wave crest higher in the air. Eventually, this imbalance in the wave reaches a breaking point, and the crest comes crashing down as wave energy [4].

Bigger and potentially hazardous waves can be caused by severe weather. Strong winds and pressure from storms cause storm surges, a series of long waves that are created far from shore in deeper water and intensifies when moving closer to the coastline. These types of waves can also occur by underwater disturbances that displace large amounts of water quickly such as earthquakes, landslides, or volcanic eruptions. The last wave type is called a tidal wave, which is caused by the gravitational pull of the sun and moon on the earth. All these wave types create energy, but what is wave energy? [4]

Ultimately, it is solar energy that starts the process, as it is differences in air temperature that cause wind. The energy that is transferred as solar radiation from the sun to the wind, and finally to waves in the ocean becomes concentrated at each step of the process. This makes wave energy a good potential energy source. The height of a wave is an important factor in determining how much energy a wave contains. The height of a wave is the difference between its highest point and its lowest point. The period of the wave also contributes to wave energy. The period of a wave is how long, in seconds, it takes for one wave crest to travel the distance between two wave crests. The greater the wave height, and the short the period, the more energy it contains. Waves travel through the ocean in groups, and individual waves appear to move through this group, from the back to the front, where they dissipate. The energy waves contain depends on the group velocity of the collection of waves, rather than on the individual wave's velocity. In deep water, the group velocity is half the velocity of an individual wave within the group. In shallow water, the group velocity and an individual wave's velocity are the same [3].

There are different classified technologies for harvesting wave energy on the market. They are divided into three main types: Oscillating water columns, oscillating bodies, and overtopping convertors.

Oscillating water columns

Oscillating water columns use wave surges to drive a stream of trapped air through an air turbine. These devices are essentially large hollow columns half-submerged in the ocean, with an underwater vent open to the sea. The movement of the waves pushes water into the chamber, forcing air through the column. As waves recede, the air is sucked back through the column in the other direction. The movement of air rotates a turbine in the column, which rapidly turns a generator to produce electricity [3].

Oscillating bodies

Oscillating bodies use floating buoys or platforms that rise and fall with the swell. They are fixed to the seabed via a hydraulic pump. The buoy moves up and down along the ocean swell crest and troughs, activating the hydraulic pump which pushes water or air through a turbine that rotates a generator to produce electricity [3].

Overtopping converters

Overtopping converters allow swell to deliver water over the top of a structure that captures it higher than sea level, and then releases the water to drive a hydroelectric turbine, like a hydroelectric dam. Ocean swells that would normally crash against the shore or a cliff are instead directed up a ramp to a water tank a few meters above sea level. The water is then released, through a turbine, back to sea level [3].

2.2 Buoyancy

An objects inherent buoyancy may be derived from the theory of hydrostatic pressure. Given a defined volume and the density of the fluid, one may calculate the total upward force known as buoyancy [5, pp. 89-90]. This idea was first formulated in ancient Greece by Archimedes and is known as Archimedes' Principle. Given a cube with a length of 1 meter,

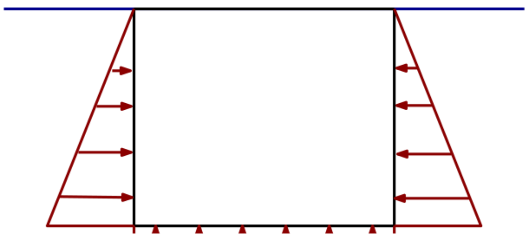


Figure 2 - Hydrostatic Pressure on Submerged Vessel

and a fluid density of 1000 kg / m^3, the total buoyancy is equal to 1000 kg. Using the formula of hydrostatic pressure, we see that

$$P = z * \rho * g \tag{1}$$

$$z = Height, \rho = Density \ \& \ g = Gravity \ (9.81 \frac{m}{s^2})$$

This gives us a pressure of 9810 Pa. Knowing the area of the cubes bottom, we know that F = P*A which gives us a force of 9810 Newtons of upward force. The hydrostatic pressure formed on the sides cancel each other, giving us a net positive force in the y-direction (upwards). We know that F = m*a, where a = g in this scenario. The buoyancy described by mass is therefore

$$F = m * g \quad \rightarrow \quad \frac{9810\ Pa}{9.81 \frac{m}{s^2}} = 1000\ kg \tag{2}$$

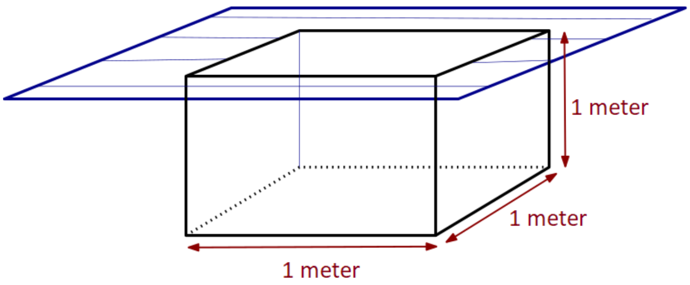


Figure 3 - Submerged Vessel

2.3 Ocean wave locations

Wave energy has a large potential for energy harvesting, but not all countries in the world can benefit from it. Countries that border the ocean can claim 12 nautical miles from its coast [6]. This means that wave energy is not suitable, nor possible for some countries. According to [7] 42 countries in the world don’t have direct access to a coastline.

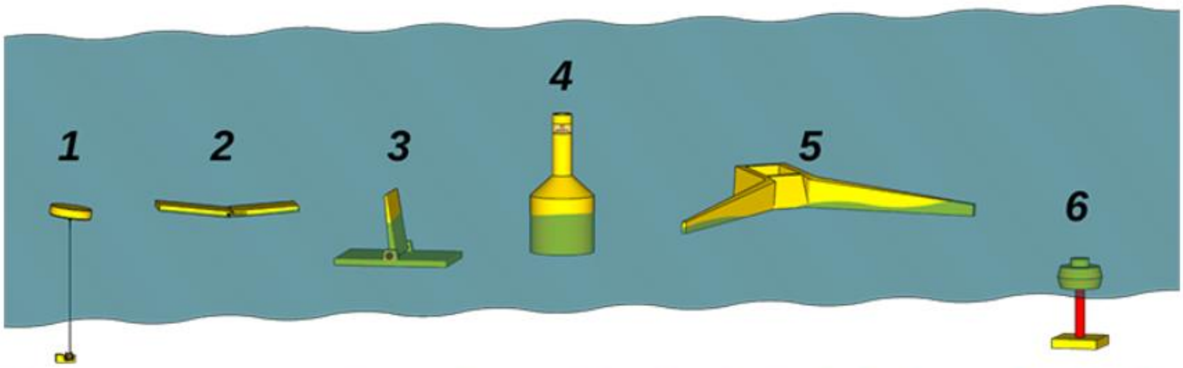
Another factor is the waves themselves differ from locations around the world. They vary in occurrence and intensity depending on the locations they appear. A location can have larger or smaller waves due to wind and the geographical appearance of the sea and seabed. Generally, waves can be found in any ocean with wind.

Norway has huge potential for wave energy with one of the world’s largest coastlines compared to the country size. The northern sea is also known for its wind and large occurrences of waves. Harvesting energy both offshore and by the coast could bring in a lot of electricity and be suitable for the country.

2.4 Historical References

Wave power is an important aspect in the quest for creating a sustainable future. It is an emerging sector with several global developers striving to harness the potential of wave energy. The waves can relieve solar and wind power when the conditions are not optimal, adding stability to the electrical grid. A reason why the group chose to create a wave energy concept is that to this date there is still no design that utilizes energy from the ocean in an effective way. The designs available on the market are either too expensive to produce and maintain or are proven to be inefficient. [8] The complexity of the process has led to a great diversity of designs, including “snake” attenuators, bobbing buoys, and devices mounted on the ocean floor. Some devices generate electricity on the spot and transmit it by undersea cables to shore, while others pass the mechanical energy of the wave along to land before transferring it into electrical energy [9].

Another aspect of why wave power is not widely used is the vast difference in wave energy from winter to summer months. In winter months, the amplitude is about ten times larger, and as a result, the energy it produces can be multiplied by a hundred. Up to this point, engineers have not built machines that survive this dynamic range. A big problem is fatigue. The ocean averages six million cycles of wave loading in a year, so any machine exposed to this environment need to withstand a lot of fatigue [10].



Wave energy generators come in many shapes and sizes. Some designs bob or float on the surface (1, 2, 4) or flip from side to side (3). Another type harnesses energy from waves as they crash onto shore (5). Still others sit near the sea bottom (6).

INGVALD STRAUME/WIKIMEDIA COMMONS (CC0)

Figure 4 - Different Wave Energy Converters [10].

3. Concept Development

Some of the ideas are shown throughout this chapter. For the rest of the ideas, please see Appendix A.

3.1 Ideas

As shown in Figure 5, the buoy moves up and down, the motion linearly translated to the magnetic rod using wires and weights. As the rod is lifted through the coil, the magnetic field induces power through the generator. As the wave descends, the mass at the bottom pulls the rod back down, switching the polarity of the induced electricity. Similarly, to the previous idea, Figure 8 shows a pulley system, where the buoy pulls on a wire threaded around a stationary disc, forcing rotation. As the buoy moves down again, the mass suspended from the wire rotates the disc in the opposite direction.

Sketches are shown on the following pages.

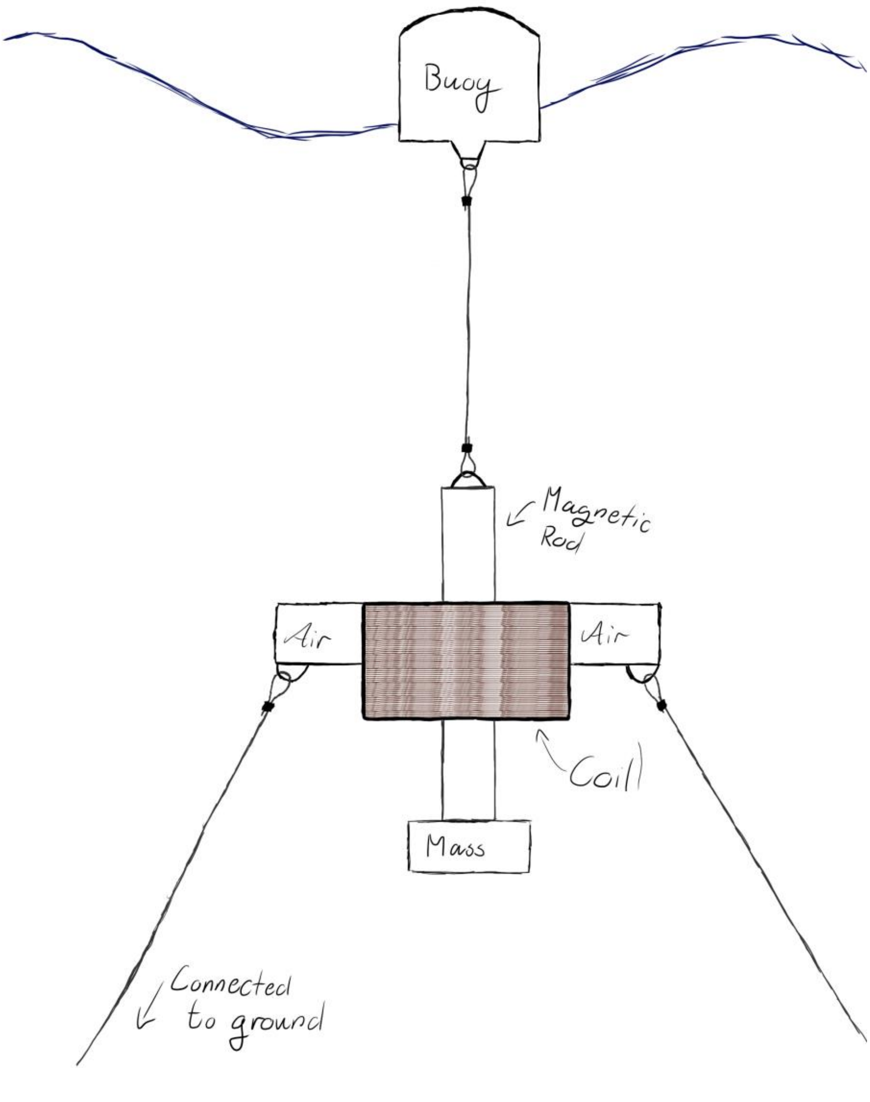


Figure 5 - Linear Generator

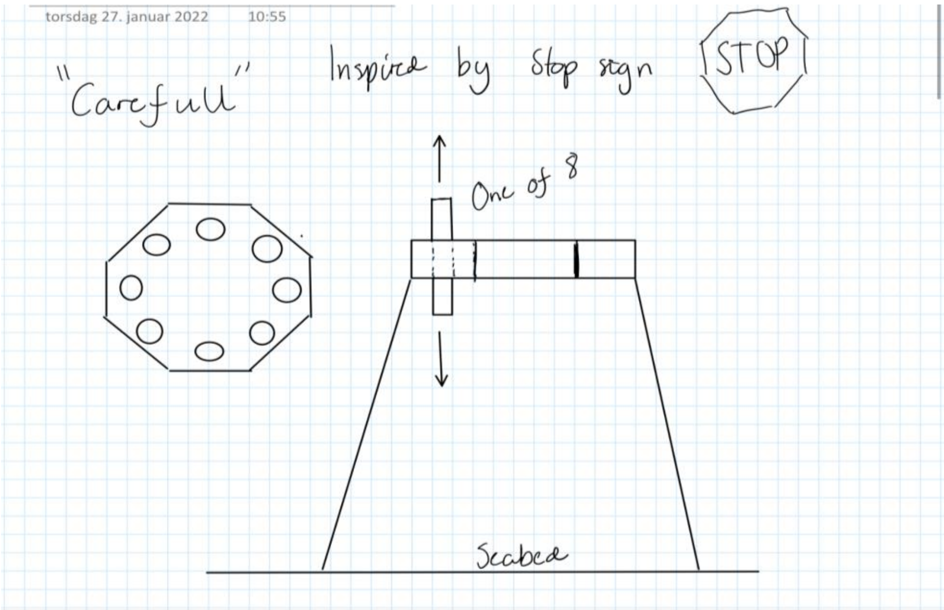


Figure 6 - Stop sign idea

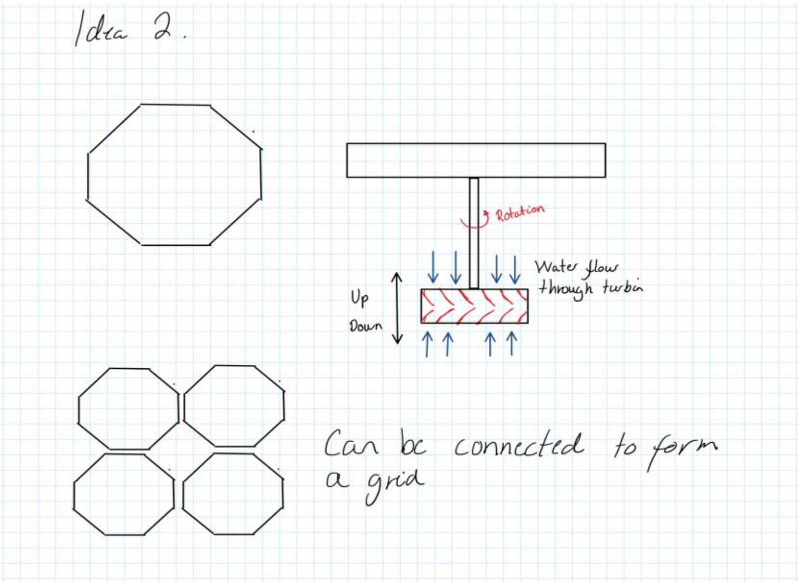


Figure 7 - Stop sign Turbine

Description of idea in Figure 6: This idea is inspired by a stop sign. The floating platform has 8 metal pistons moving up and down from wave motion to create electricity. Description of idea in Figure 7: This idea uses the same floating platform as above. The platform is connected to a rod with a turbine attached. This turbine is meant to transfer linear motion to rotational energy. The water flows through the blades to make the shaft rotate. The shaft is connected to a generator that is placed inside the floating platform.

