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Preface

This bachelor thesis is written between January 15th and June 17th, 2022, at the Department of Mechanical and Structural Engineering and Material Science at the Faculty of Science and Technology, at the University of Stavanger (UiS). The thesis is part of a project in collaboration with the student organization UiS Subsea, established in 2013. The target is to design and construct a fully functional remotely operated vehicle (ROV) and float, to compete in the Marine Advanced Technology Education (MATE) ROV Competition in June 2022.

Sincere gratitude would like to be expressed to the Faculty of Science and Technology at UiS for the possibility of participating in the UiS Subsea organization, the ROV project, and the MATE competition. The project was both challenging and educational, and it was an excellent opportunity for developing technical, creative, and collaborative skills.

With the support of and collaboration with fellow students, sponsors, and family, the project was successfully completed with functional products. Thanks to supervisor Professor Hirpa G. Lemu from the University of Stavanger for help and support throughout the project. A special thank-you would like to be given to the university's employees for excellent help and advice, especially for components manufactured in the workshop and 3D printing.

Stavanger, June 17th 2022

Christine Nordal

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Nomenclature

Actuator: A device that receives signals and converts the source energy into mechanical motion, either linear, rotary, or oscillatory.

Aspect ratio: The mean length to the mean width of the ROV.

Construction: Includes debris removal and attaching or detaching tasks.

CAD: Computer-aided design, technology for designing and creating technical documentation with the means of a computer.nd cap

Cradle-to-cradle product (C2C): A product produced in such a manner that it can be reused in new products instead of being disposed of at the end of life. It, therefore, must be easily disassembled, recyclable, and non-toxic.

Explicit need: A clear statement of the customers' wants and desires.

G-code: A set of instructions that will guide the manufacturing tool.

Inspection: Detailed examination or testing.

Intervention: Supporting drilling operations by operating valves, replacing ring seals, and attaching or detaching electrical or hydraulic lines.

IP-grad: An international standard EN 60529 for determining the level of sealing effectiveness. The first digit represents intrusion protection for dust and particles, and the second digit represents moisture protection.

Latent need: Not recognized by most customers and not addressed by already existing products.

Observation: Monitoring performed by the ROV while either moving around or being stationary.

Parbak gland: Elastomer backup rings used to prevent the O-ring from moving.

Recycling: Recovering and reprocessing waste material into new products.

SDR ratio: A standard dimension ratio referring to the pipe's geometry, which is the ratio of the outside diameter to the wall thickness.

Surveying: Mapping or observing the seabed.

Thruster: The propulsion system mounted on the ROV, consisting of propellers and an electric motor.

Trenching: Digging a ditch in the seabed for installing, inspecting, or maintaining pipelines or cables.

Summary

This thesis aims to design and construct the ROV frame, named *Fenris*, and the inner and outer construction of the float, named *Frøya*, by following the product development process (PDP). This includes the development of the float's buoyancy system. The thesis is executed in collaboration with the student organization UiS Subsea, which will compete in the MATE ROV Competition 2022 with the products. Over the last decades, the focus on sustainability and the environment has increased, both in companies and private households. This year, MATE focuses on the United Nations' 17 Sustainable Development Goals (UN SDGs) and challenges students to find solutions to global challenges like climate change, poverty, and environmental degradation. Consequently, the design for environment (DFE) concept is implemented in the PDP to minimize the environmental impact of the products' life cycles.

The PDP consisted of the main phases: planning, concept development, detail design, and testing and refinement. The process focused on planning, setting the DFE goals, and doing thorough research before starting the generation of concepts and development of the products. This made the concept generation easier and time-saving since the customers' wants and expectations were known. The most promising concepts were effectively selected based on target specifications, matrices, or calculations. During the detail design phase, further improvements, dimensioning, material choice, structural analyses, buoyancy, stability and velocity calculations, and product cost were performed. The analyses and calculations verified that the components would be strong enough to withstand the applied forces, that the buoyancy and stability would be satisfying, that the products would be fit for the tasks in the competition, that they would be within budget, and would follow the DFE guidelines. When selecting materials for the ROV, the materials needed to be as light as possible while still having the strength to endure the applied forces, to minimize the product's weight. For the float, the main focus was to select environmentally friendly and recyclable materials. The DFE guidelines, set during the concept development, were taken into account during the material selection to reduce the environmental impact of the products. In testing and refinement, improvements were made based on testing after assembling the products, testing in water, and vacuum testing the float. Both products were altered after testing. The environmental impact of the products, comparison to the DFE goals, and possible improvements were also assessed. Overall, the PDP was beneficial but was time-consuming

and required structured team members. For the best utilization of the process, companies should select the phases and steps that would be most relevant to them.

The products were evaluated using a DFE assessment tool to check whether they indeed were cradle-to-cradle products. Material chemistry, amount of recycled content, disassembly, and recyclability were considered to assess the success of the DFE process. The ROV obtained a rating of 88.2 % and the float 92 %. The results were relatively high, and the products were satisfying in terms of DFE and being C2C products.

The final products were overall satisfying and functioning, did well during testing, and were able to perform the tasks for MATE's qualification video. However, improvements and optimizations could be made to enhance the products.

The links to the demonstration videos follow: MATE Demonstration video 2022 - YouTube

Test of the float Frøya - YouTube

1 Introduction

This bachelor thesis is part of a larger project based on designing, developing, and constructing underwater vehicles. The project's origin was the participation in the international Marine Advanced Technology Education (MATE) competition. This chapter presents the student organization UiS Subsea and the thesis's objective, scope, and limitations. Next, the MATE competition, its mission objectives, and the scoring overview is portrayed. This year, MATE focuses on the environmental impact of underwater robotics, and the United Nations' Sustainable Development Goals (UN SDGs) are therefore described. The chapter also gives information about remotely operated vehicles (ROVs), floats, and the report structure.

1.1 UiS Subsea

This thesis is executed in collaboration with the student organization UiS Subsea. It is an innovative student organization at the University of Stavanger (UiS) that has engaged students in underwater technology since 2013. In the following years, the organization has gathered students from several fields of study to produce underwater vehicles and compete in the MATE ROV Competition. The aim is to give the students experience working and collaborating on a large multidisciplinary project. It provides room for evolving both their technical and collaborative skills. Due to sponsor deals and interest in the project, the organization also has a close relationship with companies working with underwater technology. This year, the team consists of 21 students in the fields of electrical engineering, mechanical engineering, computer science, and economics, writing nine bachelor theses. Together, the team will design and produce an ROV and a float for the ROV MATE Competition 2022. This thesis' contribution to the project is to design and construct the ROV frame and the float. This year's bachelor theses in UiS Subsea are as follows:

Electrical Engineering:

Power supply card:	Carl Henrik Preber Ettesvoll, Nicolai Jensen Narvesen, and Jon Arve Andersen
Machine vision and communication:	Christoffer Næss, Mats Røste, and Tage Mellemstrand
Sensor card:	Jørgen Hemnes Johannessen
Control and regulation systems:	Tomas Royal Choat, Kristian Birkeland, and Otto Nessa Ljosdal
Development of a smart floater:	Malin Harr Overland and Hanne Lovise Berger

Mechanical Engineering:

Design and construction of ROV and float:	Christine Nordal and Sandra Nygård
Design and production of manipulator:	Henrik Welde and Sindre Rød Torsteinsen

Computer Science:

Operator interface and communication:	Vebjørn Lia Riiser and Åse Jortveit Sagebakken

Economics:

The process of change in UiS Subsea:	Maren Lovise Jåsund, Sina Brunes, and Sanna Sørskår

1.2 Objective

This thesis' objective is to design and construct the ROV frame and the internal and external construction of the float by following the product development process (PDP). The float's internal structure includes the buoyancy system. The primary focus of the designs is to ensure that the products are well suited to achieve the tasks in the MATE competition.

In collaboration with the rest of the members of UiS Subsea, it is decided that this thesis's main objective regarding the ROV and float is to:

- Execute the PDP to produce an ROV and a float that can perform all the mission tasks in the MATE competition and fulfill the company requirements.

Company-specific objectives:

- Produce products within the budget that are able to perform the MATE tasks.
- Select environmentally friendly and recyclable materials for the products' components.
- Ensure a design configuration that is easy to assemble, disassemble, and maintain.
- Locating parts in the products to make them stable on land and in water.
- Design components and assemblies that cause little drag.
- Ensure a design configuration that eases the adding and removing of ballast.
- Construct a lightweight float that can operate at 10 m water depth.
- Design a lightweight ROV that weighs max. 20 kg and can operate at 50 m water depth.
- Ensure that the ROV has good maneuverability and free flow through the frame and the thrusters.
- Design the ROV in such a manner that it is easy to lift.

1.3 Scope and Limitations

The PDP is chosen as the method for designing and producing the ROV and the float since the process has been proven to help with planning, coordination, management, assuring quality, and improving products. The focus on sustainability and the environment has, over the last decades, increased, both in companies and in private households. In addition to producing products that achieve the MATE tasks, this thesis will direct attention to the design for environment (DFE) concept in the development process. The goal is to minimize the environmental impact in the products' life cycles. Furthermore, this report will include material choice, dimensioning, structural analysis, and calculations on buoyancy and stability.

Designing, producing, and building an ROV and a float is usually a time-consuming process that takes years, has large budgets, and requires specific knowledge regarding the subject. This project has limitations regarding the mentioned factors, and the limitations of the project are listed below.

- Time
- Budget
- Knowledge
- Dependency on other groups
- Resources
- Availability

Time is the most limiting factor in this thesis' product development and limits the thesis' scope. The submission date is 17.06.22, and the ROV and float must be completed before the competition in mid-June. The PDP is a generic process consisting of six main steps: planning, concept development, system-level design, detail design, testing and refinement, and production ramp-up. Every enterprise performs this process in its own way. Due to the lack of time and resources, every aspect of the PDP cannot be covered. The system-level design will not be included due to time consumption and prioritizing of the steps. The last step, production ramp-up, is not relevant to this project since only one unit of each product is produced and will not be included either. The focus will only be on the aspects in the PDP most relevant to this thesis. There are few hand calculations since finite element analyses (FEA) will be performed instead to verify if a component can withstand the applied forces.

1.4 MATE

The project's main focus, as mentioned, is to design and construct products that can compete in the international MATE ROV Competition. The competition's organizer is the MATE Center, a research center, that wants to inspire students and challenge them to use engineering, science, and technology to develop underwater vehicles. They want to stimulate critical thinking, collaboration, and innovation. The MATE ROV challenge is divided into five levels, from beginner to advanced: SCOUT, NAVIGATOR, RANGER, PIONEER, and EXPLORER. UiS Subsea will compete in the EXPLORER class. Each year, there is a different focus, and this year's headline is: *"UN Decade of the Ocean: MATE Inspires ESG (environmental, social, and governance factors)."* In this year's Mate ROV EXPLORER Challenge, the ROV must complete three tasks, Marine Renewable Energy, Offshore Aquaculture and Blue Carbon, and Antarctica Then and Now. The competition focuses on the UN's Decade of Ocean Science for Sustainable Development (2021-2030), which the UN initiated based on the 17 Sustainable Development Goals. This year's three tasks are based on 5 of the UN's SDGs. MATE wants students to learn about and be part of finding solutions to some of the most significant global challenges like climate change, poverty, and environmental degradation through the UN SDGs. In addition to encouraging participants to focus on ESG, MATE wants the participants to be a part of creating a sustainable future for the use of the world's oceans [1]. UiS Subsea has competed in the MATE competition several times and received good scores.

1.5 UN Sustainable Development Goals

The United Nations defines the UN SDGs as "The blueprint to achieve a better and more sustainable future for all. They address the global challenges we face, including poverty, inequality, climate change, environmental degradation, peace and justice" [2].

Figure 1-1 The 17 Sustainable Development Goals

Figure 1-1 [3] illustrates the 17 SDGs. The tasks in the MATE competition target the 2nd, 7th, 12th, 13th, and 14th sustainability goals. Task 1 addresses the 7th goal, Affordable and Clean Energy, and the 12th Goal, Responsible Consumption and Production. Goal number 7 inspires people to increase energy availability and use more renewable energy sources. Today, 13 % of the world's inhabitants still do not have access to electricity, and 13 billion need access to safe and clean fuel for cooking and heating. Furthermore, energy releases 60 % of the emissions of greenhouse gases. Some of this goal's targets are to ensure the availability of modern energy for all and significantly increase the proportion of renewable energy by 2030. The 12th goal aspires to do more with less. Production and consumption of resources to meet today's social and economic development are destructive and not sustainable. About one-third of the produced food is thrown away yearly, and freshwater sources are polluted faster than nature can purify them. More than two billion people experience high water stress. Some of the 12th goal's targets are achieving sustainable production and consumption, reducing waste generation, and achieving sound management of chemicals [2].

Task 2 focuses on the 2nd, 13th, and 14th sustainability goals, while Task 3 also targets the 13th goal. The 2nd goal, Zero Hunger, aims to end hunger and give everyone access to enough and nutritious food. Today, around 8.9 % of the world's inhabitants, 690 million people, suffer from undernourishment. Goal 13, Climate Action, encourages people to take action to reduce human impact on the climate and respond to climate changes. The temperature rise causes reduction in crops, increase in sea levels, and the weather becomes more extreme. Additionally, emissions of greenhouse gases have increased more rapidly in the last decades. Some of the targets in this goal are to improve awareness of climate change, include measures to reduce climate change in national policies, and strengthen the capacity to withstand natural disasters. The aim of the 14th goal, Life Below Water, is to utilize and conserve marine resources and the seas sustainably. Human exploitation and debris in the oceans have caused severe degradation. In addition, 90 % of the world's excessive heat and 30 % of the CO_2 emissions have been absorbed by the oceans, thus threatening the biodiversity and killing coral reefs. Therefore, everyone must reduce ocean pollution and overfishing and increase knowledge and ocean restoration [2].

1.6 Mission Objectives

This year's mission is divided into the three main practical tasks, Marine Renewable Energy, Offshore Aquaculture and Blue Carbon, and Antarctica Then and Now, which give 100 points each. Each task is divided into several subtasks. The subtasks, point distribution, and limitations are retrieved from the MATE competition manual.

Task 1: Marin Renewable Energy

The task is designed to replicate assignments needed to perform maintenance on offshore wind farms. This service includes replacing damaged cables and buoyancy elements, removing nets caught on a wind turbine's substructure, and deploying instrumentation to detect the presence of sea mammals. Constructions of polyvinyl chloride (PVC) pipes simulate these tasks. The tasks involve the following steps with the associated points.

UN Sustainable Development Goals:

- #7 Affordable and Clean Energy
- #12 Responsible Consumption and Production

1.1 Replacing a damaged section of an inter-array power cable

- Conducting a visual inspection of the cable – 5 points
- Cutting the cable on both sides of the damaged section – 10 points
- Removing the damaged section of cable – 5 points
- Installing a new section of cable – 10 points
- Securing the new section of cable in place with wet-mateable connectors – 5 points each, 10 points total

1.2 Replacing a damaged buoyancy module on an inter-array cable of a floating offshore wind turbine

- Removing the failed buoyancy module
    - Releasing the clamp – 5 points
    - Recovering the failed buoyancy module – 5 points
- Attaching a new buoyancy module
    - Attaching the new buoyancy module – 5 points
    - Securing the clamp – 5 points

1.3 Monitor the environment

- Deploying a hydrophone to detect and record the presence of marine mammals
    - Deploying the hydrophone in a designated area – 5 points
- Removing a ghost net caught on the wind turbine's substructure
    - Pulling a pin – 10 points
    - Removing the ghost net from the water – 5 points

1.4 Piloting into "resident ROV" docking station

- Autonomous docking – 15 points
- Manually docking – 5 points [1]

Task 2: Offshore Aquaculture and Blue Carbon

The task replicates assignments needed to inspect and maintain offshore aquaculture pens. It includes inspecting and repairing nets, removing fish mortalities (morts) and marine growth, and farming seagrass. Constructions of PVC pipes simulate the tasks. The tasks involve the following steps with the associated points.

UN Sustainable Development Goals:

- #2 Zero Hunger
- #13 Climate Action
- #14 Life Below Water

2.1 Inspecting an offshore aquaculture fish pen

- Inspecting the netting to identify damaged areas
    - Flying a transect line to identify damaged areas
        - Autonomously inspecting – 25 points
        - Manually inspecting – 10 points
    - Identifying and counting damaged net areas – 5 points
- Repairing a damaged section of netting – 10 points
- Removing marine growth
    - Removing encrusting marine growth – 5 points
    - Removing algal marine growth – 5 points

2.2 Maintaining a healthy environment

- Manage mortality by removing "morts" from the fish pen
  - Using Artificial Intelligence (AI) to differentiate "morts" from live fish – 10 points
  - Collecting a "mort" – 5 points
  - Inserting "mort" into the collection tube – 5 points

2.3 Measure fish size

- Determine the average size of the fish cohort within 2 cm – 15 points
- Determine the biomass of the fish cohort – 5 points

2.4 Farm seagrass

- Prune an existing seagrass bed – 5 points
- Plant a new seagrass bed – 5 points [1]

Task 3: Then and Now – Endurance22 and MATE Floats!

The task is designed to replicate assignments in Antarctica. The first part represents recovering a Global Ocean Biochemistry Array (GO-BGC) float and then placing the float produced by UiS Subsea in a designated area. This float should make two vertical profiles, traveling twice to the pool's bottom and back to the surface. The second part is to map the location of the wreck of the ship *Endurance*, which sank in Antarctica, and then create a photomosaic and measure the length of the wreck. Again, the wreck and GO-BGC float are simulated by PVC pipes. The tasks involve the following steps with the associated points.

UN Sustainable Development Goal:

- #13 Climate Action

3.1 MATE Floats!

- Recovering a GO-BGC float to conduct diagnostics
  - Determining the location where the float will next surface – 5 points
  - Recovering the float – 10 points
- Designing and constructing an operational vertical profiling float
  - Prior to the competition, building a float – 5 points
  - Deploying the float in the designated area – 5 points
  - Float completing vertical profiles
    - Float completes two profiles– 25 points
    - Float completes one profile– 15 points

3.2 Endurance22

- Finding and mapping the location of the Endurance
  - Flying a transect over the area of the wreck – 10 points
  - Mapping the wreck – 5 points
- Creating a photomosaic of the wreck
  - Collecting images of all sections – 5 points
  - Autonomously creating the photomosaic – 20 points
  - Manually creating the photomosaic – 10 points
- Measuring the length of the wreck from bow to stern
  - Within 10 cm of the true distance – 10 points
  - Within 10.1 to 20 cm of the true distance – 5 points
  - Not within 20 cm of the true distance – 0 points [1]

1.7 Scoring Overview

The maximum points possible to achieve in the competition are 695 points. The points are awarded in the three main categories, product demonstration, engineering and communications, and safety. These are shown in Table 1-1 with subcategories and point distribution. During the product demonstration, the products' weights and sizes are controlled. This is also where the products perform the three main tasks given, and the team has 15 min for each task. During engineering and communication, points are given for technical documentation, communication, and marketing of the products. In safety, points are awarded for safety measures presented in documentation or during the operation of the ROV and float.

Table 1-1 Scoring overview

Main Categories for Points	Subcategories	Points
Product Demonstration	Product demonstration, plus bonus*	300
	Weight	10
	Organizational effectiveness	10
Engineering and Communication	Technical documentation	100
	Engineering presentations	100
	Marketing displays	50
	Company spec sheet	20
	Corporate responsibility	20
	Virtual reality assets	25
Safety	Initial safety and documentation review	20
	Safety inspection	30
	Job safety analyses	10
Total Score		**695**

*If teams successfully complete all tasks and return the ROV to the docking station, 1 additional point will be given for every minute and 0.01 points for every second remaining under 15 minutes.

1.8 ROV History

The self-propelled torpedo is regarded as the first undersea robot. Although this torpedo was developed in the 1860s, remotely operated and autonomous underwater robots were not developed until the mid-1900s. The *POODLE*, Figure 1-2, a remotely controlled torpedo by using a cable, is regarded as the first ROV. This vehicle was developed early during the cold war and had a camera to search for shipwrecks. In the 1950s, the British and U.S navies developed underwater robots for locating and recovering weapons lost by the militaries. During the oil boom in the 1970s, the need for underwater robotics increased, and the development boosted. In the 1980s, 27 companies had developed more than 500 ROVs. The ROVs developed during the 20th century showed the potential of underwater vehicles and helped advance the technology. The goal for further development of underwater vehicles was to produce cheaper and smaller vehicles. These were typically powered by electricity, and the most recent vehicles carried the power source onboard. Today, underwater vehicles are used in national defense, resource extraction, science, telecommunication, construction, inspection, maintenance, search and recovery, archaeology, entertainment, and education [4].

Figure 1-2 The POODLE

1.9 ROV

ROVs are unmanned vehicles operated by pilots from ships or platforms above them. The pilot communicates with the ROV through a cable called a tether, which transmits power and signals. ROVs are divided into three subcategories, illustrated in Figure 1-3, tethered free-swimming [4], bottom-crawling [4], and structurally reliant [5]. Most of the ROVs are tethered free-swimming and have the following characteristics:

- High maneuverability
- Cameras
- Operate mid-water or at the bottom
- Powered through the tether
- Barely float
- Move with the use of thrusters

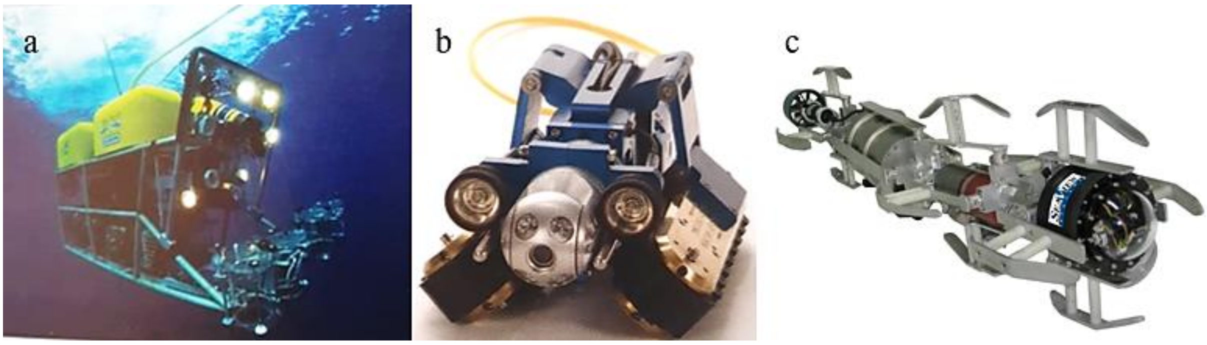


Figure 1-3 Tethered free-swimming(a), bottom-crawling(b), structurally reliant(c) ROVs

Crawling ROVs crawl on the bottom of the sea by using suction cups, caterpillar treads, legs, or wheels. They are used for trenching and burying cables or pipelines, digging in the seabed, or inspecting the inside of pipes. Structurally reliant ROVs are attached to underwater structures and used for cleaning or inspection. Instead of thrusters, most of them move by pulleys, cables, tracks, wheels, or hydraulics [4].

ROVs can perform many different tasks, and the most common ones are observation, surveying, inspection, construction, intervention, burial, and trenching. The various tasks are more suitable for certain ROV classes. There are eight classes of ROVs, from I to VIII, and examples of each of the classes are presented in Figure 1-4 with their respective numbers.

- I – Pure observation [6]
- II – Observation with payload options [6]
- III – Work class vehicles [6]
- IV -Towed and bottom crawling vehicle [6]
- V – Prototype or development vehicle
- VI – Autonomous underwater vehicles [6]
- VII – High speed survey vehicles [7]
- VIII- Fall pipe ROV [8]

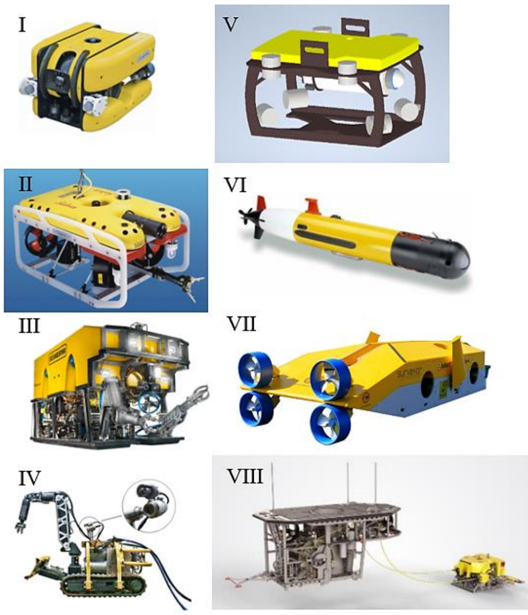


Figure 1-4 The various ROV classes

The pure observation ROVs are small vehicles equipped with lights, a camera, and thrusters. They are created for observational tasks but can have a second video camera and sensors. The observation with payload option ROVs, Class II A and B, can carry additional sensors such as sonars, measurement systems, extra cameras or color cameras, and cathodic protection. Class II B can also have a basic manipulator and conduct light construction, surveying, inspection, and intervention tasks. Work class ROVs are classified as Class III A or B based on their power rating, onboard payload, and lift capacity. These vehicles can carry additional tools and sensors and are more powerful and larger than Class I and II vehicles. They must have at least two permanently installed manipulators and allow additional tools and sensors to function while not being “hard-wired” through the tether. They execute tasks like surveying, inspection, construction, and intervention. Towed and bottom crawling ROVs are divided into Class IV A, towed vehicles, and Class IV B, bottom crawling vehicles, and move on the seabed using a winch, surface craft, belts, wheels, thrusters, jet power, or a combination of theses. These vehicles are created to perform specific tasks, such as seabed construction, dredging, digging, trenching, and inspecting pipes. Prototype or development ROVs are regarded as prototypes or vehicles under development. Class V also includes vehicles that do not belong in the other classes. The autonomous underwater vehicles (AUVs) are not connected via a tether or directly operated but are programmed to move on mission routes. The high-speed survey vehicles are designed to be fast and stable and carry quiet sensors for surveying and inspection of pipelines. The fall pipe ROVs are designed for rock- or vessel-installation and surveying [9].

The general ROV consists of subsystems, including a frame, thrusters, floatation elements, cameras, lights, sensors, manipulators, and electronics. The frame is a platform that holds all the other components and is generally box-shaped with an open structure. The flotation elements are lightweight with lower densities than water and will, therefore, float in water. These elements are attached to balance the sinking of the other components due to their weight. The thrusters propel the ROV through the water. Lights and cameras give the pilot visibility of the ROV’s surroundings. The manipulators allow the vehicle to complete work while electronics power and control the components on the ROV [4].

1.10 Float

Floats had been constructed at the National Institute of Oceanography, and Henry Melson Stommel suggested in 1955 to use floats to measure and track deep drift currents. These floats were created in aluminum and had sealings rated for a depth of 4500 m. A ship followed the floats, and signals were received at two hydrophones lowered over the ship’s sides. Six floats were used during the cruise *R.R.S. Discovery II*, 1955, and of these, four were lost, and two worked satisfactorily [10].

Biogeochemical floats are cylindrical vessels containing biochemical and optical sensors registering biochemical data. The floats are deployed at sea and drift through the ocean at different depths throughout their lifecycle. Figure 1-5 [11] shows a typical float cycle. The floats descend to 1000 m, drift for a couple of days, then descend to 2000 m before ascending to the surface. Floats are programmed to repeat this cycle throughout their life, collecting data at preprogrammed intervals. They are battery-driven and regulate the depth by using a buoyancy engine. The buoyancy engine pumps liquid from inside the floats to an external bladder. When the floats reach the surface, the data automatically transmits via satellites. The floats will continue their cycle without human assistance until the battery is worn out, about five years, and are then retrieved [12].

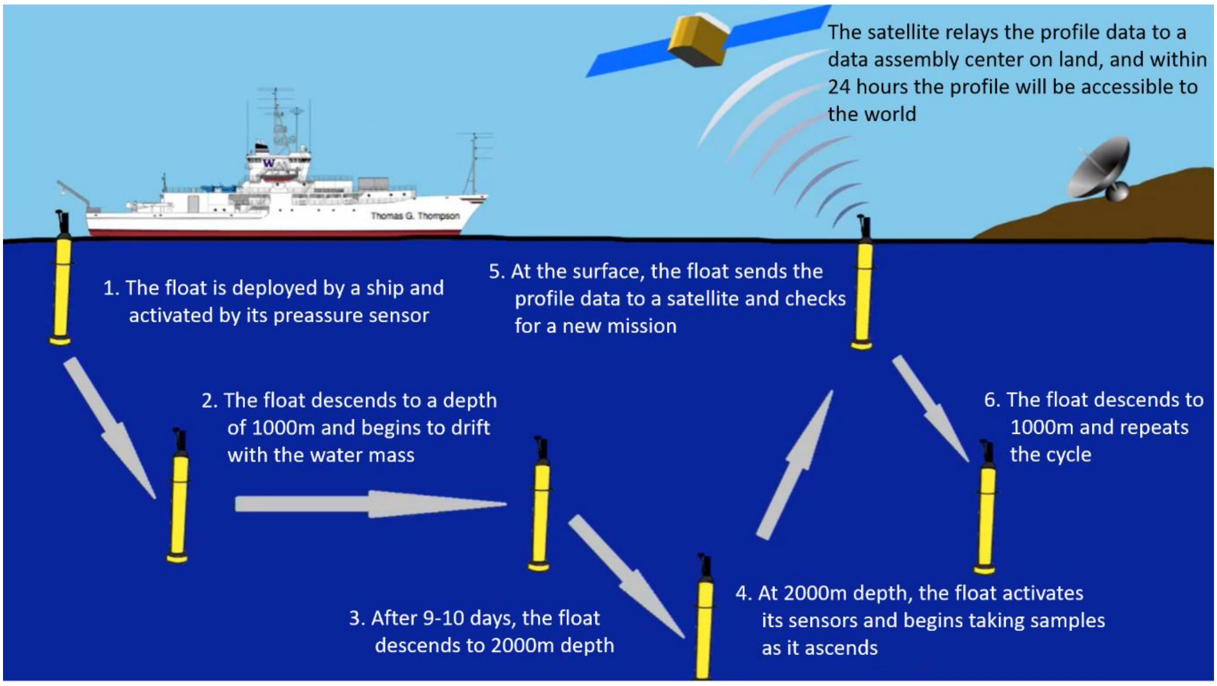


Figure 1-5 A typical float cycle

1.11 Report Structure

This thesis contains seven chapters. Chapter 1 is an introduction with background information regarding the organization UiS Subsea, the MATE organization, the competition tasks, ROVs, and floats. The chapter also presents the thesis' objective, scope, and limitations. Chapter 2 introduces the theory used in this thesis, including forces on underwater vehicles, buoyancy, drag, thruster placement, stability, 3D printing, the PDP, and the DFE concept. Through Chapters 3 to 6, the product development process for the products is described with the main steps, planning, concept development, detail design, and testing and refinement. The evaluation and conclusion are presented in Chapters 7 and 8, respectively.

2 Theory

This chapter focuses on the theory relevant to this thesis, incorporating forces acting on submerged objects, buoyancy, drag, thruster placement, and stability. In addition, theory regarding 3D printing, the PDP, and DFE concept is described.

2.1 Forces Acting on Underwater Vehicles

Several forces act on an underwater vehicle, and five types affect the vehicle's motion. These are thrust, drag, weight, buoyancy, and lift, as shown in Figure 2-1. The thrust force is created by propellers pushing or pulling the ROV in a direction. The drag force acts in the opposite direction of the ROV's motion and opposes the thrust force. The weight force (F_g) acts downward and is created due to the ROV's mass (m) and gravitational acceleration (g).

$$F_g = mg \tag{1}$$

The buoyant force (F_b) acts upwards and is created due to the water displaced by the ROV. The lift force acts orthogonal to the direction of the ROV's motion and depends on the ROV's speed. The lift force can be neglected for ROVs due to their slow movements [4].

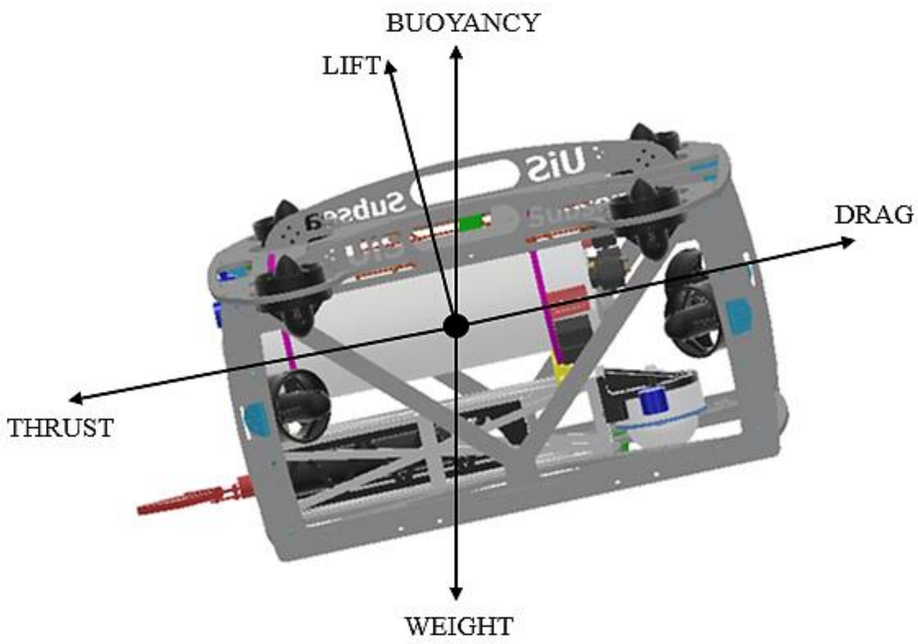


Figure 2-1 Forces acting on underwater objects

2.2 Buoyancy

When an object is submerged, a pressure presses against the object's surface and creates a force. This force equals the pressure times the surface area and acts orthogonally to the surface area. Pressure increases with depth, and the force pushing up at the bottom of the object will, therefore, be greater than the force pushing down on the top of the object. This net upward force is called the buoyant force. The buoyant force will always act on a submerged object, but it varies if the force is strong enough for the object to float. This force makes the impression that an object weighs less in water than in air [4].

Archimedes' principle states that the buoyant force acting on a submerged object is equal to the weight of the displaced fluid. The buoyancy of an object is the object's tendency to float and is the result of the competition between the object's weight and buoyant forces. If the object's weight force is less than the weight of the displaced water, the object floats and is called positively buoyant. If the object's weight force is greater than the buoyant force, the object sinks and is called negatively buoyant. If the object's weight and buoyancy forces are equal, the object will neither float nor sink but hover in mid-water. The object is then called neutrally buoyant [4]. The buoyant force is given by the equation

$$F_b = \rho g V \tag{2}$$

where ρ is the fluid's density, and V is the submerged object's volume [13]. The gravitational acceleration used in this thesis is $g = 9.81\ m/s^2$, and the density of water is $\rho = 997\ kg/m^3$. The goal of an ROV's floatation system is to counteract the ROV's weight force. Floatation elements are attached to the frame to retain a near-neutral buoyancy. This allows the ROV to hover in mid-water without using much thrust. An ROV is usually a little positively buoyant to ensure that it returns to the surface if problems occur with the propulsion system. It also allows the ROV to move near the bottom without thrusting upward, stirring up sediment. A goal should be to obtain a net buoyant force equal to about 4 % of the ROV's weight and then trim that down to 1-2 % [4]. The floatation element can, in theory, be made of anything less dense than water. However, the material should not be compressible with increasing pressure. The three main categories of materials used are rigid, lightweight material, syntactic foams, and ceramic spheres. Lightweight foams such as polyurethane (PUR) and PVC foams are used at shallower depths. PUR foam includes two types of polymers, polyisocyanurate (PIR) and PUR. Syntactic foams and ceramic spheres are used in deep water and are, therefore, not further discussed as possible buoyancy elements in this thesis [14].

2.3 Drag

Drag is the force that resists the motion between an object and the fluid it is submerged in. The drag limits the object's speed, interferes with the steering, and consumes a lot of the energy that powers the object. The object's propulsion system must overcome the drag to move and remain at work sites. Two types of drag affect an object: skin friction drag and form drag (F_d). Skin friction drag is created by the friction between the fluid and the object's surface. The surface area should therefore be reduced as much as possible. It is also desirable to have a smooth surface and gradually varying form to prevent pressure gradients from building up. The form drag is created as the fluid is displaced to make room for the object. This drag is dependent on the cross-sectional area and shape of the object. The drag can be reduced by gradually varying sections of a long body. For ROVs, the form drag is usually much larger than the skin friction drag, which can be neglected. The vehicle's form drag is given by the equation

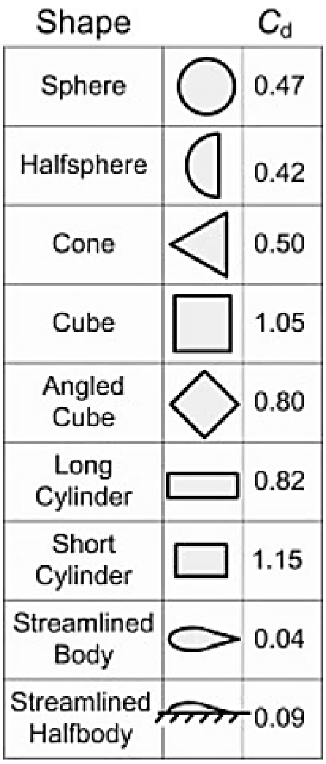


Figure 2-2 Drag coefficient

$$F_d = \frac{1}{2}\rho A v^2 C_d \tag{3}$$

where A is the cross-sectional area of the object's front, v the object's speed, and C_d the drag coefficient. Figure 2-2 illustrates the drag coefficients based on shapes, with the fluid stream flowing horizontally from left to right [14].

2.4 Thruster Placement

The propulsion system on an underwater vehicle comprises two or more thrusters. The thrusters propel the ROV, and the number of thrusters and their placement defines the vehicle's maneuverability. The optimal motion of an ROV allows six degrees of freedom, which consist of the linear motions heave, sway and surge and the rotational motions yaw, pitch, and roll, as shown in Figure 2-3.

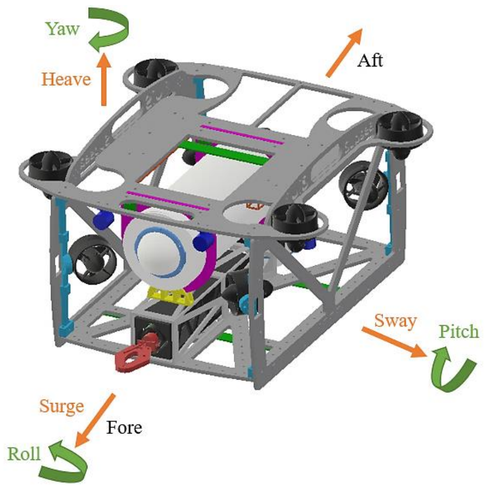


Figure 2-3 The six degrees of freedom of an ROV

As illustrated in Figure 2-4 [14], there are multiple options for thruster placement, which leads to varying degrees of freedom. The tree-thruster version results in the ROV moving fore, aft, and yaw. The four-thruster version makes it possible for lateral motion, and the five-thruster version allows the ROV to move in all horizontal directions. Adding more vertical thrusters combined with four horizontal thrusters gives the ROV all six degrees of freedom.