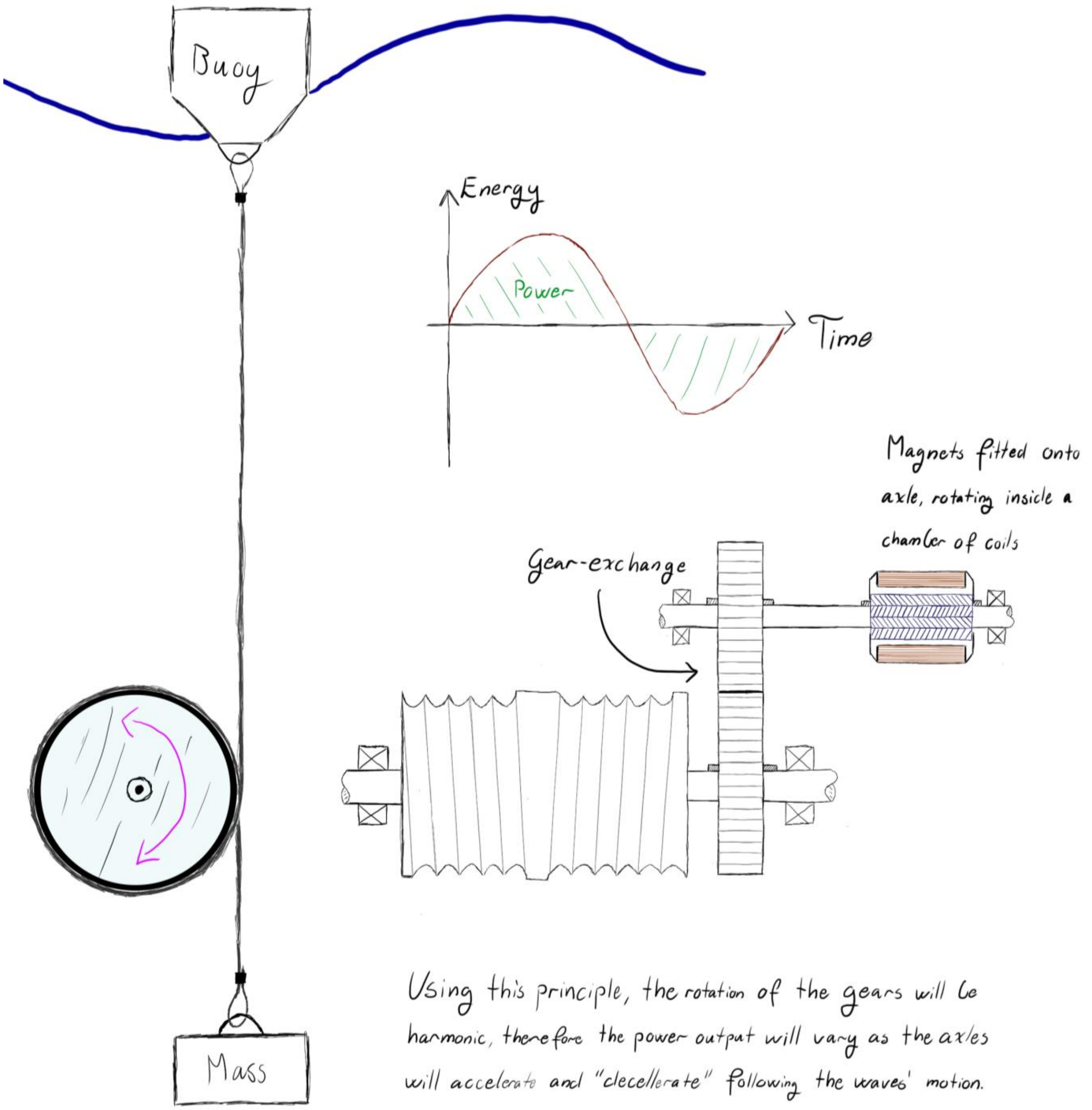


Figure 8 - Rotational Disc

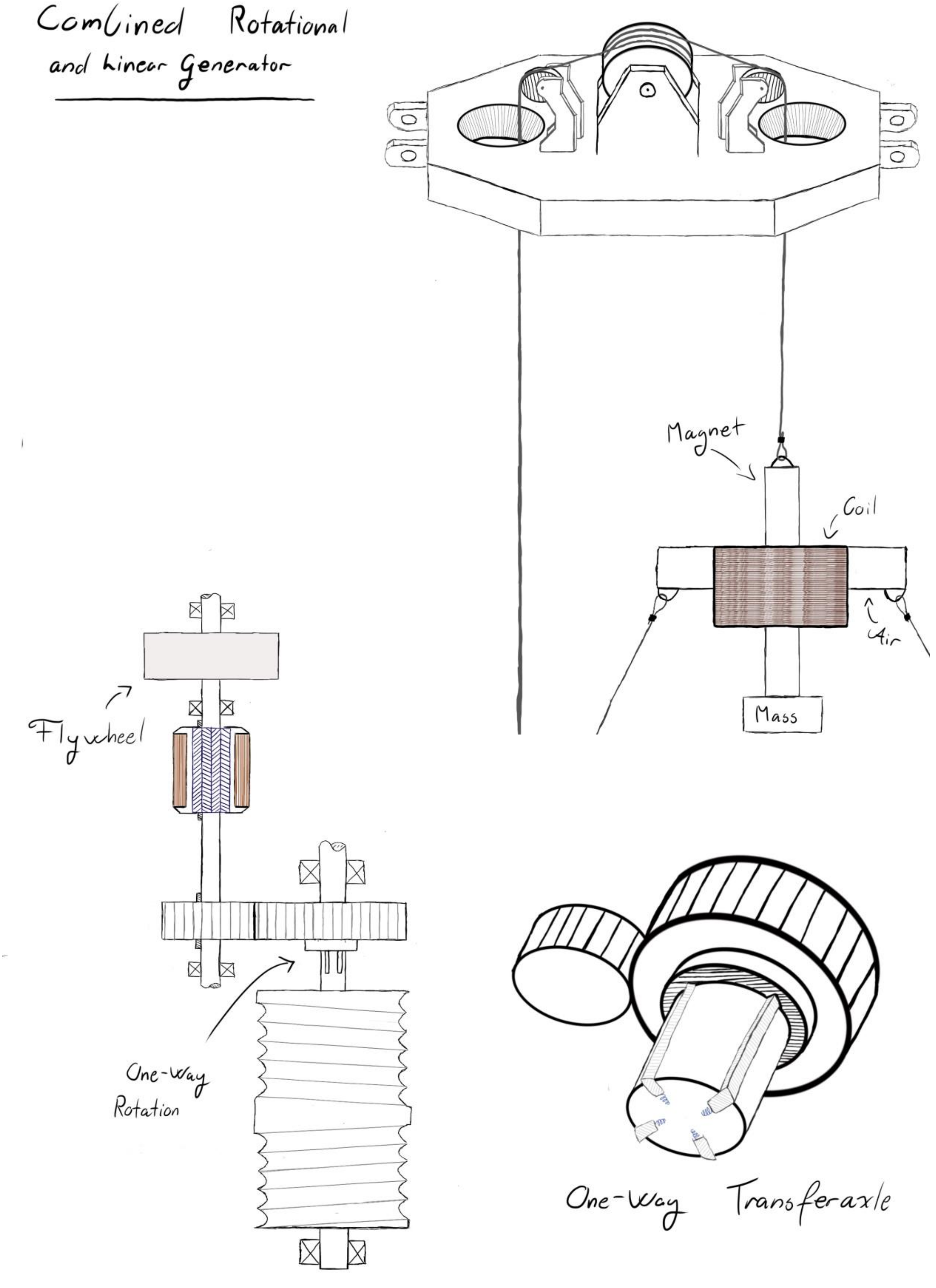


Figure 9 - Concept Illustration, Detailed

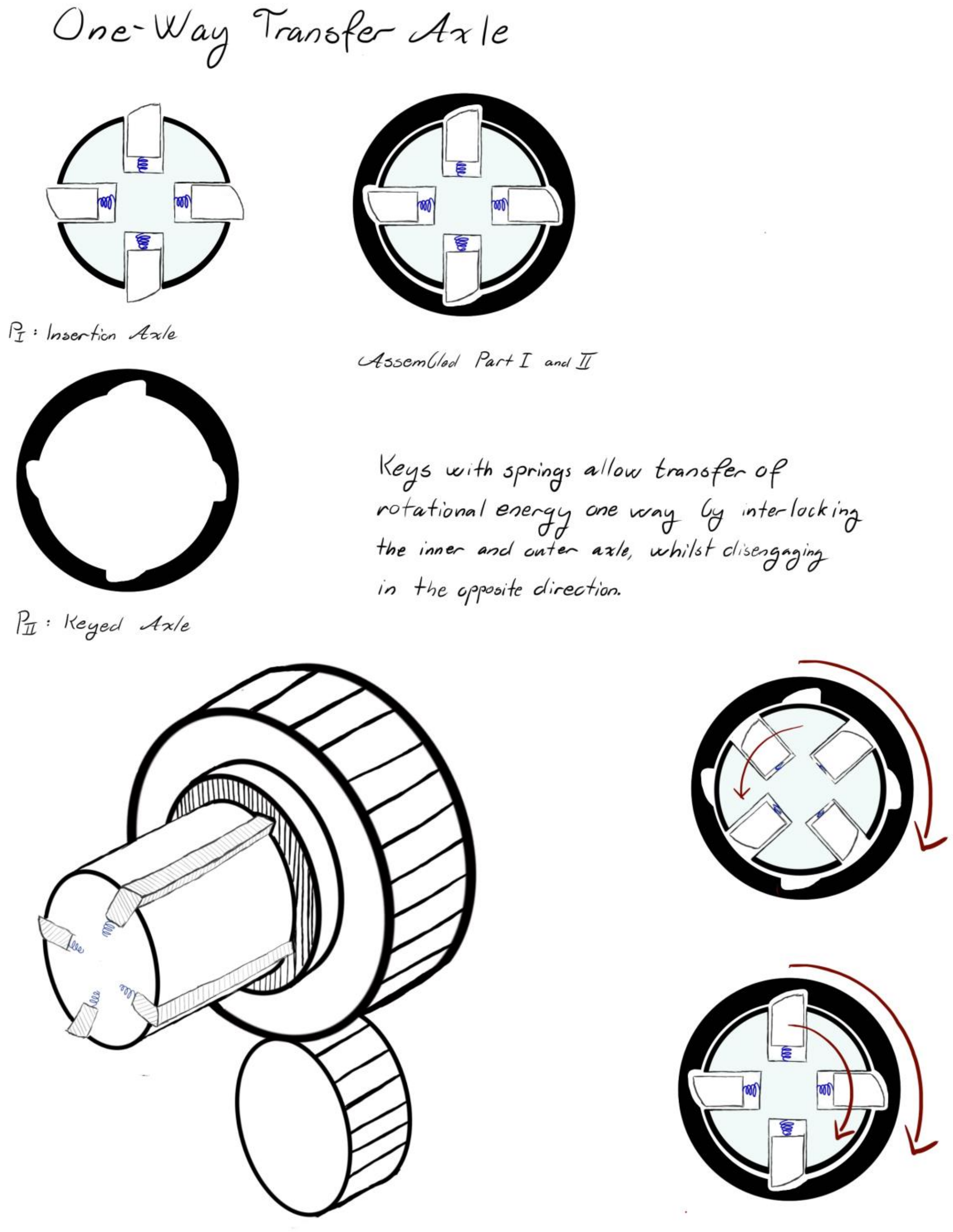


Figure 10 - One-Way gear

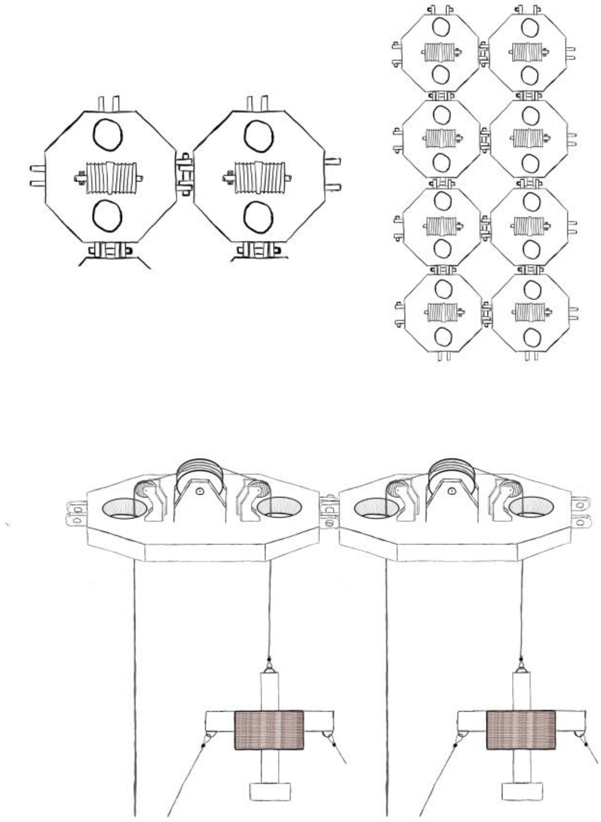


Figure 11 - Concept Grid

As shown in Figure 9, a combination of the Linear Generator and the Stop-Sign concept is shown, with Figure 10 illustrating a possible solution to the rotation caused by dynamic motion. Further advancing this idea, a possible grid system could be made as seen in Figure 11.

3.2 Ideas from the internet

Described in Figure 12 is Wave roller AW-energy, a company based in Finland. Wave roller is designed for depths from 8-20meters and to be placed 0.3 to 2.0km from the coast. The device moves back and forth to create electrical energy [11].

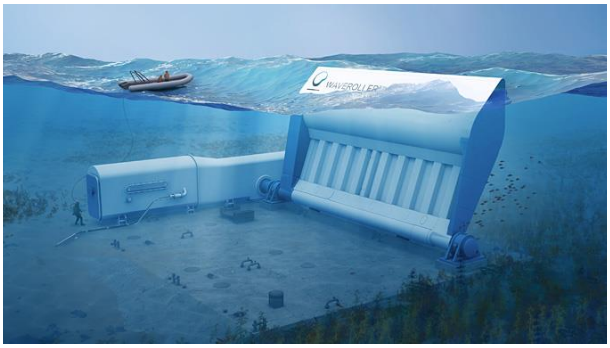


Figure 12 - Wave roller AW-Energy

In Figure 13, a concept from a Swedish company called Armatec is shown. It is placed offshore and uses technology developed by a cardiologist that used inspiration from the function of the heart to create the system [12].

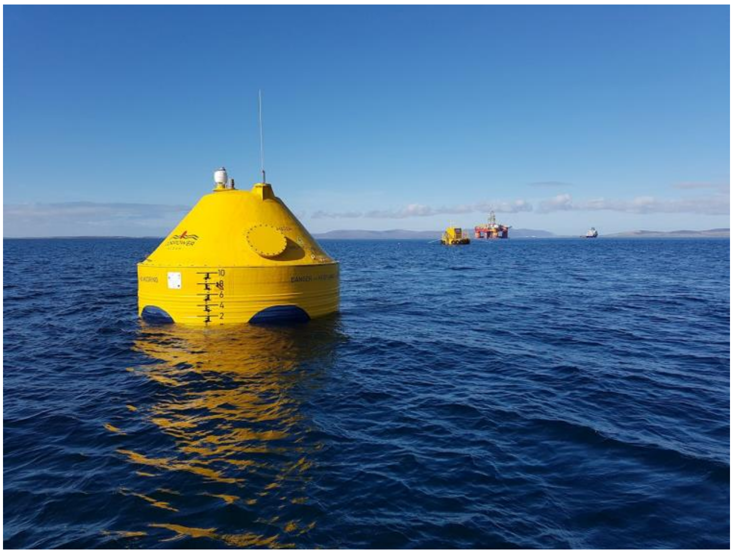


Figure 13 - Armatec

Shown in Figure 14 is a wave energy idea developed by Carnegie wave energy, a company located in Australia. They have developed the technology for over 10 years on shore. The design has no surface impact as it is fully submerged [13].

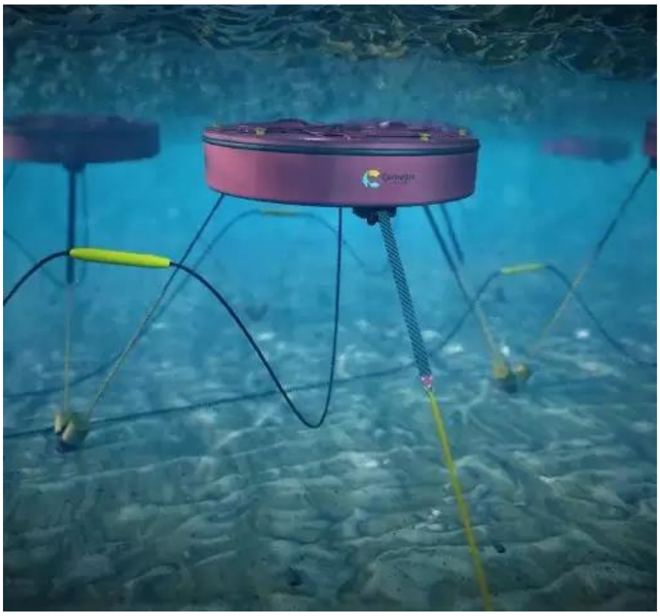


Figure 14 - Carnegie

3.3 Idea Screening

Idea screening is the stage in the new product development process that follows concept generation. The group members produced 18 different ideas, to challenge creativity and enhance the products. It was important that the group did not search for current ideas available on the market, consequently making the design heavily influenced by existing technology. After every individual in the group had produced 3 designs each, random words were given i.e., “Stop”, which was then demanded to be used in an idea. This process of product making activates the creative side of the brain, resulting in a great variety of designs. The ideas arising from this method became represented in the final design in some sort of way. The last part of the design making process became to look at products on the market to conclude what works and not in previous attempts, then combining the group ideas for optimizing the efficiency of ocean wave energy.

When deciding on which design should make the final concept, it was important that all project members agreed on the same idea. An adequate way for deciding the final design was to use an order of importance scoring system, as given by Table 1.

Table 1 - Requirement Score

REQUIREMENT / SPECIFICATION	ORDER OF IMPORTANCE (1-3)
SAFETY	**3**
STRUCTURAL STRENGTH	**3**
MATERIAL PROPERTIES	**3**
COST	**2**
EFFICIENCY	**2**
EASE OF MAINTENANCE	**2**
EASE OF INSTALMENT	**2**
EASILY ACCESSIBLE LOCATION	**2**
ENVIRONMENTALLY FRIENDLY	**3**
AESTHETICS	**1**

Each group member gave a score on the designs, from 1- to 5, which was then multiplied by the order of importance in a scoresheet in Excel, shown in Table 2. For the rest of the ideas, see Appendix B. The Linear Generator, Rotational Disc, and the Stop Sign Floater gained the highest score, and the final concept combines the three ideas with the highest scores. It became a concept of the stop sign floater combined with a linear generator that is submerged. On top of the floater, a rotation motion generator was added, with the hope of making a more effective design. The idea of doing this came from the third best scoring idea, a submerged rotational disc. The disc uses cables or belts to create a rotational motion as shown in Figure 8. This design was adjusted and placed on top instead, creating a final concept that combined all three ideas.

Table 2 - Idea Sheet

Requirement / Specification	**Order of Importance (1-3)**	***Linear Generator***	***Rotational Disc***	***Stop sign floater (linear)***
Safety	**3**	3	3	4
Structural Strength	**3**	3	3	3
Material Properties	**3**	3	3	3
Cost	**2**	5	4	2
Efficiency	**2**	3	2	5
Ease of Maintenance	**2**	2	2	4
Ease of Instalment	**2**	4	3	4
Easily Accessible Location	**2**	4	4	4
Environmentally Friendly	**3**	2	4	4
Aesthetics	**1**	4	3	3
Easily Prototyped	**3**	5	4	4
Sum		88	84	95

3.4 Final Concept

As described in the previous chapter, the final design became a combination of the highest scoring ideas from the group screening. The final concept uses a combination of a linear generator connected to a drum, which then drives a set of gears connected to a generator that produces electricity. The technical parts such as the gears, shaft, generator, and flywheel are attached to a floating platform that uses the waves for driving the components. Also, connecting the parts above the sea results in easier maintenance. The concept uses the idea of a one-way transfer axle for making the rotation efficient, which is then attached to a flywheel resulting in a smooth out delivery of power to the generator. The platforms are designed such that they can be connected and create a grid.

Required Components

- Sprocket
- Drum
- Plates
- Coil
- Mass/weight
- Cable
- Anchor
- Leading wheels
- Generator
- Dynamo
- Floaters
- Flywheel
- Dynamo
- Freewheel from bicycle
- Chain

From the start of the project, the group agreed that the product should be efficient and cheap to produce. By connecting the platforms to form a grid using the same parts, the concept would utilize more wave energy while also making it easier to mass-produce, hence saving money and time. To make the ocean wave energy converter process clear, the group decided to prepare a sequence diagram that shows the whole process from start to finish in the simplest manner. A sequence diagram is a type of interaction diagram because it describes how and in what order-a group of objects works together. These diagrams are used by developers and business professionals to understand requirements for a new system or to document an existing process [14].

In the diagram shown on the next page, the wave energy concept is described from start to finish.

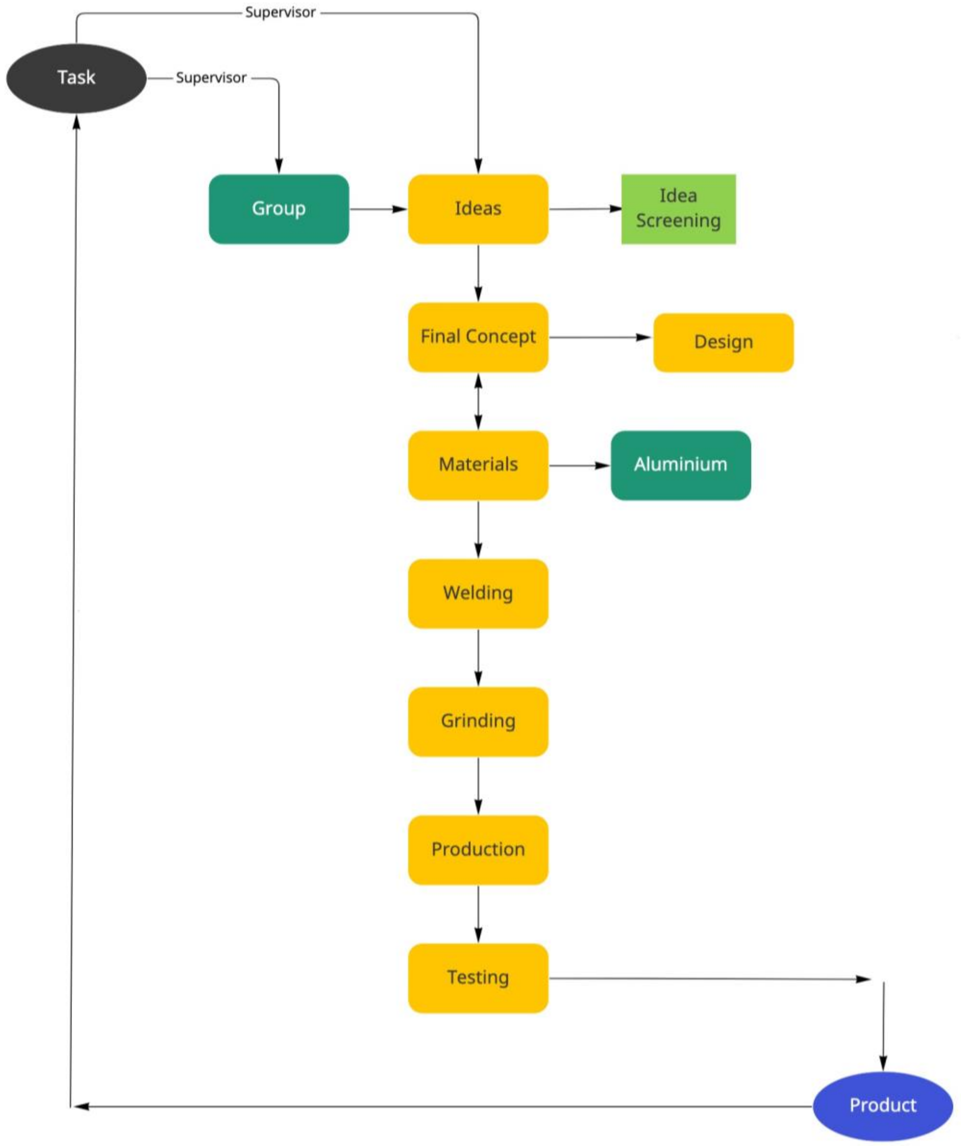


Figure 15 - Sequence Diagram (made using Miro.com)

4. Engineering

A vital part of the development phase is engineering, where some of the finer details are thoroughly explored and justified. As this is a concept project and not a full sized product, some details could be omitted. Analysing the concept, a simplified prototype was developed using Creo with some essential calculations to ensure viable test results, such as buoyancy. Some of the materials used in marine environments are also discussed, comparing their advantages and disadvantages.

4.1 3D Modelling

Before starting the design process, a thorough plan was discussed within the group for which components the model would need, and the best placement of the parts in the design. After every group member was happy with the design, Creo Parametric was used to draw accurate CAD drawings of the project, as described in Figure 16. The floater is designed in an octagon shape with angular connection points. This generates more lift force while being less affected by the force of the waves than i.e., a circular floater with straight edges.

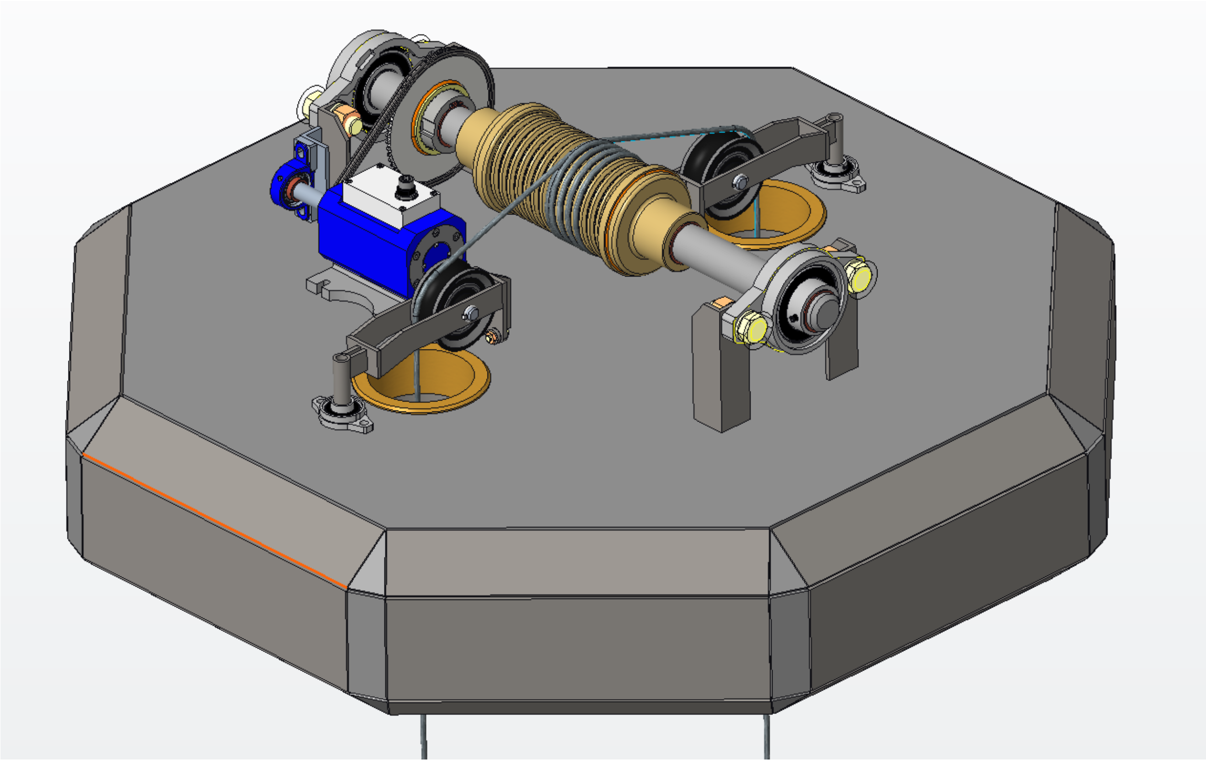


Figure 16 - Floater with parts

On the first draft of the design, the floaters on the linear generator were barrels placed in a square shape around the generator, fastened with clamps (Figure 16). The group concluded that this was not an adequate approach as the design would become unstable and harder to mount together when forming a grid. The solution became to drill holes in the barrels and weld them vertical to the linear generator, resulting in a more stable and streamlined device as shown in Figure 18 (Right). To keep the cable in constant tension in both up-and-down movement between the waves, a streamlined weight is fixed to the bottom of the design.

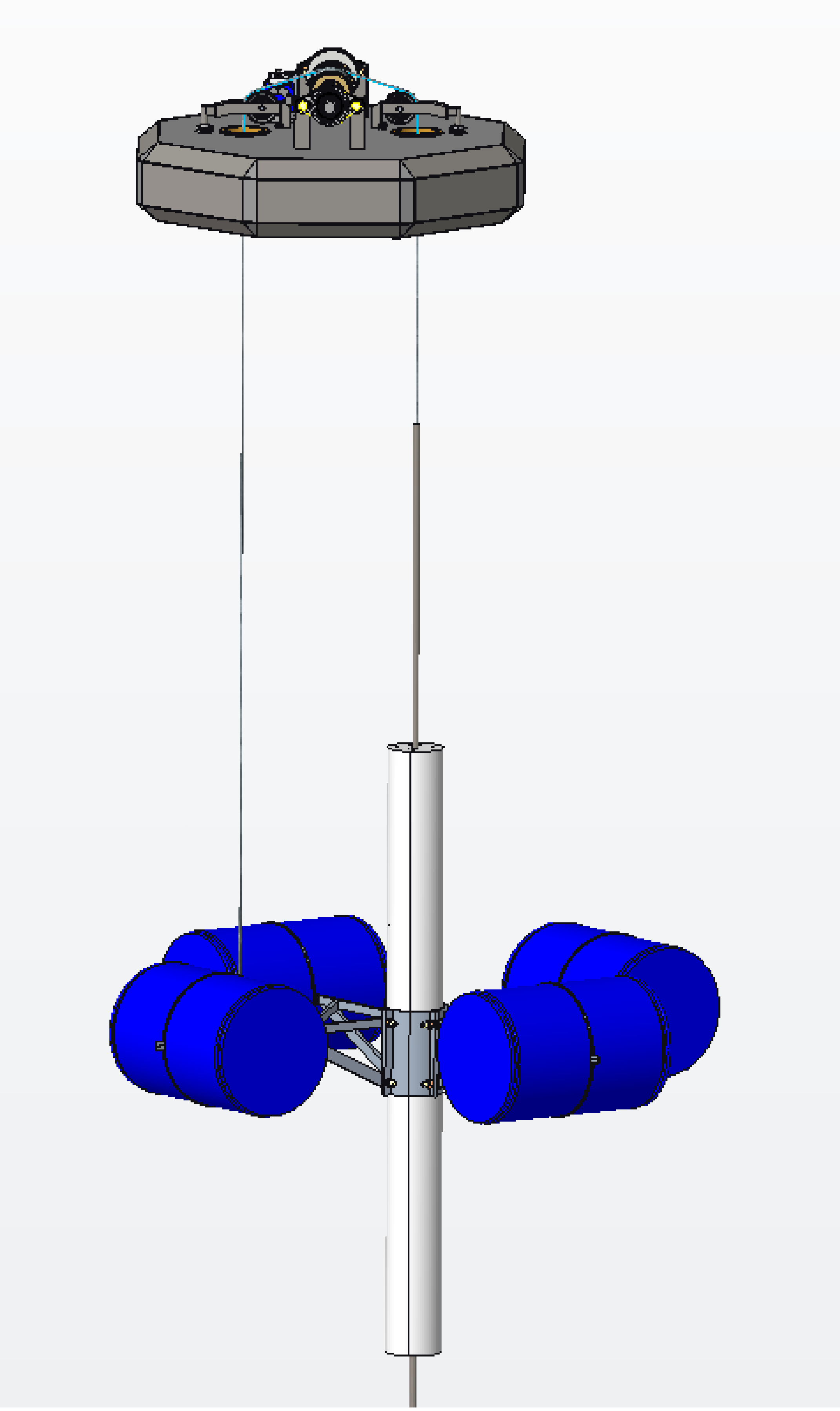


Figure 17 - the first draft of floaters

The linear generator is designed with a magnet attached to a steel rod as seen in Figure 18. The casing itself is separated into different sections. The inner casing, coloured green, is designed to protect the copper coils from seawater, while the inner tube is filled with seawater. The holes at the top and bottom ensure that the seawater can move freely inside the tube, so that it does not prevent the linear movement of the magnet rod. At each end springs are mounted to deaccelerate the magnet, preventing damage to the outer casing.