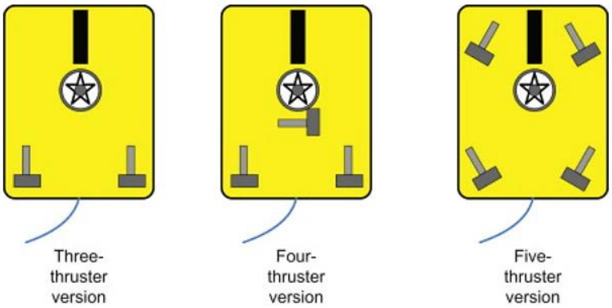


Figure 2-4 Thruster arrangements

The thrusters move an object by pushing the fluid in the opposite direction. For maximum efficiency, the thrusters need a free flow of water. Anything blocking the stream will reduce the thrusters' efficiency. Thrusters usually have higher densities than water, and their placement will affect the ROV's center of gravity (CG). Hence, the thrusters should be placed low on the ROV, which will also increase the stability. Work class ROVs typically have at least six thrusters, including four horizontal. As illustrated in Figure 2-5 a, the horizontal thrusters, represented by small black arrows, are placed close to the corners of the ROV at an angle orthogonal to the dashed line between the thrusters and the frame's center. This creates vectorial thrust forces that allow the ROV to move in several horizontal directions, as shown by large white arrows in Figure 2-5 b to e. This type of vertical thruster placement leads to good maneuverability and control of the ROV. However, using vector thrust force requires sophisticated navigational instruments and computer software [4].

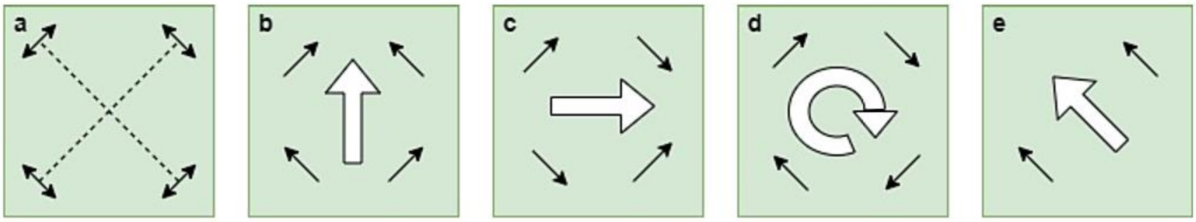


Figure 2-5 The arrangement of horizontal thrusters leading to vectorial thrust forces

The thrusters should be placed further away from the ROV's center of rotation for better turning and maneuverability. If the thrusters are placed too close to the center, the moment arm will be short, and the torque will not overcome the ROV's drag and inertia. However, if they are placed too far away from the center, the turning speed will be dependent on how quickly the thrusters can pull the ROV's corners through the fluid [4].

2.5 Stability

The weight should be placed low and the buoyancy high to achieve stability on the pitch and roll axis of the ROV. Better stability makes it easier to control the ROV and gives a stable camera platform. The aspect ratio affects the hydrodynamics and stability of the vehicle, as illustrated in Figure 2-6. Long and narrow ROVs are generally subject to less drag at higher speeds. However, they have poor station-holding capabilities. Short ROVs have better station-holding capabilities and horizontal maneuverability but are subject to higher drag at higher speed. ROVs are usually used to perform station-holding tasks or maneuver at low speed and are, therefore, short [14].

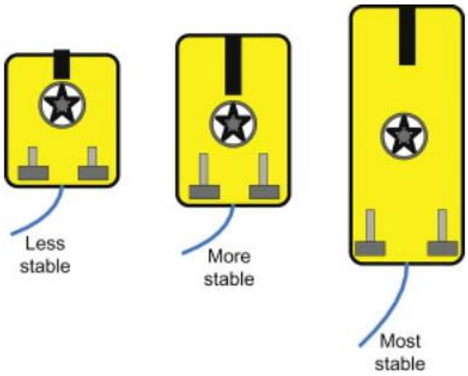


Figure 2-6 Stability due to aspect ratio

The weight of the ROV is the sum of each of its components' weights. The effect of these weights is equal to the total weight acting on a specific point, called the center of gravity. The CG can be found through calculations or experiments. The ROV also has a center of buoyancy (CB). This is the point where the total buoyant force acts and is equal to the effect of all the components' buoyant force [4].The following equations can be used for calculating CG and CB [15]:

$$X_{CG} = \frac{\sum xm}{\sum m} \qquad Y_{CG} = \frac{\sum ym}{\sum m} \qquad Z_{CG} = \frac{\sum zm}{\sum m} \tag{4}$$

$$X_{CB} = \frac{\sum xm}{\sum m} \qquad Y_{CB} = \frac{\sum ym}{\sum m} \qquad Z_{CB} = \frac{\sum zm}{\sum m} \tag{5}$$

where x, y, and z are the distances, in these directions, from the entire system's origin to the CG or CB of each component.

According to Van Dorn, the CG and the CB will always try to be on the same vertical axis, as illustrated in Figure 2-7. If they are not, the system is not in equilibrium, and the forces will create a torque that rotates the object until vertical alignment is achieved. The body is then in static equilibrium. The forces' moment that rotates the object about the rotation center, in the opposite direction of the inclination, is called the righting moment. The stability of an ROV is better when the distance between CG and CB is larger since this creates a greater righting moment if the vehicle is tilted [14].

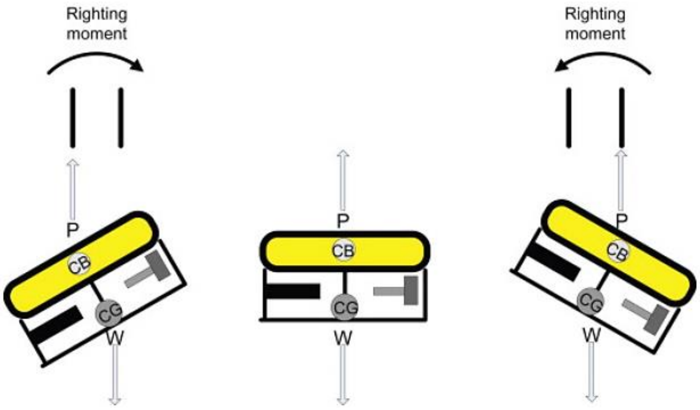


Figure 2-7 Righting moment of an ROV

2.6 3D Printing

3D printing is part of additive layer manufacturing (ALM), which aims to produce a physical part of a newly computer-designed part. After the 3D CAD model of the part has been created, the file is translated to an STL file supported by most CAD packages. This file format describes the 3D part's surface geometry and omits other characteristics like texture and color. The part is then opened in a program compatible with the 3D printer, and supports, materials, and infill structure with the desired percentage are added. The next step is to slice the part into layers that will be fused and view the simulation of the 3D printing. The program will create a g-code that can be exported from the program and imported to the 3D printer. The 3D printer will read this g-code and print the desired part.

There are three main ALM processes based on the starting material, liquid-based, powder-based, and solid-based. Only the liquid-based and solid-based 3D printing options were considered for producing components for the ROV and float and will be explained.

Solid-based processes:

Two of the most common solid-based 3D printing processes are fused deposition modeling (FDM) and laminated object manufacturing (LOM). At UiS, the Mechanical Engineers have access to some FDM 3D printers and have training in using them. Therefore, only this type of solid-based 3D printing will be considered.

In FDM, a spool of plastic polymer (filament) is supplied to a nozzle that heats it. The STL file's g-code sets the nozzle movement, and the melted plastic extruded through the nozzle solidifies at a heated build plate as the plastic is cooled down. New layers are printed on top of the previous one until the part is finished. Thermoplastics are generally used since they are easy to melt and then solidify again.

Liquid-based processes:

Stereolithography (SLA) is the primary liquid-based 3D printing method. A tank is filled with photosensitive resin, and an elevator with a support base is lowered until a thin layer, the height of the layer thickness, of liquid is above it. A UV laser cures the polymers where the beam strikes, forming solid plastic. The STL file sets the beam's path. The platform is lowered when the first layer is formed, allowing new liquid to flow on top of the first layer. A second layer is formed on top of the first one, and the process is repeated. After the entire part is formed, excess resin is removed, the part is cleaned and cured once more, and supports are removed. The post-curing improves the material strength and stability. The elevator can move both up and down, and the solidification can happen at the resin-air interface (top-down build) or the window-resin interface (bottom-up build). The top-down build is the process explained above, where the elevator moves down at each step. At the bottom-up build, the container will have a transparent window plate, and the elevator moves up at each step [16].

2.7 Product Development Process

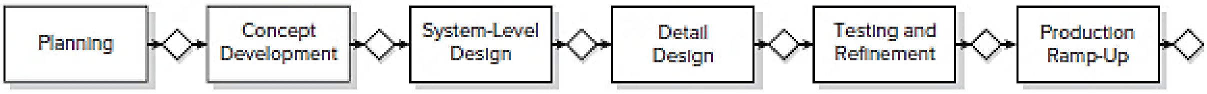


Figure 2-8 The general product development process

The PDP is the chain of activities that a company uses to create, design, and market a product. Companies generate a set of product concepts, reduce them, and increase the specifications until the product can be manufactured profitably. The process helps ensure quality, coordination, planning, management, and improvement. The general PDP consists of the six phases: planning, concept development, system-level design, detail design, testing and refinement, and production ramp-up, as depicted in Figure 2-8. The theory and figures regarding the PDP and DFE are obtained from *Product Design and Development* [17].

2.7.1 Planning

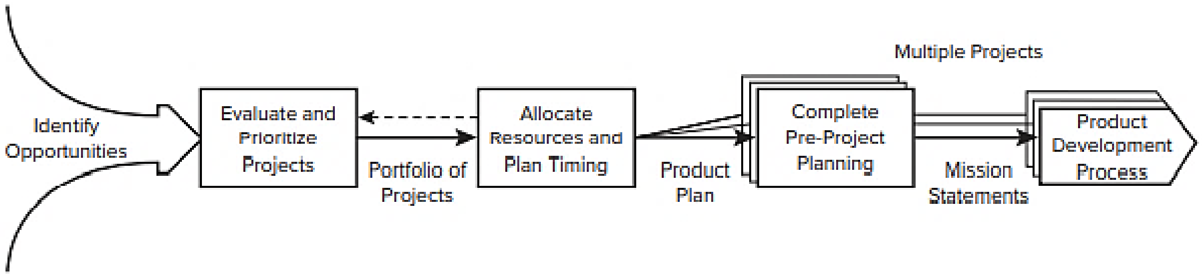


Figure 2-9 The planning phase

As illustrated in Figure 2-9, the planning phase consists of the five steps: identify opportunities, evaluate and prioritize projects, allocate resources and plan timing, complete pre-project planning, and reflect on the results and the process. The first step, identifying opportunities, is to identify product development opportunities. New opportunities may appear at any time, and every promising opportunity should be described in a short statement and saved in a database. In the second step, the opportunities are evaluated and prioritized to find the most promising ones. These are described in portfolios. Strategies used in the evaluation are product platforms, market segmentation, completive strategy, and technological trajectories. During the third step, time and recourses are allocated to the most promising concepts, and a product plan is created. The fourth step is to complete the pre-project planning, which happens after the project has been approved. The opportunity statement is rewritten into a vision statement for the product. More detailed information is written in the mission statement, containing a product description, business goals, benefits proposition, market description, assumptions, and constraints. In the last step, it is reflected on the results and the process to evaluate their quality.

2.7.2 Concept Development

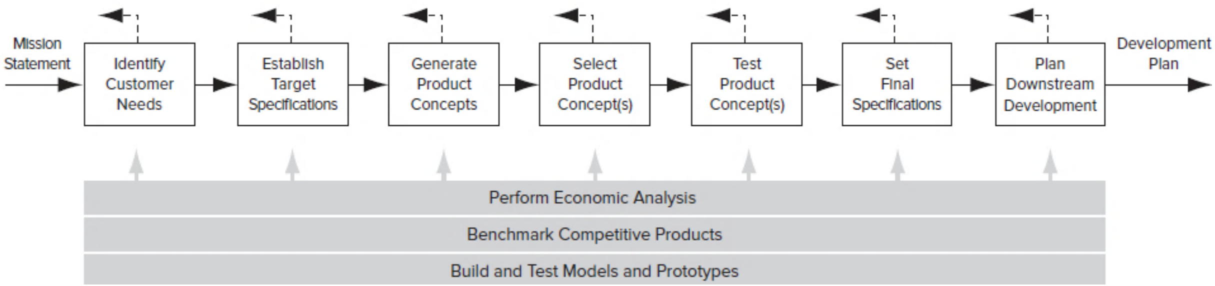


Figure 2-10 The concept development phase

The concept development phase consists of the activities: identify customer needs, establish target specifications, generate, select and test product concepts, set final specifications, create development schedule, economic analysis, benchmarking competitive products, and modeling. These are called the front-end product development activities and are illustrated in Figure 2-10. It is often necessary to repeat previous steps after receiving new information and results, and the steps are consequently overlapping. The customer needs are identified, and a hierarchical and importance weighted customer needs statement is created. The customer needs are converted into target specifications that describe the product's functions. These targets are the development team's ambitions for the product. The next step is to generate concepts that meet the customers' demands, displayed with sketches and short descriptions. The concepts are analyzed, and the most promising ones are selected. The selected concepts are tested to check whether they meet the customer needs, are attractive on the market, or have any shortcomings. The target specifications are revised, and final specifications are set based on the concept and modeling limitations. The last step is to create a development schedule that identifies resources needed and means to reduce development time. Economic analysis, benchmarking of competitive products, and modeling happen through the entire concept development phase.

2.7.3 System-Level Design

During the system-level design phase, the product architecture is defined. The architecture displays the product's subsystems and components and their purpose. Preliminary designs of the components are created in this step. Initial plans for the production systems, specifications for the subsystems, geometric appearance, and a process flow diagram for the assembly are also defined.

2.7.4 Detail Design

In the detailed design phase, further analysis takes place and leads to complete geometric, material, and tolerance specifications for the components. The production cost is also calculated. A control document that describes each part's geometry and production equipment, the specification of standard parts that can be purchased, the process plan for manufacturing and assembly, and the supply chain is created.

2.7.5 Testing and Refinement

In the testing and refinement phase, prototypes of the product are produced, tested, revised, and improved.

2.7.6 Production Ramp-Up

The product is produced with the intended production system during the production ramp-up phase. The intention is to train the workers in the process and find any remaining challenges with the product and the production process. There is a gradual transition from production ramp-up to ongoing production, where the product is launched and distributed. After the launch, the project is evaluated, and improvements in the PDP are found.

2.8 Design for Environment

Design for environment is a practical method that helps enterprises minimize their environmental impact and make a sustainable society. Effective use of DFE can improve the quality of products and reduce costs by reducing environmental impact. The environmental impacts addressed in DFE are divided into the main categories, energy and material. Focus on DFE must be present in all product development phases.

DFE was first introduced in 1971 by Papanek. He challenged enterprises to not only focus on their commercial interest but also on their social and environmental responsibilities. During the end of the 20th century, the concept was further developed and broadened, and today it includes social, ethical, and environmental considerations. In 2002, McDonough and Braungart stated that it was insufficient to produce less harmful products. The goal should be to create products that genuinely are environmentally friendly by focusing on material chemistry, disassembly, and recyclability. The firms Herman Miller and McDonough Braungart Design Chemistry (MBDC) have created an assessment tool that guides design decisions in the development process of products.

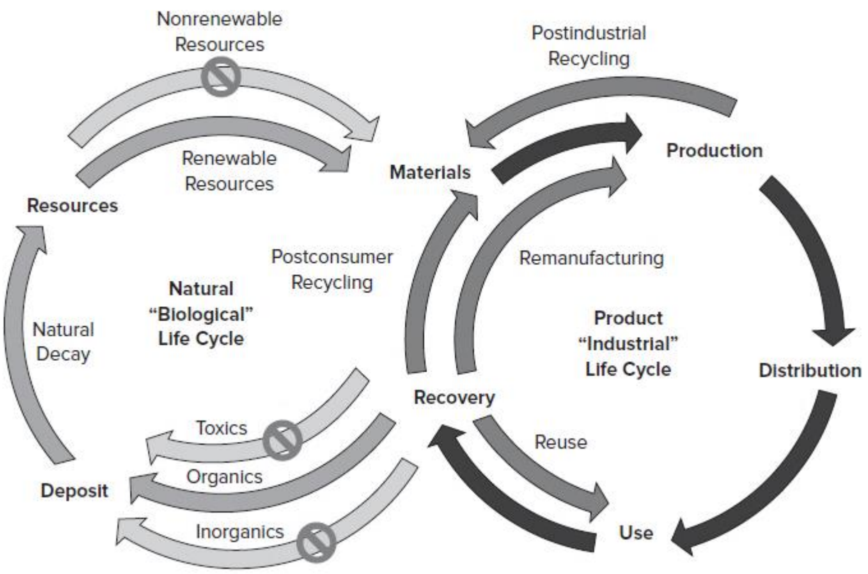


Figure 2-11 The natural life and product life cycles

The cornerstone of DFE is to focus on the product's lifecycle and the natural lifecycle, as shown in Figure 2-11. The natural lifecycle shows the evolution and decay of organic materials, which happens in a loop. The product lifecycle shows the life cycle of a product, starting with finding and processing raw materials, then production, distribution, use, and recovery. The recovery process includes reuse, remanufacturing, recycling, or disposal. The cycles intersect when using natural resources as raw materials in products and returning organic materials to the natural life cycle. As shown in the natural life cycle, to reduce environmental impact and increase sustainability, the manufacturers should reduce inorganic and toxic waste and the use of nonrenewable natural recourses.

The DFE process can be divided into seven steps, as presented in Figure 2-12. The first step happens during the planning phase and is to set the DFE agenda. This step includes determining the DFE's internal and external drivers, the DFE goals of the product, and the DFE team. The drivers are the same as the reason why an organization wishes to increase the environmental performance of its product. The internal drivers are the DFE objectives inside the company. External drivers often involve customers' preferences, environmental guidelines, and the contributions of competitors.

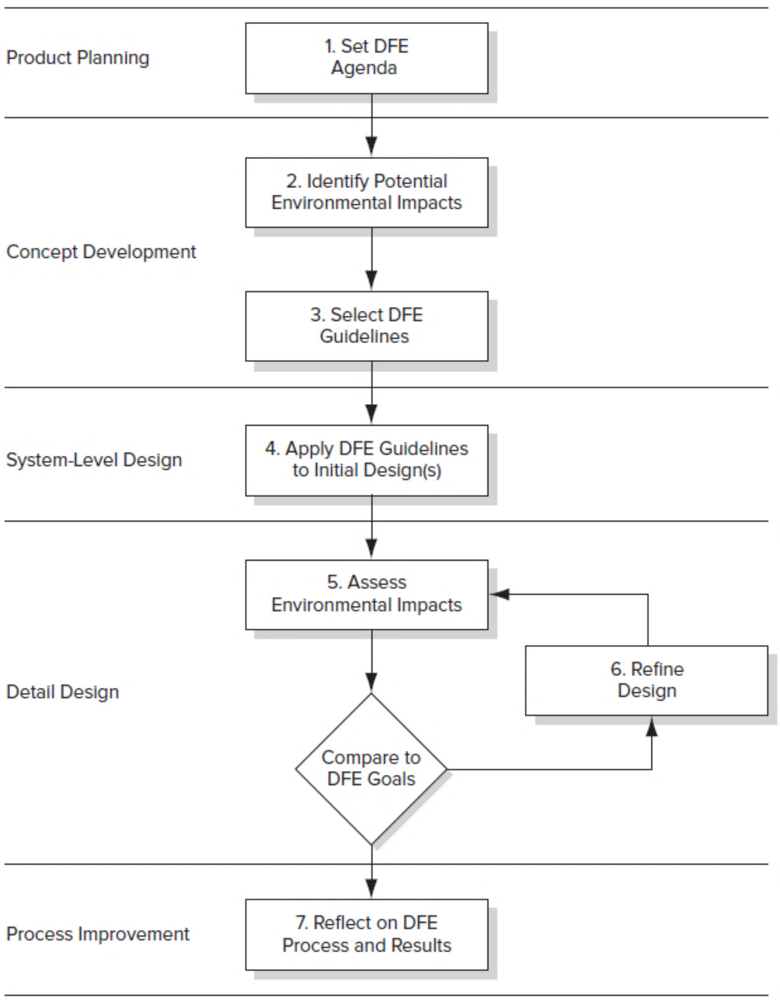


Figure 2-12 The steps in the DFE process

The second and third step happens during the concept development. The second step is to identify potential environmental impacts during the product’s life cycle. Doing this early in the concept development phase enables the team to consider the environmental impact from the beginning. The key environmental impacts expected for each stage in the cycle are listed, and a qualitative chart that evaluates the magnitude of the impacts is made. This chart shows which life cycle stages will have the most significant environmental impact and, thus, should be focused on improving. During the third step, select DFE guidelines, guidelines are created, considering the results from the qualitative chart. A table of the guidelines is created, where each stage in the life cycle has its own guidelines, that shows how to reduce the product’s environmental impact.

The fourth step, apply the DFE guidelines to the initial product design, is performed during the system-level design phase. During this phase, some decisions are made regarding materials and module design. The environmental impact can also be lowered by applying relevant DFE guidelines from the previous step. Applying the DFE guidelines affects decisions regarding the material choice, geometry, and manufacturing processes.

The fifth and sixth steps are applied during the detail design phase. The fifth step, assess the environmental impacts, assesses the product’s environmental impact during its entire life cycle. This is done by creating a detailed bill of materials (BOM), which gives awareness of the product’s production, distribution, use, and recovery. MBDC developed a DFE assessment tool, a spreadsheet listing each component, focusing on the components’ material chemistry, recycled content, disassembly, and recyclability. The detailed designs are compared to the DFE goals set in the first step, and the design with the lowest environmental impact is uncovered. The sixth step is refining the product design and reducing or eliminating environmental impact. The goal is to redesign to reduce the environmental impact until the impact is acceptable and the DFE goals are met.

The seventh and last step performed during the process improvement phase is to reflect on the DFE process and the results.

3 Product Development Process – Planning

PDP was used as the method for developing and constructing the ROV and the float. The process was chosen because it has been proven to help with planning, coordination, management, assuring quality, and improving the products. The PDP was a generic process consisting of six main steps. However, due to the lack of time and resources, the PDP for the ROV and float only followed the four steps: planning, concept development, detail design, and testing and refinement. The DFE concept was implemented throughout the entire product development process to minimize the environmental impact of the products. In the numerical tables, the most important findings have blue text.

The first step, planning, usually begins with recognizing opportunities, assessing market objectives, and technology development. These phases were already performed when UiS Subsea was founded. Thus, when establishing the organization, the two first steps, identifying opportunities and evaluating and prioritizing projects, of the planning phase were performed and were not part of this thesis.

The planning steps performed in this thesis were the third step, allocate resources and plan timing, and the fourth step, complete pre-project planning. These included setting the DFE agenda, the company's DFE goals, allocating resources and time planning, and creating the mission statement. The company referred to in this chapter is the organization UiS subsea.

3.1 Set DFE Agenda

The phase of setting the DFE agenda consisted of the three events: recognizing the external and internal drivers of DFE, setting environmental goals for the ROV and float, and deciding the DFE team. The DFE agenda helped identify an actionable path toward eco-friendly products, from material to recovery.

The DFE team consisted of everyone in UiS Subsea since everyone contributed to designing the ROV and float environmentally friendly. Nonetheless, only the members of this thesis studied the theory regarding the DFE concept and used it to improve the products. Therefore, this thesis's contribution to the final products would have the most focus on limiting the product's environmental impact.

The internal and external drivers were identified to figure out how the products could be designed and produced in an environmentally friendly manner. The internal and external drivers are described in Table 3-1 and Table 3-2, respectively. Key DFE drivers for the ROV and float were market demand, competition, moral responsibility, and public image. The MATE ROV Competition 2022 focuses on some of the UN's Sustainability Development Goals. Two of the tasks in the competition address the 13th goal, Climate Action, which encourages people to reduce their effect on the climate. Hence, the MATE competition encourages the student organizations to give attention to their products' environmental impact. UiS Subsea expected that competitors would develop eco-friendly products, and it would be in the company's best interest to produce sustainable products. In addition, the members of this thesis felt that people had a moral obligation to care for the environment and wanted to implement DFE in the thesis. Focusing on the environment would also improve UiS Subsea's public image.

Table 3-1 Internal drivers

Public Image	The company's image can be improved by focusing on its products' environmental impact.
Product Quality	The product quality may improve with higher environmental performance due to better functionality, durability, repairability, and reliability.
Cost Reduction	The company can reduce costs by using less energy and material in production, reducing waste, and using less hazardous materials that need to be disposed of in a particularly costly way.
Sponsor Deals	It might be easier to create sponsor deals if the company shows environmental awareness. The sponsors will think more highly of the product since it does not harm the environment and future generations.
Safety	By eliminating toxic materials, the product is safer for the environment, the producers, and the customers.
Employee Motivation	The focus on contributing to creating an eco-friendly product may be motivating for employees.
Innovation	Thoughts about environmental impact may cause fundamental changes in a product's design and lead to innovation.
Customer Behavior	The company may wish to change the way customers behave regarding the environment and may do so by wider the availability of eco-friendly products.
Moral Responsibility	The company may feel that they have an ethical responsibility to contribute to sustainable production.

Table 3-2 External drivers

Environmental Legislation	There exist environmental policies regarding products that companies must follow. An example is that some materials are forbidden.
Competition	If competitors focus on the environment, the company may also want to add focus.
Social Pressure	Employees may be asked about what the company does for the environment through social contacts.
Market Demand	The end-users increasingly demand more environmentally friendly products, and the company must give the customers what they want. If not, it could result in boycotts and negative publicity.
Trade Organization	Some industries encourage companies to be more eco-friendly by sharing technology and setting codes of conduct.
Suppliers	The company is influenced by suppliers and may audit environmental statements made by their suppliers.
Recyclability	The recyclability of the product may increase the number of customers. If it is easy to recycle the product, and the customers do not have to deliver parts at recycling stations, customers may choose it over another.

After the internal and external drivers were set, the DFE goals for the ROV and float were established. These were the environmental aspirations for the products that hopefully would be fulfilled by following the DFE process. The goals for each of the life cycle stages of the products are shown in Table 3-3.

Table 3-3 Design for environment goals

Life Cycle Stage	Design for Environment Goals
Materials	• No harmful emission into air or water • No use of hazardous or toxic materials • Minimize the use of raw materials • Minimize production of waste and scrap • Use recyclable raw materials • Use recycled materials as raw material if possible • Increase energy efficiency in the material extraction • Minimize the number of different materials
Production	• Increase energy efficiency in production • No generation of hazardous waste • Minimize production of waste and scrap • Recycle waste and scrap • Minimize use of process materials • No use of toxic or hazardous process materials • Use recyclable process materials
Distribution	• Minimize emissions from transport • Plan transport to be energy efficient • Minimize packaging • No hazardous packaging materials • Local production
Use	• Long product life • No emissions into air and water • Easy and efficient service • Clear instructions to avoid misuse
Recovery	• Easy to disassemble • Recyclable parts • Possible recovery and remanufacturing of components

3.2 Allocate Resources and Plan Timing

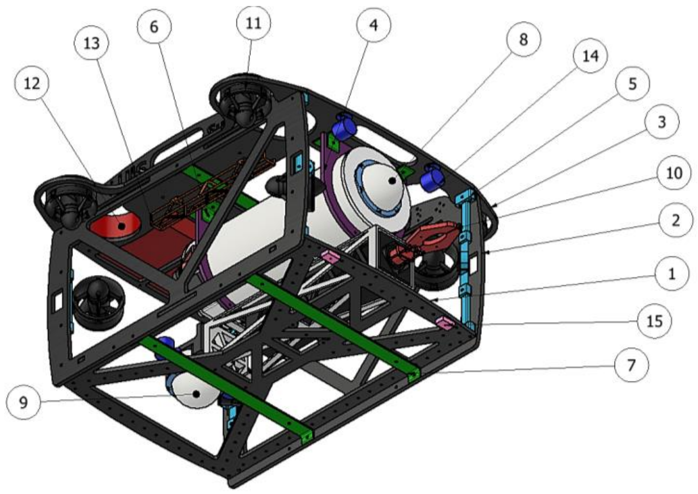
This thesis aimed to produce the ROV frame and the float with the interior structure and the arrangement of components in the buoyancy system. The allocation of resources and time planning happened during the first weeks of the project and were more extensive than first anticipated.

3.2.1 ROV

As mentioned, UiS Subsea consisted of 21 students writing nine bachelor theses. Seven electrical engineering, mechanical engineering, and computer science teams collaborated on designing the ROV. The members of this thesis had the responsibility of designing and constructing the ROV frame, and from the beginning of the project, it was known that the frame included:

- The frame itself (top, bottom, side plates)
- Buoyancy elements
- Ballast

There was more uncertainty around some of the other components of the ROV. Figure 3-1 illustrates all the ROV components with icons from 1 to 15.



Part Number	Name
1	Bottom plate
2	Side plate
3	Top plate
4	Bracket for el house
5	Bracket for thruster
6	Bracket L30x30x3-30
7	Stiffener
8	Electronics house
9	Rear-end camera
10	Manipulator
11	Thruster
12	Buoyancy element
13	Canal for wires
14	Light mount
15	Ballast

Figure 3-1 ROV components

After the first meeting with UiS Subsea, the impression was that the members of this thesis had the responsibility to construct the following parts:

- The frame itself
- Buoyancy element
- Ballast
- Bracket for el house
- Bracket for thruster
- Brackets in metal for support (parts 4 and 6)
- The electronics house
- Canal for wires
- Light mount

During the first weeks, substantial time was spent on calculations, design, and material considerations for the electronics house. However, it was then determined that another group would design and construct this component. It was also later decided that another group would design and produce the light mounts. The rest of the components for the frame would be designed and constructed by the members of this thesis, considering strength, stability, buoyancy, drag, thruster placement, and DFE.

3.2.2 Float

The float team consisted of two teams, one mechanical and one electrical. The workload was divided between the two teams during the allocation of resources. The decision about which mechanism to use for the buoyancy system was discussed and decided in close cooperation. Mechanical engineering was responsible for the dimensioning and construction of the outside and inside structure of the float, considering stability, buoyancy, strength, drag, and DFE. Electrical engineering was responsible for the circuit card, system sensors, batteries, and the programming of the float. Both teams were accountable for the buoyancy engine components.

During the first weeks, the board of UiS Subsea asked all the groups to create an activity plan, called a Gantt chart. This plan was altered and submitted in a pre-study report to the supervisor. The Gantt chart, displayed in Appendix A, Figure A-1, shows the project plan for the products during this bachelor thesis. It illustrated the planned activities during the PDP, with a scheduled start and end. The Xs demonstrated milestones during the process, and their meaning and dates are explained in Appendix A, Figure A-2, along with the status bar.

3.3 Mission Statement

The output of the planning phase was the mission statement. It was a summary of the products and included the product description, benefits of the products, the company's key business goals, the primary market, assumptions and constraints, and stakeholders. The mission statement for the ROV and float is shown in Table 3-4 and illustrates the vision of the products. It was helpful to have in mind when moving on to the concept development phase.

Table 3-4 Mission statement

Product Description ROV	An underwater vehicle that contains all necessary equipment to perform desired tasks.
Product Description Float	A cylindrical vessel using a battery-driven buoyancy engine to make vertical profiles in water.
Benefit Proposition	• Focus on the environmental impact of the products • Easy to assemble, disassemble and maintain • Structurally stable on land and in water • Little drag in water • Able to perform the MATE tasks • The ROV is lightweight and easy to lift • The ROV is easy to maneuver
Key Business Goals	• Ready for testing in water by April 15th • Products completed by May 15th • Produce within budget • Satisfied stakeholders and market • Do well in the MATE competition
Primary Market	• Subsea operations • Education
Assumptions and Constraints	• Budget of 10 000 NOK • Time limit from the 15.01.22 to 15.05.22 • Operates in chlorinated pool water • Operates at shallow depths • Environmental sustainability
Assumptions and Constraints ROV	• Lightweight • Small size
Assumptions and Constraints Float	• Buoyancy engine • Battery-driven
Stakeholders	• UiS Subsea • University of Stavanger • MATE • Sponsors • New Students at UiS

4 Product Development Process – Concept Development

The concept development phase involved the steps: identifying customer needs, benchmarking competitive products, establishing target specifications, generating, selecting, and testing product concepts. The DFE process' steps, identifying potential environmental impacts and selecting DFE guidelines, were also performed during this phase. The concept development phase was a detailed and time-consuming process where each step consisted of several steps with an organized flow of information. This thesis will not include every single step of the process but the steps that were found most relevant for developing the products.

4.1 Identify Customer Needs

MATE was the primary customer, and the customer needs were interpreted from MATE's competition manual. The manual could be seen as raw data, and when interpreting the data, it was important to remember to look for the customer needs and not try to find a solution to the problem. The focus was on finding both latent and explicit needs. Reading the manual, it was evident that MATE wanted a focus on the environment, but it was never clearly stated as a requirement. A latent need was, therefore, the emphasis on environmental impact, which had not been a focus in previous years or products. UiS Subsea also had some desires for the ROV and float early in the development process. These were listed under the company-specific objectives in Chapter 1.2. After finding the customer needs, it was essential to express them after certain guidelines. The customer needs were expressed:

- In terms of what the products had to do, not how they could do it
- As precise as the raw data was
- In a positive phrasing

4.1.1 ROV

The customer needs from MATE and UiS Subsea's specific objectives for the ROV are listed in Table 4-1. Needs numbers 1 through 9 were MATE's requirements, and needs 10 through 21 were UiS Subsea's aspirations for the ROV.

Table 4-1 Customer needs for the ROV

No.	Need	Imp.
1	The weight of the ROV is below 35 kg	5
2	The ROV functions at a depth of 7 m	5
3	The ROV can operate in fresh, chlorinated water with temperatures between 15 °C and 30 °C	4
4	The ROV can be submerged for 15 min	4
5	The ROV fits in a 1 m square hole and 1 m^2 docking station	5
6	The ROV can pick up items that weigh less than 10 N or has a 10 N buoyant force in water	4
7	It should be a focus on the environmental impact of the ROV	3
8	The ROV has no sharp edges or components that can cause damage	5
9	The ROV is launched and recovered by hand	5
10	Produce the ROV within budget	4
11	The ROV is able to perform the MATE tasks	4
12	The ROV should be produced of environmentally friendly and recyclable materials	3
13	The ROV is easy to assemble, disassemble, and maintain	3
14	The ROV is stable on land and in water	3
15	The ROV causes little drag	3
16	The ROV is easy to lift	3
17	The ROV weighs less than 20 kg	3
18	The ROV can operate at a depth of 50 m	2
19	The ROV has good maneuverability	3
20	The ROV has free flow through the frame and the thrusters	3
21	It is easy to add and remove ballast to the ROV	1

First, redundant needs were eliminated. Need number 12 was redundant since need number 7 stated that a focus should be on the environmental impact in general, and it was not necessary to limit the extent. UiS Subsea and MATE had different needs for weight and depth, and thus these needs were listed twice. The needs from MATE were redundant since UiS subsea had higher aspirations, and MATE's requirements were included in UiS Subsea's needs. The requirements for MATE were added to UiS Subsea's needs as a limit. The need, the ROV is easy to lift, could be seen as part of need number 9 and was therefore redundant. The same goes for need number 21. It could have been part of need number 13, easy to assemble, disassemble, and maintain.

Next, the customer needs were weighted after importance and sorted hierarchically, as shown in Table 4-2. The needs were rated after importance (imp.) from 1 to 5, and the importance of each need can be seen in Table 4-1. MATE's needs were more important than the development team's desires for the product. The requirements that the ROV could be disqualified for not following during the MATE competition were rated as the most important. These were needs numbers 17, 5, 8, and 9. Other requirements found in the MATE manual were rated as the second most important. UiS Subsea's needs came last, rated after importance. Being able to perform the MATE tasks and producing within budget had a rating of 4 and were rated higher than the latent need found in the manual. The rest of UiS' desires were seen as less important and weighted under the latent need. During the development of the ROV, the hierarchical list of needs was helpful to ensure that the product would fulfill the customer needs and do well in the MATE competition.

Table 4-2 The customer needs for the ROV rated after importance

No.	Need
17	The weight of the ROV is below 20 kg (MATE: 35 kg)
5	The ROV fits in a 1 m square hole and 1 m 2 docking station
8	The ROV has no sharp edges or components that can cause damage
9	The ROV is launched and recovered by hand
18	The ROV functions at a depth of 50 m (MATE: 7 m)
4	The ROV can be submerged for 15 min
3	The ROV can operate in fresh, chlorinated water with temperatures between 15 °C and 30 °C
6	The ROV can pick up items that weigh less than 10 N or has a 10 N buoyant force in water
11	The ROV is able to perform the MATE tasks
10	Produce the ROV within budget
7	It should be a focus on the environmental impact of the ROV
19	The ROV has good maneuverability
13	The ROV is easy to assemble, disassemble, and maintain
14	The ROV is stable on land and in water
20	The ROV has free flow through the frame and the thrusters
15	The ROV causes little drag

4.1.2 Float

Customer needs for the float are listed in Table 4-3. Need numbers 1 through 11 were interpreted from the MATE competition manual. The latent need found in the manual was formulated into customer need 12. UiS Subsea's desires resulted in need numbers 13 to 16.