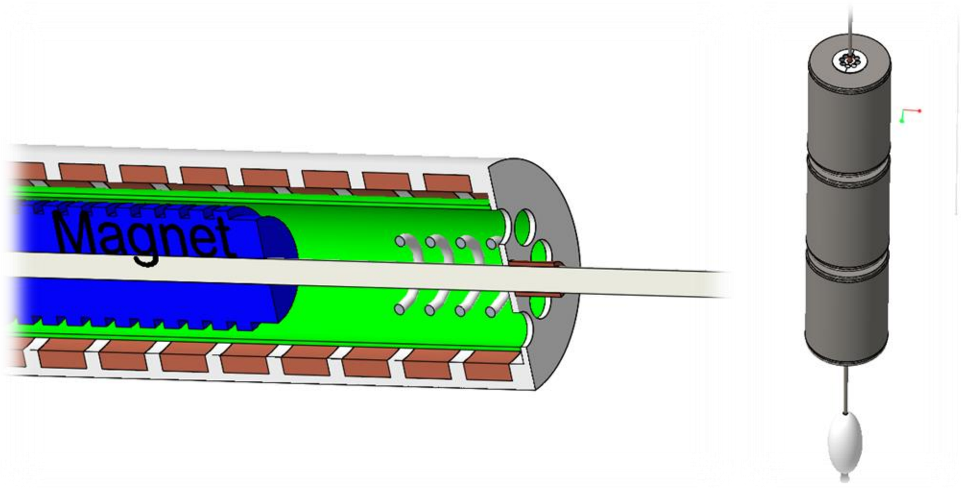


Figure 18 - Linear Generator with components (Left) and Linear Generator (Right)

The device on top of the floater has a simple design (Figure 19). On the main axle, a drum and a sprocket gear are attached. The axle is mounted on two bearings that lock it in five directions and ensures rotation, with steel cables fixed on the drum. Linear movement of the waves pulls the steel cables that rotate the axle and drum. The sprocket gear rotates with the main axle, and transfers torque to a smaller sprocket gear.

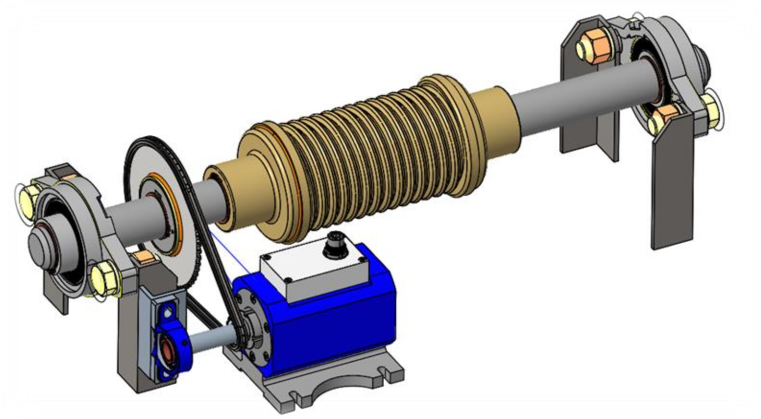


Figure 19 - Mechanical Components

The whole concept can be attached forming a grid, producing a greater amount of electricity shown in Figure 20.

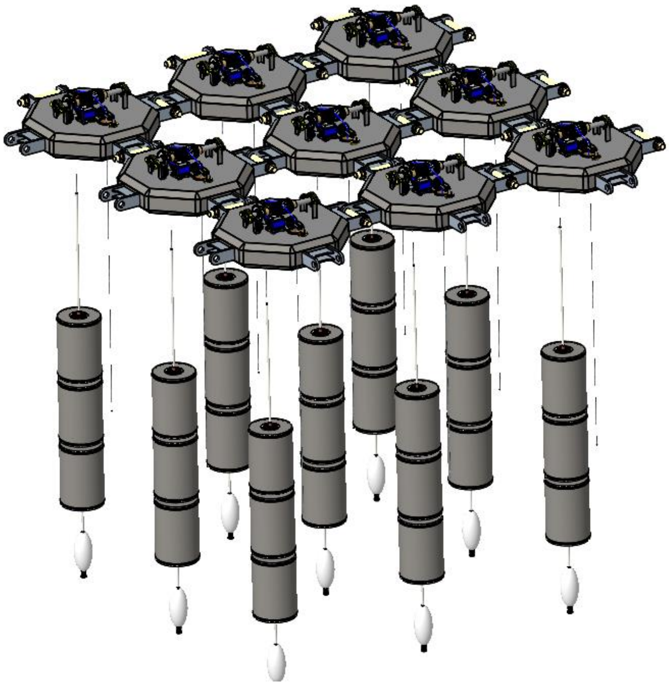
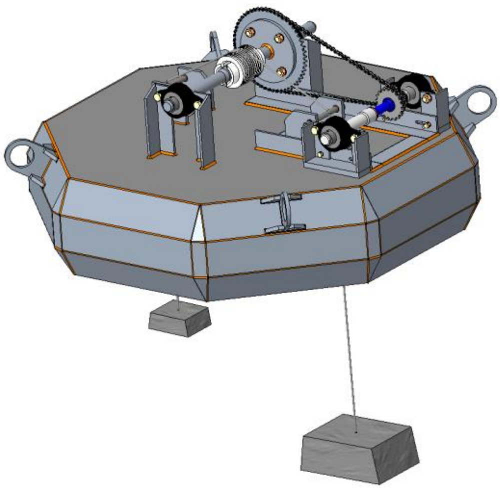


Figure 20 - Grid

4.1.1 3D Modelled prototype

Prototyping the OWEC led to a redesign of the first 3D concept as shown in Figure 16. Drawings of the components were made and followed during the production of the components. In Figure 21, two 3D models of the actual prototype are shown. Drawings were only made for the actual prototype and not for the concept 3D model. The drawings of the components that were manufactured are added in the appendix at the end of the report. (See appendix D)



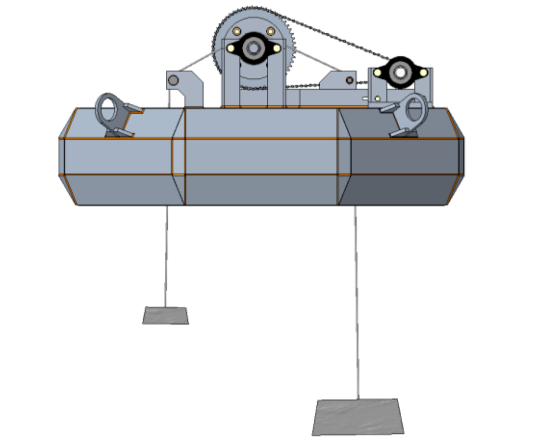


Figure 21 - 3D Modelled Prototype (Left & Right)

4.2 Buoyancy Calculations

Using the formulas from chapter 2.2, some preliminary calculations were done to ensure sufficient upward force. Knowing the weight of the floater is the primary objective, as the weight of the mechanical components is negligible in comparison. Different sizes of the structure, as well as different material thicknesses, were discussed and compared. These calculations are shown in Figure 22.

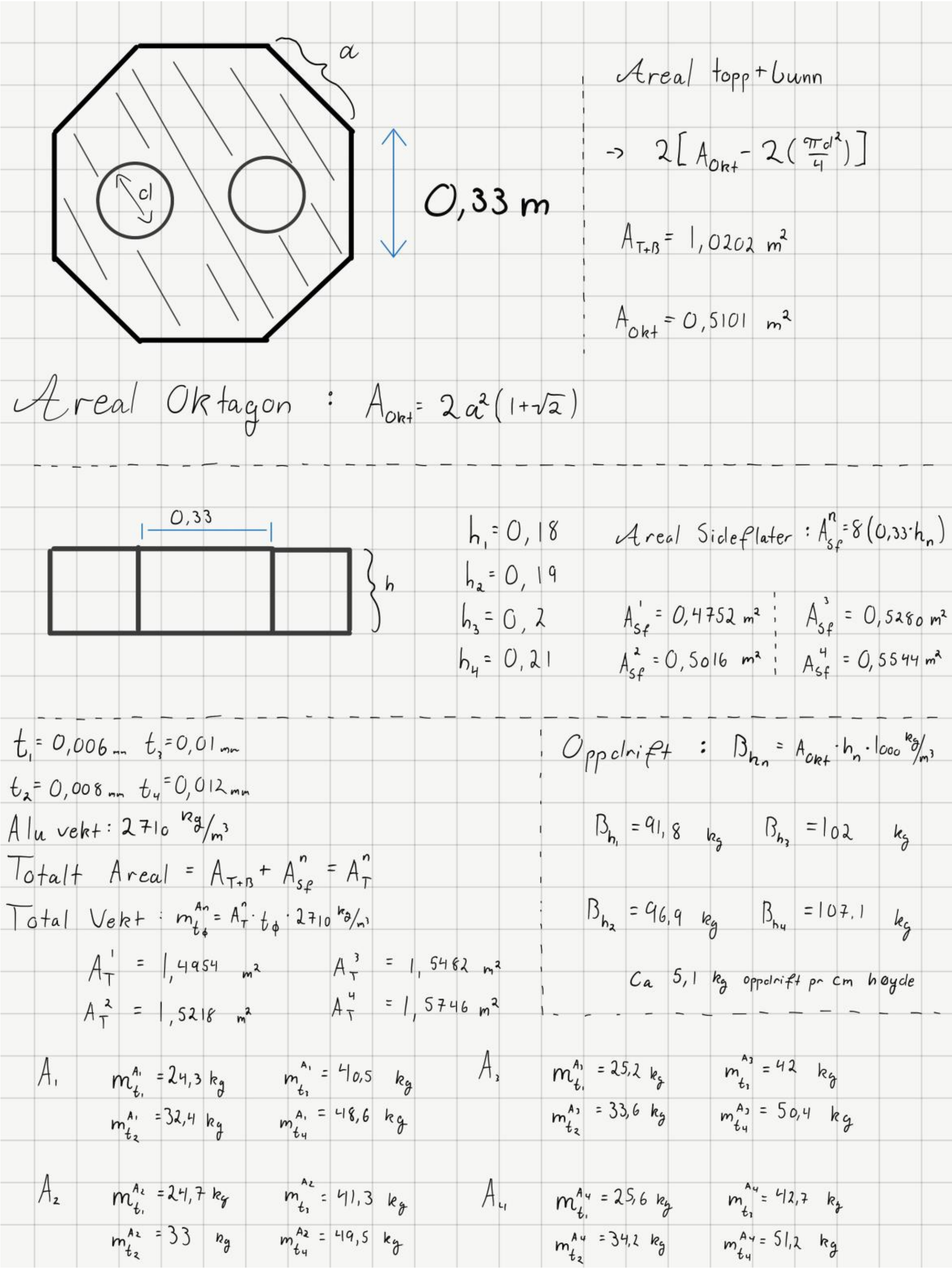


Figure 22 - Buoyancy Calculations

4.3 Engineering for Maritime Environment

Maritime structures are dynamically stressed throughout their lifetime, often spending years in a harsh and unfavourable environment. Several factors must be considered to ensure safe operation and prevent needless deterioration of mechanical and structural components. Choosing a material suited for a marine environment depends on several aspects of the project, such as usage, exposure, and lifespan. Ignoring the stress distribution for a moment, the exposure and lifespan could be covered by sufficient surface treatment. Using a corrosion-resistant material such as stainless would be expensive, especially when a routine surface-treatment plan would ensure longevity and prevent premature deterioration. Aluminium is also an option, as many vessels are constructed with an aluminium hull. Depending on which alloy is used, there are different properties concerning dynamic resistance, expansion, and contraction due to temperature, yield strength and so forth. Steel dominates the market as the most used structural material in the maritime environment due to its inherent strength, using surface treatment to prevent corrosion [15, pp. 158-159]. A surface coating can be applied, staving off oxidation.

Similarly, mechanical components may be composed of metals that are susceptible to corrosion due to oxidation. Whilst larger components such as flywheels can be coated with a layer of paint, shafts, gears, and other interacting surfaces would slowly grind away this protection. An important aspect of a mechanical system is therefore the field of tribology, described as the science of interacting surfaces. Encompassing friction, wear, and lubrication, it describes different fundamental details that work in harmony to prolong the lifespan of the machines. The lubrication covers the surface of the parts, preventing oxygen from interacting with the surface while reducing wear from friction in bearings and gears, as seen in Figure 23. Due to the minerals and salts of the ocean, it is imperative to isolate the system from its surroundings. These particles can interact with the contact surfaces, increasing wear and heat [15, pp. 295-315].

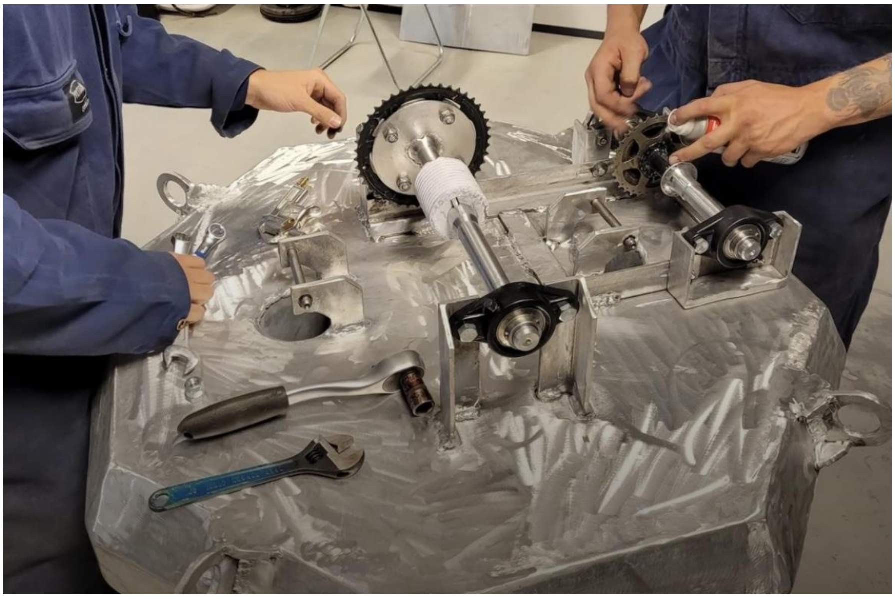


Figure 23 - Lubricating gear with Silicone-penetrant

5. Prototype

Attempting to prove our concept, a prototype was built using ISO standards for materials, fittings, and components. In this chapter the manufacturing process is described in detail, showcasing every step of the build. It was then placed in the Marin Lab, where observations were made using different scenarios.