Table 4-3 Customer needs for the float

No.	Need	Imp.
1	The float can make two vertical profiles	4
2	The float is battery-driven	5
3	The float is powered locally, not by a tether or the ROV	5
4	The float uses a buoyancy engine	5
5	The float is watertight	4
6	The float is within a diameter of 18 cm and a length of 1 m	5
7	The float completes the vertical profiles within 10 min	4
8	The float can withstand the pressure at a depth of 4 m	4
9	The float descends when the bladder is deflated and ascends when it is inflated	4
10	The float can operate in fresh, chlorinated water with temperatures between 15 °C and 30 °C	4
11	The float can be submerged for 15 min	4
12	Focus on the environmental impact of the float	3
13	The float is easy to assemble, disassemble and maintain	3
14	The float is stable on land and in water	3
15	The float is produced within budget	4
16	The float causes little drag	3
17	It is easy to add and remove ballast to the float	3
18	The float can operate at a 10 m water depth	4
19	The float is lightweight	3

The needs’ importance was rated by numbers 1 to 5. The needs that the float had to meet to attend the competition were rated as the most important and were assigned the value 5. Among those were maximum dimensions, power source, and engine choice. Needs regarding how well the team did in the competition were rated as 4. These needs were strength considerations, watertightness, operating conditions, production within budget, and ability to perform the MATE tasks. This year, the environment and sustainability were essential topics and focused on in the MATE competition. However, since it was not a requirement to compete, it was rated as 3. The aspirations of UiS Subsea were also rated as 3 because they focused more on the float design than the MATE tasks. Keeping within budget and functioning at 10 m water depth was rated higher since these were seen as more important. A rating of 3 did not mean that the needs were not essential. For instance, easy assembly, disassembly, and maintenance were vital since the team only would have 15 minutes available to perform the tasks during the competition. If something had to be fixed during the competition, it would need to be fixed quickly. The faster the assembly and disassembly were, the less time and resources would be used. It would also contribute to the product being more environmentally friendly.

Redundant needs were removed, and similar needs were merged. Need numbers 1 and 7 concerned the vertical profiles the float had to perform, and need number 1 was merged into need number 7 since the latter need limited the extent of the vertical profiles. Need number 3 was redundant and removed since need number 2 limited the extent of need 3. Similarly, need number 9 was removed since need numbers 4 and 9 involved a buoyancy engine, and it was unnecessary to limit the extent. Both needs 5 and 11 concerned watertightness, and need 5 was merged into need 11. The need from MATE regarding depth was redundant since UiS subsea had higher aspirations, and MATE's need was added to UiS Subsea's need as a limit. Need number 17 could be part of easy assembly, disassembly, and maintenance and was redundant. The final customer needs were arranged hierarchically in Table 4-4. This list was used during the rest of the product development to ensure that the final product satisfied the customers' desires and would do well in the competition.

Table 4-4 The customer needs for the float rated after importance

No.	Need
2	The float is battery-driven
4	The float uses a buoyancy engine
6	The float is within a diameter of 18 cm and a length of 1 m
11	The float is watertight for 15 min
7	The float can complete two vertical profiles in 10 min
18	The float can operate at a 10 m water depth (MATE: 4 m)
10	The float can operate in fresh, chlorinated water with temperatures between 15 °C and 30 °C
15	The float is produced within budget
12	Focus on the environmental impact of the float
13	The float is easy to assemble, disassemble and maintain
14	The float is stable on land and in water
19	The float is lightweight
16	The float causes little drag

4.2 Benchmarking Competitive Products

Part of the research for the project included reading theory regarding ROVs and floats and benchmarking previous work done by UiS Subsea and other existing products. The products were mapped and compared to find inspiration and possible solutions.

4.2.1 ROV

This year's ROV was classified as a Class II B vehicle with light intervention, survey, and construction capabilities. Most ROVs on the market were produced for purposes other than the tasks in the MATE competition. They usually operated deeper than the customer needs required and were thus larger and heavier. Most of them would be classified as work class ROVs but were still benchmarked to learn about the shape and placement of components.

The *Millennium Plus* [18], Figure 4-1, was a heavy work class ROV provided by Oceaneering. It had two manipulators with 220 hp and an enhanced thrust configuration to increase lift power. A metal frame with a flotation element on top protected all components inside the ROV. The ROV weighed 4000 kg and was 3300x1700x1900 mm. It was created for heavy-duty work in deep waters, down to 3000 m, and operated by hydraulics.

Figure 4-1 The Millennium Plus

The *BlueROV2* [19], shown in Figure 4-2, was made by Blue Robotics. The company produced affordable, high-performance commercial ROVs that came partly assembled with instructions on how to assemble the rest at home. The ROV had a modular design, with the possibility of adding extensions. For example, one could add two vertical thrusters, grippers, and sonars, as illustrated in Figure 4-2 (right). The ROV was a Class II B ROV created for adventuring, research, and inspections. It was 457x338x254 mm, weighed 11-12 kg, and was rated at a depth of 100 m. The frame was produced in polyethylene high-density (PEHD) and aluminum, and the buoyancy element was R-3318 urethane foam.

Figure 4-2 The BlueROV2 with six(left) and eight thrusters(right)

It was more relevant to study the previous UiS Subsea ROVs and extract information regarding materials used, sizes, weights, designs, pros, and cons. In addition to pictures of the designs and placement in the MATE competition, this information is shown in Figure 4-3. Looking at the previous ROVs' cons, it was decided to place the horizontal thrusters on the inside of the frame for protection. Some of the ROVs were heavy and had large safety factors, and as a result, it was focused on reducing the material thickness as much as possible, and the number of fasteners was limited. *Njord* had loose cables inside, which led to the idea of designing canals for the cables for the ROV's thrusters in the fore.

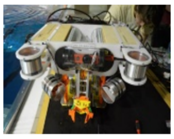
Benchmark	Njord 2014	Tor 2015	Ægir 2016/17	Vona 2018	Hymir 2021
Design					
Place in MATE	14th	19^{th}	$10^{th}/12^{th}$		NA
Size LxWxH [mm]	658x524x450	810x635x450	470x260x270	645x550x290	545x508x405
Weight [kg]	35	40.7	14.1	11.65 (without manipulator)	28
Frame Materials	PEHD 1000	PEHD 1000	Aluminum	Aluminum	Aluminum 6063, ABS, PE
Buoyancy Materials	Divinycell H80	Divinycell H100	NA	NA	HCP30
Pros	Open	Free flow	Lightweight	Lightweight	All components inside frame
	All components	Compact	Simple design	Simple design	Impact resistant
	Compact		Free flow	Free flow	Sufficient free flow
	Easy to assemble /disassemble		Compact	Compact	Stable
	Good placement of center of COG and COB		No floatation element	No floatation element	Aesthetics
				Good maneuverability	
Cons	Heavy	Heavy	Impact risk on horizontal thrusters	Impact risk on horizontal thrusters	Heavy
	Loose cables inside	Impact risk on horizontal thrusters			Large safety factor
	Limited free flow				Large number of fasteners
	Unstable on land				

Figure 4-3 Benchmarking of UiS Subsea ROVs

4.2.2 Float

This year's float was regarded as a Class VI vehicle since the power source would be on board, and the float would operate in a preprogrammed mission route. It would be a simple AUV, only required to perform vertical profiles using a buoyancy system. The National Science Foundation (NSF) grants funds to design and build robotic floats with sensors that monitor circulation, chemistry, and biology [20]. MATE used the GO-BGC float, built by the Global Ocean Biochemistry Array, a mid-scale research infrastructure project, as an example of a float. These floats were battery-driven and used oil as fluid for the buoyancy engine. The floats contained sensors that measured conductivity, temperature, depth, oxygen, pH, and nitrate. When reaching the surface, data was sent by satellite via an antenna on top of the float. The GO-BGC float comprised the *Navis*, *Apex*, and, *Solo-II* float, presented with metrics and illustrations in Table 4-5. All of the floats operated at depths much deeper and were longer than the requirements from MATE. However, the floats' diameters gave some indication regarding the necessary diameter of a float. Considering the floats' weights, it was also an aspiration to reduce the weight of this year's float. All the floats had a long cylindrical shape, which was used as a starting point for developing this year's float.

Table 4-5 Benchmarking of floats

Benchmark	***Navis*** [21]	***Apex*** [22]	***Solo-II*** [23]
Manufacturer	Sea-Bird Scientific	Teledyne Web	MRV-Systems
Mass [kg]	< 20.0	25.0	19.5
Diameter [cm]	14.0	16.5	16.5
Length [cm]	167.0	127.0	133.0
Depth [m]	2000	2000	2000
Lifetime and Number of Cycles	250 cycles of 10 days	4 years 150 cycles	325 cycles of 10 days
Design			

4.3 Identify Environmental Impacts and Select DFE Guidelines

During this stage, possible environmental impacts were identified through the ROV’s and float’s life cycles, and DFE guidelines were selected based on the impacts. Identifying the environmental impacts early in the development process helped make environmental decisions regarding the products without yet knowing the product design. The environmental impacts were found through a qualitative Life Cycle Assessment (LCA) of the products. The LCA helped assess the environmental impact of the products through their entire life cycles, from material to recovery. The objective was to make the products more sustainable and environmentally friendly by reducing their life cycle emissions, waste, and energy use. The analysis had limitations and could not go very deep because of time and complexity. Every detail of the process steps was not relevant, and neither were the social implications of the products. In addition, the LCA only considered the components of the ROV and the float that this thesis was responsible for developing. Environmental impacts expected for each stage in the p4roducts’ life cycle were first listed in Table 4-6, and then a qualitative chart was made. This chart, illustrated in Appendix B, Figure B-1, assessed the magnitude of the impacts and displayed which phase of the life cycle was most likely to have the most significant environmental impact. It exposed which phases needed the most attention and improvement.

Table 4-6 Key environmental impacts for the ROV and float

Life Cycle	Environmental Impact
Materials	• Emissions and waste due to extraction • Energy consumption in extraction processes • Depletion of natural resources • Hazardous and toxic materials • Nonrenewable or non-recyclable materials
Production	• Pollution of air and water due to factory emissions • Water pollution due to factory discharges • Generation of waste and scrap • Non-recyclable waste • Energy consumption in the production processes • Material use during the production process • Energy loss due to leaks and poor insulation • Lots of prototypes
Distribution	• Air and water pollution from transportation emissions • Waste due to packaging • Energy use in transportation, either as electricity or fossil energy • The product needs much space to be transported • Hazardous materials in packaging • Long-distance transportation • Type of transportation
Use	• Need for maintenance and cleaning • Material abrasion • Energy consumption • Broken parts • Emissions from components • Components with short life • The aesthetics life span will expire before the technical
Recovery	• Generation of waste during recovery • Possible landfill • Non-biodegradable • Nonreusable or non-recyclable • Energy during removal and recovery processes • Pollution of air and water due to emissions from the recycling station • Water pollution due to discharges from the recycling station • Difficult to disassemble

From the chart, the primary environmental impacts of the ROV were expected to be in the materials, production, and recovery stages. During the use stage, the ROV would use electricity, which mainly comes from green energy in Norway. The UiS Subsea team, the ROV, and the float will travel to the US to participate in the MATE competition. This would be part of the distribution stage and cause severe CO_2 emissions. It would have a significant environmental footprint. However, the distribution of the products will only happen in connection with the competition. The products would most likely not be distributed anywhere else but stay in proximity to the University of Stavanger when the competition is over. This thesis focus was, therefore, on lowering the environmental impact of the materials and production phases and ensuring easy disassembly and recyclability in the recovery phase.

The DFE guidelines were created considering the results from the qualitative chart. Each life cycle stage had its own guidelines on reducing the environmental impact of the products. The DFE guidelines for the ROV and float are listed in Appendix B, Table B-1. These guidelines were used throughout the design process to create more sustainable products.

4.4 Establish Target Specifications

The customer needs were converted into target specifications that gave a description of the products' functions. They described what the ROV and float had to do in technical terms and were UiS Subsea's aspirations for the products. The target specifications were translations of the needs into measurable and precise characteristics. They described what the products had to do but not how the specifications had to be accomplished. The process of establishing the target specification consisted of the steps: preparing a list of metrics, finding benchmarking information about competitors, and setting ideal and marginal target values. One or more metrics addressed each customer need. The metrics for the needs regarding environmental impact were set based on the DFE guidelines. Some metrics could not be quantified, and those were written as specifications with the unit "Subj." since they were subjective. It still had to be a way to check whether a specification was satisfied. However, this was individual for every specification. When a metric addressed multiple customer needs, the thesis members discussed the importance instead of using algorithms to estimate the importance. Each metric was assigned an acceptable marginal and ideal value based on customer needs and benchmarking of previous and competitive products. The ideal value was the best result UiS Subsea could wish for, and the marginal value was the upper or lower limit of the metric that barely would make the product viable. The marginal value had to be maintained throughout the process, but the ideal value could change. Assigning a metric to the needs would make it easier to evaluate if a target was met later in the PDP process.

4.4.1 ROV

The target specifications for the ROV are shown in Table 4-7. The marginal values were derived from MATE's requirements, and the metrics not specified by MATE were assigned a value based on benchmarking and theory. The ideal values were built on UiS' aspirations for the ROV. The ideal and marginal values regarding environmental impact were founded on the thesis members' aspirations for the frame. Metric number 19 was assigned a marginal value based on benchmarking and theory. Easy assembly, stability on land, drag, maneuverability, and free flow were assigned the unit "Subj." and checked during assembly and testing in water. Since materials were not assigned to the frame and its components yet, vertical and lateral stress could not be assigned numerical values and were also given the unit "Subj.". FEA was performed to verify that the frame could withstand the vertical and lateral stresses.

Table 4-7 Target specifications for the ROV

Metric No.	Needs No.	Metric	Imp.	Unit	Marginal Value	Ideal Value
1	3	Density of water	4	g/cm^3	990-1000	997
2	3	Operational temperatures	4	°C	15 - 30	15-30
3	4	Max time submerged	4	min	> 15	30
4	5	Length of ROV	5	m	< 1.0	< 0.8
5	5	Width of ROV	5	m	< 1.0	< 0.8
6	6	Max lifting load	4	N	±10	±15
7	7	Environmental impact: Hazardous and toxic materials	3	%	< 10	0
8	7	Environmental impact: Recycled content	3	%	> 15	> 25
9	7	Environmental impact: Waste	3	kg	< 10	< 5
10	7	Environmental impact: Recyclable materials	3	%	> 70	> 90
11	7,13	Environmental impact: Disassembly	3	%	> 80	100
12	7,13	Assembly and disassembly tools	3	List	Hex	Hex
13	13	Easy assembly	3	Subj.	OK	OK
14	8	No sharp edges or components that can cause damage	5	Subj.	OK	OK
15	9	Vertical stress	5	Subj.	OK	OK
16	9,17	Weight of the ROV	5	kg	< 35	< 20
17	10	Budget (ROV and float)	4	NOK	< 10 000	< 10 000
18	11	MATE tasks	4	Points	0 - 695	695
19	14	Distance between CBx and CGx	3	mm	0 - 10	0
20	14	Lateral stress	3	Subj.	OK	OK
21	14	Stability on land	3	Subj	OK	OK
22	15	Drag	3	Subj.	OK	OK
23	18	Operational depth	4	m	> 7	> 50
24	19	Maneuverability	4	Subj.	OK	OK
25	20	Free flow	3	Subj.	OK	OK

4.4.2 Float

The target specifications for the float can be found in Table 4-8. Most values were derived from MATE's competition manual. Metric numbers 3, 21 and 22 regarded stability, and values were chosen by the thesis members based on the stability theory. The marginal value of metric number 7 was the float's minimum velocity required to complete the profiles within the maximum time of 10 min for a depth of 4 m and the ideal value for a maximum time of 5 min. Regarding metric numbers 12 and 13, both MATE and UiS Subsea desired a watertight and robust float. The sealing could be tested by performing a vacuum test that simulated the pressure at different depths. The marginal value was the pressure, in bar, at the competition pool's depth of 4 m, and the ideal value was set to 10 m as desired by UiS Subsea. FEA would test the robustness by applying the pressure at the ideal depth to the float and finding the maximum Von Mises stress. The float needed a higher yield strength than the experienced Von Mises stresses. Metric numbers 15-19 considered the environmental impact of the float. These could be measured by the fraction of the weight of safe material, reused content, recyclable material, and readily disassembled material. Moreover, waste from production was estimated in grams (g). The thesis members set the marginal and ideal value of the environmental impacts. The marginal value would be the minimum value accepted, and the ideal value would be the ideal goal. The metrics concerning buoyancy engine, yield strength, assembly, stability on land, and drag were assigned the unit "Subj." and were confirmed by observation. The marginal and ideal values of metric number 25 was set based on UiS Subsea's aspirations.

Table 4-8 Target specifications for the float

Metric No.	Needs No.	Metric	Imp.	Unit	Marginal Value	Ideal Value
1	2	Battery	5	V	12	< 12
2	4	Buoyancy engine	5	Subj.	OK	OK
3	4,14	Distance between CBz and CGz	5	mm	> 10	> 10
4	6	Length of float	5	cm	< 100	< 50
5	6	Diameter of float	5	cm	< 18	< 16
6	7	MATE tasks	4	Points	50	50
7	7	Velocity	4	m/s	> $6.7*10^{-3}$	> $1.3*10^{-2}$
8	7	Max time to complete vertical profiles	4	s	< 10	< 5
9	10	Temperature	4	ºC	15-30	15-30
10	10	Density chloride water	4	kg/m^3	997	997
11	11	Time submerged	4	min	15	> 20
12	11,18	Sealing	4	bar	-0.489	-1
13	11,18	Yield strength	4	Subj.	OK	OK
14	11,18	Depth of pool	4	m	4	10
15	12	Environmental impact: Recycled content	4	%	> 15	> 25
16	12	Environmental impact: Recyclable materials	3	%	> 70	> 90
17	12	Environmental impact: Non-toxic materials	3	%	> 90	100
18	12	Environmental impact: Waste	3	g	1300	500
19	12, 13	Environmental impact: Disassembly	3	%	> 80	100
20	13	Easy assembly	3	Subj.	OK	OK
21	14	Stability on land	3	Subj.	OK	OK
22	14	Distance between CGx and CBx, and CGy and CBy	3	mm	5	0
23	15	Budget (ROV and float)	4	NOK	< 10 000	< 10 000
24	16	Drag	3	Subj.	OK	OK
25	19	Weight of the float	3	kg	< 10	< 7

4.5 Generate Product Concepts

A product concept is a rough description of the product's form, principles, and technology. The aim was to explore the different possible concepts by looking for inspiration within UiS Subsea, previous and competitive ROVs and floats, and the theory regarding the products. Concepts were generated based on the customer demands, target specifications, information found during benchmarking, and DFE guidelines.

4.5.1 ROV

The ROV was divided into subsystems for simplicity, the frame itself, the brackets for the horizontal thrusters, and the interface between the side and bottom plates. Product concepts were generated for each subsystem. Concepts A through G for the frame are illustrated with 3D models in Figure 4-4, and their features are described in Table 4-9.

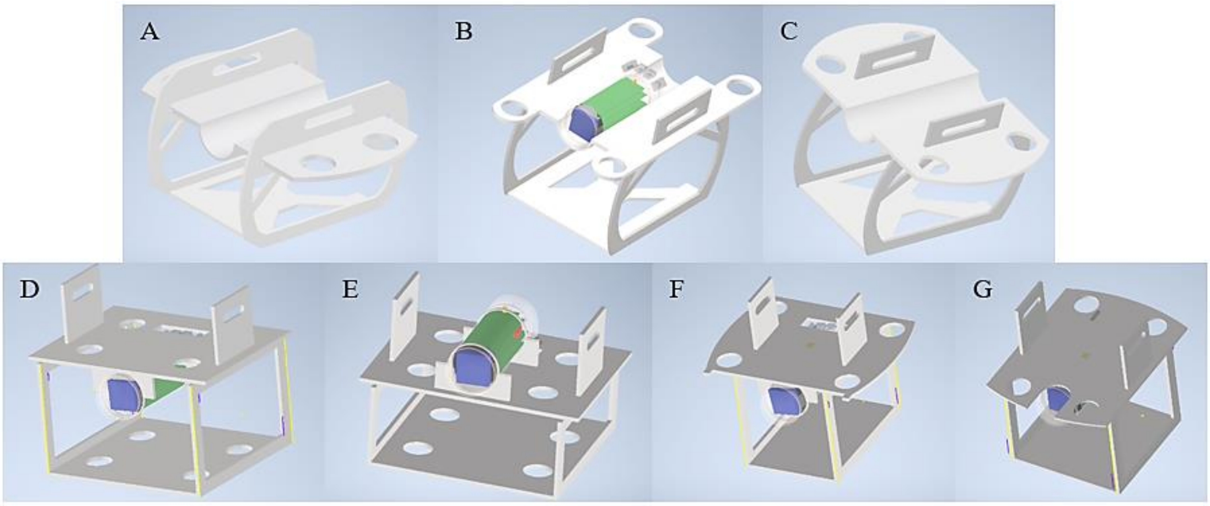


Figure 4-4 Concepts for the frame

Due to the weight restrictions in MATE and UiS Subsea's desire to construct a lightweight ROV, it was decided early in the process to produce the ROV frame of a plastic with low environmental impact. It was also an aspiration that the frame was easy to assemble, disassemble, and maintain, which correlated to the DFE guidelines for recovery. Therefore, in all frame concepts, the top and side plates slid into one another. The concepts A through D for the interface between the bottom and side plates, shown in Figure 4-5, were also generated to ease the assembly to meet the customer need. The frame design was intended to be open and simple for easy assembly and disassembly and easier attachment of extra components after completing the product. The simple design could make it possible to reuse the frame, in future years, as a base and then alter the other components. The open design would also minimize the ROV's drag and reduce the weight and material use, as defined by the target specifications and the DFE guidelines. All the frame concepts had handles in the side plates to ease the lifting of the ROV.

Table 4-9 Features of the frame concepts

Components	Feature	Concepts
Electronics House	Arc in top plate for electronics house	A, B, C
	Electronics house mounted underneath top plate	D, F, G
	Electronics house mounted above top plate	E
Plates	Open side plates	All
	Side plates slide onto top plate	A
	Top plate slides onto side plates	B, C, D, E, F, G
Vertical Thrusters	Vertical thrusters on sides, outside of the frame	A, C, F
	Vertical thrusters in the fore and aft, outside of the frame	B, G
	Vertical thrusters on the inside of the frame	D, E
	Holes in the bottom plate for vertical thrusters' flow	D, E

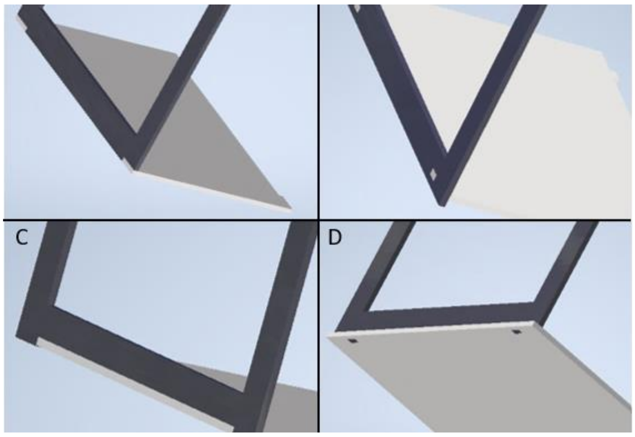


Figure 4-5 Concepts for the interface between side and bottom plates

Concepts A and D for the interface between the bottom and side plates were created as mortise and tenon joints. It was spacing between the adjoining pieces since the joint was a mean for easier assembly and not intended as a fastening method. The bottom plate slid onto the side plates in concept A, whereas in concept D, the side plates slid onto the bottom plate. Concept B had an open rectangular space in the bottom corners of the side plates and a corresponding rectangular extrusion in the corners of the bottom plate. Concept C was equal to B but had spaces in the bottom plate and corresponding extrusions in the side plates.

The ROV's motion depended on the number of thrusters and their placement and angle, and full motion of the ROV required six degrees of freedom. Early in the development process, it was decided together with the control and regulation systems team that it should be four vertical thrusters and four horizontal thrusters placed at a 45-degree angle to the frame.

The reason was that the ROV then would have equal force in sway and surge and have six degrees of freedom. This would give the ROV optimal maneuverability, achieving the customer needs. The horizontal thrusters would cause a more extensive turning moment if placed further away from the center of the ROV. The maneuverability would thus increase, and it was decided to place the thrusters in the corners of the frame. The concepts A through E generated for the thruster brackets are shown in Figure 4-6.

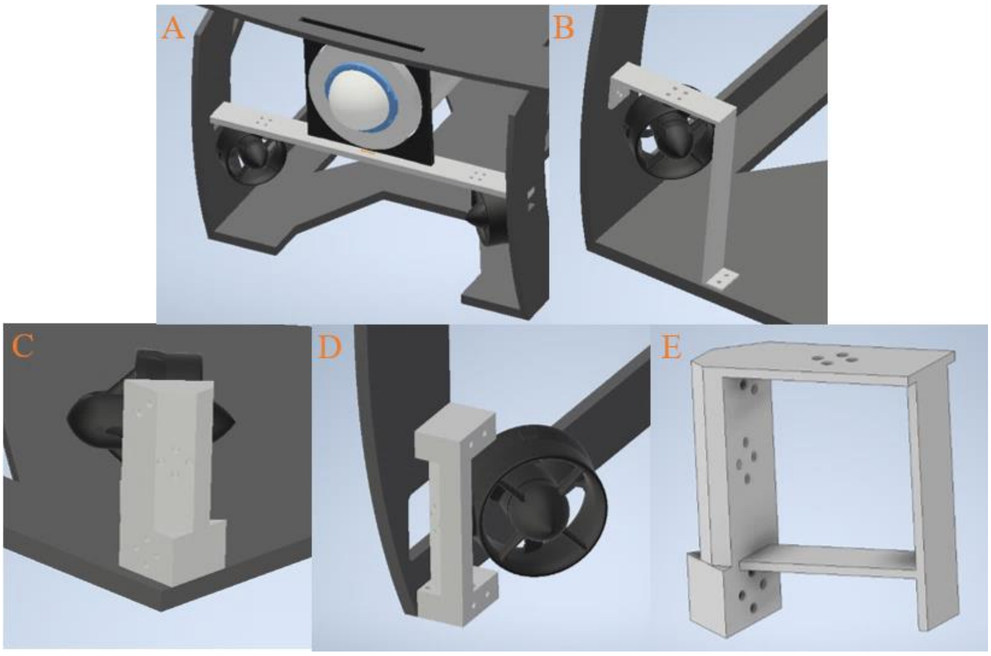


Figure 4-6 Concepts for the horizontal thruster bracket

In all the concepts, the thruster bracket had holes at 45 degrees angle to the holes in the thruster for the thruster to obtain a 45-degree angle to the frame. Concepts A and C were fastened only at the side plates, while concepts B, D, and E were fastened both at the bottom and side plates. Concept A would, in addition to fastening the thruster at the right angle, function as a stiffener and support the electronics house. In concept E, the thrusters could be fastened both at the top and side of the bracket.

4.5.2 Float

Since the float's task was to make vertical profiles in water, choosing a hydrodynamic shape with little drag was essential. More drag would cause more resistance in water and more forces acting in the opposite direction of the speed. The drag was based on the object's form and the friction between its surface and the fluid. From the benchmarking, it was discovered that existing floats all had a cylindrical shape. According to Figure 2-2, the spherical shape had a drag coefficient of 0.47, one of the lowest drag coefficients of the commonly known geometric shapes. Nonetheless, the spherical shape would not be space-efficient and unstable on land. A cube would be space-efficient and stable on land but had a drag coefficient of 1.05. The long cylindrical shape had a drag coefficient of 0.82, and the short cylindrical shape 1.15. The float was subjected to pressure operating underwater. The pressure in water would be uniformly distributed and press equally on all sides of a shape, and it was essential to select a pressure-resistant shape. When the pressure was applied on all the cube sides, there was no counterforce from the inside, and the cube could collapse. This made the cube a poor pressure-resistant shape. The sphere was the most pressure-resistant shape since the adjacent section of the sphere would add a counterforce when subjected to pressure. This self-supported shape made the sphere more rigid and unbreakable. The cylinder also had a self-supported shape in the longitudinal direction. A long cylindrical shape was chosen as the shape for the float because of its hydrodynamic shape, rigidity, low drag, and inside space efficiency. The long cylinder had little drag and a rigid self-supporting form, satisfying customer needs regarding drag, operational depth, stability, and vertical profiles.

Oil had a density of 880 kg/m^3 [4], against water's density of 997 kg/m^3 and air's of 1.204 kg/m^3 [13]. Oil and water were noncompressible and would not be impacted by increased pressure. On the contrary, air, a gas, was very compressible and would be affected by the increase in external pressure. Considering the DFE guidelines, oil was not a good option and was discarded. Using oil could lead to environmentally harmful spills that would be difficult to recover. Additionally, oil was inorganic, making it more difficult to recycle. The competition would be at a depth of a maximum of 4 m, and the external pressure was not too excessive. Hence air could be used as buoyancy fluid and taken from inside the cylinder, and an extra container for the buoyancy fluid would be unnecessary. Using water would have required an extra container, which would have been more complicated and time-consuming. Air was therefore selected as the buoyancy fluid, and would satisfy the customer need regarding focus on the environmental impact.

The three different buoyancy engine concepts considered were:

- **Concept 1:** Syringe-actuator - an actuator used to manipulate the syringe piston to inflate and deflate a bladder of air to change the buoyancy.
- **Concept 2:** Pump-valve - an air pump and valve used to inflate and deflate a bladder of air to change the buoyancy.
- **Concept 3**: Water pump - a water pump used to transport pool water in and out of the float to change the float's mass and thus the buoyancy.

All three concepts satisfied need number 2 about being battery-driven with no support from land. Concepts 1 and 2 satisfied need number 4 regarding using a buoyancy engine. According to the MATE manual, the customer required a buoyancy engine, including a buoyancy bladder. Concept 3 did not have a bladder and was thus eliminated. Concepts 1 and 2 were chosen for further inspection.

4.6 Select and Test Product Concepts

After the concept generation, was the concept selection and testing. The concepts were evaluated regarding the customer needs and the DFE guidelines. Matrices, calculations, or comparisons based on the needs and guidelines were used to select the most promising concepts.

4.6.1 ROV

Based on the hierarchical list of customer needs previously found, screening matrices were used to rate, rank, and select the most promising concepts for the frame and thruster brackets. The concepts were rated as “better than” (+), “equal to” (0), or “worse than” (-) a reference concept that fulfilled all the customer needs. Then a score was calculated, and the concepts were ranked. It was decided to screen the frame concepts first since the frame was most important, and the other subproblems could depend on this concept. Table 4-10 shows the screening for the frame, and Table 4-11 the screening for the thruster brackets.

Table 4-10 Concept screening matrix for the frame

Selection Criteria	Concepts						
	A	B	C	D	E	F	G
Weight below 20 kg (max weight 35 kg)	0	0	0	0	0	0	0
Fits in a 1 m square hole	+	+	+	+	+	+	+
No sharp edges or components that can cause damage	0	0	0	0	0	0	0
Launched and recovered by hand	+	+	+	+	+	+	+
Functional depth of 50 m (min depth 7 m)	0	0	0	0	0	0	0
Can be submerged for 15 min	0	0	0	0	0	0	0
Operates in fresh, chlorinated water (15-30 °C)	0	0	0	0	0	0	0
Can pick up items of +/- 10 N	-	0	0	0	0	0	0
Focus on the environmental impact	-	-	-	0	0	0	0
Able to perform the MATE tasks	0	0	0	0	0	0	0
Produced within budget	-	-	-	+	+	+	+
Good maneuverability	0	0	0	0	0	0	0
Easy to assemble, disassemble, and maintain	-	+	+	0	0	+	+
Stable on land and in water	0	0	0	0	0	0	0
Free flow through the frame and thrusters	+	+	+	+	+	+	+
Causes little drag	0	0	0	-	-	0	0
Sum +'s	3	4	4	4	4	5	5
Sum 0's	9	10	10	11	11	11	11
Sum –'s	4	2	2	1	1	0	0
Net Score	-1	2	2	3	3	5	5
Rank	4	3	3	2	2	1	1
Continue to Develop	**No**	**No**	**No**	**No**	**No**	**Yes**	**Yes**

Table 4-11 Concept screening matrix for the thruster bracket

Selection Criteria	Concepts				
	A	B	C	D	E
Weight below 20 kg (max weight 35 kg)	0	0	0	0	0
Fits in a 1 m square hole	+	+	+	+	+
No sharp edges or components that can cause damage	+	+	+	+	+
Launched and recovered by hand	0	0	0	0	0
Functional depth of 50 m (min depth 7 m)	0	0	0	0	0
Can be submerged for 15 min	0	0	0	0	0
Operates in fresh, chlorinated water (15-30 °C)	0	0	0	0	0
Can pick up items of +/- 10 N	0	0	0	0	0
Focus on the environmental impact	+	0	+	+	-
Able to perform the MATE tasks	0	0	0	0	0
Produced within budget	+	+	+	+	0
Good maneuverability	0	0	0	0	0
Easy to assemble, disassemble, and maintain	-	+	+	+	+
Stable on land and in water	+	-	-	+	+
Free flow through the frame and thrusters	0	0	0	0	-
Causes little drag	0	0	0	0	-
Sum +'s	5	4	5	6	4
Sum 0's	10	11	10	10	9
Sum –'s	1	1	1	0	3
Net Score	4	3	4	6	1
Rank	2	3	2	1	4
Continue to Develop	**No**	**No**	**No**	**Yes**	**No**

From the concept screening matrices, concepts F and G for the frame and concept D for the thruster brackets were selected for further development and testing. It was only generated four concepts for the interface between the side and bottom plates, and a screening matrix was therefore not used to decide which concept to develop. The ROV would most likely need some ballast, which would be placed underneath the bottom plate. Thus, the bottom plate was desired to be placed some distance above the ground. Only concept A was able to accomplish this and was therefore selected for further development.

It was created 3D models in Autodesk Inventor of the two frame concepts, selected for further development, with some improvements. The program was also used to perform stress analyses to check whether the frames could withstand the maximum loads. FEA predicted how a product would react to real-life forces and pressures. It could be problematic for parts experiencing multiaxial stresses to analyze when they would yield. The Von-Mises hypothesis is a hypothesis that corresponds with the results of experiments. It states that failure is expected in the multiaxial state when the deformation energy per unit volume exceeds or is equal to the deformation energy per unit volume in a uniaxial state when the same material fails. The stress that represents the uniaxial stress is called equivalent stress (σ_e), and yielding will happen when $\sigma_e > \sigma_y$, where σ_y is the yield strength [24]. Von Mises stress is a value used in FEA to determine whether a part will yield or fracture. When performing FEA, constraints, contacts, loads, materials, and mesh had to be specified.

The frame was assigned the material PEHD, used in previous UiS Subsea ROVs, which had a lower environmental impact than other materials. At this point in the process, PEHD was a plausible material for the ROV frame, and it was natural to do the analyses with this material. The maximum mass of the electronics house was set to 5.7 kg, and the manipulator combined with the rear-end camera to 3.7 kg. The loads were found with Eq.(1) from Chapter 2.1. The weight of the electronics house was then $5.7\text{x}9.81 \approx 56$ N, equally divided between the two brackets for the el house. Similarly, the weight of the manipulator and rear-end camera was calculated to be $3.7\text{x}9.81 \approx 36$ N. These loads and the frame's weight force were used in the analyses, with fixed constraints in the handles where one would lift. Mesh and bonded contacts were applied before the analyses were run. The designs were developed before the electronics house, and manipulator dimensions were set. The frames' dimensions were just set to make sure that all components would fit inside and the frames was within the customer needs. Illustrations of the revised concepts, the FEA analyses, and the outer dimensions are shown in Figure 4-7. Technical drawings of the concepts with dimensions can be found in

Appendix C, Figure C-1, and Figure C-2. The drawings showed that the frame’s size most likely could be reduced in all directions.

Concept F (814x769x539 mm)	**Concept G** (1000x633x539 mm)

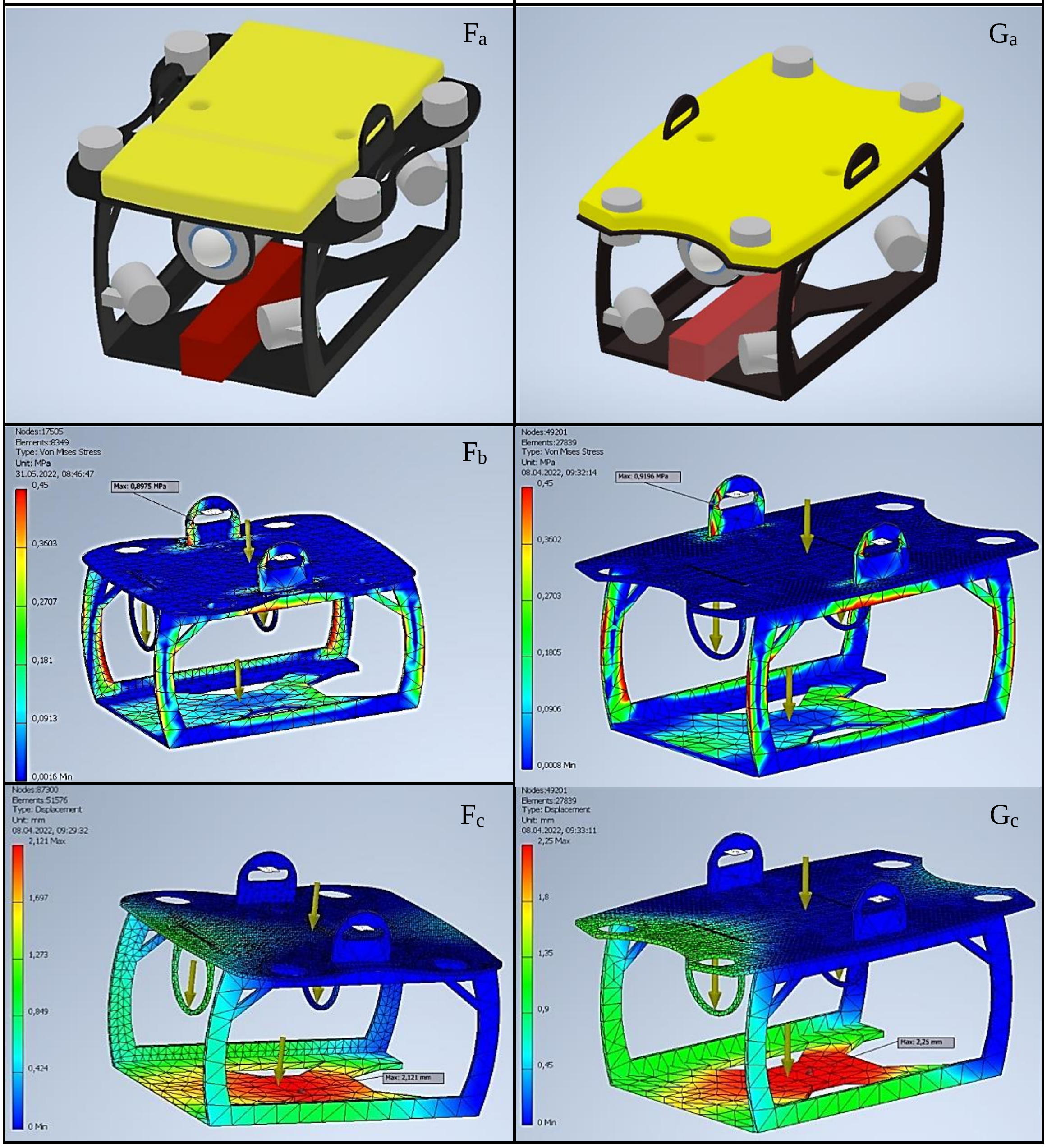


Figure 4-7 Revisions of the frame concepts F and G

After discussion with the other members of UiS Subsea, looking at the dimensions in the technical drawings, and the FEA analyses, it was decided that concept F was the best concept to proceed with. From the drawings, concept F gave the potential for designing the smallest ROV. The FEA provided relatively equivalent results. However, if arguing that one concept was better, concept F would be the best. Concept G had slightly higher values in displacement and Von Mises stress, and from Figure 4-7 F_c and G_c, it was visible that concept G would have more displacement in the top plate than concept F. Concept G had more green color distribution in the top plate and thus a more significant downward displacement.

4.6.2 Float

During concept selection, calculations were performed to decide between concept 1 actuator-syringe and concept 2 pump-valve. Both buoyancy engines used a bladder to alter the float's buoyancy, and it was necessary to find the approximate volume of the bladder for the float to ascend. The air would be compressed when entering the flexible bladder. It was, therefore, essential to find the amount of air needed to be pumped out of the float to obtain the preferred bladder volume at the desired depth. Approximate dimensions of the float's size and mass were assigned and used in the calculations.

The volume of the float (V_f) was found by using the equation for the volume of a cylinder.

$$V_f = \pi r^2 h = 5.39 * 10^{-3}\, m^3$$

where $r = 0.07\ m$ and $h = 0.35\ m$. The buoyant force was found with Eq. (2) Chapter 2.2

$$F_b = \rho g V_f = 52.72\ N$$

The weight force was found by Eq. (1), Chapter 2.1

$$F_g = mg = 53.96\ N$$

where $m = 5.5\ kg$. Due to the weight and volume, the float had a negative buoyancy of $52.72 - 53.96 = -1.24\ N$. The positive buoyancy of the float with an inflated bladder was chosen to be 3 N excluded the float's negative buoyancy. The net buoyancy X of the float, when ascending, would then be $X = 3 - 1.24 = 1.74\ N$. The float would be neutrally buoyant if F_b equaled F_g. To obtain positive buoyancy, F_b had to be larger than F_g. This was used to find the bladder volume (V_b).

$$F_b > F_g + X$$

$$g\rho V_{tot} > mg + X$$

$$g\rho(V_f + V_b) > mg + X$$

$$V_b > \frac{mg + X}{g\rho} - V_f = 3.045 * 10^{-4}\, m^3 \approx 3.05\ dL$$

For the float to ascend with the approximated size and mass, the volume of the bladder had to be 3.05 dL.

Bladder volume at the surface

Since air was compressible and the pressure and depth would increase proportionally, the 3.05 dL bladder volume would be compressed, and the volume of the bladder decrease. Calculations were performed to examine how much more air would be required to keep the bladder at a 3.05 dL volume at the desired depth of 10 m. Assuming that air behaved like an ideal gas, the ideal gas equation could be used. When a gas expands, the temperature decreases. For the float, the process could be viewed as isothermal since the surrounding water would quickly cool down the air to the initial temperature. The heat from the batteries and circuit cards was not taken into consideration.

Boyle's law, Eq. (6), states that the pressure and volume are constant in a closed system with constant mass and temperature. The equation could be used to compare substances under different conditions.

$$P_1V_1 = P_2V_2 \tag{6}$$

The absolute pressure, Eq. (7), was used when calculating the change in pressure with the change in depth.

$$P_{abs} = P_{atm} + \rho g \Delta z \tag{7}$$

The absolute pressure at 10 m (P_{10}) was found using Eq. (7)

$$P_{10} = P_{atm} + \rho g \Delta z = 199130.7\ Pa$$

where $P_{atm} = 101325\ Pa$ and $\Delta z = 10\ m$. Eq. (6) could be used to calculate the bladder volume (V_{b0}) at the surface if 3.05 dL was inflated to the bladder at 10 m depth. In this case, the pressure and volume of the bladder at the surface were (P_{atm}, V_{b0}), and pressure and volume at 10 m depth were (P_{10}, V_b). The volume of the bladder at the surface would be

$$V_{b0} = \frac{P_{10}V_b}{P_{atm}} = 5.98 * 10^{-4} \approx 6\ dL$$

If the bladder had a volume of 3.05 dL at 10 m, the volume would expand to 6 dL during ascending due to the decrease in pressure. The float was rigid, and the air inside would be unaffected by the pressure outside the float. To obtain a volume of 3 dL at 10 m depth, the bladder would have to be inflated with 6 dL from the float's inside volume.

Concept 1: Actuator and syringe to increase the volume of the external bladder

In concept 1, Figure 4-8(right), an actuator would push the syringe piston down, moving air from inside the syringe to the bladder outside the float. This would alter the float's buoyancy, and the float would ascend. When reaching the surface, the actuator would pull the piston back, extracting air from the bladder back into the syringe, making the float descend, Figure 4-8(left). All components would be located inside the float, except for the bladder.

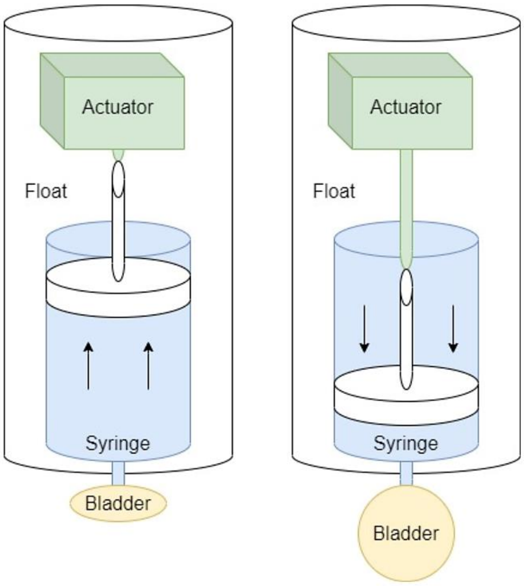


Figure 4-8 Concept 1: Actuator-syringe with deflated(left) and inflated(right) bladder

To inflate the bladder, the actuator had to push the syringe piston with a force that could exceed the pressure outside the float. The depth in the competition would be 4 m, but UiS Subsea desired to construct a float that could operate down to 10 m, and calculations were performed for this depth. The electrical team suggested an actuator meeting the electrical limitations, cost, and availability. This actuator had a pushing force of 80 N and an elongation of 10 cm. Calculations were conducted to find the required force of the actuator to overcome the pressure at 10 m. Assuming the inside of the cylinder had a pressure of 1 atm, Eq. (8), could be used to find the differential pressure(ΔP_{10}) at 10 m (Δz).

$$\Delta P = \rho g \Delta z \tag{8}$$

$$\Delta P_{10} = \rho g \Delta z = 97805.7\ Pa$$

As shown in Figure 4-8 (right), there would be a volume expansion inside the float when the piston was pushed down. Assuming the piston had a volume of $V_{piston} = 2 * 10^{-4}\ m^3$, the float's inside volume when the piston was pulled back and the bladder deflated would be $V_{in} = V_f - V_{piston} - V_{b0} = \ 4.59 * 10^{-3}\ m^3$, where $V_{b0} = \ 6 * 10^{-4}\ m^3$ and $V_f = 5.39 * 10^{-3}\ m^3$. When the piston was pushed down, the float volume would increase with the volume of the bladder to $V_{out} = V_{in} + V_{b0} = 5.19 * 10^{-3}\ m^3$. The volume expansion would decrease the float's inside pressure. Still assuming an isothermal process, Eq. (6) was used to find the pressure inside the cylinder after the syringe was pushed down.

$$P_{out} = \frac{P_{atm}V_{in}}{V_{out}} = 89611.1\ Pa$$

The decrease in the cylinder pressure would increase the total pressure differential (P_{tot}) the syringe had to overcome right before the bladder achieved the desired volume.

$$P_{tot} = P_{atm} + \rho g \Delta z - P_{out} = 109519.6\ Pa$$

In addition, there would be friction between the wall of the syringe and the piston, which would act in the opposite direction of the motion. To overcome the pressure differential, with a pushing force (F) of 80 N, the syringe piston would need an area of

$$A_1 = \frac{F}{P_{tot}} = 7.3 * 10^{-4}\ m^2$$

The radius of the cylinder would then require to be

$$r_1 = \sqrt{\frac{A_1}{\pi}} = 0.0152\ m \approx 1.5\ cm$$

Calculating the necessary height

$$h_1 = \frac{V_{b0}}{\pi(r_1)^2} = 0.827\ m$$

The syringe would have needed a height of 83 cm, with a radius of 1.5 cm with the given force. Considering that the elongation of the actuator was only 10 cm and the float had to be less than 1 m long, this solution would not work. Inflating 6 dL of air by pushing a piston with an elongation of 10 cm would have required a radius of

$$r_2 = \sqrt{\frac{V_{b0}}{\pi h_2}} = 0.0437\ m = 4.37\ cm$$

where $h_2 = 0.1\ m.$ The force of the actuator was then required to be

$$F_2 = P_{tot}\pi(r_2)^2 = 657\ N$$

An actuator of 657 N would be outside the electrical specifications. Given the chosen actuator, the actuator-syringe concept was not efficient. The actuator would be too weak, or the syringe would have too short elongation or too small area. A different mechanism for the piston would have to be applied to use a syringe.

Concept 2: Pump and valve to increase volume of external bladder

Concept 2 would use a pump and vale to change the float's buoyancy, as illustrated in Figure 4-9. The pump would take air from inside the float and transfer it to the external bladder to make the float ascend. When reaching the surface, the pump would stop, and a valve would open to let the air back into the float, making it descend.

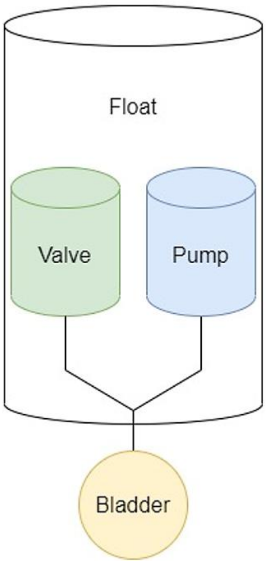


Figure 4-9 Concept 2: Pump-valve

The air needed to be pumped into the bladder with a pressure higher than the pressure differential at 10 m, 97805.7 Pa. Several pumps were available that satisfied the required electrical and mechanical specifications. The pump would run until it was programmed to stop, and the only limitation was the float's total volume. 6 dL of air required for the bladder, was relatively small compared to the float's total inside volume of 5.2 L. Based on the small amount of air necessary, there was no need for an extra container of compressed air inside the cylinder. Pumping air out of the cylinder would cause an under-pressure on the inside. The lower pressure inside the container and the higher external pressure surrounding the bladder would contribute to the air flowing back into the cylinder.

Concept 2 was chosen for further exploration and detail design, since there were several pumps on the market, and it was a fairly straightforward system. Concept 1 was not viable, due to the difficulty in finding a suitable actuator.

5 Product Development Process - Detail Design

In the detail design phase, further analyses were performed on the developed concepts, and it led to a detailed design with specifications for geometry, material, and production method. The cost of the products was also calculated. The steps, assess potential environmental impacts and compare to the DFE goals, from the DFE process would usually be performed during the detail design phase. However, since some of the components were altered and final dimensions were set after testing, these steps were implemented and executed in the testing and refinement phase instead.

5.1 ROV

During the concept development, concept F was selected for the frame, concept D for the thruster brackets, and concept A for the interface between the bottom and side plates. These concepts were further developed throughout the detail design phase and assembled into one system. Autodesk Inventor was used to create multiple revisions of the concepts and improved designs of the entire frame. FEA was performed rapidly to make choices regarding placement of components, material removal, and the number of fastening points needed. Part of refining the design was also material selection, and buoyancy and stability calculations.

5.1.1 Frame

Since it was decided to proceed with concept F, this concept was further developed. The plates designed during the concept generation phase were just designed to show the form of the ROV. They had no structural or aesthetic purpose. All the plates were, therefore, designed considering first their structural purpose, then their aesthetics.

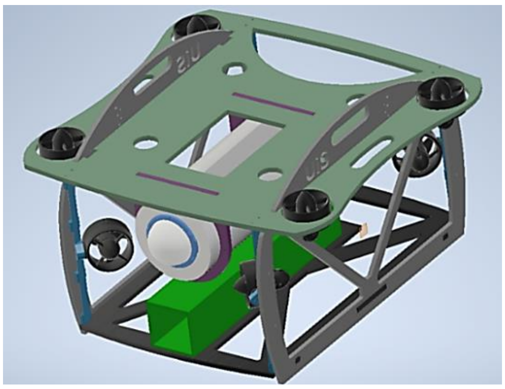


Figure 5-1 Revision 1 of the frame's detail design

One of UiS Subsea's objectives was to minimize the drag. Consequently, the amount of material in the plates and the surface area in all directions were reduced. In addition, this would reduce the environmental impact and the weight of the ROV, which would help meet the target specifications. The plates were also designed with rounded edges to minimize drag and as a safety measure. The first revision of the frame's detail design is shown in Figure 5-1. The electronics house needed 150 mm open space behind it for cables, and the

ROV's dimensions (671x699x440 mm) were based on the dimensions of the electronics house, the manipulator, and the thrusters. The side plates had a v-structure in the middle to strengthen and stiffen the plates due to the weight of the attached components. To ease the assembly, the top plate was designed to slide onto the side plates. The top plate had holes for the four vertical thrusters to protect them against impact. The four large holes in the middle of the top plate were for fastening the flotation element. Both the side plates and top plate had handles for lifting since it had not yet been decided where the best placement was. The electronics house was placed underneath the top plate for easy assembly and disassembly and a lower center of gravity. In this way, the electronics house would not lie directly underneath the flotation element, and the flotation element was not required to be removed to access the electronics house. It was designed brackets (purple), shown in Figure 5-2, that the electronics house easily could slide into and be fastened to with brackets (red). The brackets for the el house would be fastened to the top plate using metal angles. Since concept A was chosen for the interface between the side and bottom plates, three tenons were created on the sides of the bottom plate and three corresponding mortises on the side plates. The following revisions aimed to reduce the ROV's size and further minimize the material use in the plates. The design of the thruster bracket is described in Chapter 5.1.2.

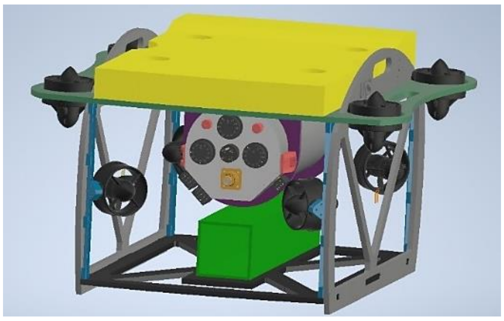


Figure 5-2 Fastening of electronics house

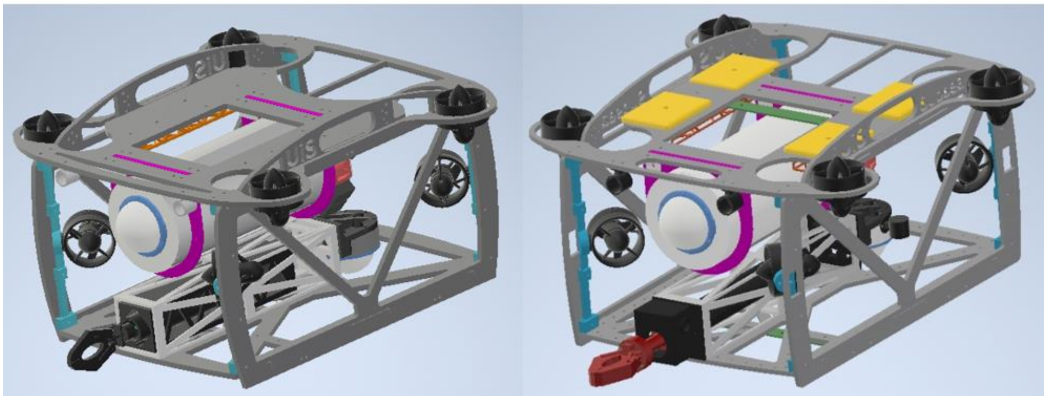


Figure 5-3 Revisions 2(left) and 3(right) of the frame's detail design

Figure 5-3 illustrates the second and third (final) revisions of the detail design. All the plates were altered some to reduce their size, volume, and ascetics. The frame would be exposed to less bending moment if the handles were placed on the side plates than on the top plate, and the handles were therefore kept on the side plates. One of UiS Subsea's objectives, which also was important for the DFE guidelines regarding recovery, was easy disassembly. Openings were thus created in the side plates where the horizontal thrusters were mounted to the thruster brackets. Similarly, openings in the top plate were created where the vertical thrusters were mounted. Rectangular openings were crafted for the brackets for the el house, and the brackets had a corresponding tenon that would slide into the opening. All loose cables and wires had to be fastened somehow, and if nothing had been thought of, cable ties would have been used. This solution would not have been environmentally friendly since cable ties were not reusable and would cause considerable waste over time. Canals for the thruster cables and light wires in the ROV's fore were designed, colored orange in Figure 5-3. Holes were created in the PEHD plates for all the components that would be assembled, and several holes in the bottom plate, with 30 mm in between, for ballast. The holes were in one size to use M4 bolts and nuts to assemble the frame easily and limit assembly and disassembly time. The thrusters had specifications for M3 bolts, and these holes were created accordingly. The number of bolts and nuts was reduced, by reducing the number of holes per component, to limit assembly and production time. Reducing the types and numbers of bolts and nuts could reduce the time sorting and finding the correct bolts, nuts, and tools during assembly.

When reducing the amount of material in the top and bottom plates, it was a risk of the plates bending down in the middle. After removing material, especially in the middle of the top plate and an extensive amount in the bottom plate, it would be a substantial risk of downward displacement. This is illustrated in Figure 5-4, which exaggerates the bending motion to show a possible scenario. The preliminary plan was to fasten the top/bottom and side plates with metal angels between these plates. However, due to the large displacement in the middle of the top and bottom plates, it was decided to apply metal stiffeners to both plates. FEA was used to find the best placement of the stiffeners by locating the placement that would reduce the displacement the most.

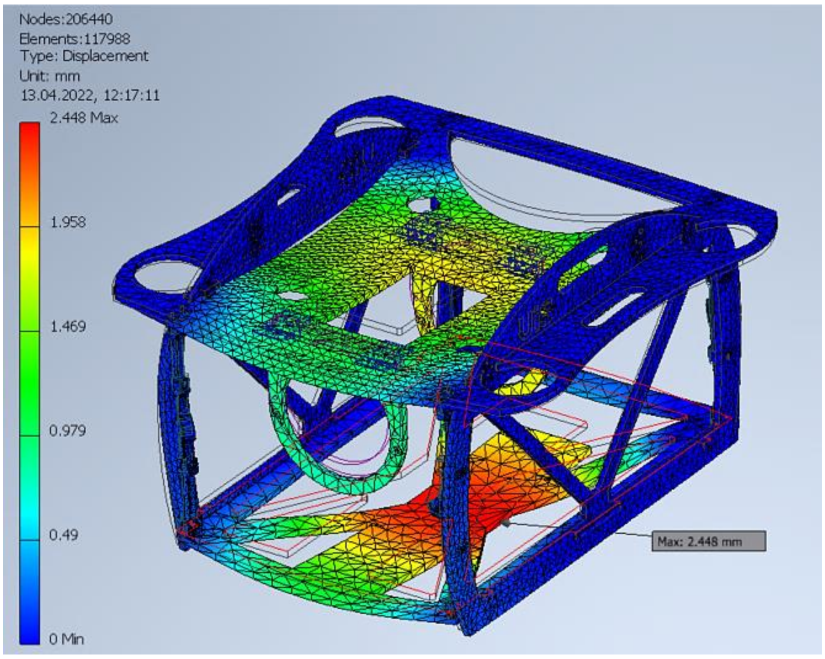


Figure 5-4 Exaggerated displacement of the frame

The components of the final design of the ROV are illustrated in Appendix C, Figure C-3, with icons and a parts list. The outer dimensions of revision 3 were 674x698x408 mm, hence within the ideal value for the target specifications for the length and the width of 0.8 m. The frame had been designed as small and compact as possible, given the size of the other components. As shown in Appendix C, Figure C-4, only 20 mm space remained between the manipulator and the brackets for the el house, and less between the thrusters and the brackets for the el house. It was sensible to have some room between the components for mounting and in case of unforeseen problems. From the first revision, only the height was reduced from 440 to 408 mm. The reason was, as mentioned, that the length and width had already been set by the dimensions of the electronics house, manipulator, and thrusters. The height was reduced as much as possible to minimize the space inside the frame and only make room for the handles above the frame. The buoyancy element would not affect this alteration since the element could have openings in the sides to make room for the hands lifting the ROV.

5.1.2 Thruster Bracket

The development of concept D for the thruster bracket is demonstrated in Figure 5-5, and stress analyses of the concepts are shown in Appendix D, Figure D-1.

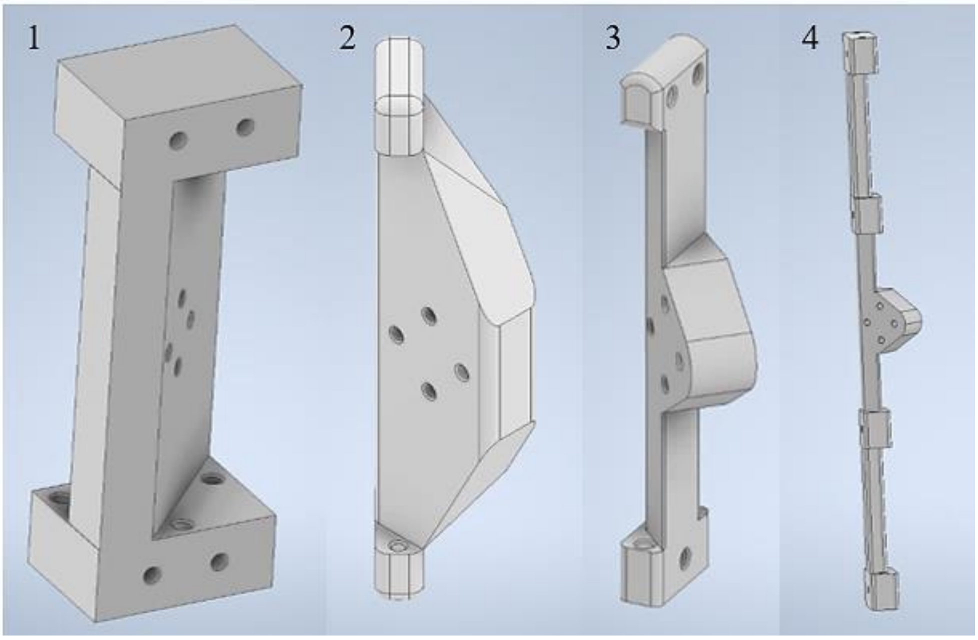


Figure 5-5 Revisions of the thruster bracket

It was initially designed a bracket with a 45-degree angle that would be fastened in the side and bottom plates. The thought behind this design was that the bracket also could function as a stiffener between the plates. This would reduce the number of metal brackets needed to support the frame since one of the DFE guidelines was to minimize the number of components. Reducing the amount of metal in the frame would also make the frame lighter and reduce the drag. Fastening the bracket both on the side and bottom plates would also reduce the vibration in the bracket due to the thrust force. FEA was performed to remove material from the bracket designs and reduce the use of raw material in the designs. The bracket was planned to be produced in a plastic material, but it was not yet decided which type. The bracket was therefore assigned acrylonitrile butadiene styrene (ABS) as material since the material properties of the plastics were quite similar. The force was set as the thrusters' max force, 35 N, the weight force was added, and fixed constraints were set at the bottom and back of the bracket where it would be fastened to the plates. Revision 3 ended up with a much slimmer body than revision 1. The maximum stresses the part experienced were around 5 MPa, which was low compared to the yield strengths of all the materials considered. The material choice and the materials considered will be discussed later. The maximum displacement of 0.227 mm was also minimal. The ideal placement of the thrusters for achieving the lowest possible center of gravity would have been near the bottom plate.

However, this was impossible since the manipulator would obstruct the thrusters' flow. The horizontal thrusters had to be placed at least 100 mm, the maximum height of the manipulator, above the bottom plate to obtain free flow. Since the thrusters had to be at this height, and the idea already was to use the bracket as a stiffener, the bracket's length was adjusted the distance between the bottom and top plates, 320 mm. The bracket would now stiffen the side plates, as well as hold all the plates together. The 45-degree angle was placed at the middle of the bracket to make it easier during manufacturing and assembly. In this way, all the brackets were equal, and some were placed the right way and some "upside down" for the angle to be positioned the desired way. If the angle was not placed in the middle, some brackets would have needed to be manufactured "mirrored." It was performed FEA on the last revision, revision 4, and the stresses and displacements found were still acceptable, as shown by the small displacement experienced by the bracket in Figure 5-6.

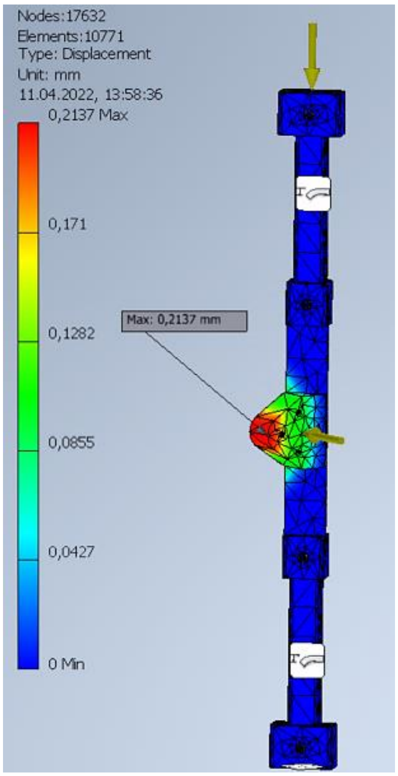


Figure 5-6 Displacement of the thruster bracket revision 4

5.1.3 Material Choice

After the concept for the frame and its components were created, the time had come to assign materials and reach out to companies to make deals and ask for sponsorships. When considering materials, knowledge from previous years in UiS Subsea, material properties, and the DFE guidelines in the products' life cycles' material phase were studied. It was important to find local suppliers for the materials and production to limit the environmental footprint due to transportation. The 12th UN SDG aspired to achieve sustainable production with less waste generation and chemicals. Therefore, it was essential to find easily recyclable materials that could be used in new products at the end of life and select production methods that reduced the need for chemicals and limited the waste. Considering the 13th and 14th goals, it was also an aim to select materials that caused less emissions into the environment. These goals' targets were implemented in the DFE guidelines, and it was given a high focus on these guidelines in the material selection.

Frame

The frames of previous UiS Subsea ROVs and small ROVs from other companies have been constructed of different polymers or aluminum. MATE and UiS Subsea required a lightweight frame. Thus, the frame had to be as light as possible while still having the strength to endure all the equipment. Using metal as the base material was excluded, and the aim was to find a polymer with low weight and high strength. The plastics considered were PEHD [25], polyoxymethylene (POM) [26], and PVC [4]. The ROV would only be used in shallow water, and the strength-to-weight ratio for these plastics was satisfying. Plastic also had better corrosion resistance than metals but would be worn by chloride over time. However, since the ROV only would spend a small amount of time in the pool, that would not be an issue. When considering the three materials, it was a high focus on the DFE guidelines, in addition to the material properties. Some material properties retrieved from Vink’s, a Norwegian plastic supplier, technical data sheets for PE100 [27], POM-C [28], and PVC [29], the environmental impact, pros, and cons are listed in Table 5-1. The environmental impact of PVC was found in one of Greenpeace’s articles [30].

Table 5-1 Comparison of materials for the frame

Properties	**Materials**		
	PE100	**POM-C**	**PVC**
Density [g/cm^3]	0.96	1.41	1.42
Yield Strength [MPa]	23	66	55
Notched Impact Strength [kJ/m^2]	21	8	3
Water Absorption [%]	0.1	0.8	
Environmental Impact	Easy to recycle	Recyclable	Toxic emissions
	Used in new products		Chlorofluorocarbon (CFC) Dioxin
	No decrease in material properties		Additives
			non-recyclable
Pros	Impact resistant	Impact resistant	Inexpensive
	Durable	Durable	Availability
	Low water absorption	Low water absorption	Small tolerances
	Corrosion resistant	Corrosion resistant	Corrosion resistance
	Easy to machine	Easy to machine	
	Inexpensive	High strength	
	Lightweight	Rigid	
	Ductile	Abrasion resistant	
Cons	Low strength	Sink in water	Brittle
			Sink in water

ROVs should be able to withstand impact, and since PVC was brittle, this would not be a viable choice. PVC was also very toxic and released hazardous pollutants during production, use, and recovery. Additionally, only a small fraction of PVC would be recycled due to all the additives. Comparing PE100 and POM -C, POM-C had much higher yield strength and was more rigid. One the other hand, one benefit of choosing PE100 was that it would float in water while POM-C sank. If selecting PE100, the frame's weight would be reduced while the material simultaneously would have a minimal effect on the buoyancy. PEHD also had better impact strength and was more ductile than POM. Upon impact, PEHD would be able to absorb more energy and deform plastically without fracturing, which was a considerable advantage since ROVs could hit objects in the water. POM-C had a more extensive water absorption than PE100, and over time this could cause problems with buoyancy and stability. Three of the previous ROVs constructed by UiS Subsea used PEHD in their frames and had success using this material. Nonetheless, both materials could be used, and the recyclability of each of them had to be examined before deciding.

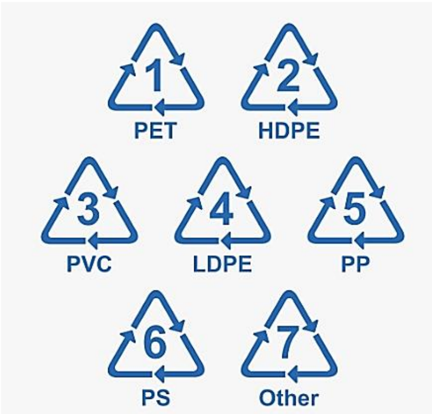


Figure 5-7 Plastic recycling codes

For a plastic material to be recycled, it first had to be separated from the rest. This could be done based on the densities since some would sink and some float. However, not all plastics were easy to separate. The plastic recycling codes, shown in Figure 5-7 [31], have been created for the recycling centers to identify which materials the products consist of. Even though both PEHD and POM were recyclable since they were thermoplastics, only PEHD had a recycling code. This could be because POM was challenging to separate from other materials. From SL Recycling [32], a recycling station in the UK, information was found regarding which plastic materials were easiest to recycle based on how easy they were to separate from the rest and then recycle. The commonly recycled plastics at this station were PET, PEHD, and PP, and specialist facilities could recycle the materials with recycling codes from 1 to 6. SL Recycling also accepted POM and ABS but specified that they recycled more plastic types than standard facilities due to their advanced facility and partnerships. The station stated that some recyclable plastics were not recycled in reality because they were too difficult to recycle and that generally, lower recycling codes meant easier recyclability. Since POM did not have a recycling code and could easily be recycled by melting, it was most likely difficult to separate at the recycling station. PEHD would be easier recyclable, and based on the DFE guidelines, PEHD would be the best material choice.

Combining the DFE guidelines, the material properties, and UiS Subsea's previous experience, PE100 was chosen for the plates in the frame and the brackets for the el house. Since PEHD was a thermoplastic, cutting it could cause it to melt. Therefore, the right tools and lubricants were required. UiS Subsea had used water cutting in previous years, and it would be the best option this year as well. Using water cutting would minimize the risk of altering the properties or quality of the plates. Furthermore, it would have a lower environmental impact than traditional cutting. There would be no need for lubricants that could contaminate the scrap and make it more difficult to recycle. Water cutting used little water during the process, typically around 2 L/min, and the water could be recycled and reused in the cutting. Little material was removed during the cutting, which led to minimal scrap [33]. Water cutting was therefore chosen as the production method for the PE100 plates. It was reached out to companies to see if they were interested in sponsoring or creating a price estimate. IKM Industrigravøren AS[1], located at Bryne, was interested in sponsoring materials and production for the ROV. Technical drawings, in Appendix C in Figure C-5 through Figure C-14, of the plates were sent to IKM on March 3rd, and the finished cut plates were delivered on March 17th.

Buoyancy element

PUR, PIR, and PVC foams were considered for the buoyancy element. PVC foam had the same environmental impact as plastic PVC and was eliminated due to its negative environmental impact. Both producers of PUR and PIR had a high focus on reducing the environmental impact of the materials and recycling. The Flexible Polyurethane Foam (FPF) industry had one of the world's best recycling records. The industry focused on energy-efficient manufacturing, minimizing produced scrap, recovering and recycling the scrap, and recycling the foam. In the last decade, bio-based raw materials had been used to produce the foam [34]. Similarly, PIR production required little energy and used blowing agents that were non-ozone depleting and CFC-free. Manufacturers used high levels of recycled materials in the PIR production [35]. The two materials had quite similar material properties. The properties of PUR were found on General Plastics' website, and the material was inexpensive, water, rot, and impact resistant, easy to work with, had good compressive-strength, and low

[1] www.ikm.no/ikm-industrigravoren

density [36]. PIR foams were inexpensive, had low densities, and good compressive strength. However, one disadvantage with PIR was that it would need a coating to be water and abrasion-resistant, as opposed to PUR [34].This would make it more challenging to recycle, and the coating layer would need to be separated from the PUR before recycling, causing more waste. PUR would therefore be the best option from an environmental point of view.

Mechman AS[2], located at Jørpeland, delivers PUR buoyancy elements and sponsored last year's ROV with the buoyancy element and the corner covers. It was, therefore, natural to ask Mechman AS if they were interested in sponsoring this year's ROV as well. The company was interested in sponsoring the buoyancy element and resin 3D printed plastic components. The sponsoring included support in designing, materials, and production of components. Mechman AS stated that to reduce the environmental impact, they repaired buoyancy elements to extend the products' lifetime and that it was possible to use materials from old elements to produce new ones.

Thruster Brackets

The thruster brackets were quite complex, and this would cause a lot of waste if using traditional manufacturing methods where the material would be subtracted from the workpiece. This process would also be very time-consuming and require several different tools, cutting fluids, and careful planning. ALM and 3D printing would consequently be a better manufacturing process for the thruster brackets. The option was between using a solid- or liquid-based process. Mechman AS used EPD 2006 [37] as resin in their SLA 3D printer and offered 3D printing components for the ROV. The FDM 3D printers at UIS used either polylactic acid (PLA) [38] or ABS [39].

PLA was a bio - and thermoplastic created from natural or recycled materials like corn starch or sugarcane. Since the material was made of plants, it was eco-friendly, non-toxic, and biodegradable, as illustrated in Figure 5-8. However, even though PLA was biodegradable, it would take three months to decompose under ideal conditions [40].

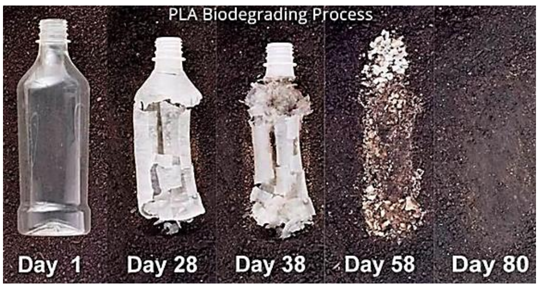


Figure 5-8 The biodegrading process of PLA

Material properties of the 3D materials EPD 2006 [41], PLA [42], and ABS [43], with 100 % infill, are shown in Table 5-2 along with environmental impact, pros, and cons.

[2] www.mechman.no

Table 5-2 Comparison of 3D print materials

Properties	Materials		
	EPD 2006	**PLA**	**ABS**
Density [g/cm^3]	1.20	1.24	1.10
Tensile Strength [MPA]	50.0	49.5	39.0
Hardness [Shore D]	80	83	76
Elongation at Break [%]	10.3	5.2	4.8
Environmental Impact	Toxic before cured	Natural or recycled raw material	Petroleum-based
	Power consumption	Biodegradable	Not biodegradable
	Cleaned with biofriendly cleaner and tap water	Recyclable	Recyclable
		Long time to decompose	Power consumption
		Non-toxic	Hazardous particle emission
		No fumes	
		Need less power	
Pros	Very hard	Easy to print	High strength
	Durable	Low printing temperatures	Durable
	Rigid	Fast printing	Temperature resistant
	Good detail quality	Inexpensive	
	Temperature resistant	Good detail quality	
	Smooth surface finish	Large color range	
Cons	Limited colors	Brittle	Tricky to print
	High cost	Strength dependent on print settings	Warping and cracking
		Not heat resistant	Temperature sensitive
		Deform when exposed UV light	Require high printing temperatures
			Crack in the cold
			Degrade when exposed UV light and moisture

The brackets had to withstand the thrusters' successive forces and be rigid since they would function as stiffeners. PLA would be too brittle for this use, and the brackets could risk breaking. During solid-based printing, the print would be printed in layers that could cause layer line gaps. This could reduce the strength, durability, and water resistance of the material. On the other hand, liquid-based printing led to a smooth surface finish and watertight, rigid, and durable components. SLA would be a better production method than FDM to ensure that the brackets could withstand the force of the thrusters and be durable and water-resistant. Looking at the DFE guidelines, EPD 2006 would not be the best option. The resin was toxic before being cured, but with the right precautions, components could be 3D printed without harming the environment [44]. It was important to use safety equipment like gloves and goggles when handling the resin and cure everything that had been in contact with the resin. This meant that the water that was used to clean the components and paper that had been used to clean up spill had to be cured before disposal. The curing process could be executed by leaving the items out in the sunlight to expose them to UV light. The water then had to be strained to remove plastic particles before pouring it into the drain. 3D printing allowed all six brackets to be printed simultaneously, and the 3D printed brackets with supports are shown in Figure 5-9. SLA may have a larger power consumption than FDM since the components first would be printed, cleaned, then cured using the same machine. Nevertheless, one benefit would be that SLA worked faster than FDM, and this could reduce the power consumed. It would have taken 3 days and 23 min to print the brackets using the FDM printer at UiS, while Mechman spent 5 hours including pre and postprocessing. The only way to recycle resin products would be by shredding and using them in new products.