5.1 Choosing a suitable material

Whilst a potentially less time-consuming method to develop the prototype would be to 3D-print every component, this would drastically reduce the ability to alter the design throughout the manufacturing process. It is difficult to machine 3D-printed parts, as the inside is a matrix of plastic. The density of the part is decided by the percentage of infill, which also alters the printing time. As will be mentioned later in the report, one part was 3D-printed using 100% infill which took a substantial amount of time, compared to the size of the part. An advantage of using metal is therefore the ability to modify the different parts to fit the project. As an example, one may consider a drilled and tapped hole. If the floater was 3D-printed with x<100% infill, moving this hole would be a difficult process. Drilling a new hole in the material would reveal the matrix inside, which is not suitable for tapping. As an addition, filling the previous hole would require using a filler material such as glue, to then be sanded down for flatness. Using metal, this process becomes far easier. As the material is comparatively equal throughout the part, one simply drills a new hole and taps it, before quickly welding the previous hole and grinding it down with e.g., an angle grinder. Another consideration is the time spent waiting for a new part to be printed, due to an alteration. If for example a beam, was too short, the 3D-printed part would need to either be reprinted, or time spent waiting for a new section to be printed and then carefully glued to the original beam. With metal, a longer section could simply be welded on. Choosing which metal to use is also an important process. Several different metals and alloys were therefore compared, evaluating their individual properties, pros, and cons.

Table 3 - Example of different alloys [2, pp. 432-455]

Material	**Density**	**Ductility (%EL in 50 mm)**	**Yield Strength (MPa)**	**Corrosion-Resistant**
Steel: S235JR	7.8 g/cm^3	25	340-470	NO
Steel: S355J0	7.8 g/cm^3	22	410-560	NO
ALU: 1100	2.7 g/cm^3	35-45	35	YES
ALU: 7075	2.7 g/cm^3	11	505	YES

Whilst the complete and full-size model will require more consideration, only a few factors are relevant to the prototyping process. We require a low density for maximum buoyancy, a low ductility to prevent deformation during operation, and a low cost, to ensure the project remains within the budget. Due to the geopolitical climate of these times, material prices have skyrocketed and the difference in price between steel and aluminium is close to negligible. The low density of aluminium is therefore a valuable advantage for the project. The available alloy from our supplier was Al-Mg2,5.

5.2 Budget

For prototyping, Western Norway University of Applied Sciences gave the project a budget of 10k Norwegian kroner. This quickly became a problem due to the huge increase in commodity prices. The plan for the prototype floater was to use aluminium because of weight saving, corrosion resistance, and how it can be easily cast, machined, and formed. With the school’s purchase price, the total cost for the materials reached 16 000 KR which was way above the budget. However, one of the group members is fortunately working at “Solund Verft“, which were able to offer a significantly lower material pricing. The total material price reached just below 7 000 kr with the help from Solund Verft AS, as seen in

Produktnr	Beskrivelse	Antall	Pris	Rabatt %	Beløp
21M0800800	ALU.PLATE 57S 8.0 mm	3,05	1 589,64		4 848,40
21M0200071	ALU.SKINNER 75X6	6,5	52,37		340,41
21M0501005	ALU.RØR RUNDE 100 X 5.0 MM	0,6	138,00		82,80
21M0100300	ALU.BOLT RUND 51S-WP Ø 30 mm	1,5	59,93		89,90
21M0300041	ALU.VINKEL 40 X 40 X 5MM 3.1.B 6082-T6	1,9	72,04		136,88
	25 % mva av 5 498,39				1 374,60
	Ordresum				6 873,00

Figure 24 - Material Invoice

5.3 Manufacturing preparations

The Western Norway University of Applied Science offered the project a workshop. They have all the tools required for the project, like wielding tools, lathe, 3d printer, milling cutter, CNC plasma cutter, etc. To be able to use the workshop, the group members had to go through an HSE course.

The standard workshop clothing is protection- clothes, -gloves, -glasses, safety shoes, and hearing protection. In Figure 25 (Right), the standard protection clothes for welding are shown. It is required to wear a welding helmet, the standard workshop clothes, gear, and heat protecting gloves. (Figure 25 [Left]) In Figure 26, one of the group members is welding with all the required safety equipment. The helmet protects the eyes from the UV lights caused by the welding. Gloves protect from heat. The clothing in general is also protecting the skin from getting exposed to heat and harmful UV lights. As pictured, a lot of smoke is created from the welding process. It was important in terms of HSE to place the exhaust right beside the weld spot. The smoke from the welding is sucked into the exhaust, which is important to minimize the impact the smoke has on the lungs.

Figure 25 - Grinder (left) and Welding (right) HSE Equipment

After finishing the course, the members could use the workshop between 08.00 to 16.00 Monday-Friday.

Figure 26 - Welding

5.3.1 Floater

Deciding on a total area of 1.5482 square meters and a thickness of 8 mm due to both price and manoeuvrability during the manufacturing-process, a total weight of 33.6 kg gave 68.4 kg of buoyancy, which was considered suitable. After the floater was finished, its weight came to a total of 34.1 kg which was a negligible difference. The floater is assembled by aluminium plates and two aluminium pipes which are to be used to create the Ocean wave energy converter (OWEC). A CNC plasma cutter was used to precisely cut the aluminium plates to the right dimensions as shown in Figure 27 (Right). By using a hacksaw machine, the aluminium pipes were cut to the right dimension as shown in Figure 27 (Left).

Figure 27 - Hacksaw (Left) and CNC Plasma Cutter (Right)

Welding the plates together and making the floater airtight was the next task at hand. Due to the properties of aluminium, an oxidation layer is produced at the surface. This layer has a higher melting temperature than the inner layers and must therefore be removed before the welding can commence [2, pp. 447-450]. If it isn't removed, the inner layers will melt completely before the outer layer, causing it to pour out when the oxidation layer finally melts. This layer is quickly removed by using an angle-grinder and a grinding-disc to sweep over the surfaces. Another difficulty with welding aluminium is its tendency to deform when heated.

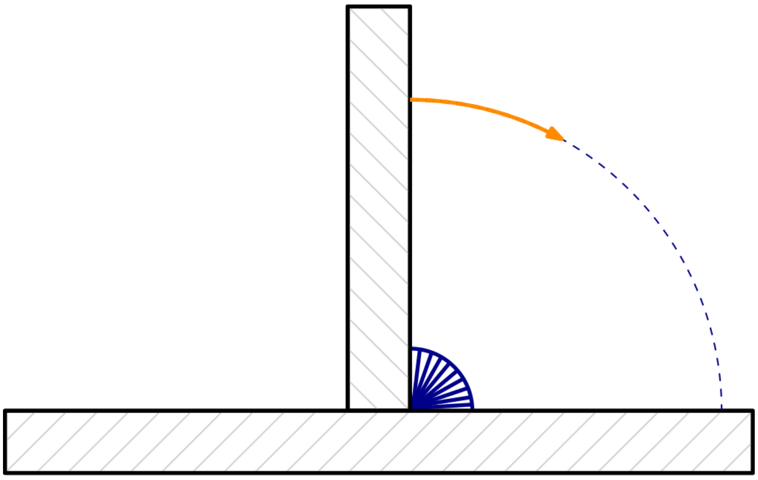


Figure 28 - Illustration of motion in the material due to welding

The filler material bonds to the base material, and as it cools it contracts and adds tension to the structure. This can be mitigated by several methods, such as welding the opposite side to counteract the tension or preventing the parts from moving during the cooling process. This is the method chosen, as it also had another advantage. It was desired to split the sides of the floater into 3 sections, with the first section having an angle of 120 degrees from the horizontal plane. Triangles were machined with the correct angle and welded to the bottom/top plate.

Figure 29 - Orientation Triangles

These were only spot-welded, so that they could easily be removed after the bottom section was complete as the geometry of the structure would then brace the parts. The top and bottom of the floater were spot-welded as seen in Figure 29, and then placed together using the inner pipes as spacers. The middle section was then spot-welded to the top and bottom, as shown in Figure 30. The structure was now braced against most of the potential tension that would be generated due to the welding process. To prevent unnecessary high temperatures (which again, lead to higher tension), the structure was welded in a diagonal pattern. Welding one side of a plate with a V-weld, the floater was turned 180 degrees before welding the next part. It was then turned

90 degrees, and so forth. This is to evenly spread the heat and prevent the plates from becoming too hot to weld, which makes the welder blow through the material. The welding is illustrated in Figure 30. After the welding was done, the welds were ground down to make the floater look fine, as well as to make the outer surface as smooth as possible. The grinding is shown in Figure 31. The next step was to establish if the floater was airtight, to prevent accumulation of water during testing which would depending on the volumetric flow, quickly reduce the buoyancy effect and potentially cause the prototype to sink. There are several methods of testing for bad welds, below of which are some of the commonly used non-destructive testing techniques (NDT) [16, p. 905]

- Visual
- Ultrasonic
- Liquid-Penetrant
- Radiographic

All welds were first visually inspected; however, incomplete fusion could lead to micro-holes and porosity in the beads which might not be visual to the naked eye. A liquid penetrant could be a viable option, which involved spraying the beads with a penetrant, allowing it to sink into the base material given time. After cleaning the area, a revealing spray is used which makes the penetrant extrude, showing cracks and holes with a sharp colour (normally red). However, in the interest of saving time as well as making the process easier, it was decided to use pressure testing. Normally, such procedures are done using either water or an inert gas such as nitrogen for safety. The floater was only meant to be airtight at atmospheric pressures and could therefore be tested using pressures of only 1.4 bar (ABS pressure).

A hole was drilled into the surface, with a diameter of 11.5 mm. It was then tapped with threads to ½ - 20 UNF [17], as these were the threads of the available air-inlet. This was then installed using thread-tape, to prevent leaks. Increasing the pressure inside the floater, water and soap were used and sprayed onto the surface, so that leaks could be observed as soap bubbles. See Figure 31 (Right). Leaks that were found were fixed using gas tungsten-arc welding (GTAW), or TIG as it's more commonly known. By melting the surrounding base material, the holes collapsed and made the weld airtight. This was a time-consuming method, as an obstacle concerning the gas metal-arc welder (GMAW / MIG) was unaware of. The welder available was not meant for such thick plates, having a maximum material-thickness of 6 mm for small operations. The device was therefore not capable of fusing the materials at a satisfying quality, which led to many leaks and tiny holes. All major leaks were therefore repaired using the GTAW, before covering the ground beads with a layer of adhesive (TEC 7), which adequately sealed the floater.

Figure 30 - Floater Unfinished (Left) and Weld Beads (Right)

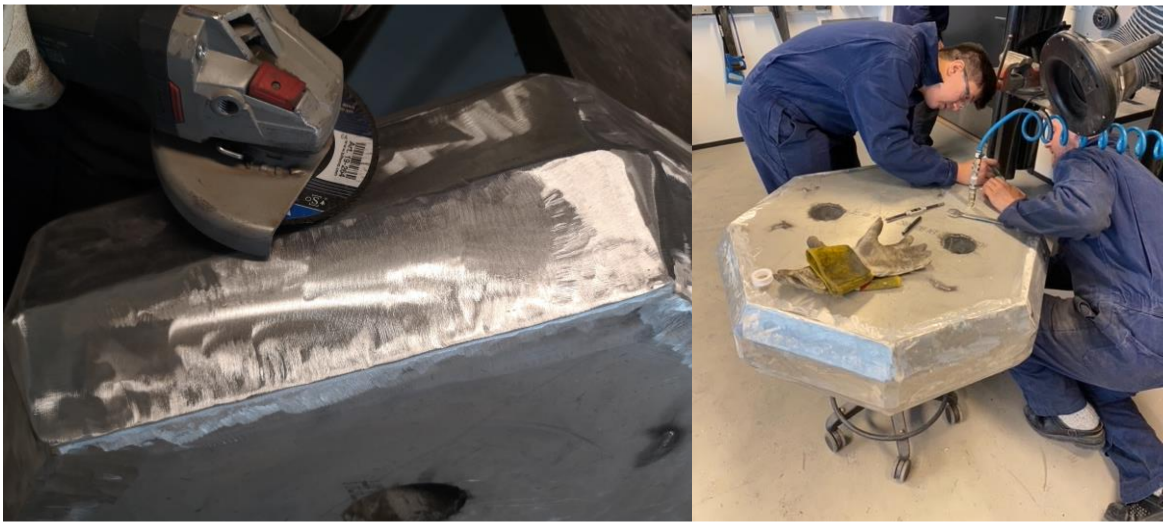


Figure 31 - Grinding Floater (Left) and Pressure Test (Right)

5.3.2 Shafts

Due to the transmission of torque along the axis and torsion throughout the part, this component is defined as a shaft [15, pp. 426-430]. The shafts are some of the key components, as their function is integral for the viability of the concept, transforming the linear motion of the floater into rotational energy. These were therefore designed using available material and for the necessary functions, beginning with the main driveshaft on which the wire pulls the drum. Every part after this was designed as extensions of this shaft, using its measurements to place and alter further parts. The reason for this is simple. If every part had been drawn and designed through Creo, and then produced before assembly, chances are that large obstacles would've occurred. Due to the nature of welding, plates and beams can easily move during the heating process. The process of placing the segments could lead to further errors, which again could cause problems upon assembly. This would require large amounts of bracing to prevent any motion during welding, high amounts of precision during both production and machining, and so forth. This amounts to a lot of time spent on things that aren't necessarily important in prototyping. Problems can also occur during assembly, such as lack of necessary equipment, or alterations necessary due to problems with the concept that might be discovered along the way. The concept is therefore decided on first, designing the necessary components for the viability of the concept-test, and then designing the different parts such as the bearing-structure by measuring and observing how the project came along.

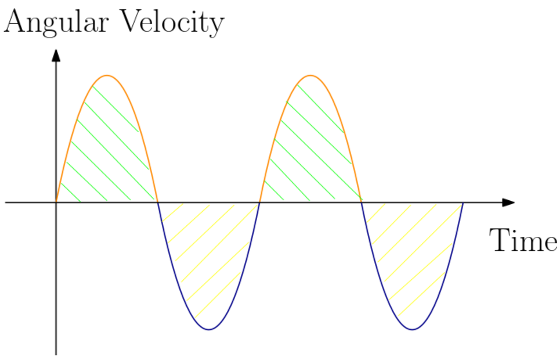


Figure 32 - Angular Velocity of Driveshaft

The harmonic motion of the waves and therefore the floater meant that any input would also be harmonic due to the setup defined by the concept. In practical terms, this meant that the driveshaft would constantly change direction, as shown in Figure 32. This meant that if the output shaft was a slave shaft, it would also behave identically. Several ideas were discussed, and details are explained further in 5.3.2. In this section, only the production of the shafts is detailed.

Beginning with the driveshaft, both size and function needed to be considered. Due to potentially interlocking several of these floaters into a large grid, containing the components within the borders of the top plate was preferred. Furthermore, the bearings available had an inner diameter of 25 mm. Using 30 mm axles was therefore suitable, with the ends turned down to the required bearing-diameter. A multidiameter-shaft was designed, using aluminium as a base-material to reduce weight. This was modelled using Inventor 2022, then produced using a CNC-Lathe. After measuring the required height for the components to function (e.g., to prevent the chain from grinding along with the plate), the bearing-structure was produced using an L-50x6 profile as shown in Figure 33 on the next page.

Figure 33 - Bearings mounted on L-50x6 Profiles

The second shaft is a combined shaft where the two different sections can move independently from the other. The bicycle gear had a complex geometry on the shaft-input for both sides, which was an advantage. After measuring and modelling the inputs, two separate shafts were designed which would self-centre when inserted into the bicycle gear. As one side was aluminium and the other steel, their corresponding shafts were made of the same materials. These were inserted and then spot-welded. Due to the thin base-material of the bicycle gear, the welding process required diligence to avoid burning through the gear and into the inner bearings and gearing-components. The heat of the welding could also cause the shafts to deform, causing misalignment. The gear was filled with an oil-based lubricant, which expanded and boiled through openings. This was expected, and it was therefore slowly welded using a criss-cross pattern, ensuring an even temperature along the circumference of the shafts while also avoiding needless loss of oil. This design process is further explained in 5.3.4.