Figure 5-9 3D printed brackets for the thrusters

Canal for wires

The canals had to be in some sort of plastic material to affect the weight of the ROV as little as possible. A couple of designs were drawn in Autodesk Inventor, and the volume and material use were reduced as much as possible. The final design is shown in Figure 5-10. Like for the thruster brackets, it would be best to use 3D printing to produce the canals. Traditional manufacturing would subtract a lot of material, produce a substantial amount of waste, and be time-consuming. The same three 3D printing materials PLA, ABS, and EPD 2006 were considered. The canals did not need impact resistance nor any major load-bearing capabilities, and all the materials would be possible. It was therefore decided to focus on the DFE guidelines and decide which material was best regarding them. Table 5-2 was again used to compare the materials. ABS was initially eliminated since it led to hazardous emissions. Then, comparing EPD 2006 and PLA, PLA was more environmentally friendly. PLA was made of biological materials and was non-toxic, while EPD was toxic before being cured. If

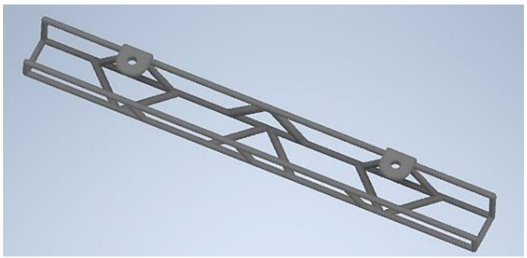


Figure 5-10 Canal for wires

not handled the right way, it caused a risk of polluting the community and environment. PLA was also both biodegradable and recyclable, and PLA waste could be shredded and melted to make new filaments or other products. EPD, on the other hand, could, after it was cured, not be melted, only shredded and used in new products. Mold injection was a commonly used method for manufacturing new products. EPD could be used in larger products, as fill material, like the chair in Figure 5-11 a [45], since the EPD would need some melted material to bond with the shredded EPD particles to form a solid product. PLA was easily melted and could be used to produce various products, like smaller products with colorful batik patterns, as illustrated in Figure 5-11 b and c [45].

Figure 5-11 Reuse of 3D printed plastic

Since PLA was biodegradable, the components could degrade over time, especially if used outdoors. However, this year’s ROV was produced for use in a pool for short durations. It would always be possible to 3D print new components after a while, and organic plastic had less environmental impact than fossil-based plastic. Therefore, PLA was considered to be a suitable material for the canals. Other small, non-load-bearing components on the ROV were also 3D printed in PLA.

Metal Brackets

The metal brackets included the angles, Figure 5-12, used to fasten the brackets for the el house, and the stiffeners, Figure 5-13. It was preferred to use metal for these components to ensure that they were strong and rigid since they would be exposed to the highest stresses on the ROV frame. This is shown in Chapter 5.1.4. The two most common corrosion-resistant materials, aluminum [46], and stainless steel [47], were considered for the metal brackets. Both materials were inexpensive, strong, durable, easily

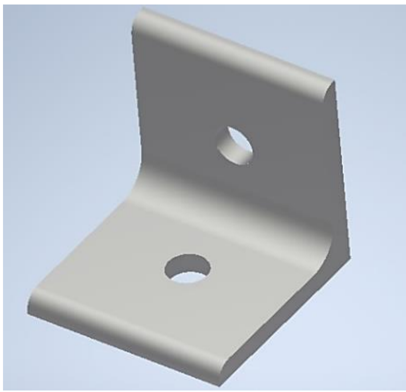


Figure 5-12 Bracket L 30x30x3-30

recyclable, and could be manufactured using recycled materials. The information regarding aluminum's recyclability was found in one of AzoCleantech's articles [48]. The most significant difference between aluminum and stainless steel was their densities. Aluminum had a density of 2.7 g/cm^3 and stainless steel 7.5-8 g/cm^3 based on the alloy. Stainless steel would, thus, be almost three times heavier than aluminum. Since one of the customer needs was lightweight, aluminum was selected to minimize the ROV's weight.

Figure 5-13 Stiffener

The components could either be manufactured in the workshop at UiS or bought as finished parts. If the components were ordered, they would most likely be produced partly from new materials, and there would be a delivery time. In the workshop, there were boxes for recycling metal waste that could be remanufactured into new components. Using that waste to manufacture the metal components would reduce the amount of aluminum that had to be extracted from the earth. The technical drawing used for manufacturing the metal brackets can be found in Appendix C, Figure C-15, and Figure C-16. For the metal angles, 3 mm thick 30x30 mm angled profiles were found in the recycling boxes. Eight pieces were cut in lengths of 30 mm, using a horizontal band saw, and holes were drilled. For the stiffeners, some 3 mm thick plates were found in the recycling boxes pieces of 30 mm width were cut since some spare parts were desired, and the frame could need some more stiffening. The holes in the ends were then drilled, the ends bent, and the holes for fastening to the top and bottom plates drilled. All stiffeners and angles were ground, and the holes countersunk for safety reasons.

Ballast

Lead was often used as ballast due to its high density but was discarded since it was toxic and could affect the entire ecosystem [49]. The ballast needed corrosion resistance and durability, and stainless steel and aluminum were good options. As mentioned, when deciding on materials for the metal brackets, the two metals were quite similar, except for their densities. In contrast to the rest of the ROV, the ballast aimed to be heavyweight and stainless steel was thus selected for the ballast. Like the other metal components, waste material was found in the boxes for recycling in the workshop. A piece of stainless steel was found, and it was cut into small rectangles, using the horizontal band saw, of different sizes to obtain the desired masses. Holes were drilled into the rectangles, the pieces ground, and the holes were countersunk. The ballasts' masses, including fasteners, and the numbers of the different sizes are presented in Table 5-3. The total mass of the ballasts was calculated by multiplying the mass by the number of each size and then summing them, which was 3208 g. The buoyancy calculations are presented in Chapter 5.1.5.

Table 5-3 Ballast Mass

Mass [g]	Number
25	5
30	7
40	3
50	9
55	2
70	2
100	6
229	1
254	1
307	1
773	1

5.1.4 Structural Analyses

After materials were assigned to the components, FEA could be performed on the frame to find the frame's stresses and displacements and verify that the design would hold. FEA was also used to determine the plates' thickness and determine how many fasteners were required.

To perform the analyses, the materials selected for the ROV components were assigned to the components in Autodesk Inventor, and the material properties were confirmed. The frame was only bonded in the holes where fasteners would be. It was first added automatic contacts and tried to analyze with these bonds, but they were causing the side plates to be too stiff and not buckling at all. The movement was unrealistic, and the automatic bonds were changed to sliding with no separation to obtain the proper motion in the system. Manual bonded contacts were then added to every contact point where a fastener would be in real life.

In previous years, the safety factors for the thickness of materials had been unnecessarily high. The cost of materials could have been reduced by reducing the material thickness. This would also have reduced the ROVs' weight and drag. In the years that PEHD had been used, the thickness was between 12 and 15 mm. When the plates were first designed, they were therefore created 10 mm thick, but with the help of FEA, the thickness was reduced to 8 mm. The number of fasteners in the metal brackets was also halved based on FEA results. Initially, the metal angles had two holes on each face, and the stiffeners had two holes on the faces fastened to the side plates and four on the one fastened to the top or bottom plate. Then again, with the support of FEA, the holes in the metal angles were reduced to one on each face, and the stiffeners obtained one hole on the sides facing the side plates and two on the side facing the top or bottom plate. Hence, the number of fasteners was halved in the metal brackets.

The ROV frame was mainly a platform that had to be able to hold all necessary equipment when diving. The lifting analysis, Figure 5-14, was performed to verify that the ROV design could endure the main components of the ROV, like the electronics house, manipulator, rear-end camera, and thrusters. The analysis was performed on the final design of the frame, thus with 8 mm thick plates and the reduced number of fasteners.

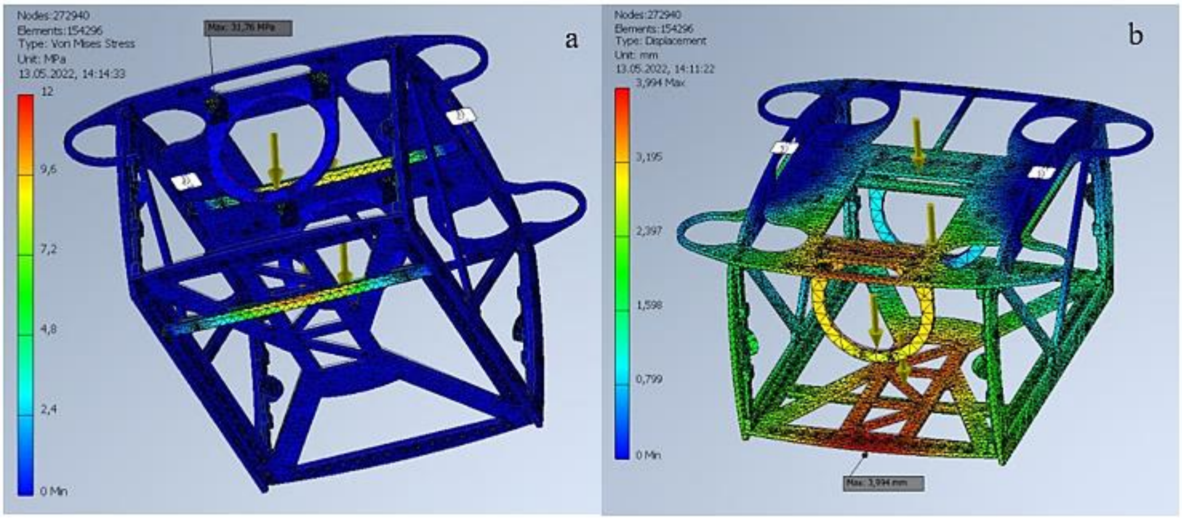


Figure 5-14 Lifting Analysis: Von Mises(a) stress and displacement(b) in the frame

During the lifting analysis, the frame had a fixed constraint in the handles where one would lift. The weight of the electronics house, manipulator, and rear-end camera were still not set, and thus the maximum allowed masses for these were used. The electronics house caused a weight of 56 N, 28 N in each bracket for the el house, and the manipulator and rear-end camera caused a weight of 36 N combined on the bottom plate. In addition, the weight force was added on the top plate. As seen in Figure 5-14 a, the color bar was adjusted to 12 MPa to observe the stress distribution over the frame. All the PE100 plates were blue, which indicated that they experienced extremely low stresses. The stiffeners had some green and yellow areas and would thus experience higher stresses. The maximum stress of 31.76 MPa was located in the fastening point to the top plate at one of the metal angles in the front of the fore bracket for the electronics house. The color bar was adjusted to 16 MPa, Figure 5-15, to illustrate the higher stresses at this location. The yield strength of aluminum was 276 MPa, and the

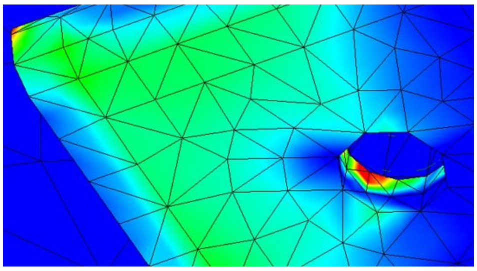
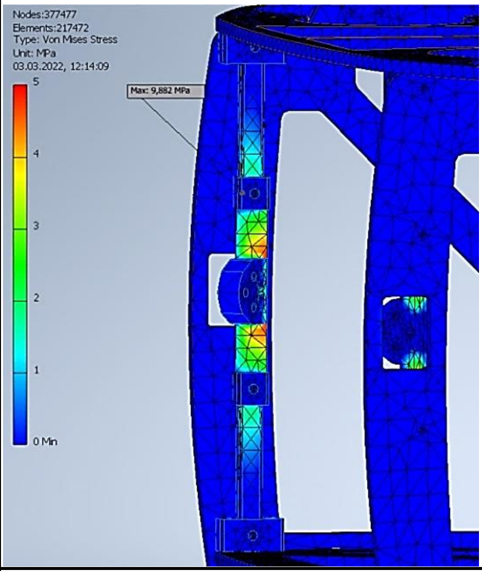
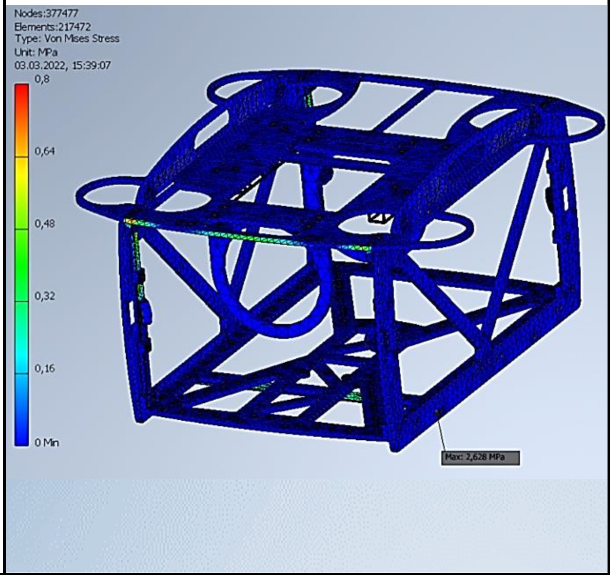
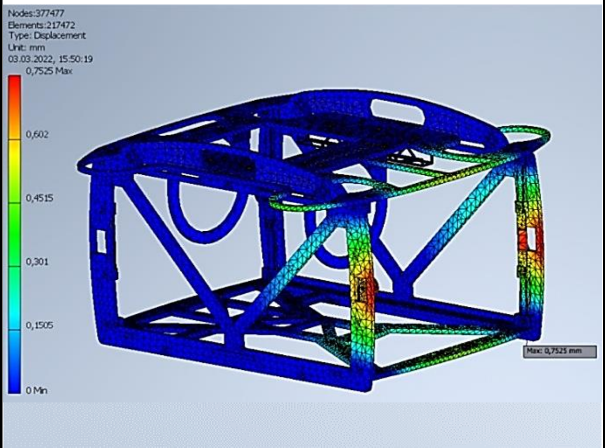


Figure 5-15 Location of maximum stress in the frame

minimum safety factor was $N = \frac{\sigma_y}{\sigma_w} = \frac{276\,MPa}{31.76\,MPa} \approx 8.7$. This safety factor was quite large, but it was a prominent color distribution over most of the frame when looking at the displacement in Figure 5-14 b. As a result, the top and bottom plates would experience bending and the side plates buckling, and the bottom plate would undergo a maximum displacement of 3.994 mm. PEHD was ductile and would deform elastically, and a displacement of 3.994 mm would therefore be acceptable. However, it would be preferred not to reduce the plate thickness further and, by that, increase the displacement. Even though the material was ductile, it had a risk of deforming plastically or fracturing if the stresses were too high. For the same reason, the number of fasteners was not further reduced. The number of fasteners in the metal components was satisfying, but it was still a high total number of fasteners in the frame. Reducing the number of fasteners would increase the stresses the frame experienced and, as a result, also the displacements. The maximum displacement was caused at the fore of the bottom plate where the manipulator was located, and too much displacement would interfere with the manipulator's movement. This year's manipulator would only extend and rotate. Large displacement in the bottom plate could cause the manipulator to pitch downward. The ROV would then need to spend more thrust force on righting itself, especially when the manipulator was in use, due to the manipulator's momentum. Another option would be adding more ballast back on the ROV to compensate.

The thruster analyses, shown in Figure 5-16, was performed to verify that the frame could withstand the force of the thrusters and that the thruster brackets would hold. During the analyses, the fixed constraint was set in the fore of the frame, imitating that the ROV drove forward for the horizontal thruster analysis, and on top of the frame, imitating upward movement for the vertical thruster analysis. Both horizontal and vertical thrusters had a maximum thrust force of 35 N, and this was applied. In the horizontal thruster analysis, the maximum Von Mises stress was 9.88 MPa at the thruster bracket in one of the mid-fastening points between the bracket and the side plates. This stress was small compared to EPD 2006's tensile strength of 50 MPa. The maximum displacement was under 1 mm. Similarly, in the vertical thruster analysis, the maximum stress of 2.63 MPa was minimal. This was located at the bottom stiffener, which had yield strength over 100 times stronger. The displacement was also in this analysis under 1 mm, which would be insignificant. The analyses confirmed that the frame and thruster brackets would have no problem resisting the force from the thrusters and would be stable in water. The lift and thruster analyses concluded that the frame was well dimensioned regarding yield and fracturing.

<table>
<tr><th>Horizontal Thrusters</th><th>Vertical Thrusters</th></tr>
<tr><td>Von Mises stress: Max 9.88 MPa

</td><td>Von Mises stress: Max 2.63MPa

</td></tr>
<tr><td>Displacement: Max 0.75 mm

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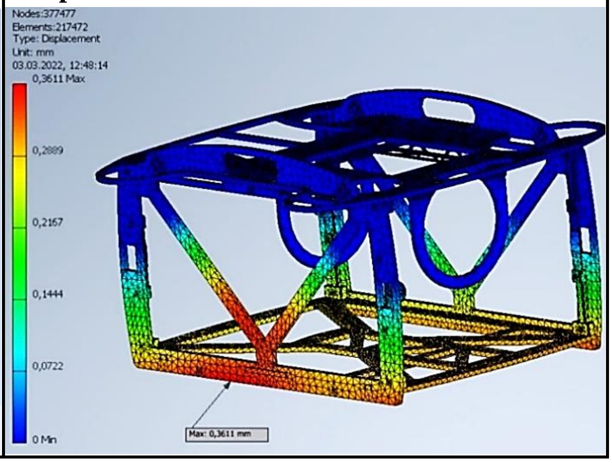
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Figure 5-16 Thruster analyses

5.1.5 Buoyancy and Stability

The buoyancy element from Mechman AS required some production time and had to be ordered early in the project. Buoyancy calculations, therefore, had to be performed before all components of the ROV were finished designed and dimensioned. The maximum weights and the designs at this time were used for these components. Autodesk Inventor was used, and some hand calculations performed to estimate the components' mass, volume, weight, buoyancy, CG, and CB. CB was found by making hollow parts solid and setting their densities equal to the density of water in Autodesk Inventor. The calculations were performed to ensure the stability of the ROV and the proper buoyancy. Table 5-4 was used to calculate the overall mass and weight of the ROV. The mass of each component and their CGs were found in Autodesk Inventor. The masses were summed, and the overall mass of the ROV was found to be around 17.67 kg. This mass was excluded cables and the tether but was still within the customer need using the maximum weights of the components.

Table 5-4 Weight statement for the ROV

Project	ROV					
Planned Dive Site	Pool					
Water Density at Site [kg/m^3]	997					
Part	**Number of Parts**	**Mass of Part [g]**	**Total Mass of Parts [g]**	**Weight of Parts [N]**	**Center of Gravity in x [mm]**	**Center of Gravity in z [mm]**
Bottom Plate	1	1073.1	1073.1	10.5	-24.0	4.0
Side Plate	2	735.9	1471.8	14.4	0.0	174.0
Top Plate	1	1363.8	1363.8	13.4	-17.3	332.0
Bracket for El House	2	118.2	236.5	2.3	-90.5	250.8
Bracket for Thruster	4	91.2	364.9	3.6	0.0	168.0
Bracket L30X30X3-30	8	14.0	112.0	1.1	-90.5	319.6
Stiffener	2	117.0	234.0	2.3	-82.3	161.8
Electronics House (everything inside generic)	1	5734.8	5734.8	56.3	-42.4	230.9
Rear-End Camera with Mount	1	797.9	797.9	7.8	177.1	59.4
Manipulator	1	3040.0	3040.0	29.8	-182.5	57.9
Horizontal Thruster	4	332.0	1328.0	13.0	0.0	168.0
Vertical Thruster	4	332.0	1328.0	13.0	0.0	329.0
Buoyancy Element	1	0.0	0.0	0.0		
Canal for Wires	2	30.9	61.8	0.6	0.0	309.2
Light Mount	4	30.0	120.0	1.2	-66.8	184.1
Bolts	100	3.0	300.0	2.9		
Nuts	100	1.0	100.0	1.0		
Total	**238**		**17666.4**	**173.3**		

The weight of the components was found by using Eq. (1), and for the ROV to float, the net buoyant force had to be greater than the net weight of 173.3 N. The buoyant forces and buoyancies were calculated in Table 5-5, and the CBs for the components were listed. The buoyant force was calculated using Eq. (2), and the buoyancy was calculated by subtracting the weight from the buoyant force of the component. The net buoyant force was 183.7 N, and thus the net buoyancy was $183.7\ \text{N} - 173.3\ \text{N} \approx 10.40\ \text{N}$. The ROV was positively buoyant without buoyancy elements, mainly due to the large volume of the electronics house. Consequently, at this moment, it was no need to add floatation elements but rather trim the

ROV with ballast. The ROV should be slightly positive to let it hover in mid-water at a minimal thrust and return to the surface in case of problems with the propulsion system. Applying the theory from Chapter 2.2, the net buoyant force should be around 1-2 % of the ROV's weight. The total weight of the ROV was still unknown, but the estimated value from Table 5-4 was used to calculate the approximated ballast required. 1.5 % of 173.31 N equaled $\frac{1.5}{100} * 173.31 \approx 2.6\ N$. Hence, that the buoyancy had to be reduced by $10.4 - 2.6 \approx 7.8\ N$, $\frac{7.8}{9.81} \approx 0.8\ kg$. Ballast of 0.8 kg had to be added, and to figure out the positioning of the ballast, the CG and CB had to be calculated.

Table 5-5 Buoyancy statement for the ROV

Part	Volume of Displaced Water per Part [cc]	Total Volume of Displaced Water [cc]	Buoyant Force [N]	Buoyancy [N]	Center of Buoyancy in x [mm]	Center of Buoyancy in z [mm]
Bottom Plate	1117.8	1117.8	10.9	0.4	-24.0	4.0
Side Plate	766.5	1533.1	15.0	0.6	0.0	174.0
Top Plate	1420.6	1420.6	13.9	0.5	-17.3	332.0
Bracket for El House	123.2	246.3	2.4	0.1	-90.5	250.8
Bracket for Thruster	76.0	304.1	3.0	-0.6	0.0	168.0
Brackets L30X30X3-30	5.0	40.3	0.4	-0.7	-90.5	319.6
Stiffener	43.5	86.9	0.4	-1.9	-82.3	161.8
Electronics House (everything inside generic)	10368.5	10368.5	101.4	45.2	-77.1	234.9
Rear-End Camera with Mount	884.6	884.6	8.7	0.8	178.5	47.6
Manipulator	1120.7	1120.7	11.0	-18.9	-231.2	58.7
Horizontal Thruster	195.1	780.2	7.6	-5.4	0.0	168.0
Vertical Thruster	195.1	780.2	7.6	-5.4	0.0	329.0
Buoyancy Element	0.0	0.0	0.0	0.0		
Canal for Wires	24.9	49.8	0.5	-0.1	0.0	309.2
Light Mount	31.2	31.2	0.3	-0.9	-67.3	183.2
Bolts	0.5	51.5	0.5	-2.4		
Nuts	0.1	10.1	0.1	-0.9		
Total		**18826.2**	**183.7**	**10.4**		

The stability of the ROV was fundamental for obtaining a functional vehicle that could complete the tasks in the MATE competition. To acquire maximum stability, CB had to be placed high and CG low and as far apart as possible in the vertical direction. Increased distance between the points would increase the stability. On the other hand, the closer the two points were, the easier it would be to maneuver the ROV. The pitch and roll movements would then be more effortless. It was essential to keep CB and CG on the same vertical axis for the system to be in static equilibrium. If they were not, the forces would create a torque and rotate the ROV until vertical alignment was achieved. The ROV could then have ended up in a tilted equilibrium. The righting moment would be more significant for larger vertical distance between CG and CB. The z-values were measured from underneath the bottom plate, and the x- and y-values were measured from the ROV's center since the frame was symmetric. Positive x-direction was backward and positive z-direction upward. Components were designed symmetrically in the y-direction and centered in this direction when mounted to the frame to ensure linear vertical alignment. By doing so, the CG and CB in the y-direction would be 0 for all components, and the overall CGy and CBy would also be 0. Equal components were placed symmetrically about the x-axis for the same reason. This included the thrusters, thruster brackets, canals for wires, and side plates. The righting moment would always try to keep CB directly above CG. Heavy components were therefore placed as low as possible. If CG happened to lie above CB, the entire ROV would flip upside down. The heaviest components were the manipulator, rear-end camera, and electronics house. The manipulator and rear-end camera were placed as low as possible, thus at the bottom plate. The electronics house was placed underneath the top plate and as close to the manipulator as it could to lower its CG.

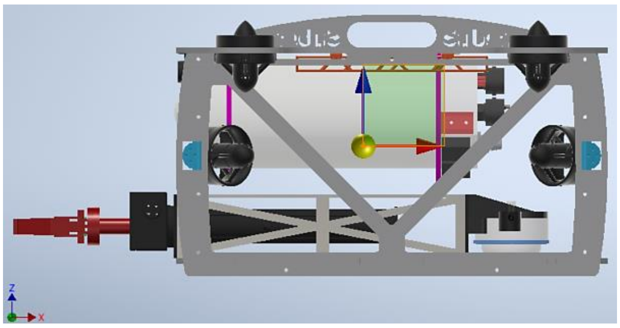

Figure 5-17 Location of the ROV's CG

The CGs and CBs for each component, the weight of the components, the weight of the displaced water due to the part, the total weight of the ROV, and the total weight of displaced water were found in Table 5-4 and Table 5-5. The calculations of the ROV's CGs and CBs were performed in excel using Eqs. (4) and (5), and the results are shown in Table 5-6. Figure 5-17 illustrates, with a yellow point, the position of the ROV's CG for. Ideally, CB_x and CG_x should be on the same vertical axis. The calculations showed that the distance between the two points was $-52-(-43) \approx -9\ mm$, which was small compared to the length of the ROV. If no measures were taken, the righting moment would cause some tilt in the pitch direction with the fore turning upwards. This would have to be corrected by adding ballast to compensate. The distance between the CB_z and CG_z was $204 - 179 \approx 25\ mm$. The distance was satisfying, and the ROV would be stable and have a suitable righting moment. Ballast could be added to the bottom plate to lower the CG to improve stability further. Otherwise, if better maneuverability was desired, ballast could be added at the top plate to raise the CG. The decision regarding whether to increase the stability or the maneuverability by the ballast placement would be taken based on the testing of the ROV in water. Since the weights of the components were not set at this point, the calculated CGs and CBs were only estimated and would change in reality. Testing in water would be used to make adjustments to increase stability and maneuverability and obtain the desired buoyancy with the means of ballast and buoyancy elements.

Table 5-6 Center of gravity and buoyancy of the ROV

Center of Gravity			**Center of Buoyancy**		
CGy was 0 since everything was symmetric and centered			CBy was 0 since everything was symmetric and centered		
CGx without buoyancy element	**-43**	mm	CBx without buoyancy element	**-52**	mm
CGz without buoyancy element	**179**	mm	CBz without buoyancy element	**204**	mm

5.1.6 Product Cost

The estimated value of the product cost for the ROV frame, including value-added taxes (VAT), is given in Table 5-7. Almost the entire frame was sponsored by local companies, like Mechman AS, IKM Industrigravøren AS, and the University of Stavanger. Only the fasteners were bought using the budget given for the ROV and float. Subsea-related companies have shown a great interest in this and previous year's ROV projects, and it was relatively easy to acquire sponsorships. Mechman AS and IKM Industrigravøren AS were open to sponsoring the ROV and UiS Subsea from the beginning. UiS has been helpful with material, advice, and support throughout the process.

Table 5-7 Product cost of the ROV

Components	**Value [NOK]**	**Sponsored**
PEHD plates	6250	IKM Industrigravøren AS
Thruster brackets	6000	Mechman AS
Buoyancy element	10 000	Mechman AS
Aluminum brackets	62	University of Stavanger
3D printed PLA	200	University of Stavanger
Ballast	100	University of Stavanger
A4 fasteners	987	NA
SUM	23599	

5.2 Float

The detail design phase consisted of material and design choices, buoyancy and stability calculations, and structural analyses. The float's exterior included the cylinder, the endcaps, and the support bracket, Figure 5-18. In addition, the inside structure holding the components and the buoyancy system transporting the buoyancy fluid were included in the detail design. Concept 2 selected for the buoyancy system, was further developed and improved. Autodesk Inventor was used to create and improve the cylinder, endcaps, inside structure, and support bracket designs. The components of the float assembly can be found in Appendix E, Figure E-1, with icons and a parts list.

Figure 5-18 Float assembly

5.2.1 Material Choice

After selecting the float's shape and concept, materials and production methods were chosen for each of the float's components based on the customer needs, DFE guidelines, and material properties. Existing floats were constructed of metal, but because of the shallow depth requirements and the limited time in water, the thesis team also wanted to explore plastic options that could be delivered as pipes. Using plastic would reduce the float's weight, excluded ballast. PE100, PMMA [4], PVC and aluminum [4] were considered as material for the cylinder and their material properties, environmental impact, pros, and cons were compared in Table 5-8. The information regarding PE100 and PVC was retrieved from Table 5-1. Material properties for PMMA were found in Vink's technical data sheet [50] and aluminum from MatWeb Material Property Data [51]. The environmental impact of PMMA [52] and aluminum [48] were found in online articles.

Table 5-8 Comparison of material for the cylinder and endcaps

Properties	Materials			
	PE100	**PMMA**	**PVC**	**Aluminum 6060**
Density [g/cm^3]	0.96	1.19	1.42	2.70
Yield Strength [MPa]	23	72 (Tensile)	55	276
Water Absorption [%]	0.1	2.1		0.0
Environmental Impact	Easy to recycle	Recyclable but not easy	Toxic emissions	Recyclable
	No decrease in material properties	Releases CO_2 in UV light	CFCs, dioxin	Energy-consuming production
	Used in new products		Additives	Production of new metal harms the environment
			Non-recyclable	
Pros	Impact resistant	Corrosion resistant	Inexpensive	Sink in water
	Durable	Sinks in water	Availability	Availability
	Low water absorption	Rigid	Small tolerances	Easy to machine
	Corrosion resistant	Low water absorption	Corrosion resistant	Ductile
	Easy to machine			Corrosion resistant
	Inexpensive			
	Ductile			
Cons	Low strength	Brittle	Brittle	
	Deforms at high temperatures	Difficult to machine	Difficult to machine	

All materials were widely available at low cost, PVC being the cheapest and aluminum the most expensive. The materials came in premade extruded pipes saving waste and work hours compared to turning a bolt. Less waste production was positive when considering the environmental impact. Pipes of the different materials existed in diameters that accomplished the customer need of a maximum diameter of 18 cm. All pipes were sold in standard lengths of 6 m, except PMMA which existed in lengths of 2 m. The maximum length of the float that would satisfy the customer needs, was 1 m. In addition, it was necessary to produce a waterproof container and meet the customer needs, and when comparing the materials, they all had low water absorption. All materials had good corrosion resistance and were suitable for operating in a wet environment. Aluminum was the least resistant to corrosion, but it would not be an issue when considering the tasks in MATE. PE100 was the weakest material with a yield strength of 23 MPa, whereas aluminum was the strongest with a yield strength of 276 MPa. Nevertheless, all materials would be strong enough considering withstanding the pressure at 10 m depth. Both PVC and PMMA were very brittle and difficult to machine, while PE100 and aluminum were more ductile and easier to machine. When looking at the environmental guidelines, none of the materials were biodegradable, but all were recyclable. However, in reality, PVC would not be recyclable due to all the additives. Comparing the polymers, PE100 would be the most attractive for recyclability. PE100 had no harmful emissions in contact with the environment, while PMMA and PVC did. PVC and PMMA were discarded as materials for the cylinder since they were brittle, difficult to machine, and did not meet the DFE guidelines.

Aluminum pipes came with tolerances, while PE100 pipes did not. However, because the PE100 material was machinable, the inside diameter could be turned to the desired tolerance. Aluminum had a higher density than plastic, and using aluminum would minimize the need for additional ballast. The process of producing aluminum would require melting alumina powder at high temperatures. This would be expensive, consume a lot of energy, and damage the environment. However, recycling aluminum into new aluminum products would be less damaging to the environment and only require 4 % of the energy needed to produce new aluminum. For PEHD, it would also be more cost-efficient to produce a product from recycled material than to produce the plastic first. When purchasing aluminum or PEHD pipes, it would not be known whether the material came from recycled or new material since the raw material would come from a third party, and the information would be difficult to acquire. According to Norsk Hydro ASA, an aluminum and renewable energy firm, aluminum would produce 3.4-3.9 kg of CO_2 per kg of aluminum produced [53]. On the other hand, PEHD would produce 1.6 kg CO_2 per kg PEHD produced [54]. One of the DFE guidelines stated the desire to use as few different materials as possible. PE100 was already selected for the ROV frame and based on the carbon footprint of the materials and the DFE guidelines, PE100 was selected for the float's cylinder.

Materials considered for the endcaps were PE100 and aluminum 6060. Both materials were machinable and could be turned from solid extruded bolts. It was possible to create high-precision threads, due to the materials' machinability. As shown in Table 5-8, aluminum had a density of 2.7 g/cm^3 and PE100 0.96 g/cm^3. Since aluminum had a higher density than water, it would sink, while PE100 would float. The aim was to make the float slightly negatively buoyant, and the aluminum could contribute to the weight, needing less ballast. Nonetheless, to obtain the desired buoyancy, adding ballast to a positively buoyant float would be easier than increasing the volume or adding flotation elements to a negatively buoyant float. Like for the cylinder, based on the DFE guidelines and environmental impacts, PE100 was selected for the endcaps. This fulfilled the DFE guideline of limiting the number of materials used in the products, to ease the recyclability of the products.

The inside structure and the support bracket would not be exposed to any large loads, and 3D printing was chosen as the production method. Materials considered were PLA and ABS, which both were commonly used in FDM. By using 3D printing as production method, the amount of waste would be reduced and this was a DFE goal. It was shown in Table 5-2 that PLA and ABS had similar densities, and that both materials would sink in water. PLA had a tensile strength of 49.5 MPa, which was slightly higher than ABS' 39 MPa. Neither the support bracket nor the inside structure would require large load-bearing capabilities or impact resistance; thus, both materials had satisfying strengths. PLA would be biodegradable under the right conditions, while ABS would not. However, both were recyclable, while ABS would have harmful emissions and PLA not. Since both materials would be acceptable considering material properties, PLA was selected due to its better impact on the environment. PLA was also easier to print and would be a wise choice because of the thesis team's lack of experience in 3D printing.

Table 5-9 compares the material properties of stainless steel [55], lead [56], and steel [57] found in MatWeb Material Property Data. The environmental impact of stainless steel [47] and lead [49] were found in online articles.

Table 5-9 Comparison of materials for the float's ballast

Properties	**Materials**		
	Stainless steel	**Lead**	**S355 Steel**
Density [g/cm^3]	7.86	10.22	7.80
Yield Strength [MPa]	275	18	355 (t=16mm)
Brinell Hardness [kJ/m^2]	147.0	4.2	170.0 (t=16mm)
Environmental Impact	Easy to recycle	Toxic	Recyclable
Pros	High strength to weight ratio	Denser than common metals	High strength to weight ratio
	Corrosion resistant	Corrosion resistant	Corrosion resistant (galvanized)
	High density		Easy to machine and weld
Cons	Expensive	Soft	Corrode in humid environment if not treated
	Difficult to machine and weld		

Lead had the highest density of 10.22 g/cm^3, compared to stainless steel's 7.86 g/cm^3, and S355 steel's 7.8 g/cm^3. Lead was the heaviest and would be the most space-efficient with the highest weight-to-volume ratio. Even though lead would be the most space-efficient ballast material, it was harmful to the environment and was ruled out. Steel also had a satisfying weight-to-volume ratio and was recyclable. Regular carbon steel would corrode in humid environments and had to be coated or alloyed. Stainless steel and galvanized steel were corrosion-resistant, but stainless steel was more expensive and difficult to machine than galvanized steel. Galvanized steel was, therefore, chosen as ballast material.

5.2.2 Cylinder

The PE100 pressure pipes selected for the cylinder were widely available and inexpensive. The pipes were extruded from granules and melted into a movable mold, making it possible to produce long pipes. The Pipelife catalog for PE Pressure pipes [58] was used to find the desired outside diameter for the cylinder. An outside diameter of 125 mm was selected based on the target specifications and ensuring space for inside components. According to Pipelife [59], for large-diameter piping, PE100 was an elastic material, and the E-modulus would vary with temperature, duration of loading, and the level of stress in the material. A PE100 pressure pipe at 20 ºC exposed to a pressure of 4 MPa for 1 hour had an E-modulus of 550 MPa. When an infinitely long pipe was subjected to external pressure, the Von-Mises buckling equation could be used to find the critical pressure [60].

$$P_{Critical} = \frac{2E}{(1-v^2)} * (\frac{t}{D})^3 \tag{9}$$

Solving for t, the minimum wall thickness due to critical pressure could be found. The cylinder was regarded as an infinitely long pipe as a worst-case calculation. The Eq. (7) was used to find the critical pressure at 10 m depth (P_{10}) in Chapter 4.6.2, and it was 199130.7 Pa. Minimum thickness of the cylinder to withstand the pressure

$$t = \sqrt[3]{\frac{P(1-v^2)}{2E}} * D = 6.53\ mm$$

where $P = 0.199\ MPa$, $v = 0.46$ for PEHD [61], $E = 550\ MPa$, $D = 0.125\ m$. The wall thickness of 6.53 mm was used as a guidance when selecting pipe sizes for FEA.

5.2.3 Endcaps and Sealing

PE100 was selected for the endcaps and had to be CNC-turned to obtain the desired shape. The turning was outsourced to Bryne Plast[3]. For sealing, O-rings were chosen because they would result in good waterproofing and were easy to use, satisfying the customer need regarding watertightness. PE pipes would not have accurate tolerances and would often be slightly oval-shaped from storage. Therefore, obtaining a good seal between the endcap and the pipe was challenging. The solution was to design the diameter of the endcaps a little larger than the inner diameter of the pipe and then turn the pipe's inside to the desired tolerance. The endcaps and the O-ring groove were dimensioned using the *Parker O-Ring Handbook* [62]. The O-ring seal was static, meaning adjacent sides were not moving relative to each other. The O-ring and O-ring groove could be placed on the outside of the bolt, called a male gland. Alternatively, it could be placed on the inside of the cylinder, called a female gland, as illustrated in Figure 5-19. It was easier to manufacture the O-ring groove on the endcaps than inside the cylinder, and thus a male gland was chosen. A general requirement was to use a parbak gland or a backup ring when pressure exceeded 103.5 bars [63]. This was not required in this year's float since the external pressure would not exceed 103.5 bars. The catalog suggested using an industrial static seal gland for radial design to obtain the proper O-ring stretch, squeeze, and gland fill. Figure 5-19 was used to find the needed measurements to dimension the O-ring groove and select an O-ring size [62].

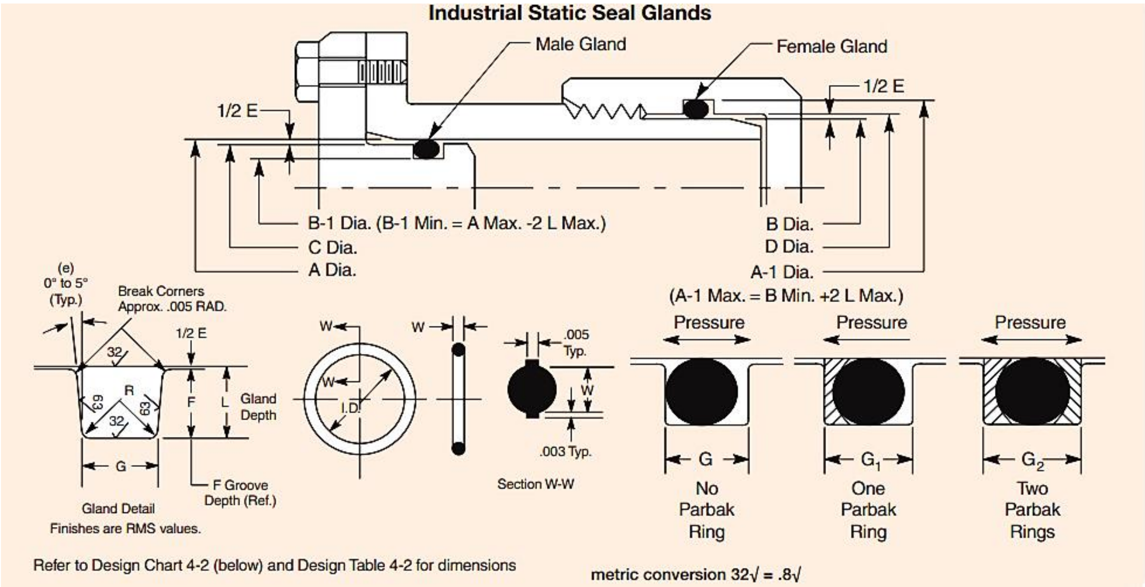

Figure 5-19 Industrial static seal glands from the Parker O-ring Handbook

[3] www.bryne-plast.no

Dimensions and tolerances for the endcaps and cylinder are listed in Table 5-10, and the O-ring size Parker O-ring 2-246 was chosen based on the table values. To squeeze the O-ring correctly, the plug diameter would have to be machined to $4.747^{+0,000}_{-0,001}$ inches ($120.57^{+0,000}_{-0,0254}\ mm$), and the inside diameter of the pipe machined to $4.750^{+0,002}_{-0,000}$ inches ($120.65^{+0,0508}_{-0,000}\ mm$).

Table 5-10 Metrics for the O-rings

Description	Symbol	Value
Inside diameter pipe		115.4 mm ≈ 4.484 inches
O-ring diameter	W	0.2 inches
Inner diameter (diameter of whole O-ring)	I.D.	ID 4.747 ± 0.030 inches
Inside diameter of cylinder	A-Dia	$4.750^{+0,002}_{-0,000}$ inches
Width of O-ring groove	G	$0.187^{+0,005}_{-0,000}$ inches
Plug diameter (endcap diameter)	C-Dia	$4.747^{+0,000}_{-0,001}$ inches

The *Seal Engineering's Technical Handbook* [64] was used to select material for the O-ring. Nitrile rubber was an elastomer and the most common O-ring material. It would provide a good seal at moderate pressure and temperature in water. The thermoplastic FL5 had particularly good resistance to chemicals, among them chloride. The FL5 was not in stock, but after consulting Seals Engineering[4], it was established that nitrile rubber was sufficient due to the low concentrations of chloride in the pool and the limited exposure time.

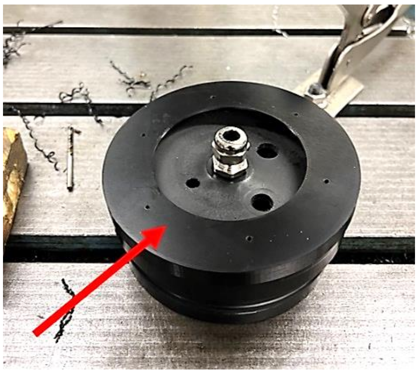

Figure 5-20 Hole transfer template

M4 socket cap bolts were used to fasten the support bracket to the bottom endcap. The endcaps were hand-threaded in the workshop. The 3D printed template shown in Figure 5-20 was designed to correctly transfer the holes for fastening onto the bottom endcap. A 3.3 mm drill bit for M4 treads was found in the Thread table [65]. Holes were pre-drilled with a thinner drill bit before the tread tap was used for threading. The float needed five cable penetrators, and it was decided to place them on the endcaps since they had a flat surface. To complete the MATE competition task, the top of the float had to reach the surface, and the bladder was placed at the float's bottom to ensure this. To accomplish the customer needs, the pressure sensor, power switch, and sensor switch contained electrical cords and were placed on the bottom endcap to ensure easy assembly, disassembly, and maintenance. The pressure release

[4] www.sealengineering.no

valve was cordless and was placed on the top endcap. The endcaps were preordered without holes because of delivery time. Holes for the penetrators were later manufactured in the workshop by the technical drawings displayed in Appendix E, Figure E-2, and Figure E-3. To ensure a tight fit between penetrators and troughing, 0.1 mm was added to the penetrator holes' diameter. When deciding on the placements of the holes, space for tools was taken into account. Figure 5-21 shows the 3D models of the endcaps from different angles.

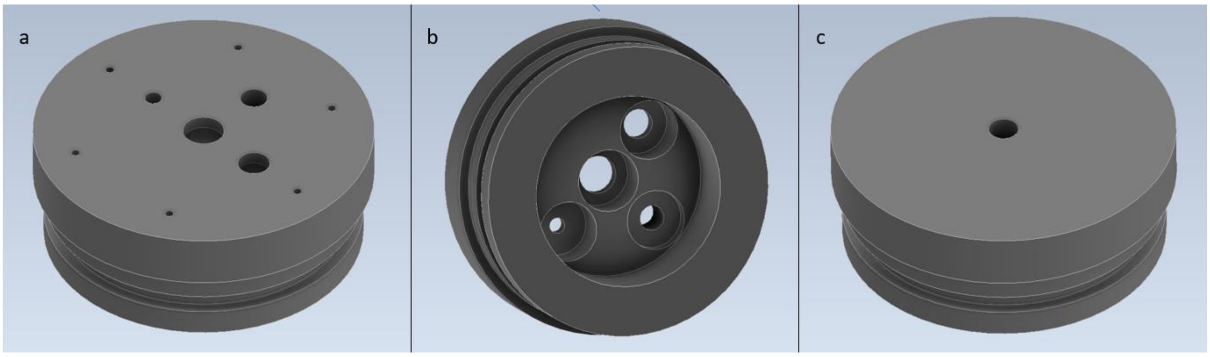

Figure 5-21 Bottom endcap front(a) and back view(b), and top endcap(c)

5.2.4 Structural Analyses Float Assembly

FEA was performed on the float assembly finding Von Mises stress, displacement, and safety factor to dimension the cylinder and ensure the float's resistance to the experienced pressure. The minimum wall thickness of an infinitely long pipe found in Chapter 5.2.2 was 6.53 mm and was used to select pipe sizes for the FEA. Since the length of the cylinder was less than 1 m, pipes with a wall tackiness of 3.1 mm to 7.4 mm were selected for the analyses to examine whether the wall thickness could be less than 6.53 mm for shorter pipes. The external pressure of 199131 Pa at 10 m depth was added to all surfaces. The yield strength of the PE100 endcaps was 23 MPa. The breaking strength of the PE100 pipe for the cylinder was found in the Pipelife catalog [66] and varied with the wall thickness from 5.12 MPa to 12.8 MPa, including a design factor of 1.6. The breaking strengths of each pipe size are listed in Table 5-11. Assuming that the float was descending, a fixed constraint was applied to the bottom endcap. The endcaps and cylinder were bound at the cylinder's rim, and all other surfaces were chosen as sliding with no separation. Analyses were performed for five different wall thicknesses, and the results from the analyses are exhibited in Table 5-11.

Table 5-11 Results from FEA of the SDR pipe sizes

Pipe Size	Outer Diameter [mm]	Wall Thickness [mm]	Breaking Strength [MPa]	Max Von Mises Stress [MPa]	Max Displacement [mm]	Safety Factor
SDR 41	125	3.1	5.1	4.4	0.31	1.17
SDR 33	125	3.9	6.4	4.4	0.31	1.46
SDR 26	125	4.8	8.0	2.8	0.27	2.86
SDR 21	125	6.0	10.1	2.3	0.22	4.31
SDR 17	125	7.4	12.8	1.9	0.18	6.79

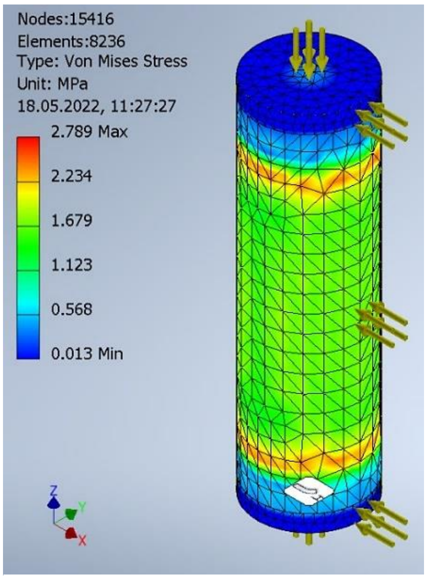

Figure 5-22 Von Mises stress in the float

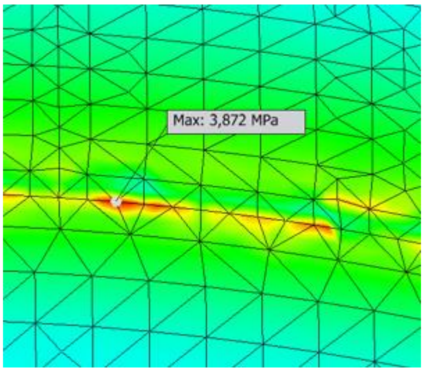

Figure 5-23 New maximum Von Mises stress in the float

The pipe with a wall thickness of 3.1 mm was subjected to a Von Mises stress of 4.4 MPa. The breaking strength of the pipe was 5.1 MPa and had thus a safety factor of $N = \frac{5.12\ MPa}{4.376\ MPa} \approx 1.17$. The safety factor preventing fracturing should lie between 2.0-3.0 [24], and because of this, the pipe with the thinnest wall was discarded. The pipe size SDR 33 had a safety factor of 1.46, which would be insufficient, and this pipe was also discarded. The cylinder with a wall thickness of 4.8 mm had a maximum Von Mises stress of 2.8 MPa where the cylinder had been turned, as shown in Figure 5-22. This was the location subjected to the highest stress, and the mesh was adjusted to be finer, with an element size of 2 mm. The new maximum Von Mises stress was then 3.9 MPa, Figure 5-23. The maximum stress the pipe could be exposed to before fracturing was 8 N, which gave a safety factor of $N = \frac{8\ MPa}{3.87\ MPa} \approx 2.86$, enough to prevent fracturing. The maximum displacement, located at the top endcap, was 0.27 mm, Figure 5-24, which was minimal. The bottom endcap had no displacement due to the fixed constraint. The endcaps were subjected to a Von Mises stress of 0.6 MPa, and the endcaps had a yield strength of 23 MPa and thus no risk of yielding.

The pipe size SDR 26 with a wall thickness of 4.8 was selected for the cylinder. This pipe could withstand the pressure at 10 m depth, and there would be enough material for turning to ensure a tight fit between the cylinder and the endcaps. The selected pipe achieved the ideal values of the target specifications regarding length, diameter, and yield strength. More illustrations from FEA of the different pipe sizes are found in Appendix F, Figure F-1.

Since suppliers only delivered pipes with 6 m length, the local entrepreneur Hervik Rør[5] was contacted and agreed to sponsor with a 2 m cut-off for the project. The cylinder was cut, and both ends turned to fit the endcaps' tolerances. The technical drawing is exhibited in Appendix E, Figure E-4.

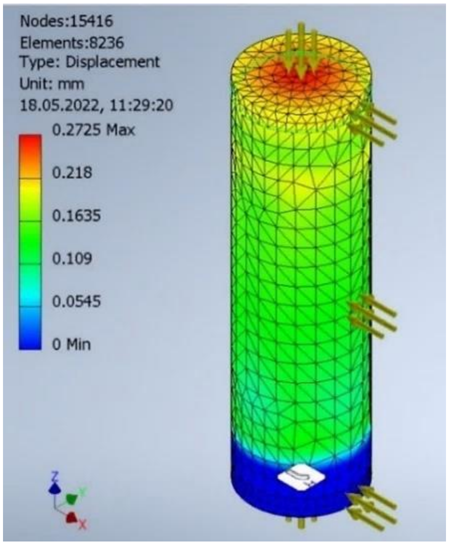

Figure 5-24 Displacement in the float

5.2.5 Inside Components

After deciding on the pump-valve mechanism for the buoyancy engine, the components and arrangement of components were selected. The pump needed a minimum capacity of 199130.7 Pa at the desired depth. It also had to meet the electrical specifications with a maximum of 12 V. Several pumps were considered, but ordering from outside Europe was not desirable due to the DFE guidelines and uncertain in delivery time. Some pumps were excluded due to price or low pumping pressure. The solution was a vacuum pump delivering 3 bars and a pumping speed of 9-15 L/min. The pump was a membrane pump preventing air from leaking the opposite way.

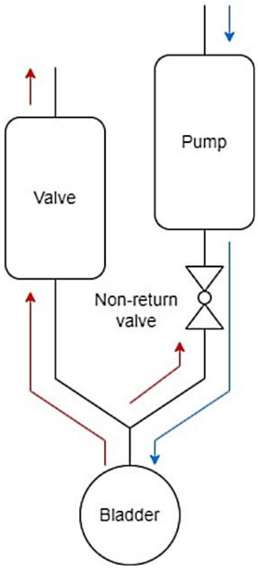

Figure 5-25 Buoyancy system

The electrical team chose a solenoid valve to let air back into the float when the bladder deflated. The fluid path was followed to find the rest of the components needed, Figure 5-25. A non-return valve was connected to the system on the pump side as an extra precaution. The non-return valve prevented air from flowing back from the bladder through the pump and into the float. All components were selected to fit together to make the system leakproof. The hose connectors were reinforced with miniature hose clamps to ensure that the system was airtight. All components in direct contact with water had an ingress protection (IP) grade of IP68. This grade was rated to be dust-tight and

[5] hervik.no

could be completely submerged in water. Table 5-12 shows all the components in the buoyancy system with specifications.

Table 5-12 Specifications of the components in the buoyancy system

Parts	No.	Total Mass [g]	Dimensions [mm]	Details
Batteries	8	1000	D=30, L=60	1.5 V
Battery brackets	2	166	L=90, W=30, H=140	
Bladder	1	10		
Blanking plug	1	10	D=7, L=5	M5 male, brass with seal
Cable gland	1	19	D=19, L=30	Cable size 4 mm – 8mm, IP68, nickel plated brass
Circuit board	1	19	L=90, W=100, H=10	
Cords		50		
Microcontroller	1	4	L=20, W=10, H=2	Placed on circuit board
Miniature hose clamp	11	26		6 mm – 9 mm
Non-return valve	2	14	D=15, L=30	OD 6mm, plastic, air valve, P_{open} > 1.0 kPa P_{max} > 0.3 MPa
Power switch	1	8	D=10, L=10	IP68
Pressure sensor	1	19	D=16, L=25	OD 10 mm, ID 6 mm, IP68, painted aluminum
Pressure release valve	1	19	D=18, L=25	OD 10 mm, IP68, painted aluminum
Silicone tube	1	26	D=8, L=100	OD 8 mm, ID 6 mm, L=1 m, silicone
Solenoid valve	1	120	L=27, W=27, H=71	12 V, 3 port, M5 female, air valve, low vacuum
Sensor switch	1	9	D=14, L=10	IP68
Thread to tube adapter	2	18	D=5, L=20	M5 male – 6 mm (OD), nickel plated brass, soft tubes, Pmax = 1.5 MPa
Tube T-connector	1	29	D=20, L=30	OD 7 mm, ID 5 mm, stainless steel
Vacuum pump	1	280	L=87, W=38, H=60	12 V, 12 W, 9-15 l/min, connection ¾” ≈ 6 mm, P = 0-2.2 bar, vacuum level: 0-16” Hg

5.2.6 Inside Structure

By creating estimated sizes of the inside components, Table 5-12, and arranging them inside the cylinder in Autodesk Inventor, the length of the cylinder was set to 40 cm. The float’s inside structure would be designed with a maximum diameter of 100 mm, leaving some space to pass cords on the sides.

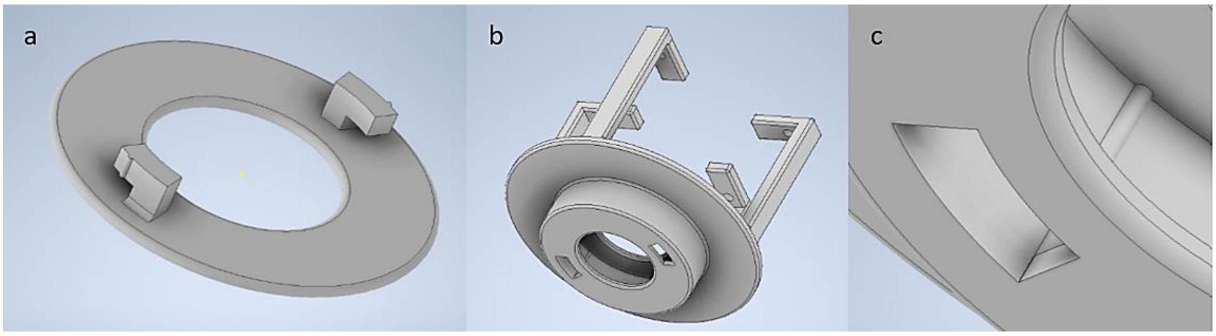

Figure 5-26 Design 1: Endcap bracket(a), ballast section(b) and closeup ballast section(c)

When designing the inside structure, it was given attention to ease the assembly, disassembly, and maintenance. The float was designed to remove the top endcap and cylinder as one piece. The inside structure was self-supported and rested on the bottom endcap, making maintenance, testing, and adjustments easy. Two designs were considered to secure the inside structure to the bottom endcap, designs 1 and 2, as illustrated in Figure 5-26 and Figure 5-27 a, respectively. In design 1 the inside structure was secured by a place and turn solution. The endcap bracket, Figure 5-26 a, was fastened to the endcap, Figure 5-26 b, then the ballast section was placed on top and turned to secure it. The small extrusion, Figure 5-26 c, was created to prevent the inside structure from loosening. Design 2's inside structure was separated into one ballast and one component section and comprised the components illustrated in Figure 5-27. This design only used a tight fit between the ballast section and the endcap for securing and would only work when the float was positioned upright, not upside down. Design 1 had the advantage of securing the inside structure completely, even when upside down. However, the place and turn solution was fragile and had a significant risk of breaking during assembly and disassembly. Since the structure was a costume-made part, no replacement could be found quickly during the competition. It was also a poor design for production since it was difficult removing the support material from the 3D print. Therefore, design 2 would be the best option. This design only used a tight fit to secure the structure, and the method would thus be easy and effective.

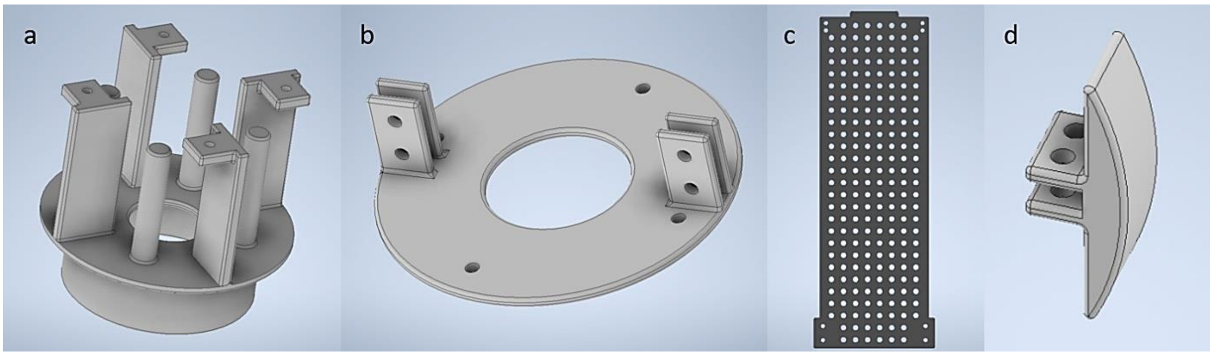

Figure 5-27 Design 2: Ballast section(a), divider(b), component plate(c), rocker bracket(d)

Design 2's ballast section was designed to prevent ballast from moving around inside the float during task execution and transportation. This section was located at the bottom of the structure to lower the CG and ensure the float's stability. It was divided into four sectors that allowed specific adjustment of stability in the required direction. Hand-cut steel would be the most space-efficient ballast, but because of the project's time limitation, it was decided to use galvanized steel washers. Cable ties were used to fasten all the components to the component plate since this was a safety requirement in the competition. The component plate was held in place by rocker brackets fitting the cylinder. The inside structure would not be in direct contact with water but could risk being subjected to water. Hence, it was desirable to have some corrosion-resistant fasteners. Stainless steel had better corrosion resistance than galvanized steel, but it was also more expensive. Since the structure would not be in direct contact with water, it was decided that galvanized fasteners were sufficient. M3 galvanized slotted machine screws were used as fasteners. Since there was no movement in the inside structure and it was not subjected to any large loads, lock nuts were not necessary, and hex nuts were used. The inside structure was 3D printed using FDM at UiS, with an infill of 20 % since the structure would not be in direct contact with water.

5.2.7 Support Bracket

A support bracket, Figure 5-28, was designed to make the float stable on land and the pool bottom and to protect the bladder, pressure sensor, and switches from damage. The cable connector for the buoyancy bladder protrudes 2 cm from the bottom endcap. This made the float unstable and prevented it from keeping an upright position on land or at the pool bottom. The plastic bladder and switches were also exposed and could easily be damaged when transported or upon impact with the pool bottom. The support bracket would help guide the bladder when inflating, preventing it from sliding to either side and shifting the float's CB. Autodesk Inventor was applied to remove material from the bracket to reduce the float's weight, drag, and material use. To fasten the support bracket to the endcap, M4 stainless steel socket cap bolts were utilized. The bolts would be in direct contact with water, and stainless steel was chosen because of its corrosion resistance. Counterbore hole dimensions were found to fit the M4 bolts [67].

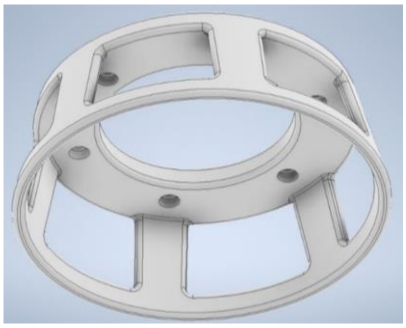

Figure 5-28 Support bracket

FEA was conducted to examine the stresses and displacements the support bracket experienced when the bracket was mounted to the float and standing on land. The float's weight of 55 N was added at the bracket's top surface. PLA, with a tensile strength of 49.5 MPa, was assigned to the bracket, and a fixed constraint was set at the bottom of the bracket. The analysis resulted in a maximum Von Mises stress of 0.65 MPa, located at the bracket's inside, as shown in Figure 5-29. Figure 5-30 illustrates the maximum displacement of 0.017 mm located at the inside of the rim. Using PLA's tensile strength, the safety factor of the bracket was $N = \frac{49.5\, MPa}{0.6518\, MPa} \approx 76$. This safety factor was extremely high, and the thickness of the bracket could have been reduced. However, the tensile strength of 49.5 MPa applies to 3D printed PLA with 100 % infill, and the bracket was printed with 50 % infill. It would therefore have weaker material properties and a lower safety factor. The infill percentage was chosen to be 50 % since the support bracket would be in direct contact with water, and a higher infill percentage would limit the water absorption. The normal setting for FDM 3D printing was 10 % infill. Using FDM as production method would result in a weaker component due to the layering. Since it was desirable to have a stable and durable float, it was decided to keep the tested thickness for the support bracket.

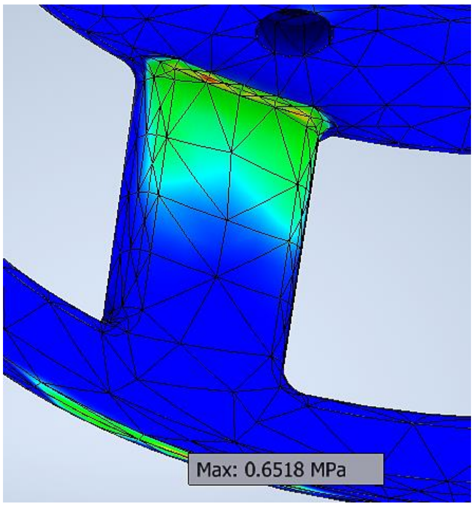

Figure 5-29 Maximum Von Mises stress in the support bracket

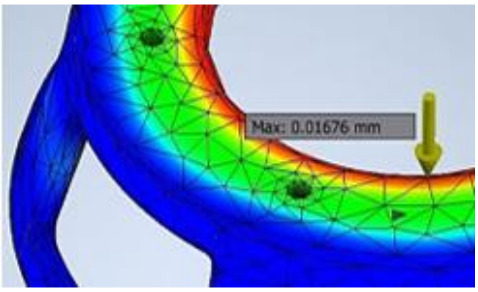

Figure 5-30 Maximum displacement in the support bracket

5.2.8 Buoyancy and Stability

The float would descend and ascend due to the change in buoyancy and not by an external power source. To descend when bladder was deflated, a negative buoyancy was required. The float's buoyant and weight forces were found to estimate how much ballast was required for the float to obtain a negative buoyancy of 1.5 N. The weight force of each part was found with Eq. (1), $F_g = mg$, where m was the mass of each part and $g = 9.81\ m/s^2$. The metrics of the designed parts, cylinder, endcaps and support bracket, were found in Autodesk Inventor, and the metrics of the purchased components in Table 5-12. The buoyant force was found with Eq. (2), $F_b = \rho g V$, where the density of displaced water was $\rho = 997\ kg/m^3$ and V the volume of each part. The volume of displaced water due to the purchased components was approximately zero, affecting the total volume marginally.

Table 5-13 Buoyancy statement for the float

Part	Mass of Parts [g]	Weight of Parts [N]	Volume of Displaced Water [cm^3]	Mass of Displaced Water [g]	Buoyant Force [N]	Buoyancy [N]
Cylinder	1123.9	11.0	4908.7	4894.0	48.0	37.0
Bottom endcap with O-ring	385.0	3.8	245.4	244.7	2.4	-1.4
Top endcap with O-ring	385.0	3.8	245.4	244.7	2.4	-1.4
Support bracket	49.0	0.5	118.8	118.4	1.2	0.7
Cable gland	19.0	0.2	0.0	0.0	0.0	-0.2
Power switch	8.0	0.1	0.0	0.0	0.0	-0.1
Pressure sensor	19.0	0.2	0.0	0.0	0.0	-0.2
Pressure release valve	19.0	0.2	0.0	0.0	0.0	-0.2
Sensor switch	9.0	0.1	0.0	0.0	0.0	-0.1
Components (not displacing water)	1772.0	17.4				-17.4
Inside structure	159.0	1.6				-1.6
Fasters and nuts	11.0	0.1				-0.1
Total	**3958.9**	**39.0**	**5518.3**		**54.0**	**15.0**

As shown in Table 5-13, the float had a net buoyant force of 54.0 N and a net weight force of 39.0 N without ballast, resulting in a positive buoyancy of 15.0 N. To obtain a negative buoyancy of 1.5 N, the ballast was required to be $\frac{15.0+1.5}{9.81} = 1.7\ kg$.

When the float was submerged, its righting moment would always orient the float for the CB to be directly above the CG. Therefore, CB was required to be above CG to prevent the float from flipping upside down, leading to a stable float in water. Furthermore, since the float only made vertical profiles and did not maneuver, stability would increase with larger vertical distance between CB and CG. An object's CB would be located by finding the CG of the object's shape with water's density. Since the float was cylindrical, CB would be in the float's center. CG was the average location of an object's mass, and an object with uniformly distributed mass would have the CG in its geometric center. The float assembly consisted of components with different shapes and masses. For easier calculations, assumptions were made. The mass of all components was assumed to be uniformly distributed, and the shapes

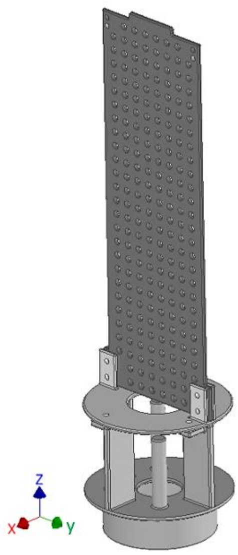

Figure 5-31 Coordinate system for the float

were estimated by choosing the closest geometrically known shape. Calculations were performed in Autodesk Inventor and by hand. Positions were calculated in mm coordinates, where the origin was chosen to be underneath the bottom endcap's center. In design 1, Figure 5-31, the component plate was placed along the y-axis and the batteries were located at the side facing the negative x-direction. All other components were placed opposite the batteries in positive x-direction. Each part's mass and the distance from the origin to the part's centroid are listed in Table 5-14.

Table 5-14 Weight statement for the float

Parts	Centroid Coordinates			
	Mass [g]	CGx [mm]	CGy [mm]	CGz [mm]
Cylinder	1124	0	0	40
Bottom endcap with O-ring	385	0	0	20
Top endcap with O-ring	385	0	0	420
Support bracket	49	0	0	-25
Ballast section	78	0	0	61
Divider	24	0	0	114
Component plate	57	0	0	254
Battery x8 and battery brackets x2	1166	-30	0	249
Cable gland and bladder	19	0	0	10
Circuit card and microcontroller	39	20	0	338
Cords	50	10	0	220
Non-return valve and hose clamp x2	19	25	20	234
Power switch	8	0	30	0
Pressure sensor	19	20	0	10
Pressure release valve	19	0	0	430
Sensor switch	9	0	-30	0
Silicone hose	26	5	0	200
Solenoid valve, hose clamp x2, thread to tube adapter x2, and blanking plug x1	141	25	20	234
Tube T-connector and hose clamp x3	39	20	-30	240
Vacuum pump and hose clamp x2	292	32.5	-15	157
Fasteners x10 and nuts x10	11	0	0	81
Ballast	1700	0	0	81
Total	5659			

Eq. (4) was used to find the CG in the x, y, and z-directions.

$$X_{CG} = \frac{\sum xm}{\sum m} = \frac{-19820}{5659} = -3.5\ mm$$

$$Y_{CG} = \frac{\sum ym}{\sum m} = \frac{-2110}{5659} = -0.4\ mm$$

$$Z_{CG} = \frac{\sum zm}{\sum m} = \frac{794431.9}{5659} = 140.4\ mm$$

Eq. (5) was used when calculating CB in the x, y, and z-directions.

$$X_{CB} = \frac{\sum xm}{\sum m} = 0\ mm \qquad Y_{CB} = \frac{\sum ym}{\sum m} = 0\ mm \qquad Z_{CB} = \frac{\sum zm}{\sum m} = \frac{1185696.55}{5488.12} = 216\ mm$$

The results showed that CGz was 75.6 mm lower than CBz, which led to a significant righting moment that would make the float stable. The mass was shifted 3.5 mm in the negative x-direction and 0.4 mm in the negative y-direction. The instability would be adjusted by moving some of the ballast from these sides to the opposite sides before testing in water.

5.2.9 Time and Velocity

According to need number 7, the float had to complete two vertical profiles within 10 min. Therefore, it was essential to determine the time the float would take to descend to the pool bottom and then ascend. The time descending and ascending would differ due to the float's buoyancy difference. The depth of the pool in the competition was 4 m.

Velocity descending

The float's velocity had to be found to determine the time it would take to complete two vertical profiles. When descending, the float would start with zero velocity and then accelerate due to the gravitational acceleration until the float reached terminal velocity. Terminal velocity is an object's maximum velocity when descending through a fluid. When reaching terminal velocity, acceleration would be zero, and the velocity constant. To ease computations, the float was assumed to descend with terminal velocity the entire distance from the surface to the pool bottom. The terminal velocity would provide an approximation of the float's velocity and the time it would take to reach the bottom.

Several forces would act on an object descending. The weight force would pull the object down, and the buoyant force would push it up. The velocity would work in the motion direction, which in this case would be downward, and the drag force, in the opposite direction, upward. Terminal velocity would be reached when the drag (F_d) and buoyant forces (F_b) were equal to the weight force (F_g). The drag force of the float with deflated bladder was

$$F_d + F_b = F_g$$

$$F_d = mg - \rho g V_{deflated} = 1.46\ N$$

where $m = 5.65\ kg$ and $V_{deflated} = 5.518 * 10^{-3}\ m^3$. The terminal velocity was found solving Eq. (3) for velocity.

$$v_{descend} = \sqrt[2]{\frac{2F_d}{\rho C_d A}} = 0.54\ \frac{m}{s}$$

where $C_d = 0.82$ for a long cylinder and $A = 0.0123\ m^2$ for the projected float area. The approximated terminal velocity of 0.54 m/s was the maximum velocity the float could reach. Due to the time to reach terminal velocity, the float's actual velocity would be less. The definition of velocity, solved for time, was used to find the time to descend to the bottom of a 4 m (s) deep pool.

$$t = \frac{s}{v_{descend}} = 7.4\ s$$

7.4 s would be the minimum time for the float descending. In reality, it would take longer.

Velocity ascending

For the float to ascend, the bladder had to be inflated to obtain a positive buoyancy. The float's volume with an inflated bladder of 3.05 dL was

$$V_{inflated} = V_{deflated} + V_{bladder} = 5.823 * 10^{-3}\ m^3$$

where $V_{deflated} = 5.518 * 10^{-3}\ m^3$ and $V_{bladder} = 3.05 * 10^{-4}\ m^3$. When ascending, the buoyant force would still act upward and weight force downward. However, since the motion direction would be upward, the drag force would act downward.

$$F_b - F_d = F_g$$

$$F_d = F_b - F_g = \rho g V_{inflated} - mg = 1.53\ N$$

Assuming the bladder was instantly filled with 3.05 dL, the float's velocity would be

$$v_{ascend} = \sqrt[2]{\frac{2F_d}{\rho C_d A}} = 0.55\ \frac{m}{s}$$

The approximation of the float's velocity ascending from the pool bottom was 0.55 m/s. The definition of velocity was used to find the time to reach the surface of a 4 m (s) deep pool.

$$t = \frac{s}{v_{ascend}} = 7.3\ s$$

7.27 s would be the shortest time the float would spend ascending. By choosing 12 s between the ascends and descends, the approximated time to complete two vertical profiles would be 77 s at the fastest. A doubling of the time estimate would give 2.5 min for the float to complete the vertical profiles. This would add a margin for assuming terminal velocity as the float's constant velocity. The float would most likely use less than 2.5 min to complete the vertical profiles, which would be well within the customer need of 10 min.

5.2.10 Product Cost

Table 5-15 shows the product cost for one float, including VAT, excluding the pump's electrical components: vacuum pump, solenoid valve, pressure sensor, cords, switches, and circuit card. These components were bought by the electrical team using their budget. Most components for the float were bought by the thesis members using the budget of the ROV and float. All the 3D printed parts, the pipe, and the O-rings were sponsored. The price per unit would have been reduced if more floats were produced due to shipping costs and components delivered in multipacks. In addition, the cylinder would generally come in a standard length of 6 m. Combining the cost of the purchased parts for the ROV and the float, the team managed to stay within the budget.

Table 5-15 Product cost of the float

Components	Value [NOK]	Sponsored
Cylinder	232	Hervik Rør
Endcap x2	2188	NA
3D printed inside structure and support bracket	400	University of Stavanger
O-rings and consultation	1000	Seals Engineering
Ballast	400	NA
Blanking plug*	8	NA
Cable gland*	44	NA
Miniature hose clamp x7*	105	NA
Non-return valve	39	NA
Nuts M3 x12	25	NA
Plastic cable ties	60	NA
Pressure release valve*	90	NA
Silicone tube 1m*	69	NA
Slotted machine screws M3 x12	25	NA
Socket cap bolts M4 x6	38	NA
Thread to tube adapter x2*	28	NA
Tube T-connector*	46	NA
SUM	**4797**	

*Delivery fee in addition

6 Product Development Process - Testing and Refinement

The products were produced, tested, revised, and improved in the testing and refinement phase. All components were drawn in Autodesk Inventor and were not ordered from retailers before it was certain that they would fit together, and the analyses gave satisfying results. It was only produced prototypes of some 3D printed parts, and all 3D printed parts were improved as much as possible before printing to minimize the need for prototypes. The products' potential environmental impact was assessed, and the products were compared to the DFE goals. When assessing the environmental impact of the ROV frame and float, the material chemistry, disassembly, and recyclability were considered. The assessment only took into account the components of the ROV and float that were developed during this thesis. Possible improvements for the products were also discussed.

6.1 ROV

The testing of the ROV included assembling the frame and the components mounted to it and testing in water. During the modular testing, the frame's stability was inspected, and during testing in water, the ROV's buoyancy, stability, maneuverability, free flow, and drag were examined.

6.1.1 Assemble and Modular Testing

After the components for the frame had been manufactured in the workshop, 3D printed and delivered from sponsors, the frame was ready for assembling. The frame could be fastened using either bolts and nuts or bolts and threads in the PEHD plates. The frame should be able to be assembled and disassembled multiple times, and this would be a problem with the threads. Threads in plastic plates would wear over time, and the bolts would eventually have problems fastening the plates together. The frame was therefore fastened using M4 A4 stainless steel socket cap bolts, nuts, and washers. The idea was first to use only bolts and lock nuts and examine whether this was sufficient. After assembling the frame once, it was visible that the bolts went into the PEHD plates and the thruster brackets if tightened too hard. It was, therefore, decided to use washers to increase the frame's life and durability.

The frame was assembled in a modular manner based on the four PEHD plates. Instructions on assembly order and which components should be assembled on each plate are given under.