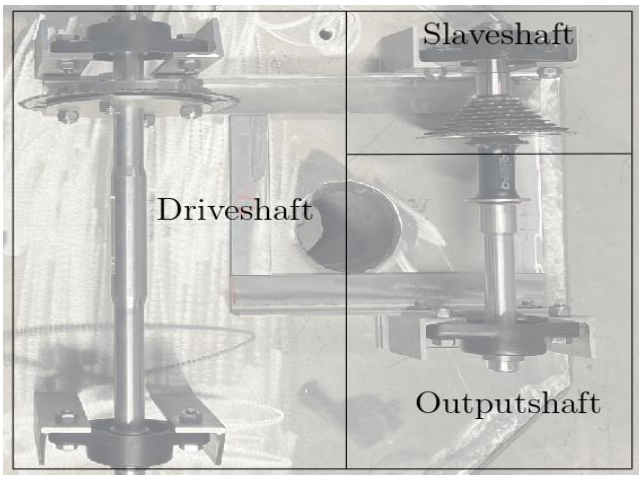


Figure 34 - Illustration of the different shafts

5.3.3 Drum

The drum is an important part of converting the motion from the ocean waves to rotational motion and energy. The steel cables are threaded around the drum, causing friction, and creating rotational motion when pulled in a vertical direction by the buoyancy of the floater. It was decided that this part was to be 3D printed, due to the size of the drum. Whilst it could easily be made using the CNC-lathe, it would require a massive axle with a diameter of a minimum 110 mm due to the design, which wasn't available at our supplier. It was also an educational experience to learn how to use and manufacture a part using a 3D printer. The drum was designed using CREO, after which the file is converted to an STL file, which is compatible with flashprint 5. Flashprint 5 prepares the part to be 3D printed. In this program, insert-settings direct how the part is printed. Some of these settings are infill, geometrical patterns, supports, etc. The first 3D print is shown in Figure 35. This part was quickly rejected since it didn't fit properly, and the infill was too low. At first, the infill was on 20%, which made the part too weak. The threads were also bulky and not satisfactory with the project's standard due to the rough mesh made by the STL file.

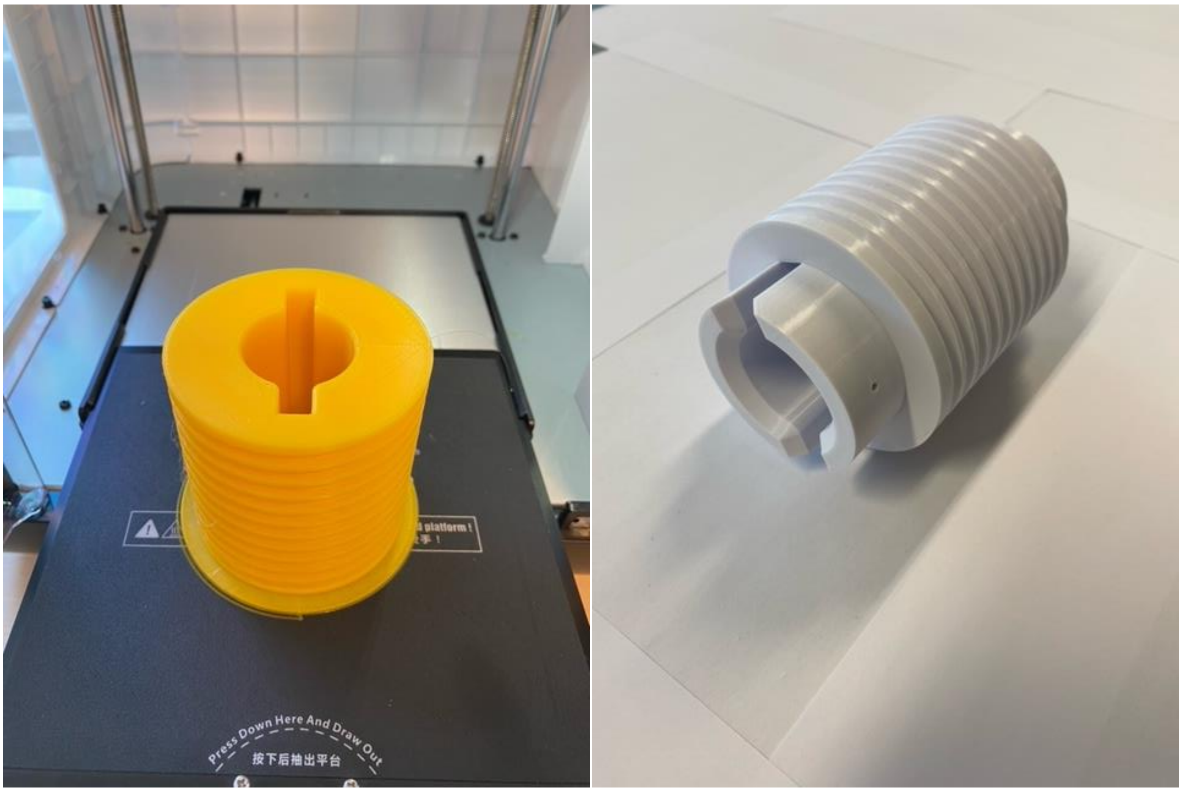


Figure 35 - First 3D print (Left) and Final Redesigned Drum (Right)

The final and redesigned drum is shown in Figure 35 (Right). This model had a detailed mesh, which made the features on the part satisfactory in terms of the requirements. The part itself was significantly stronger because of infill settings set to 80%. This led to a print time of 32 hours, but it was necessary for reaching the project standards.

Chamfers were added to the drum, making it easier to assemble with the axle. To ensure that the drum fitted the axle, and did not slide off, extensions in which screws could be used to tighten the drum into the axle were designed. The group later found out that screw extensions were not necessary and ended up being discarded. The drum was press-fitted to the axle and knocked in place with a rubber mallet when assembled. To ensure hundred percent transmission from the drum, keyholes were printed on the drum.

5.3.4 Bicycle gear

The group sourced through many ideas on how to convert the wave motion into rotational motion in an effective way. A one-way rotational axle was concluded to be the most efficient to sustain the created motion. At first, it was planned to create this component, but with creative thinking and methods, the group found a concept that utilizes this design. A bicycle transmission system is designed in this way, with an axle that only rotates one way. This makes sure that the person pedalling the bike doesn’t stop the motion by moving the bicycle pedals in the opposite direction. By using parts from a bicycle, the designing and building of this part were not needed. The bicycle was free of charge and resulted in savings in time and money.

The parts were roughly disassembled using an oxy-acetylene torch, as seen in Figure 36. This was more practical in terms of transportation to HVL Bergen. In Bergen, the parts were disassembled and washed to be used and redesigned for the project.

Figure 36 - Using Oxyacetylene torch

A few challenges were encountered during this redesign process. The main problems were:

- Centering the gear to the driveshaft illustrated in Figure 37 (Left)
- Centering and designing the axles for the gear illustrated in Figure 37 (Right)

In Figure 37 (Left), two circular plates are designed to be placed on each side of the sprocket gear. The plates are drilled with four holes with a diameter of 12 to fit inside the original holes on the sprocket gear. The holes are drilled at the same distance to the centre, ensuring that the axle is centered when the parts are assembled.

Figure 37 - Sprocket Flange Assembled (Left) & Output-shaft assembled (Right)

Figure 38 - Steel Axle (Left) and Aluminium Axle (Right)

For enhancing the performance of the prototype and make the parts move independently of each other, two different axles needed to be machined and fitted to the gear system. Also, the material on the left and right sides of the gear system is not the same. Assembling the axles requires welding, therefore, the axel material need to match the material where it is to be welded. The left side component with the sprocket gears is made from steel, Figure 38. The right side of the part consists of aluminium, Figure 39 (Right). After the machining of the axles was finished, they were spot-welded on the correspondent side. After the spotwelding, the axle was peripherally welded on the component. This is illustrated in Figure 39.

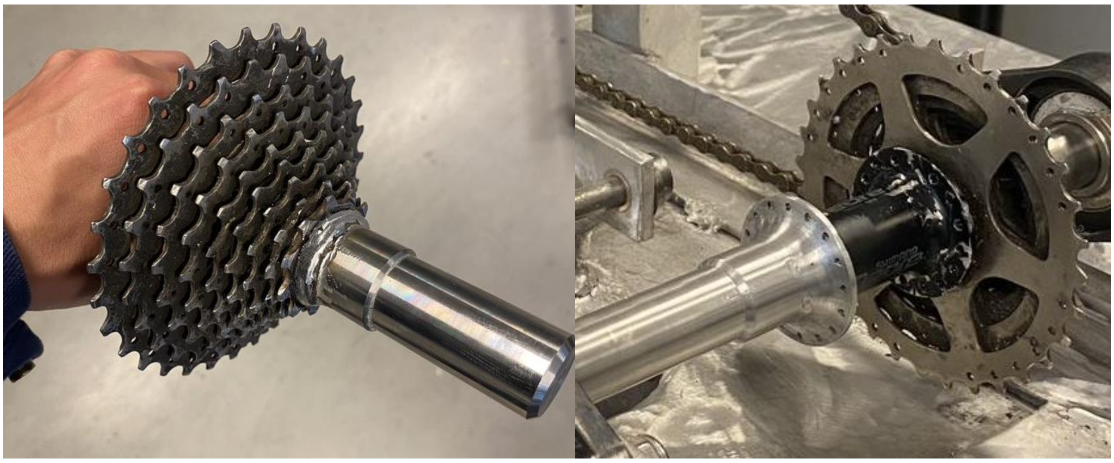


Figure 39 - Steel shaft welded to gears (Left) & Aluminium shaft welded to flange (Right)

5.3.5 Bearings

The bearings provided from WNUAS were mounted rolling bearings, as seen in Figure 40. These bearings support the rotating shafts and can be bolted on a machine frame or any other substructure. In this case, the bearings are bolted on two L-50x6 profiles which are welded to the floater giving a solid support structure. There is no need to precisely machine a bearing housing in a surrounding casing. This makes the solution cost-efficient and easy to use, while providing full rolling bearing performance. [18] However, the bearings provided were old and worn out. This resulted in a source of error in achieving full performance from the prototype.

Figure 40 - Bearing

5.3.6 Roller

For making the prototype efficient the cable must have the correct angle between the drum and the holes located at the floater. The solutions for this matter were initially to 3D print hoists that would be attached with the correct angle over the holes. This would assure that the drum could operate with maximum efficiency without causing too much tension in the cable, thus reducing the risk of failure. Another benefit of using the principle of hoists is that the weight of the mass of the linear generator would be distributed evenly on the drum, not casing any angular lift on the floater.

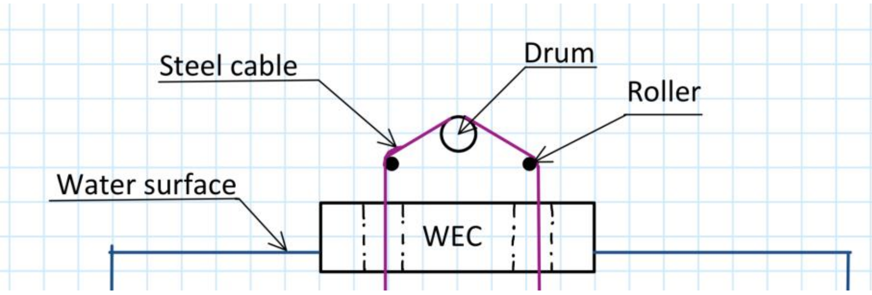


Figure 41 - Illustration of roller

After some discussion, the group decided to discard the plan of 3D printed hoists, and rather use aluminium leftovers from the floater to make a more robust alternative. The solution was to design a support structure for the roller in Creo Parametric, and then use the plasma cutter for cutting the profile in aluminium. The next step was to drill accurate holes for fitting the shaft, such that the cable could operate over the part. A problem that needed to be solved was how to make the shaft move freely with the cable. With some creative thinking by the group, the solution became to machine bronze rings that were press-fitted into the profile, making a natural roller bearing for the shaft. This allowed it to rotate freely with minimal friction.

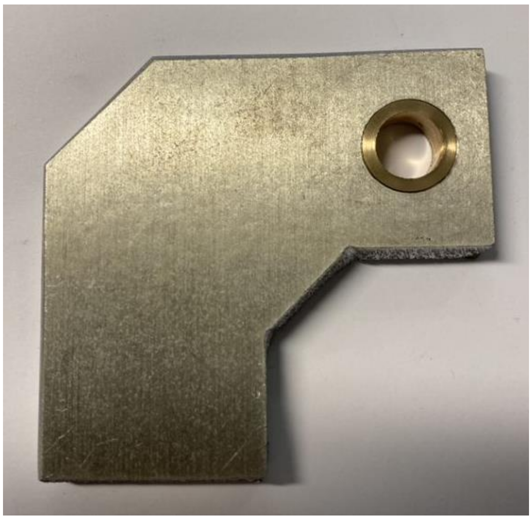


Figure 42- Alu Roller profile

A critical stage in assembling the aluminium profiles was to have accurate placement of the parts by the drum. This was achieved by precise measurements, and ensuring that the hinges remained perpendicular to the floater during the welding, as shown in Figure 43.

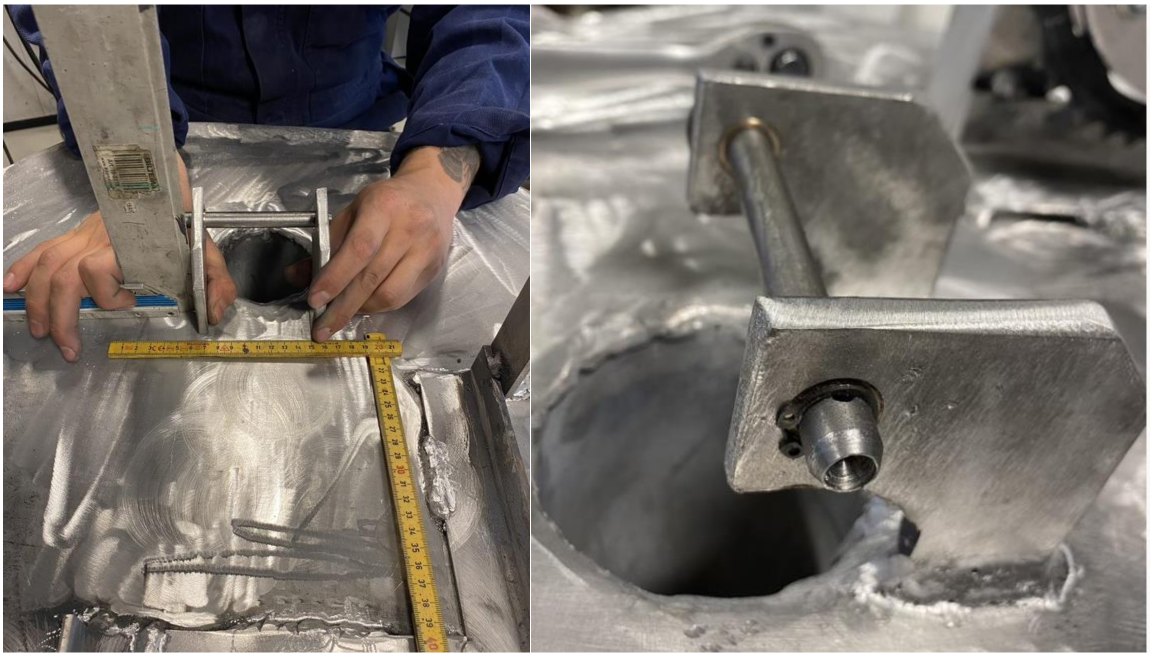


Figure 43 - Installing Rollers (Left) and Finished Rollers (Right)

After the aluminium parts were perfectly aligned, they were spot welded in place assuring they did not deform and move by the heat of the weld. Due to the lack of equipment in the lab, it was difficult to find perfect dimensioned shafts to fit the roller. The solution became to turn a threaded rod in a lathe. By this, the threads were removed forming a perfect axle that fitted the needs of the part. Grooves were made for fitting circlips perfectly on the axle, locking it in place.

5.3.7 Hook

To be able to attach the steel cable to the bottom of the tank, a hook needed to be manufactured. The hook was designed very simply, because it is only going to be used for the tests. It was designed to easily attach and detach from the bottom of the tank. For this purpose, a corrosion-free steel rod was bent to form a hook as shown in Figure 44. This material is suitable to be placed under water since it is corrosion-resistant. An illustration of how the hook is attached is shown in Figure 54.

Figure 44 - Bending of steel rod

5.3.8 Mooring attachment points

To be able to safely conduct testing, it must be possible to moore the Ocean wave energy converter (OWEC) inside the wave tank. These attachment points needed to be able to withstand the eventual tension and pull coming from the mooring ropes.

The component was made by cutting the parts needed in the CNC plasma cutter from an aluminium plate. These were then welded together to form the attachment point and welded on the floater, as shown in Figure 45. To be able to moore the OWEC effectively and safely, the attachment points were placed evenly on the floater. This is shown in Figure 45.