1. **Top plate:** 1 stiffener, 2 brackets for el house with 8 metal angles, 2 light mounts, 2 canal for wires

   2 side plates: 4 vertical thrusters, 4 thruster brackets with 4 horizontal thrusters

   Bottom plate: 2 stiffeners, manipulator with 2 stiffening brackets
2. Fasten the side plates to the bottom plate by the thruster brackets and the stiffeners
3. Fasten the top plate to the side plates by the thruster brackets and the stiffener
4. Fasten the stiffening brackets to the brackets for el house
5. Fasten the rear-end camera and 2 light mounts
6. Insert and fasten the electronics house

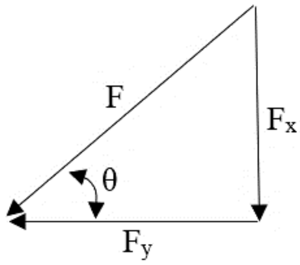

Figure 6-1 Decomposition of the thrust force

Assembling the ROV frame was easy and effective and required few tools, and fulfilled thus these target specifications. When the frame was assembled, it was visible that it was slightly unstable in the y-direction. Some sideways motion was detected in the structure when the frame was jiggled in this direction. Keeping the frame as was would have been acceptable since it would be sufficiently stable in water and on land. The frame would only be unstable if forces were applied in the y-direction. The ROV was not subjected to forces like this, except for the decomposed horizontal thrust force $F_y = F * sin\theta = 35N * sin(45°) \approx 24.75N$. The decomposition of the thrust force seen from above is illustrated in Figure 6-1. This was calculated and deemed okay by FEA during the detail design phase. Even though the frame was not subjected to any large forces in the y-direction, it was desired to improve the stability to meet the customer needs. It would increase the ROV's impact resistance and make it more durable and rigid in all directions. The frame was already very stable and rigid in the z- and x-directions but needed support in the y-direction to prevent sideways motion when forces were applied in this direction. There were only around 20 mm between the manipulator and the brackets for the el house. Therefore, it was decided to 3D print stiffening brackets in PLA, as illustrated in Figure 6-2 a, since the frame almost already had a beam in the middle. Together with the manipulator's aluminum frame and the brackets for the el house, the stiffening brackets would form two vertical support beams in the middle of the frame. This was the first and easiest option and attempt to stiffen the frame in the y-direction, and is illustrated in Figure 6-2 b.

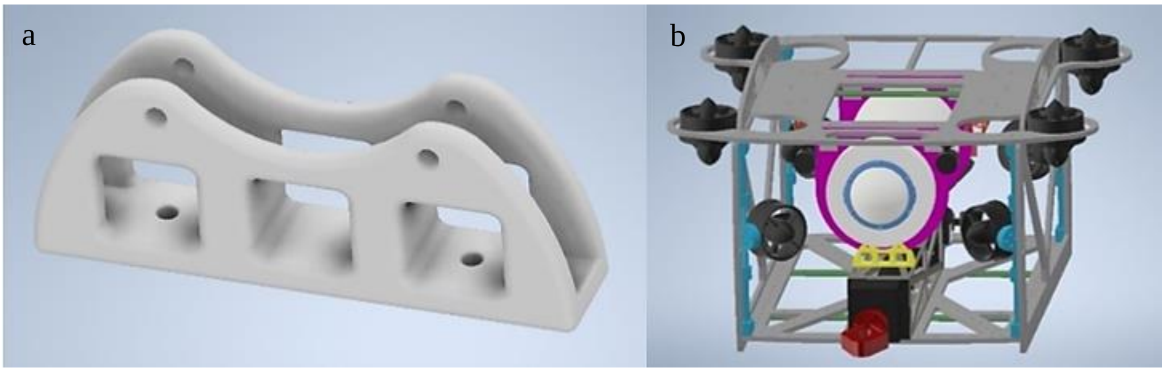

Figure 6-2 Stiffening bracket(a), stiffening bracket in frame(b)

After the stiffening brackets were attached, the frame's stability in the y-direction improved significantly and no sideways motion was detected when jiggled. The frame was rigid and stable in all directions, and the impact resistance and durability had thus been improved. Another stiffener was attached further back at the bottom plate to prevent bending since some more weight would be distributed underneath the brackets for the el house.

6.1.2 Testing in Water

Through testing in water, many of the metrics in the target specifications assigned the unit "Subj." were tested and verified. This included drag, maneuverability, and free flow. Distance between CBx and CGx was also adjusted during the testing and would regulate the buoyancy and stability of the ROV.

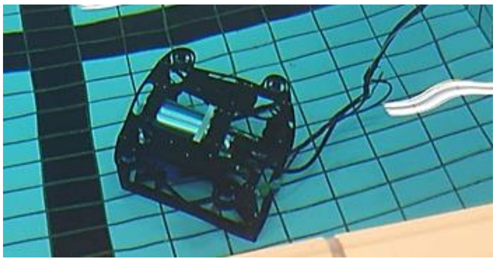

Figure 6-3 The ROV's firsts test in water

In the mission statement, it was stated that one of the key business goals of UiS Subsea was to have the ROV ready for testing in water by April 15th. This date was in the middle of Easter, and the date was moved to April 19th. All components for the frame were ordered or manufactured to be ready by April 4th. This would leave one week to assemble the frame and one week for the other groups to attach the rest of the components before April 15th. Some delays in manufacturing the electronics house and the manipulator caused the ROV's first test in water to be postponed to April 25th. This test, Figure 6-3, was short due to leakage in the electronics house, but while the ROV was in the water, stability was considered. The rear-end camera was not mounted during this test, and the manipulator was not ready, but its aluminum frame was fastened. This affected the buoyancy and stability results. However, as expected from the buoyancy and stability calculations, the righting moment caused some tilt in the pitch direction, and the ROV's fore turned upward. The frame was stable in the roll direction, as anticipated, due to the focus on symmetric components and symmetric placement of components. During the following tests, the righting moment was corrected by ensuring that CBx and CGx were on the same vertical axis. This was done by adding ballast on the bottom plate's front and floatation elements on the top plate's back, as illustrated in Figure 6-4.The intended manipulator was not completed in time for the rest of the tests in water, and the buoyancy and stability corrections were performed using a backup manipulator weighing 1383 g. The ROV weighed 25.4 kg and should thus have a buoyancy of $1.5\ \% * mg = 1.5\ \% * 25.4 * 9.81 \approx 3.74\ N$. From the testing in water, it was calculated that the ROV needed a buoyancy element with a net buoyancy of around 19.4 N in the aft and 550 g ballast in the fore. The buoyancy element was designed in Autodesk Inventor, as illustrated in Figure 6-5 in red on the top plate, to obtain the required buoyancy.

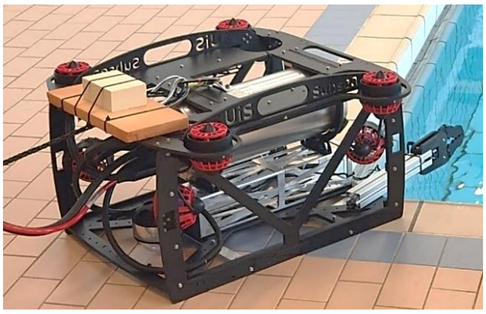

Figure 6-4 The ROV adjusted with ballast and buoyancy element

Figure 6-5 The ROV with buoyancy element

After the stability and buoyancy adjustments, the maneuverability, drag, and flow through the frame and thrusters were examined. The ROV's aspect ratio was $\frac{Mean\ length}{Mean\ width} = \frac{661.5}{466} \approx 1.42.$ Hence, the shape of the ROV corresponded to the middle ROV in Figure 2-6, which implied good station holding capabilities and horizontal maneuverability. It was verified whether the ROV could maneuver in all six degrees of freedom. After adding ballast and a buoyancy element, the ROV was very stable in water, had great station-holding capabilities, and maneuverability in the surge, heave, sway, yaw, pitch, and roll directions, thus all six degrees of freedom. The thrusters could easily overcome the drag force, and the target of minimizing drag was therefore successful. Since the ROV had excellent maneuverability and the thrusters easily overcame the drag, free flow through the frame and thrusters were indicated.

6.1.3 Asses Environmental Impact

When assessing the environmental impact of the ROV frame, the material chemistry, amount of waste, disassembly, and recyclability were evaluated only considering the components of the ROV developed during this thesis. The amount of hazardous or toxic materials and recycled content were estimated to find the material chemistry. During the material selection, measures were taken to prevent all toxic and hazardous materials. Nonetheless, the resin used to 3D print the thruster brackets was toxic before being cured, and the brackets were regarded as toxic during the environmental assessment. Based on Table 6-1, the percentage of toxic and hazardous materials in the frame was $\frac{365}{6597} * 100 \approx 5.5\ \%$, which was within the marginal value of the target specification but exceeded the ideal value. The amount of recycled content was challenging to measure. Due to limited time and resources, it was difficult to find retailers that sold or produced products from recycled content. The retailers bought raw materials from third parties, and the information regarding the materials was therefore difficult to obtain. The only components known to have been recycled and remanufactured were the aluminum components and the ballast. This accounted for $\frac{463+550}{6597} * 100 \approx 15.4\ \%$ of the frame's weight, thus exceeding the ideal value of the target specification but staying within the marginal value.

Table 6-1 Weight of parts in the frame

Part	Number of Parts	Mass of Parts [g]
PEHD plates	6	4145
Thruster brackets	4	365
Aluminum components	11	463
Buoyancy element	1	503
3D printed PLA	2	171
Ballast	4	550
Fasteners	100	400
Total	**238**	**6597**

Table 6-2 Waste of the ROV

Part	Mass [kg]
PEHD plates	6.79
Thruster brackets	0.05
Metal components	0.10
3D printed PLA	0.30
Total	**7.24**

The amount of waste could not be reduced as much as desired but tried to be minimized by the production methods and fewer prototypes. The PEHD plates would create waste due to their large openings, as exhibited in Table 6-2. The amount of waste during the production of the PEHD plates was estimated using Autodesk Inventor. Both the masses of the final plates and the workpieces were found by assigning the material PE100 and setting the correct dimensions. For all the plates, a rectangular workpiece was created that the plates could be manufactured from by water cutting. The waste for the plates was found by subtracting the masses of the final plates from the masses of the workpieces, and it resulted in a total waste of around 6.79 kg PEHD. This was a higher value than preferred but understandable due to the design of the plates. The aim was to minimize the weight of each plate, and consequently, material was removed everywhere possible. A consequence of this would be waste during manufacturing. Another production method, such as molding, had to be selected to reduce the waste during production. Having said that, molding the plates would require a mold that would have needed manufacturing first. This would cause more energy consumption and CO_2 emissions, and since the mold was only going to be used once, it would be disposed of afterward. The best production option to minimize waste for these plates would have been 3D printing, and SLA would have been used to ensure water resistance and durability. While this would have reduced the waste to 0 kg since no supports were needed, the resins were toxic before being cured and only recyclable if shredded and used in new products. It was better with more recyclable waste and components that could be recycled at the end of life, rather than zero waste, non-recyclable components, and a hazardous production if not the proper safety measures were taken.

The thruster brackets and the other 3D printed components had a relatively low amount of waste. This was also a reason why 3D printing was chosen as the production method. Unlike traditional manufacturing, 3D printing did not subtract material from a workpiece, and the only waste created during production came from supports. Since PLA and EPD 2006 had low densities, this was not much, and the weighing and approximations of the supports, prototypes, and failed prints were around 0.35 kg. As one of the DFE guidelines stated, an effort was made to minimize the number of prototypes to reduce waste, and the low value of waste by 3D printed PLA illustrated this. However, some 3D prints failed due to wrong settings and problems with the printers, Figure 6-6, which could have been avoided. The manufacturing of the metal components used traditional manufacturing like cutting, drilling, and bending. These processes caused some waste, but minimal compared to other subtracting processes like milling and turning. The estimated value of the metal waste was around 0.1 kg, which was relatively low. The total waste generated by the frame was approximately 7.24 kg during production. During recovery, the thruster brackets would most likely end up as waste if a substantial effort was not spent

Figure 6-6 Failed 3D prints

finding a recycling station that shredded cured plastics and used them to produce new products. Due to the time limit on this thesis, research on the possibilities of recycling the brackets was not performed. Therefore, the thruster brackets would have to be regarded as waste at the end of their life cycle, and 365 g of waste, found in Table 6-1, would be added. The total amount of waste for the ROV frame would be $7.24 + 0.365 \approx 7.60\ kg$. When establishing the target specifications, the ideal value of waste was set to under 5 kg and the marginal to 10 kg. The waste produced could not be pushed under the ideal value but was kept under the marginal value. Even though 7.60 kg of waste was produced, this might not be too bad if it was easily recyclable.

One of the ideal values for the target specifications was that the frame should be 90 % recyclable. PEHD, aluminum, stainless steel, PUR, and PLA were easily recyclable, and PEHD, stainless steel, and aluminum could be recycled multiple times without degrading quality. PLA was, in addition to being recyclable, also biodegradable. Stainless steel was used for the fasteners, like the ballast, due to its corrosion resistance. This material was 100 % recyclable, and a lot of the material on the market was manufactured from recycled content. Of the components in the frame, only the EPD thruster brackets had limited recyclability. They were possible to recycle if the correct recycling station and manufacturing plant were located. Due to the time limit on this project, this was not done, and the brackets was regarded as waste. The ROV frame would then be $\frac{(6597-365)}{6597} * 100\ \approx 94.5$ % recyclable, satisfying the target specification.

In theory, the frame’s recyclability was satisfactorily by the percentage of the frame’s weight recyclable. For the frame to be recycled in reality, it had to be easily disassembled and the materials separated and sorted. The disassembly could be measured in the percentage of materials that could be readily disassembled. All the frame components were fastened with M4 bolts, washers, and nuts that could easily be removed with standard hex tools such as an electric drill and a wrench. All components could, therefore, without difficulty, be separated and thus also all the materials. Hence the frame was 100 % readily disassembled, corresponding to the ideal value of the target specification.

Herman Miller’s DFE assessment tool evaluated the ROV and checked whether it was a C2C product. The DFE assessment tool used the material chemistry, amount of recycled content, disassembly, and recyclability to assess how successful the use of the DFE process had been. A product being truly cradle to cradle would have a score of 100 % when rated. The assessment of the ROV is illustrated in Table 6-3, with the scores for the assessment factors, their factored weights, and weighted scores. The recycled content had a factored weight of only 10 % since there was little focus on this factor compared to the other factors during the production process. As already mentioned, the reason was the limit on time and resources. The three other factors were weighted equally since they had been given an equal amount of focus and time. The weighted scores were calculated by multiplying the ROV score by the factor weight of that score. When summing all the weighted scores, the ROV attained a rating of 88.2 %. This was relatively high, and the product was satisfying in terms of DFE and when it came to being a C2C product. The ROV was pleasing regarding disassembly, material chemistry, and recyclability. As expected, the factor reducing the rating and needing the most improvement was the amount of recycled content. Given more time, this could have been enhanced, and the rating and quality of the ROV improved.

Table 6-3 DFE assessment tool for the ROV

DFE Assessment Factor	ROV Score [%]	Factor Weight [%]	Weighted Score [%]
Material chemistry	94.5	30	28.3
Recycled content	15.4	10	1.5
Disassembly	100.0	30	30.0
Recyclability	94.5	30	28.3
Overall score		**100**	**88.2**

6.2 Float

The testing and refinement of the float included assembling the float, evaluating the effectiveness of the assembly, and testing the buoyancy engine. A vacuum test was performed to check whether the seals were working, and several tests in water were executed, making necessary adjustments to improve the float.

6.2.1 Assembling and Modular Testing

The inside structure consisted of three parts and was assembled using galvanized slotted machine screws. The component plate had lots of holes to choose from, making it easy and quick to adjust the placement of the components. Components were fastened on both sides of the component plate using cable ties, but it was a time-consuming and tedious process. When one side was finished, it was challenging to fasten components to the other side due to components blocking holes in the component plate. The electrical team also wanted more distance between the metal components and the circuit card, which was not known due to unclear communication between the teams. The current arrangement made separating the circuit card from the metal parts difficult. Initially, it was planned to use steel wire instead of cable ties for fastening. However, this was no longer possible because metal could not be near some electrical components since it could affect the electrical signals. To center the weight, ballast was supposed to be mounted opposite the pump but had to be removed since it was too close to the electrical components.

The outer structure consisted of three parts and was assembled by placing both endcaps on the cylinder ends, Figure 6-7. O-ring grease was used during assembly to protect the O-rings from damage by abrasion. The time to maintain and adjust ballast was rapid since the float was stable on land, and only one part, the cylinder with the top endcap, had to be removed. The buoyancy system was tested on land, and worked well. The testing was possible and easy since the bladder and switches were clear from the ground. All parts were easily accessible for adjustment and maintenance. Hence, the target specifications concerning buoyancy engine, stability on land, and disassembly were achieved. The system was airtight except around the bladder, where the cable gland's threads cut into the bladder. An aluminum connector was manufactured to connect the hose and the bladder to solve the cutting issue, Figure 6-10. The float's external and inside structures were easy to assemble, and the accessibility of parts was satisfying. Hence, the target specification regarding assembly was accomplished.

Figure 6-7 The Float and its inside structure

6.2.2 **Vacuum Test**

A vacuum test was conducted to ensure that the float was sealed before testing in water where it would contain the electronic components. When the float was submerged in water at 10 m, the differential pressure would be 97806 Pa. The pressure would be more significant on the cylinder's outside than the inside. Since a pressure chamber was not available at UiS, a vacuum machine was used to induce a vacuum of -1.0 bar inside the cylinder, thus inducing the same differential pressure the float would experience at 10 m depth, Figure 6-8. A connection

Figure 6-8 Vacuum test of the float

tube had to be constructed to connect the float to the vacuum machine, fitting both the machine and the float. A CEJN male quick connect coupling and a costume-made adapter with M10 threads fitting the endcap were fastened to an armed hose using hose clamps, as shown in Figure 6-9. The technical drawing of the M10 adapter is shown in Appendix E, Figure E-5. The float was airtight at -1.0 bar when the pressure was kept constant for 10 min. The result was that the seals were watertight for 10 min at 10 m depth and that the float was ready for testing in water with the electronics inside. The float would only descend to 4 m depth during the competition, and based on the estimations of time from Chapter 5.2.9, the float would most likely use less than 2.5 min to complete the task. When passing the vacuum test, the float fulfilled the ideal values of the target specifications regarding sealing, time submerged and depth of the pool.

Figure 6-9 Connection tube

6.2.3 Testing in Water

During the first test in water, the lack of ballast in the component section was visible. The float was not balanced and tilted to one side. There was not enough space in the ballast section for the washers to obtain the desired ballast weight, and as a result, some of the ROV’s ballasts were supplemented in the space around the washers. Additionally, some ballast had to be attached on top of the float to attain enough and balanced weight. The float was then able to descend and ascend but was unstable due to the high CG resulting from the ballast on top of the float.

The new hose connector in Figure 6-10 connecting the hose and the bladder worked well, eliminating the problem with the threads damaging the bladder material. Nonetheless, due to friction between the cable ties and the bladder, the bladder would still be worn over time. During testing, the bladder also tended to lay to one side, causing a shift in the CB during ascending. The technical drawing for the hose connector can be found in Appendix E, Figure E-6. Rubber was applied between the endcap and the metal to achieve a good seal, which was successful, and the float was watertight. However, the temperature in the pool was higher than the air temperature making the air expand inside the

Figure 6-10 Hose connector

cylinder when it was submerged. The overpressure prevented the air in the bladder from deflating back into the float. The solution, during testing, was to open the manual valve and release the overpressure, then close the valve. The long-term solution would be to pump a slightly negative pressure inside the float before submerging the float or installing an automatic pressure relief valve.

For the second test, the inside structure was redesigned (design 3), Figure 6-11. The batteries were moved down, which shifted the center of mass closer to the float's center and lowered the CG. It would be preferable if the pump could be placed horizontally, which would center the mass even more, but the pump was too large. Computations on the distance between CB_z and CG_z in Chapter 5.2.8 showed a distance of 75.6 mm. Since the weight of the inside components had been positioned lower in the final design, design 3, and CB still would be the same, an even greater distance would be achieved between CB_z and CG_z. The ideal value of that target specification would thus be fulfilled. For the circuit card, an additional component plate was designed and produced. The circuit card could then be fastened on a separate card and onto the component plate. This measure made assembling more efficient and less complicated, and ensured more distance between the circuit card and the metal components. The height of the ballast section was adjusted to fit ballast of 2 kg. The float was still watertight and airtight during the second test. The float was placed in the pool and weighed down until it sank to find the point where it was slightly negatively buoyant. An increase in the float's negative buoyancy would cause it to descend faster but would demand more air in the bladder to ascend. It was desirable to find the weight where the float would ascend and descend at a reasonable speed. The float descended at a ballast mass of 1788 g. This mass was placed in the ballast section almost symmetrically by shifting 27.5 g from the pump side to the opposite section to balance the float. This resulted in a stable float when submerged in water. The float quickly adjusted to the upright position when placed in water off balance, having a satisfying righting moment. The stability in water confirmed that the float was symmetrically loaded and that the ideal target specification regarding CG and CB in the x and -y direction was fulfilled. In addition, the float had no problem overcoming the drag force and achieved that target specification.

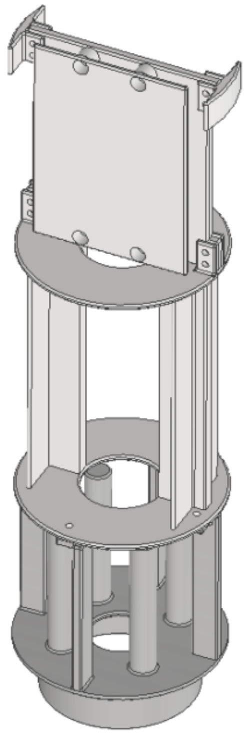

Figure 6-11 Inside structure of design 3

The float completed continuous cycles, two vertical profiles, for 30 minutes to examine the battery capacity and the buoyancy engine for errors. The time was recorded, and the times to complete one vertical profile in a 3 m (s_1) deep pool were as follow:

- 16 s from the float was turned on until the bladder deflation started.
- 16 s (t_{decend}) to descend to the bottom of the pool.
- 18 s form reaching the bottom until the inflation of the bladder started.
- 7 s (t_{ascend}) to ascend to the surface.

Instantaneous velocity was used to approximate the float's velocity descending and ascending. The velocity of the float descending

$$v_{descend} = \frac{s_1}{t_{descend}} = 0.18 \approx 0.2 \ \frac{m}{s}$$

The velocity of the float ascending

$$v_{ascend} = \frac{s_1}{t_{ascend}} = 0.42 \approx 0.4 \ \frac{m}{s}$$

The float had a velocity accomplishing the ideal value of minimum $1.3 * 10^{-2} \ \frac{\mathrm{m}}{\mathrm{s}}$ of that target specification. During the tests the float used 114 s to complete two vertical profiles. The pool in the competition would have a depth of 4 m (s_2). The times to descend and ascend would then be

$$t_{descend} = \frac{s_2}{v_{descend}} = 22.2 \approx 22 \ s$$

$$t_{ascend} = \frac{s_2}{v_{ascend}} = 9.52 \approx 10 \ s$$

By including the time at the surface and the bottom, the float would use 132 s to complete two vertical profiles during the competition. This time frame was well within the ideal value of maximum 5 min specified in the target specifications.

Before the next test in water, the bladder should be altered to a more durable material. A smaller bracket, shown in Figure 6-12, should also be produced to fit around the bladder to keep the float's CB centered in the x- and y-directions. The bracket was designed to be fastened to the hose connector. Figure 6-13 shows the final assembly of the float and its inside structure.

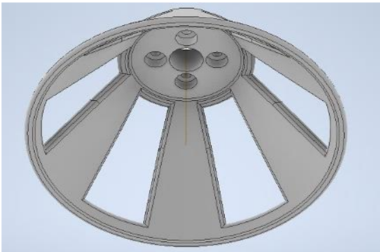

Figure 6-12 Bracket guiding the buoyancy bladder

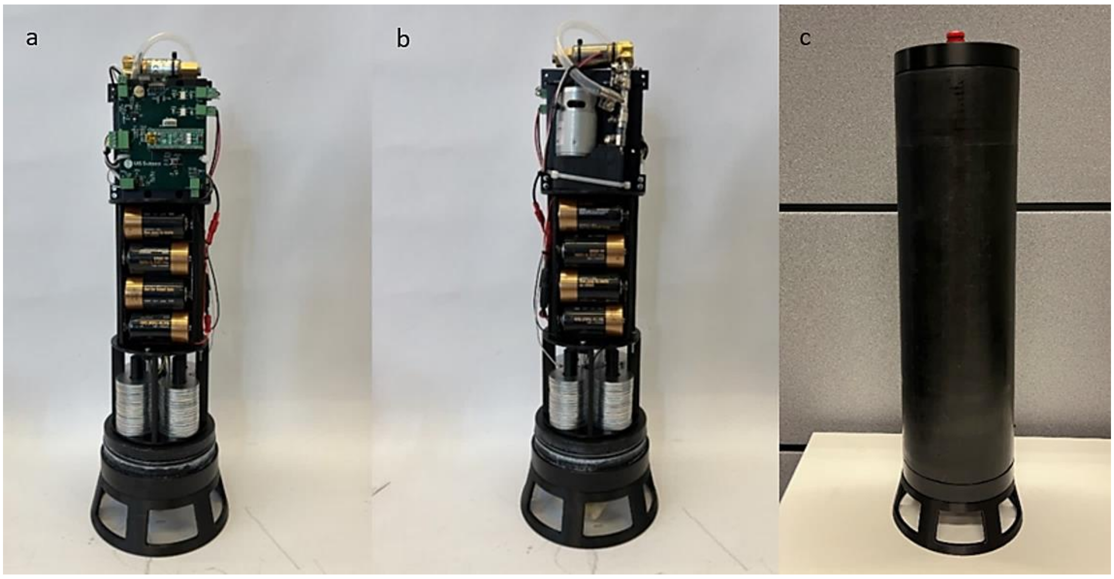

Figure 6-13 The inside structure front(a) and back view(b), and the float exterior(c)

6.2.4 Asses Environmental Impact

The float's environmental impact assessment evaluated the float's material chemistry, waste, disassembly, and recyclability considering only the float components developed during this thesis. The amount of waste from production was measured in grams. The material chemistry was measured in the amount of safe material and recycled content. The safe material, recycled content, and recyclable material were measured by their fraction of the total weight. Likewise, the ease of disassembly was measured by the fraction of the weight of materials that could easily be disassembled.

One of the DFE goals was to minimize waste during the production of the float. Therefore, the cylinder was ordered as a pipe instead of a bolt. The pipes were extruded from granulate and caused minimal waste during production. However, the pipes were delivered in standard 6 m length, and the float required a length of under 1 m. An effort was, therefore, made to contact local retailers for a cutoff to avoid unnecessary waste. The only waste from the cylinder was from the short turned length on the pipe's inside, which was estimated to be around 5 g. The endcaps were manufactured using CNC-turning from a PE100 bolt. Turning the 12.5 cm diameter bolt of a 5 cm length into the desired shape caused some waste. The two endcaps generated 410 g of waste. The float's inside structure was 3D printed instead of CNC-turning plates. 3D printing saved time and reduced the production of waste. The support material was considered the waste generated from 3D printing and had a total weight of 258 g for all the 3D printed parts. In addition, there was 500 g of waste from failed 3D prints or prints not used. Table 6-4 shows the total waste generation of 1173 g. The mean that reduced the most waste was the selection of the pipe instead of turning a bolt for the cylinder. Waste from all components except the battery bracket was little. The battery bracket had a lot of support material because it was printed as one part to ease assembly. If the bracket had been printed in two separate parts, they would not have needed any support material, and the waste could have been reduced to zero. The PE100 waste was attractive when it came to recycling, and the PLA would degenerate under the right conditions. More training in using the 3D printers before the beginning of the project could have reduced the portion of failed prints. Better communication between the groups working on the float could have prevented redesigning the inside structure, causing waste of already printed components. The amount of waste was within the marginal value of the target specifications but exceeded the ideal value of 500 g and did thus not meet the ideal value of this target specification.

Table 6-4 Waste of the float

Part	Mass [g]
Endcaps	410
Cylinder	5
Support bracket	10
Ballast container	46
Battery bracket	192
Component plate	0
Circuit card plate	0
Rocker bracket	0
Buoyancy bladder bracket	10
Failed prints	500
Total	**1173**

During material choice for the cylinder and internal structure, it was focused on selecting materials that were non-toxic to humans and the environment. None of the materials selected released toxic emissions in contact with air, water, or UV light, and no toxic materials were used to construct the float. The amount of toxic and hazardous material was thus 0 kg. The fraction of material by weight non-toxic or non-hazardous to humans or the environment was 100 %, corresponding to the ideal value of that target specification. Material made of recycled content, was difficult to find for the float's components. It was not possible obtaining PE pipes made of recycled content. Since high quality was required for PE pressure pipes, they were only produced with virgin materials, where content and chemistry were known precisely. When PE pipes were recycled, they had a risk of being polluted, and it could be difficult to guarantee the quality of the material. For the same reason, PLA in the float was neither recycled content. Finding products made of recycled content was very time-consuming, and the impression was that the industry was not yet organized to provide an option of recycled content of high quality. PLA filaments existed as recycled content, but due to budget, time, and delivery distance, it was better to use the resources already available at UiS. The cylinder was produced from PE pipe cut-off, which would have been waste otherwise, and was therefore considered recycled content. The cylinder weighed 1124 g, and the total weight of the float was 4306 g, found in Table 6-5. As a result, the recycled content in the float was $\frac{1124}{4306} = 26\ \%$, satisfying the ideal value of that target specification.

Table 6-5 Weight of parts in the float

Parts	Mass of Parts [g]
Float exterior parts	1953
Inside structure **Components**	251 238
Ballast	1788
Silicone tube and cable ties	76
Total	**4306**

The materials that could readily be disassembled were not mixed materials that could easily be disassembled from the float. The float was assembled with metal screws and O-rings. The hose for the buoyancy engine were either fastened using hose clamps or hose adaptors with threads. The cylinder, the inside structure, and the buoyancy engine could easily be disassembled into separate parts consisting of different materials. None of the materials were welded, painted, or glued together. The fraction of the materials by weight that easily could be disassembled was 100 %, and the float achieved the ideal value of that target specification.

The material for the cylinder and endcaps, the PE100, was attractive for recycling. This was the same material chosen for the ROV plates. In that way, the materials could all easily be recycled together. Since the materials were not painted or mixed with other materials the recycling process would be easier. PLA, used for the inside structure, was recyclable and would degenerate under the right conditions. The steel used for the ballast, machine screws, and hose clamps could also be recycled. Cable ties and the silicone hose were the only non-recyclable components in the float. The float's recyclability would thus be $\frac{4306-76}{4306} * 100\ \approx 98\ \%$, accomplishing the ideal value of that target specification.

When looking at the DFE assessment tool for the float, Table 6-6, the main focus was material chemistry, disassembly, and recyclability. All these factors were assigned a factor weight of 30 %. Considering these factors, the thesis team succeeded in focusing on the environmental impact. There was less focus on the use of recycled content, and as a result, it was assigned a factor weight of 10 %. The thesis team noticed that the use of recycled material in the industry was little, and it was very time-consuming to gain an overview in this field. As a result, the float obtained a DFE assessment factor of 92 %, which was high and satisfying. However, to achieve an even higher assessment factor, the team could have increased the focus on the use of recycled content.

Table 6-6 DFE assessment tool for the float

DFE Assessment Factor	Float Score [%]	Factor Weight [%]	Weighted Score [%]
Material chemistry	100	30	30.0
Recycled content	26	10	2.6
Disassembly	100	30	30.0
Recyclability	98	30	29.4
Overall Score		100	**92.0**

6.3 Compare to DFE Goals

In this step, the environmental impacts of the detail design were compared to the DFE Goals. The products were measured against the DFE goals in each of the life cycle stages, stage by stage, to check whether the products fulfilled all the goals.

Materials were considered carefully during material selection to ensure that they were non-toxic, non-hazardous, and did not release harmful emissions into air or water. Only the thruster brackets did not achieve these goals. However, they would not be toxic after production. The materials should be recyclable, and if possible recycled materials should be used. Aluminum for the metal brackets and stainless steel for the ballast were found in the boxes for recycling in the workshop and remanufactured into new components. The use of raw materials was reduced by reducing the size and amount of material in components. The number of different materials was also reduced to increase the recyclability and make it easier to sort by choosing PEHD as the base material for both products and 3D printing in PLA. During the material stage, two of the DFE goals were to minimize waste production and increase energy efficiency during material extraction. All products were delivered from companies that received raw materials from retailers that did not extract them themselves. Therefore, it was not known how the extraction of the varied materials was performed, nor the extent of the waste or energy consumption.

In the production stage, the goals dealt with waste, process materials, and energy consumption. The aim was to minimize waste production, and the waste produced should be recyclable. In addition, process materials should be reduced, non-toxic and recyclable. The energy efficiency in production should also be increased. 3D printing of smaller components reduced the use of chemicals like cutting fluids and raw material, and the lead time was shortened. 3D printing allowed multiple components to be produced simultaneously with all the features, while traditional manufacturing would manufacture one component at a time and spend time on each feature. 3D printing also freed the workforce to perform other tasks and reduced the amount of waste compared to traditional production, where the material would be subtracted from a solid workpiece. In 3D printing, only the amount of material needed for the component and supports would be added. Water cutting was chosen as the production method for the PEHD plates. From the environmental perspective, it would be better since there would be no need for lubricants that could pollute the scrap and decrease its recyclability. Water cutting was very precise and caused little material to be removed from the cut face and led to minimal scrap. The PEHD cylinder for the float was extruded from granulation and molded into a pipe of the desired dimension. During this process, no waste was generated. By selecting production processes, energy efficiency was increased to some extent, waste and process materials were reduced, and hazardous waste and process materials were eliminated as much as possible. There was still used resin to print the thruster brackets, which was toxic before curing. When assessing the environmental impact, it was found that the production of the ROV frame resulted in around 7.60 kg of waste, and the design could have been improved when considering that DFE goal. The waste due to failed and unused 3D prints could have been reduced to limit the environmental impact in the float's production stage.

The distribution would only be a small part of the products' life cycle since they would stay in Stavanger and at UiS most of the time. The goals were to minimize emissions, have energy-efficient transportation, minimize packaging materials, use non-hazardous materials, and use local retailers to minimize transportation distance. The goal that would have the most significant impact and was given the most attention was the use of local vendors. Much effort was given to finding sponsors and retailers located in the area around Stavanger to ease delivery or picking up components. Only some small components that could not be found elsewhere were ordered online from companies located further away and had to be shipped. The float was relatively small and compact, and the ROV frame could easily be disassembled and packed flat for energy-efficient transportation and to minimize packaging. The products would take up less space, and it would be possible to ship them in bulk or containers. The ROV and float should preferably have been transported to the MATE competition in the US by a container ship or a train instead of an airplane to increase energy efficiency and reduce CO_2 emissions. Flying would be a very environmentally harmful way of transport. Nonetheless, shipping would not be an option due to the time limit to reach the competition.

During the lifecycle stage use, the goals were to produce products with long life, clear instructions, easy and efficient service, and no emissions. Both the products would have a long product life due to the material choice, design, and ease of replacing components. The float would have some wear and need to change the bladder regularly. The ROV and the float would be easy to maintain and perform services on. The ROV had an open structure with good visibility of all components. It would be easy to clean with a water hose and change desired parts. The outside of the float consisted of the cylinder and two endcaps, which could easily be disassembled by hand. The inside consisted of the inside structure and the buoyancy system, which could be maintained after removing the cylinder. All the components were easily accessible and visible. One goal was to give clear instructions on the products, to avoid misuse. Instructions on how to assemble the ROV frame are given in Chapter 6.1.1. Instructions on the float's buoyancy system would have to be submitted to MATE but are not described in this thesis. Other instructions were also given to the rest of the UiS Subsea team, and documents with instructions might be made at a later point. Neither of the products would have emissions into air or water due to the choice of materials and since both were electrical. The minimization of the ROV's drag could increase its energy efficiency.

When it comes to the recovery stage, the products should be easy to disassemble and the components recyclable or able to remanufacture. Both the float and the ROV were easy to disassemble with a limited number of tools. The ROV frame was calculated to be 94.5 % recyclable from the environmental impact assessment, which was satisfying. Only the thruster brackets could not be recycled. For the parts considered during this thesis for the float, only cable ties and the silicone hose were non-recyclable. Both had low masses, resulting in a 99 % recyclability of the float, which was very pleasing.

6.4 Product Improvements

Even though the products were finished and well suited to compete in the MATE competition, improvements and optimizations could be made to enhance the products. Improvements that could have been made for the ROV and float, if given more time, are described in this chapter, along with some recommendations.

6.4.1 ROV

The ROV's development process was affected by the short time limit before the sponsors needed finished drawings of the components. Mechman AS needed the drawings six weeks before the desired delivery date of the components, which meant that the design had to be finished, analyzed, and tested on February 21st at the latest. Since the thruster brackets were 3D printed, technical drawings were not required, only an STL file. IKM Industrigravøren AS, however, which sponsored the PE100 plates, needed technical drawings with all dimensions and features the following week. The buoyancy calculations were also performed during this period due to Mechman AS' production and delivery time of six weeks. This meant that the entire PDP, except for the last step, testing and refinement, had to be performed during the project's first one and a half months. It required a steep learning curve, and a lot of information had to be acquired in a short amount of time.

FEA, environmental assessment, material choices, and buoyancy and stability calculations had to be performed to complete the design of the frame and the components. The design process and programs used for designing, calculations, and analyses, like Autodesk Inventor, were very time-consuming. Learning and using the programs, functions, and analyses beforehand would have been beneficial and smart. Autodesk Inventor had been taught in courses where it was learned to design components and make assemblies and 2D drawings. The FEA and other functions in Autodesk Inventor had to be learned during the project by the thesis members to be able to design functional products. Improvements could have been made in the frame's design if more time had been given and more knowledge regarding the subject had been acquired beforehand. The buoyancy calculations were performed after the design for the frame was finished and the materials for the components selected. Thus, it was realized a little late that there was no need for a large buoyancy element. The calculations were postponed as long as possible due to a lack of information on the volume and weight of components from other UiS Subsea teams. It was desired to have as realistic calculations as possible for the buoyancy element to be dimensioned correctly and to reduce the need for trimming with ballast. After receiving numbers from the other teams, it was realized that a floatation element was not required due to the volume of the electronics house. If this had been discovered earlier, it might have resulted in a smaller, more compact design that did not need to consider room for the flotation element. For example, all components could have been assembled on the same plate. In the future, it would be recommended to calculate the net buoyancy of the electronics house as early as possible and ask the other teams to have estimated sizes and weights ready early in the process.

If there had been more time to design the frame, more focus would have been given to easier assembly and disassembly of the frame and its components. The frame had the potential of removing the components more effortlessly and using fewer fasteners. The horizontal thrusters were challenging to remove without removing the side plates first. It was possible with a small Allen key, but removing the side plates with an electric drill was faster. A smarter solution should have been designed and could easily have been created by altering the design of the side plates. The holes created in the side plates for a tool to fit inside were too small. The thickness and sizes of the plates had been reduced to minimize cost and weight. Nonetheless, the safety factor was still high and could possibly be reduced additionally by reducing the thickness and sizes of the plates.