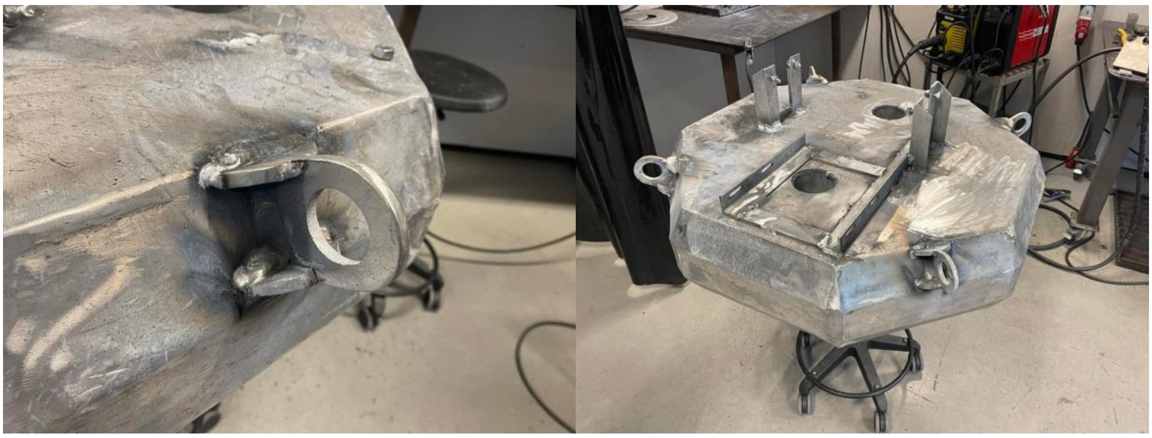


Figure 45 - Mooring attachment (Left) & Placement of Mooring attachment points (Right)

5.3.9 Adjustable Axle Alignment

To be able to change gears, a railing system was designed. The railing system can be shown in Figure 34. As seen from the figure, the output shaft and the slave-shaft can be moved closer to the input shaft. It is a simple way to change the gear ratio. First, the shafts must be adjusted so that the preferable gears of the slave and input shaft are aligned. This is done by loosening the setscrews in the bearings on the driveshaft, and firmly applying axial pressure to slide the axle in the desired direction. Afterward, the position of the bearings at the slave and output-shaft can be adjusted towards or away from the input shaft. This will make sure the chain is fitted properly on the sprocket gears. If it is too loose, it can lead to less efficiency and the chains could jump off the gears.

5.3.10 Steel cable and lock

The steel cable is an important component. In combination with the drum, this component is essential in transferring linear energy created by the waves, to rotational energy to the drum and input shaft. The cable is threaded around the drum as shown in Figure 46. The friction between the cable and drum creates rotational motion on the input shaft. For locking the drum with the aluminium shaft, keyholes were created to transmit the maximum moment created by the cables on the drum.

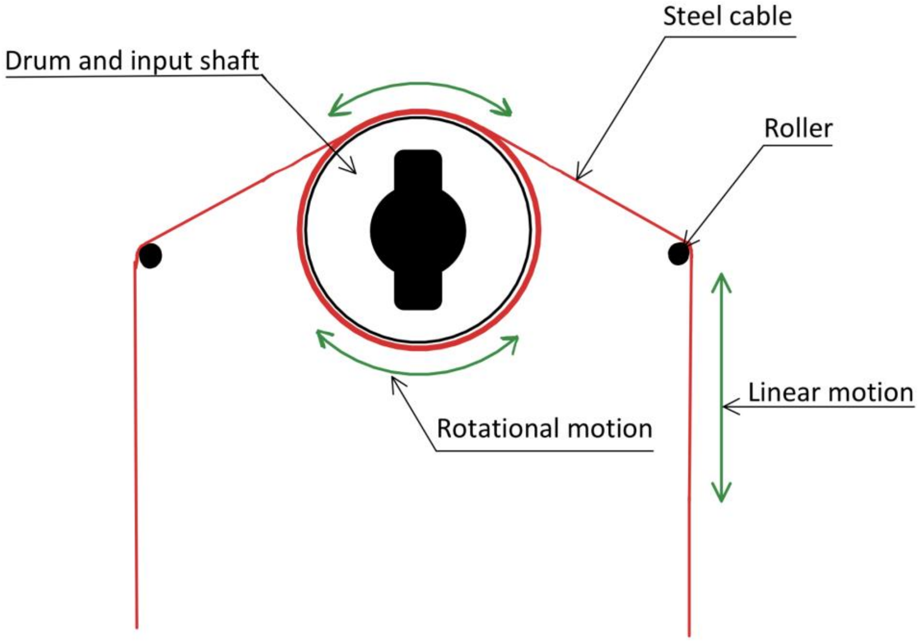


Figure 46 - Illustration of steel cable placement

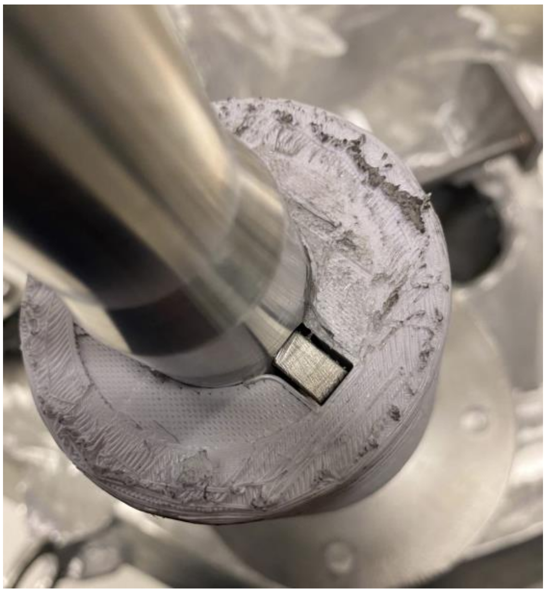


Figure 47 - Drum with keys inserted

5.4 Final assembly

During welding and production, the floater became dirty. This was ground down to prepare it for assembly of all components. All the components were then assembled as shown in Figure 48, Figure 49, and Figure 50. The OWEC weighed in at 44,3 kg with all parts, which is close to the theoretical calculations of buoyancy combined with the weight of the mechanical components.

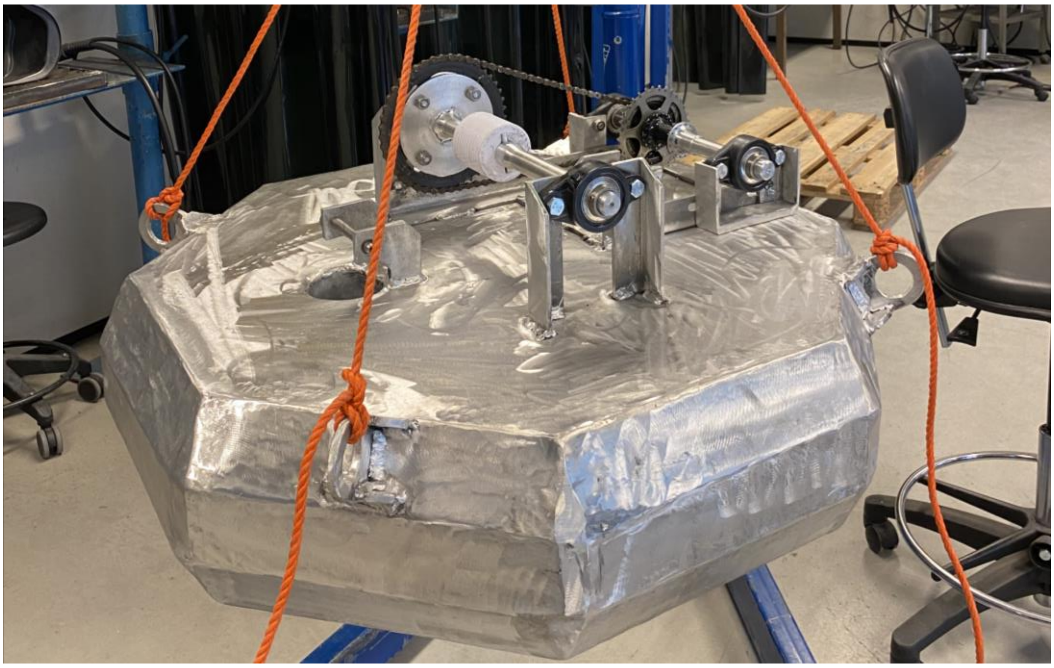


Figure 48 - Final assembly

Figure 49 - Final assembly

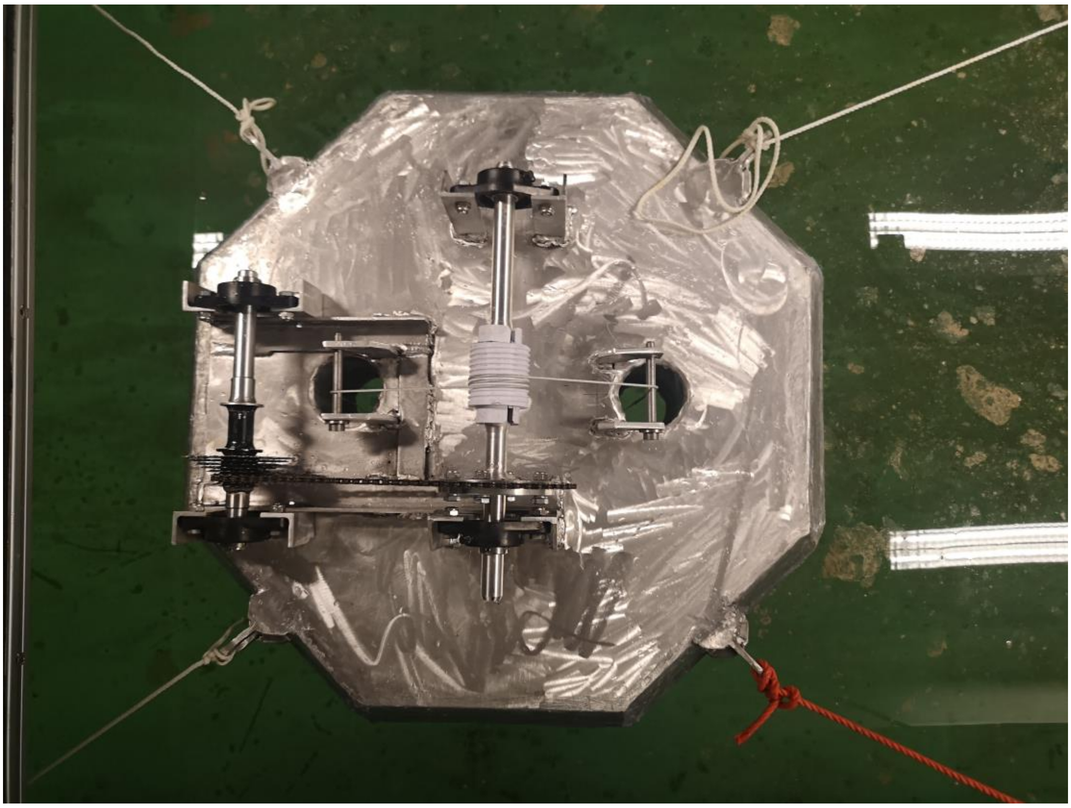


Figure 50 - OWEC in wave tank

5.5 Prototype testing

It was essential to test the prototype to learn if the floater would operate the way it was intended to when exposed to different wave dynamics. In the marine lab at WNUAS, various wave types could be simulated to create natural waves and movement in the water.

5.5.1 Marin lab HSE course

Before testing, an HSE course is needed to be able to use the wave generator and to be given access to the marine lab. The requirements for safety gear in the marine lab are not as strict as in the machine lab. The most important information is to follow safety protocols in case of an accident. It is mandatory to wear a floating west when operating close to the tank, Figure 51.

Figure 51 - Clothing Marin Lab

5.5.2 Marin lab test preparation

Before conducting the test in the wave-tank, the OWEC was put inside a small tank, as illustrated in Figure 52. The tank has a water height of approximately 0,3m. It is used to test the OWEC in two criteria, which it needs to pass before the main test in the wave-tank. The first criteria was that it needed to be waterproof. A leakage test was done, as shown in Figure 52, to check for any leakage. Testing it in the small tank was to confirm if the results from the pressure test were fulfilling or not. After placing it in this pool for one hour, the test concluded it was waterproof.

The test was also used to see how the weight was distributed on the finished assembly when floating. Since the components on top of the floater are placed on one side, a concern was that the OWEC would lean too much on one side when placed in water. Fortunately, it was much less than anticipated and could be neglected in the test.

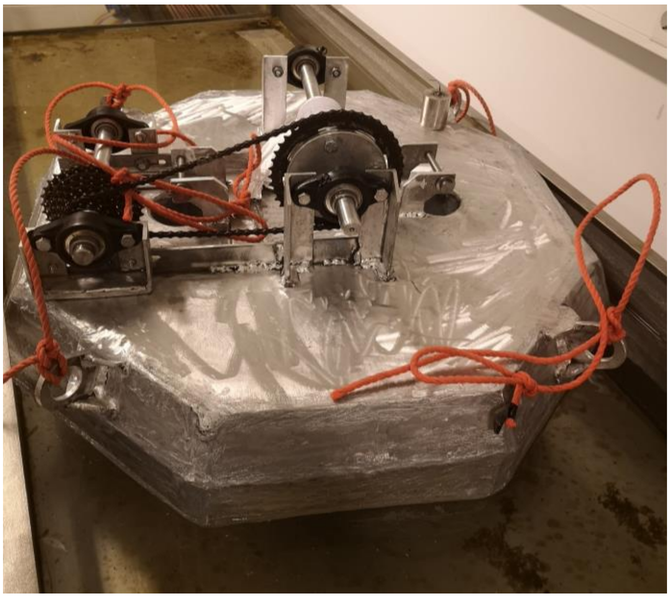


Figure 52 - Balance and leakage test

Main test preparation:

Before putting the OWEC in the tank, some components needed to be made and prepared. To attach the steel cable to the bottom of the tank, a hook was needed. A simple corrosion free steel rod was bent to form a hook. The hook was then assembled to one of the ends of the steel cable. On the other side of the steel cable, a suitable counterweight was needed. To find the right counterweight, the OWEC was placed in the water with the hook attached to the bottom of the tank. Then a couple of different counterweights were attached to the steel cable and lowered into the tank. By observing how the OWEC reacted to the different weights, the right one was chosen. The counterweight ended up with a weight of approximately 8kg. An illustration of how the hook and the counterweight are assembled is shown in Figure 53.

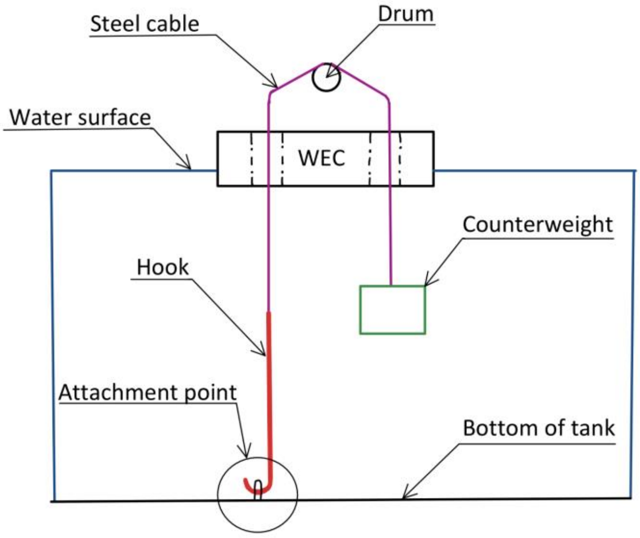


Figure 53 - Illustration of hook and counterweight

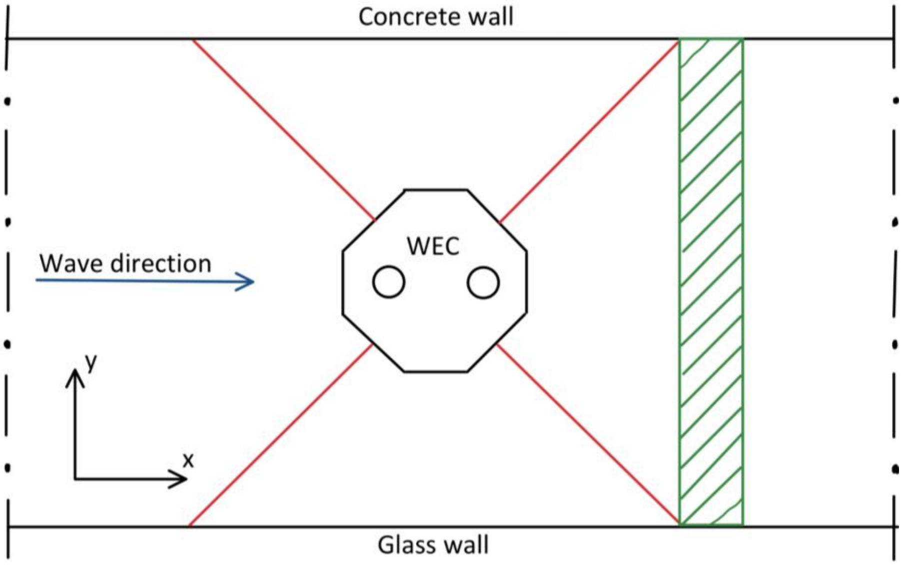


Figure 54 - Illustration of Mooring Nr.1

Important preparations were needed before starting the test. Mooring is needed to keep the OWEC and wave tank safe. Without mooring the OWEC could crash into the tank, damaging itself or the glass walls of the tank. As shown in Figure 54, the floater is moored in four points. Two of the points are static, while two of them can be moved. In Figure 54, the mooring ropes are marked with red. Two of the ropes are connected to an aluminium railing which is shown in Figure 56, and marked green in Figure 54. This railing can be moved in the x-direction and makes it possible to tighten or loosen the mooring ropes as long the OWEC can move freely in the z-direction. With this function, the degree of freedom of the prototype could be adjusted during testing, without compromising the safety of the tank and OWEC. During some of the tests, the mooring was changed as shown in Figure 55. This was done to give the OWEC more room to move freely and to see how it would react and move due to the waves.

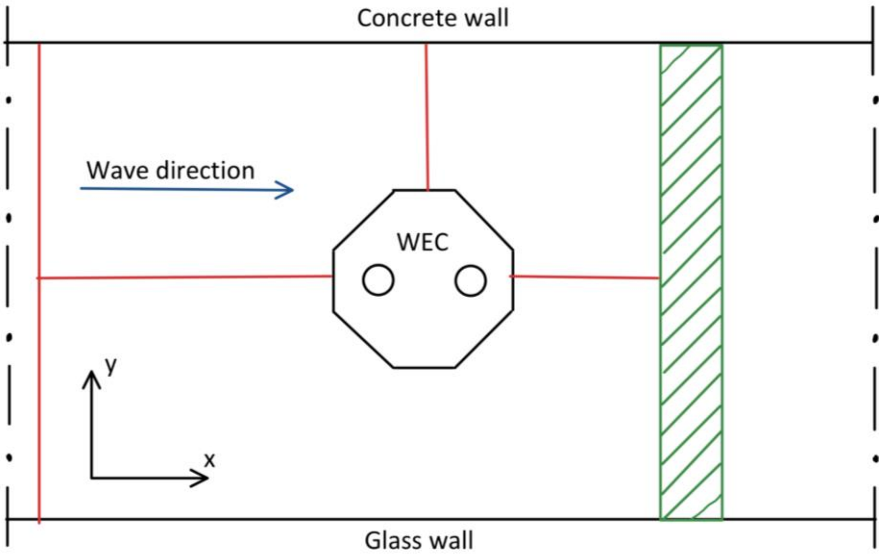


Figure 55 - Illustration of Mooring Nr. 2

A tutorial on how to operate the wave tank was given to the group before testing. There were mainly two parameters that changed between the tests, frequency, and the height of the waves. These parameters are dependent on each other, as shown in Figure 57 (Left). When preparing the OWEC for the test, a section of the tank wall is lowered to give easier access. This section is shown in Figure 57 (Right) and must be closed during testing so that water doesn't flow over the tank walls.

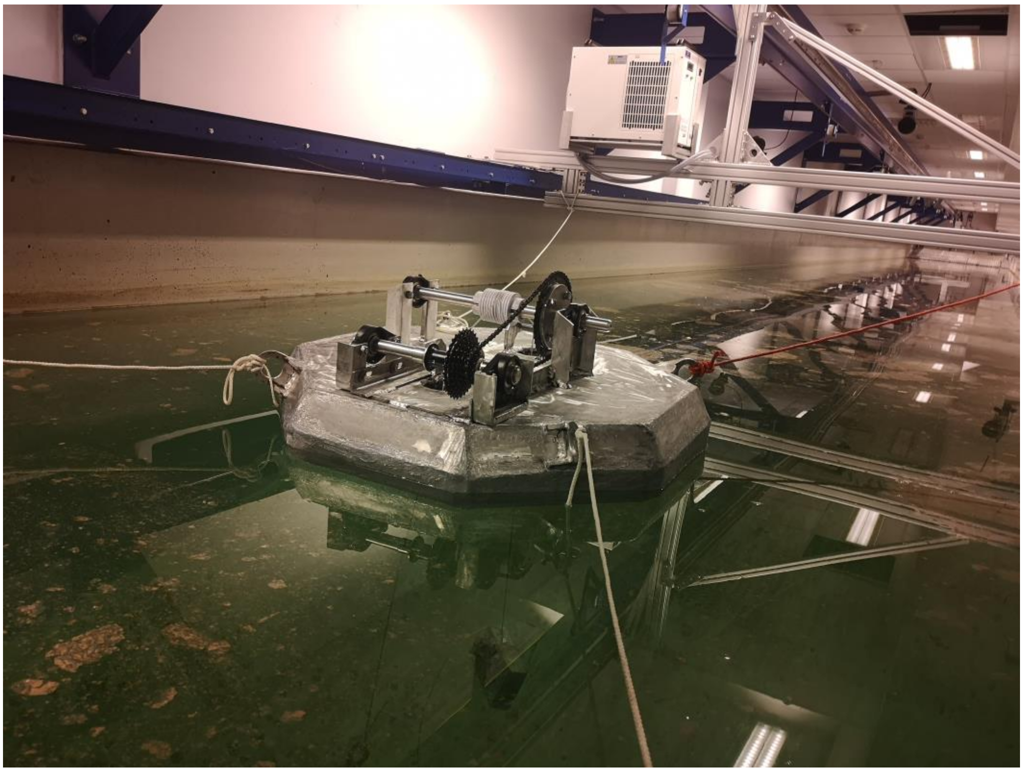


Figure 56 - Mooring Nr. 1

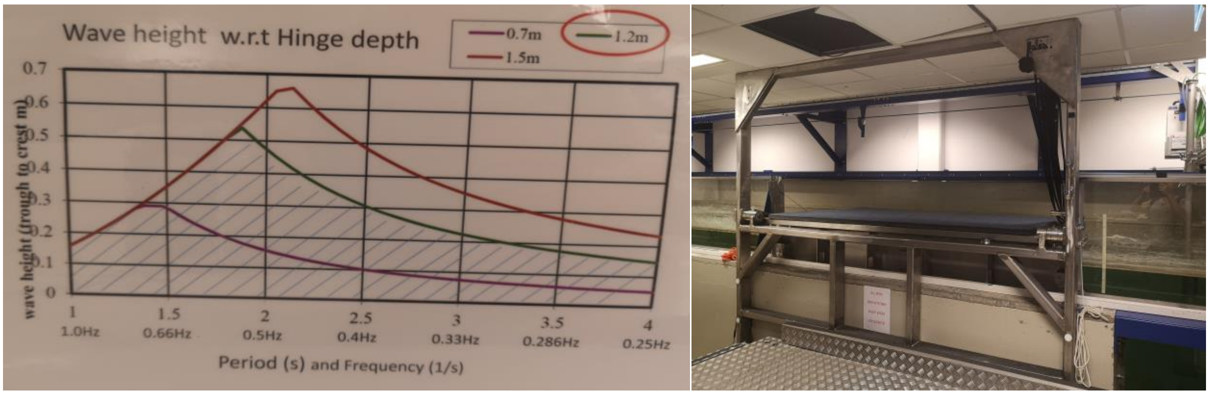


Figure 57 - Wave Height and Frequency (Left) & Tank Platform (Right)

5.5.3 Test results

Background:

Several tests were done to simulate the dynamics of the waves at sea. The waves are not constant and change due to several factors. National ocean service (NOAA) has an explanation for this: [19]

Wave height is affected by wind speed, wind duration (or how long the wind blows), and fetch, which is the distance over water that the wind blows in a single direction.

Due to this, the frequency and height of waves were different between the tests.

Goal:

Due to a lack of equipment for measuring torque, RPM, and such, the prototype could only be used for a conceptual test. As our goal for this thesis was to create a feasible design, the output energy of our prototype is not as relevant as proving its functionality. Several factors could impede the efficiency of the OWEC, such as alignments, bearings, manufacturing-errors, and other unforeseen problems. If the device were to be developed further, the efforts of the group would move towards lowering energy loss and increasing overall output. However, for this project, our goal was only to prove that it is mechanically feasible and to investigate how different types of waves influence the results.

Table 4 - Sine-Waves tested in Marinlab (See Appendix C)

Amplitude: Y [m]	***Period: λ [s]***	***Time (Start–End)***
0,5	0,1	0:15 – 0:33
0,1	0,3	0:33 – 1:07
0,14	0,5	1:07 – 1:25
0,5	0,05	1:25 – 1:44
0,256	0,5	1:44 – 2:20

Observing the OWEC through different wave-models, the preliminary results were optimal. Immediately after the first impact, the device began to move upwards along the wave-crest, initiating rotation along with the driveshaft. The friction between the steel-cable and the drum appeared sufficient, and no slipping between the components could be observed. The chain also began transferring torque to the slave-shaft at a 5 to 1 ratio, increasing the RPMs by a noticeable factor.

The counterweight moved up and down, which proves that the idea of a linear generator placed underneath the OWEC would work, creating even more energy from the waves and still acting as a counterweight.

Observations:

Video of the test can be viewed in Appendix C. The tests showcased the OWEC performed best when the waves had an amplitude of 0.3 Hz and a period of 0.1 s. With the parameters set to these numbers, the system on the OWEC generated sufficient torque and would produce energy. With higher waves the OWEC began to pull the mooring ropes, making the system unstable and less efficient. This could be fixed by slacking the ropes. However, due to safety reasons, this was not an option and remained a problem for the test.

Problems:

Problems during testing:

- Size of the waves:
  During a test with a wave height of 0.250m, the steel cable fell off the drum. This probably happened because our prototype is designed in much smaller scale than reality. Therefore, it probably cannot withstand such big waves because of the prototype scale. The counterweight was accelerated towards the surface, and when the OWEC began its decline, the wire lost its tension. This caused the wire to unthread itself from the drum.

- Rotation of OWEC:
  When the waves hit the OWEC, the OWEC wanted to rotate in one direction. Since the group members are not marine engineers, our competence might not be enough to explain this. It could come from the weight distribution on top of the floater and the movement of the counterweight under the water, or it could be the shape of the floater itself.

- Bad performance during high frequency waves:
  During the test with small high frequency waves, the OWEC didn’t perform well. This is however not relevant since the OWEC is to be placed offshore, and such waves are mostly seen very close to land. The short period between waves caused the OWEC to tilt back and forth instead of going up or down.

Conclusion:

The prototype managed to generate torque, which was the main goal of the test. It performed well at waves with an amplitude up to 0.250m with longer periods between the waves. Waves with small periods made the OWEC perform quite poorly. The OWEC did also rotate a small amount during the test because of the mooring in the tank. When placing the system offshore in a larger scale this will not become a problem. The test showcased that the design could work in a natural environment and become a valuable offer to the energy industry.

6. Future improvements

The tests show that the concept is feasible from a mechanical perspective, and there could be a large potential for further development.

Gear ratio:

The prototype was designed with a gear ratio of 1 to 5. The reason for this was mainly a lack of resources and time, while a higher gear ratio wasn't needed for the proof of concept. In the future design, it would be preferred to design the OWEC with a much larger gear ratio to gain more efficiency from the wave motion. This requires more complex designs and calculations.

Cover:

Protecting the components from harsh seawater is important to ensure longevity. A cover over the components would ensure protection from the seawater and rough weather. The inside of the cover could be equipped with monitoring equipment, like cameras and sensors. The prototype was made without this to make the observations during testing easier.

Surface Treatment:

The OWEC would be placed offshore with seawater and harsh surroundings. To protect the material of the OWEC from this, paint can be added. It would be sufficient to paint the OWEC with a NORSOK standardized paint. "The NORSOK standards are developed by the Norwegian petroleum industry to ensure adequate safety, value adding and cost effectiveness for petroleum industry developments and operations." [20]

Scale:

The scale of the OWEC would be larger in a future design. The offshore waves could be much larger and unpredictable. How large the OWEC should be designed is dependent on several factors. It must be designed large and robust enough to handle the offshore environment and generate adequate energy. Expenses versus the potential energy coming from the OWEC is an important factor.

Solar panels:

The OWEC would be designed quite large compared to the prototype leaving room around the components in the middle. To get more out of the OWEC, solar panels could be placed on the floater, or on top of the covers. Investing in solar panels could be a good addition to the design for harvesting more energy from the environment.

Flywheel:

To preserve the rotational motion of the output-shaft, a flywheel could be assembled. The flywheel could help with creating a more stable electricity production, since it will create a more stable rpm on the output-shaft.

Linear generator:

From testing, it could be observed that the counterweight moved up and down. This motion can be used to implement the linear generator into the design of the OWEC. This can be achieved by taking a rod with a counterweight at the end of the rod. In the middle of the rod magnets can be placed which will slide up and down inside a tube of coils, and in that way create energy. This design is illustrated in Figure 18.

Battery:

Batteries could be mounted by the OWEC, giving the option of storing excessive energy when it is not needed. This could be beneficial for placing the system in accordance with orders from i.e., fish farms. Fish farms need power to operate the salmon reserves. They often use a generator that runs 24/7. By replacing the generator with the OWEC, the farms would become more environmentally friendly while still maintaining the salmon reserves.

7. Conclusion

The main goal of the project was to produce a design that could harvest energy from the ocean waves. If we had time, creating a prototype optimized for testing was desired. The group started brainstorming and gathering a bunch of ideas, which we later reviewed to find the best option. The best idea became an idea that combined from three different concepts that we called the Ocean wave energy converter. After the group had manufactured and created a prototype, it was tested in the wave tank at HVL.

We learned a lot from the tests and most important that the concept works, even with small wave amplitudes. If the periods between the waves were long, the OWEC performed as it should. One problem was that the OWEC started rotating, but that would probably be fixed by implementing the linear generator, which would stop the OWEC from turning. The test results could be called a success, proving the concept could also work in a large scale.

The project itself has given us quite a lot. The group has gained experience in project management and achieved valuable insight in combining theory with practical solutions. We learned much about the process of manufacturing a design, and how to solve problems occurring along the different stages. The project has showcased the importance of HSE and helped the group members see the value of accurate planning and measurements before starting a task.

Our team has worked extraordinarily well. We have been fortunate to be working together on all projects from the start of our education here at HVL. We have different levels of expertise in certain areas. Combining our knowledge, we tend to succeed with the projects we take part in. Deadlines during this project have never been a problem since we have been working in a disciplined way, also with good help from our supervisor Saeed Bikass.

In all, the project has demanded every aspect of what we have learned during our education, giving us a challenging and exciting task that we have gained a lot from. The satisfaction of seeing calculations accord in practice and drawing 3D functional models that are later mounted on the project gives greater understanding between theory and real life.

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List of figures

List of tables

Appendices

Appendix A – Concept Drawings

Shows all our concept-sketches that were not included in this report.

Appendix B – Score Table

For the complete scoring of all our concepts

Appendix C – OWEC Testing

Video of tests with OWEC in different wave-models plus some other views to illustrate the concept.

Appendix D – Drawings

Collection of all drawings for recreating the prototype