6.4.2 Float

The development of the float and its components were affected by limited time, knowledge, and inadequate communication. If given more time and a presence of better communication, improvements and changes in the design could have been made to enhance the product. More focus could have been on designing the float smaller to reduce the buoyancy and the need for ballast. This would also have reduced the float’s weight, drag, and material use. Currently, the float weighed 5.77 kg, satisfying the target specification regarding lightweight. However, there was still potential for reducing the weight. Components requiring less energy were needed to reduce the float’s size, because they would require smaller batteries and take up less volume. Due to the float’s volume, aluminum could have been used as endcaps to increase the float’s weight, to reduce the amount of ballast, while maintaining the negative buoyancy. Since PEHD was a thermoplastic, it would deform at high temperatures, and precautions had to be made when drilling. If aluminum had been selected for the endcaps, deformation due to temperature would not have been an issue, and the threads would have been more durable. A disadvantage of selecting aluminum would be increased weight at the float’s top, raising the CG. This would have reduced the righting moment, demanding more focus on the symmetry of the inside components. When the material choice for the float components was taken, the DFE guidelines were rated higher, thus selecting PE for the endcaps.

In retrospect, the placement of the switches should have been altered. One of the switches was a power switch, also functioning as emergency switch, which should have been located easily accessible at the top endcap. The sensor switch should also have been placed at the top endcap for easier accessibility. This solution required the switches to be cordless, which was possible if the switches received electricity when in contact with the inside structure. Contact would occur when the endcap was fastened, and the switches would be activated. This solution would have enabled the switches at the float's top while still retaining an easy and effective assembly and disassembly. Better communication between the UiS Subsea members could have enabled cordless switches in the design. However, this possibility was not known until it was too late in the process to make changes. Better communication could also have prevented designing and producing the inside structure design over again. The float would then probably have been balanced in water during the first test, saving time and resources.

The bladder moved slightly to the sides when inflated, changing the float's center of buoyancy. The bladder design could have been improved by constructing a bladder, which covered the entire surface of the endcap and was held in place by the support bracket, Figure 6-14. This bladder would extend evenly downward, keeping the CBx and CBy centered. This solution required all switches to be placed at the top endcap. It would also be advisable to use a more durable bladder material.

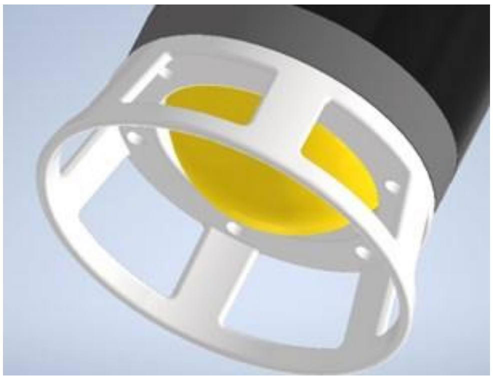

Figure 6-14 Improvement of the bladder design

7 Evaluation of the product development process

Making a Gantt chart with the project plan showing the planned activities, their timelines, and milestones was useful in keeping track of the process and its progress. Getting an overview of the entire project and important deadlines limited unforeseen problems and ensured a steady workflow. Following the chart, it was easy to know what to do at all times. Due to the Gantt chart, the thesis team realized that drawings had to be sent to manufacturers quite early in the PDP to have enough time to assemble and test the products before the testing in water. This meant that even though no groups had finished product designs at this point, estimates on dimensions and weights had to be used to finish the ROV and float designs. The chart was checked regularly to see if the project was on schedule. The timelines set for the planned activities were followed most of the time.

The planning phase was performed in the assigned timeframe, except for spending more time to allocate resources because of some unclarity in dividing work tasks. This taught the thesis team that it was important to define everyone's area of responsibility early in the process, not to waste time and resources. The concept development and detail design with necessary analyses were within the set timelines, and all components were ordered within the desired time. Product cost calculations were completed later than the set timeline because of the lack of information and values from manufacturers. Due to the project's time limit, the focus was on staying within budget. If more time was available, more resources could have been used to map different qualities and prices of different suppliers. The ROV was ready for assembling, testing and refinement as planned. It was enough time to assemble, test, and make adjustments before the testing in water with all the other members of UiS Subsea. The assembling of the float was delayed by one and a half weeks since one of the manufacturers failed to deliver. This taught the thesis members that it was important to have written confirmation and follow up manufacturing. The manufacturing delay caused the assembling of the float to be postponed, and the workload was more extensive in that period to make the float ready for testing in water. Despite the delay, the float was still ready for the testing in water since the test date was postponed because of Easter. The time estimate for the testing and refinement phase would have been sufficient if all components for the products had been delivered at the set time and the previous phases had been within their timelines. However, some of the activities were performed after their set timeframe due to delays in the PDP.

The planning phase was useful in obtaining an overview of the project and creating the Gantt chart with the project plan. Setting the DFE agenda early in the process helped the thesis team focus on DFE throughout the project. Producing the mission statement brought awareness regarding the product, business goals, market, stakeholders, assumptions, and constraints. During the initial stages of the concept development, customer needs were identified and sorted hierarchically, benchmarking of previous UiS Subsea ROVs and existing ROVs and floats were performed, environmental impacts were identified, and DFE goals were set. These stages were used to establish the target specifications for the products. The thorough planning and research made concept generation easier and less time-consuming since it was known what the customer expected and what was relevant to the project. The most promising concepts were effectively selected based on the target specifications, matrices, or calculations. This systematic selection of concepts helped improve the quality of the products. During the detail design phase, further improvements, dimensioning, material choice, structural analyses, buoyancy, stability and velocity calculations, and product cost were performed. The calculations and analyses were time-consuming and had to be performed several times due to alterations in components. The thesis members had minimal previous knowledge, and the calculations and analyses required more time and resources, thus also the detail design phase. The DFE guidelines, set during the concept development, were taken into account to reduce the environmental impact of the products. These guidelines have been easy to follow and implement throughout the entire PDP. The DFE assessment tool verified that the use of the DFE concept had been successful. The testing and refinement phase was generally easy to follow, and some changes were made to both products during this phase.

Overall, the product development process was beneficial. Nonetheless, the process was time-consuming and required structured team members. For the best utilization of the process, companies should select the phases and steps that would be most relevant to them. This year's PDP could have been improved by clarifying responsibilities and requesting estimates of volumes and masses of the components from the other UiS Subsea teams earlier in the process. This could have prevented unnecessary misunderstandings, the use of time and resources, and delays. It is essential that future teams take their responsibilities and can say no when given other teams' tasks. Good communication is the key to performing well. Even though there were some misunderstandings early in this project, this year's team members collaborated very well.

8 Conclusion

This thesis aimed to design and construct the ROV frame, in addition to the inner and outer construction of the float, by executing the product development process with a focus on the design for environment concept. The main objective was to produce products that would fulfill the MATE tasks and company requirements. The PDP and DFE phases were followed thoroughly and helped produce successful products.

PDP was chosen as the method for designing and producing the ROV and the float since it had been proven to help with planning, coordination, management, assuring quality, and improving products. The process was beneficial in the initial stages with setting the DFE goals and target specifications and doing thorough research before starting the generation of concepts and development of the products. This made the concept generation easier and less time-consuming since it was known what the customer wanted and expected. The systematic selection of concepts also helped improve the quality of the products. The detail-design phase was time-consuming and required more resources due to minimal previous knowledge. The testing and refinement phase was generally easy to follow, and some changes were made to both products during this phase. Overall, the PDP was helpful but was time-consuming and required structured team members. For the best utilization of the process, companies should select the phases and steps that would be most relevant to them.

The target specifications were UiS Subsea's aspirations for the products and were a translation of MATE's needs and UiS Subsea's objectives into measurable characteristics. If the products achieved all the specifications, they would exceed expectations. Most target specifications were accomplished for both products within the ideal values. For both products, some of these were the targets regarding maximum dimensions, assembly, budget, stability, and drag. In addition, the ROV fulfilled the targets concerning no sharp edges, lateral stress, maneuverability and free flow. The float fulfilled the targets concerning batteries, buoyancy engine, sealing, velocity, time to complete the vertical profiles, and weight. The environmental impact regarding waste for both products and the ROV's hazardous materials and recycled content, in addition to the ROV's total weight, were the only target specifications that exceeded the ideal values. However, they were within the marginal values. The ROV caused 7.60 kg of waste during its life cycle, where the majority came from the production of the PEHD plates due to their design. This waste could have been reduced by using another production method, such as molding, and would be recommended for mass production of the ROV. However, water cutting was the best option when producing only one unit. It was better to produce more easily recyclable waste than less non-recyclable or toxic waste. The float had a waste of 1173 g, and a substantial portion resulted from unused 3D prints and failed prints due to wrong settings and problems with the printer. This could have been reduced by more experience in 3D printing prior to the project and better communication that could have prevented the need for redesign. The amount of hazardous material in the ROV frame had potential of being reduced, and the recycled content potential of being increased. The amount of recycled content was the environmental factor given the least attention during the design of the products, due to the limited time and resources. The frame's percentage of hazardous material was caused by the resin used in the thruster brackets. Given more time, research could have been done to find a non-hazardous material for the brackets and increase the amount of recycled content. This would have contributed to achieving the ideal values of those target specifications. The total mass of the ROV was 25.4 kg, while the ideal value set by UiS Subsea was 20 kg. However, during this thesis, measures were taken to reduce the frame's weight as much as possible. FEA was applied to reduce the thickness and mass of the plates and the number of fasteners, and the thruster brackets were designed to function as stiffeners to reduce the need for metal brackets. This resulted in the frame, including the components developed during this thesis, only weighing 6.6 kg.

Herman Miller's DFE assessment tool evaluated the products and checked whether they indeed were cradle-to-cradle products. Material chemistry, amount of recycled content, disassembly, and recyclability were considered to assess how successful the DFE process had been. The ROV obtained a rating of 88.2 % and the float a rating of 92 %. The results were relatively high, and the products were satisfying in terms of DFE and C2C products. The products were pleasing regarding disassembly, material chemistry, and recyclability. The search for recycled materials was very time-consuming, and given more time, the amount of recycled content in the products could have been increased.

Even though the products were finished and well suited to compete in the MATE competition, improvements and optimizations could be made to enhance the products. The buoyancy calculations on estimated metrics for the ROV's components should have been performed earlier in the process. It could have resulted in a different and more compact design for the frame. Given more time, more focus would have been on easier assembly and disassembly of the frame and its components, especially the horizontal thrusters. The plate thickness and sizes had been reduced to minimize cost and weight. However, there was still a possibility of reducing the plate thickness and safety factor additionally.

If more time had been given for the float, the main focus would have been on reducing the volume and altering the bladder design. It would have been better to have a bladder that covered the entire bottom endcap to ensure that the bladder was inflated symmetrically and straight down. This would have made the float even more stable in water. In addition, the switches should have been placed on the float’s top endcap for better accessibility and to enable the bladder to cover the bottom endcap. This would have required cordless switches. The bladder design and cordless switches would have been possible if communication was better between the UiS Subsea members. Better communication could also have prevented designing the inside structure over again.

It has been a fantastic opportunity to participate in the UiS Subsea organization and the ROV project and to be able to compete in the MATE competition. The project has been both challenging and educational, and the learning steep. It has been great for developing technical, creative, and collaborative skills. Overall, the final products were satisfying and functioning, did well during testing, and were able to perform the tasks for MATE’s qualification video. The simple ROV design could make it possible for the frame to be reused in later years as a base and then make changes to the attached components.

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Appendix A: Gantt Chart

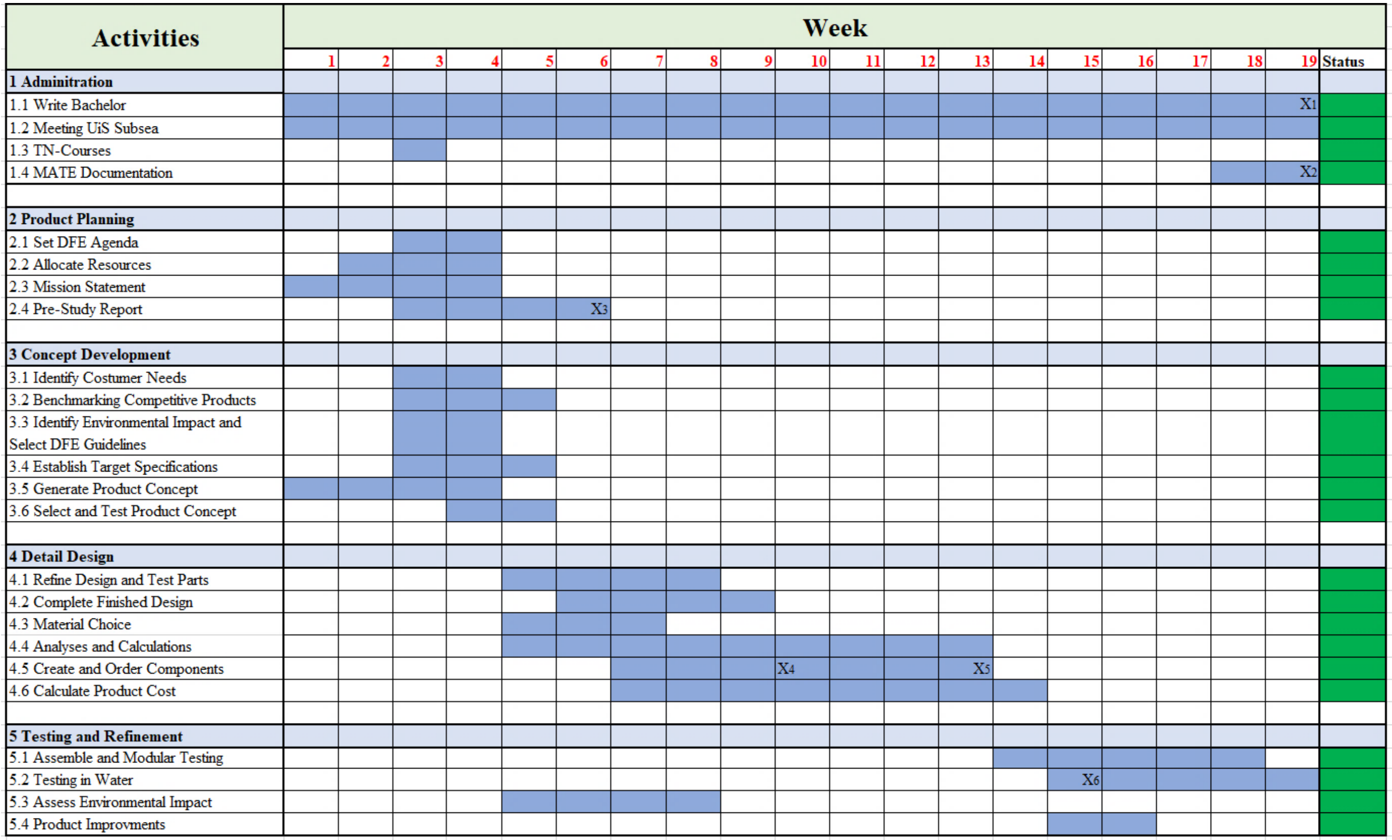


Figure A-1 Gantt chart

Status		
	(green)	**Completed**
	(yellow)	**Current**
	(red)	**Not Completed**

Milestones	Submission	Date
X1	Bachelor	15.05
X2	MATE Documentation	15.05
X3	Pre-Study Report	11.02
X4	CAD Files Mechman	21.02
X5	Technical Drawings IKM	11.03
X6	Ready for testing in water	15.04

Figure A-2 Status bar and milestones tables

Appendix B: Identify Environmental Impacts and Select DFE Guidelines

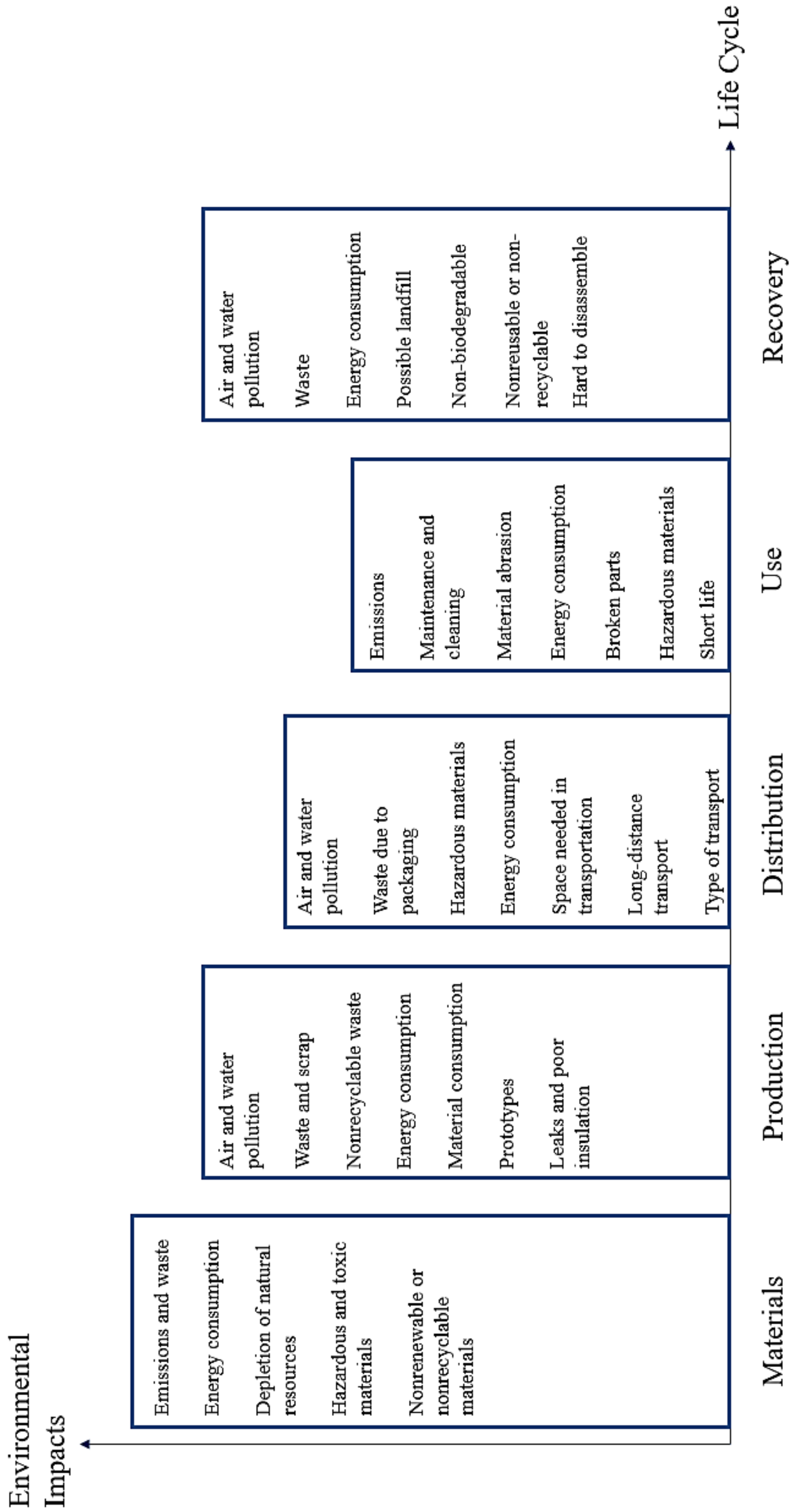


Figure B-1 Quality chart

Table B-1 DFE guidelines

Life Cycle Stage	**Design for Environment Guidelines**	
Materials	**Sustainable Resources**	• Identify recyclable or recycled materials • Identify renewable and plentiful resources • Identify renewable energy sources • Use remanufactured components • Minimize the number of materials used • Identify nonblended, non-composite materials, and non alloys • Reduce use of materials that have to be extracted • Reduce waste during extraction or production
	Non-Hazardous and Toxic Inputs and Outputs	• Identify non-hazardous and non-toxic materials • Identify materials that does not need surface treatments or coatings • Set in order safety measures to minimize pollution into air and water • Include instructions for safe handling of toxic materials • Ensure that waste is recyclable or biodegradable
Production	**Minimal Use of Resources**	• Reduce number of components • Reduce use of raw material when designing components • Reduce number of manufacturing steps • Use materials that do not need coating or surface treatment • Reduce material waste • Reduce energy consumption during the production processes • Reduce number of prototypes
	Reduce Emissions	• Set in order safety measures to minimize pollution • Reduce production of scrap and waste • Ensure that waste is recyclable • Reduce energy loss due to leaks and poor insulation • Reduce use of hazardous or toxic materials
Distribution	**Minimal Use of Resources**	• Reduce use of packaging • Use recyclable or recycled packaging and materials • Use reusable packaging

		• Use non-hazardous and non-toxic materials • Use more environmentally friendly transportation if possible • Design the product to be easily disassembled or folded for distribution in a compact state • Use lightweight materials and components • Reduce the total volume
	Minimal Distribution	• Use local suppliers • Use the local market and customers • Transportation in bulk
Use	**Durability**	• Ensure that the durability of the aesthetics will last as long as the technical life • Reduce need for maintenance • Reduce failure modes • Simplify repairs and upgrades • Identify materials and fasteners that protect against corrosion, dirt, and wear • Instructions on how to use and maintain the product • Allow for multiple assembly and disassembly
	Efficient Use of Resources	• Implement reusable or easily swappable components • Reduce volume and weight to reduce energy use • Near neutrally buoyant • Use materials and design components with long life
Recovery	**Disassembly and Recyclability**	• Ensure that the system is easy to disassemble • Ensure easy access to fastens and joints • Reduce the variety and number of fasteners • Use limited amounts of tools for the disassembly • Ensure that different materials are easy to separate • Ensure that disassembly does not harm components • Use reusable and easily swappable components • Reduce number of parts • Use one disassembly direction • Use an open structure for easy accessibility to components • Use recyclable or reusable materials and components • Minimize emissions during the recovering process • Reduce waste during recovery

Appendix C: Technical Drawings ROV

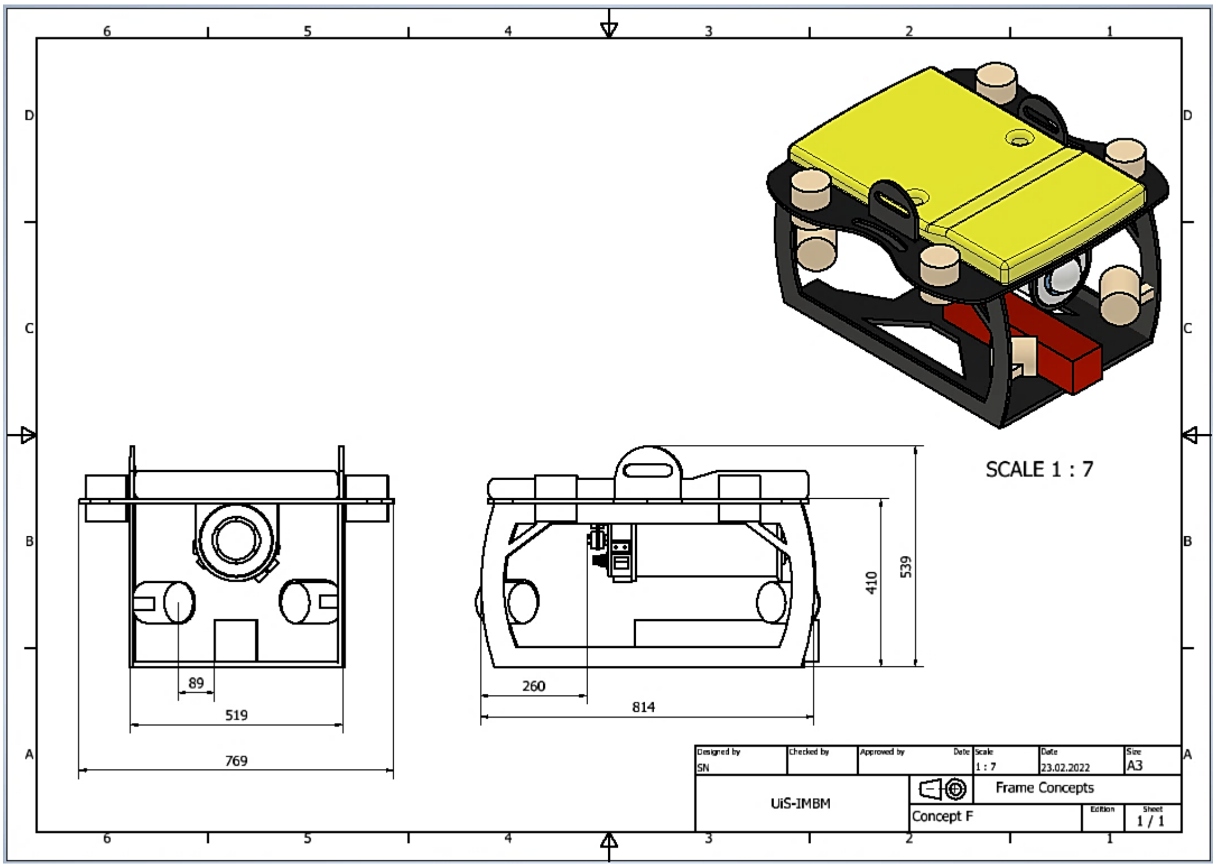


Figure C-1 Technical drawing of concept F

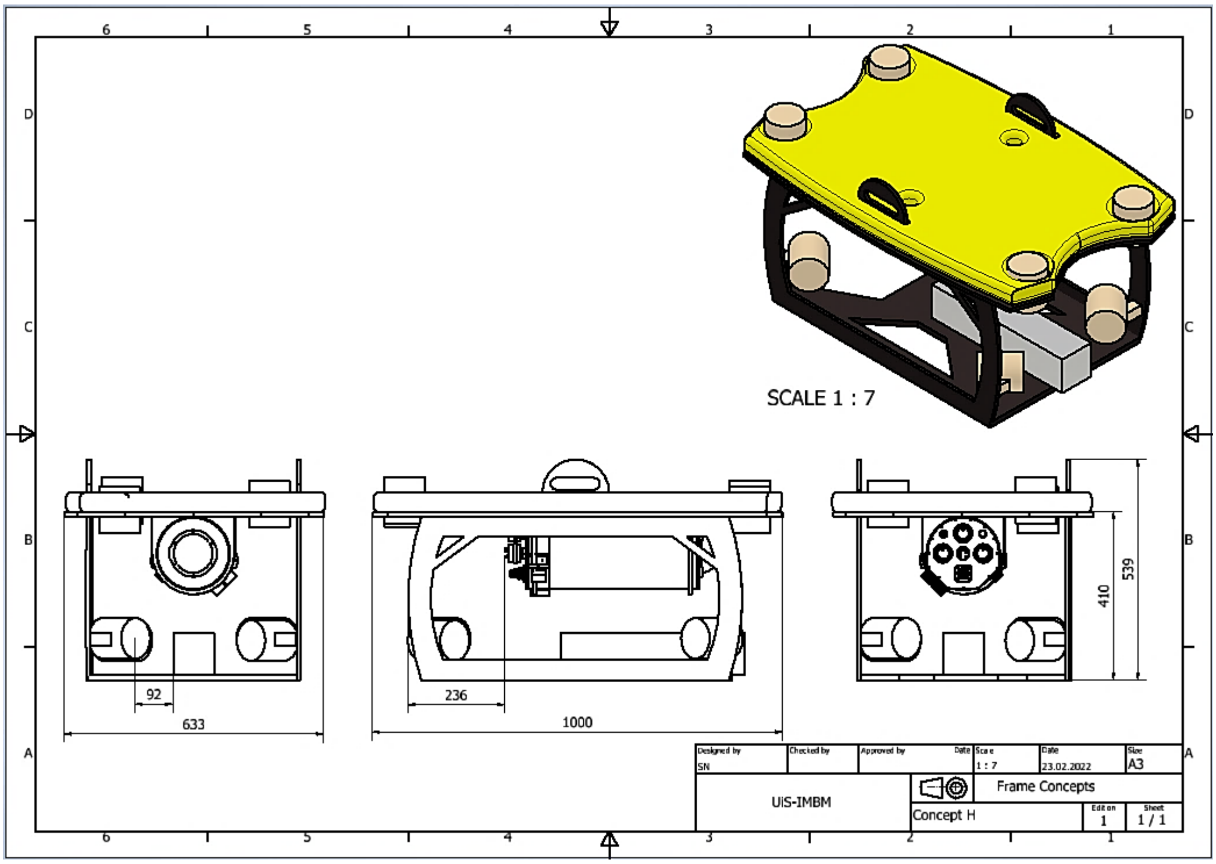
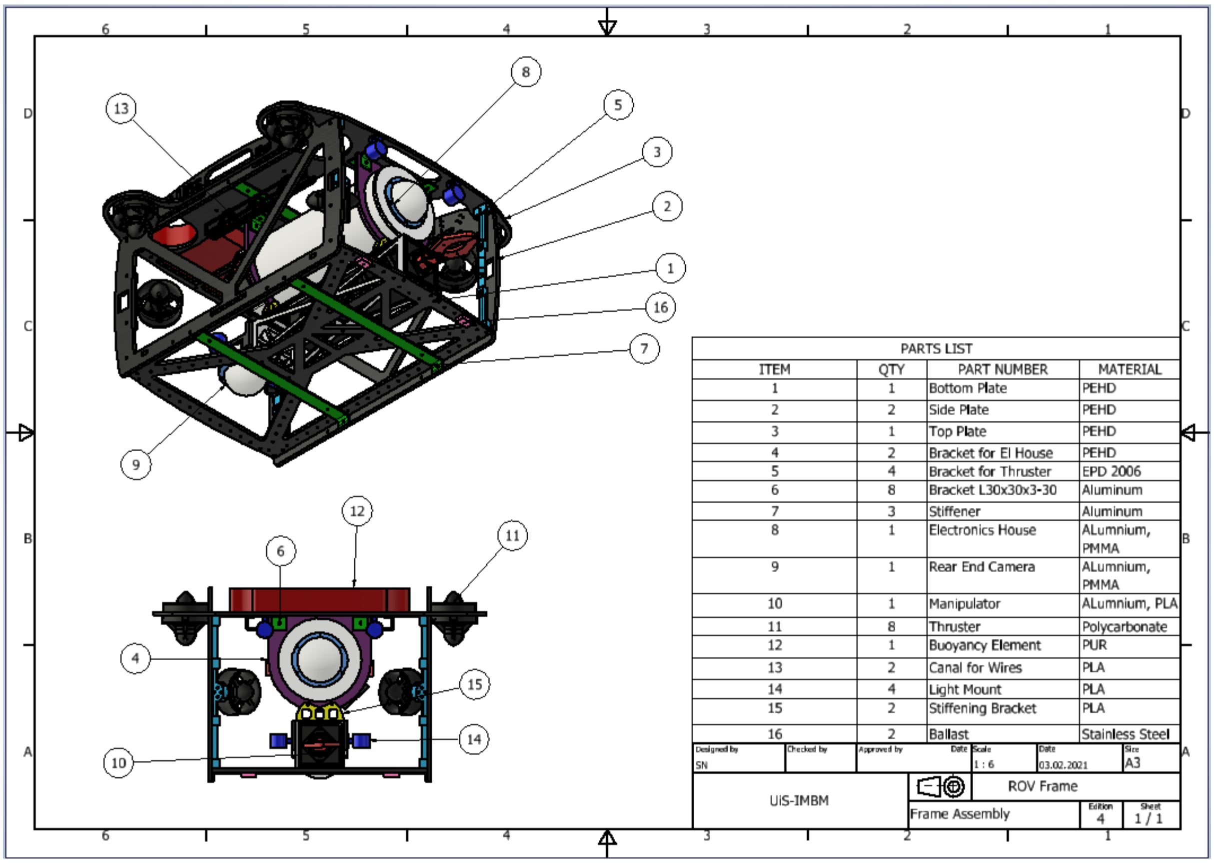


Figure C-2 Technical drawing of concept H



ITEM	QTY	PART NUMBER	MATERIAL
1	1	Bottom Plate	PEHD
2	2	Side Plate	PEHD
3	1	Top Plate	PEHD
4	2	Bracket for El House	PEHD
5	4	Bracket for Thruster	EPD 2006
6	8	Bracket L30x30x3-30	Aluminum
7	3	Stiffener	Aluminum
8	1	Electronics House	ALumnium, PMMA
9	1	Rear End Camera	ALumnium, PMMA
10	1	Manipulator	ALumnium, PLA
11	8	Thruster	Polycarbonate
12	1	Buoyancy Element	PUR
13	2	Canal for Wires	PLA
14	4	Light Mount	PLA
15	2	Stiffening Bracket	PLA
16	2	Ballast	Stainless Steel

Figure C-3 Technical drawing of the frame assembly with parts list

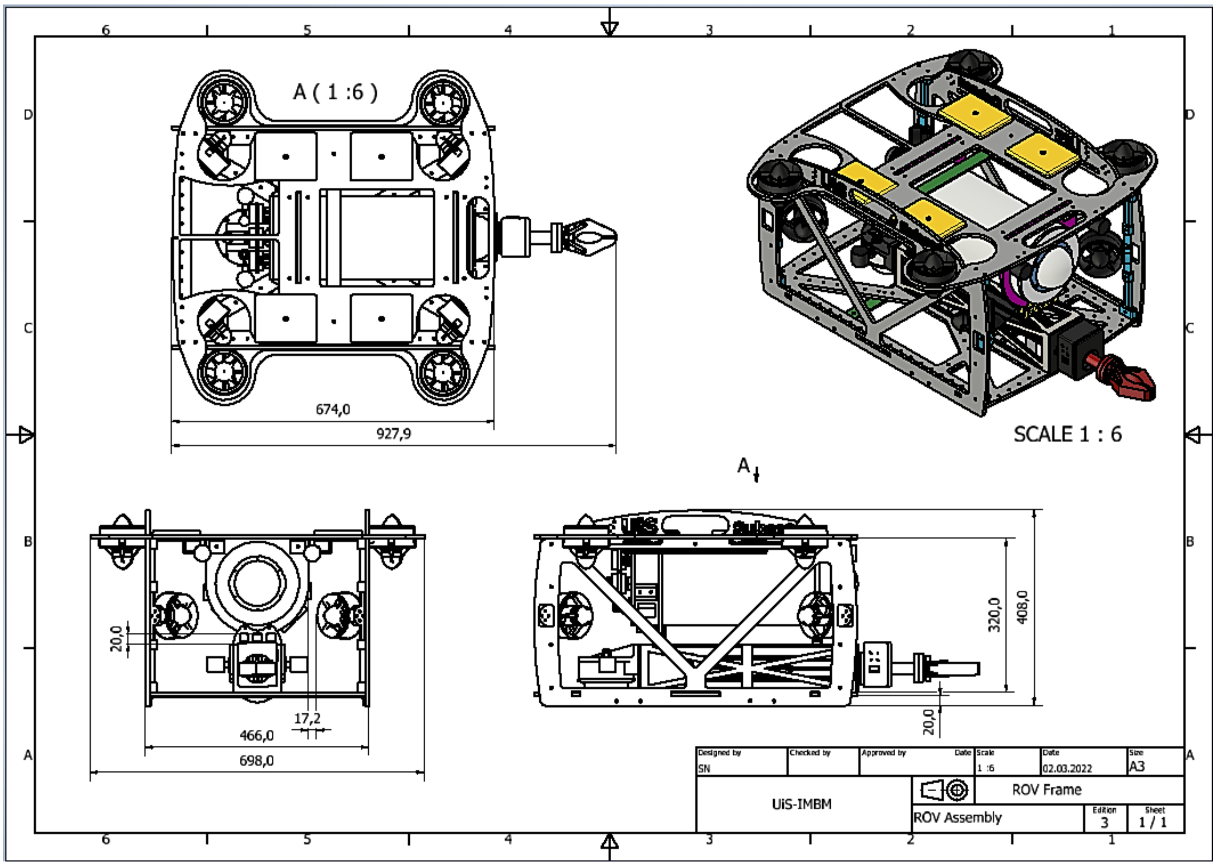


Figure C-4 Technical drawing of the frame assembly

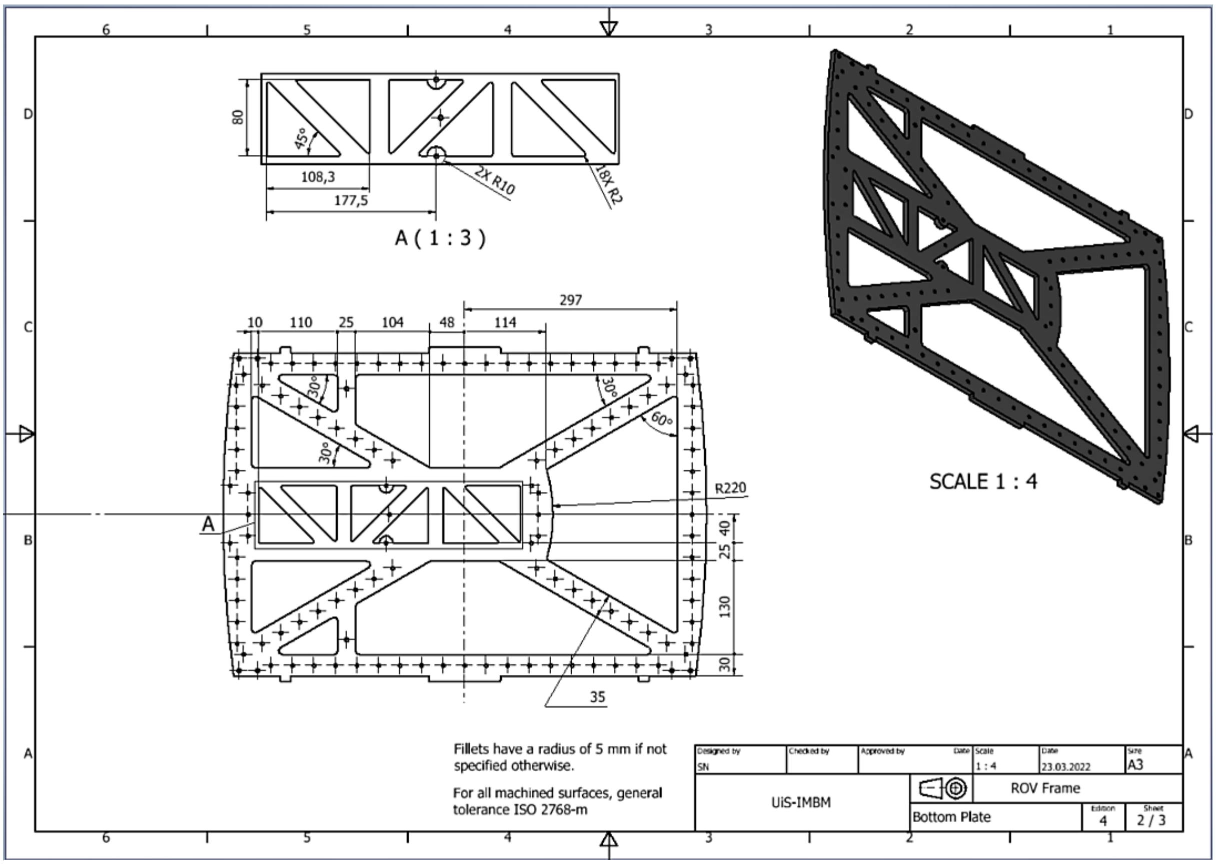


Figure C-5 Technical drawing of the bottom plate sheet 1/3

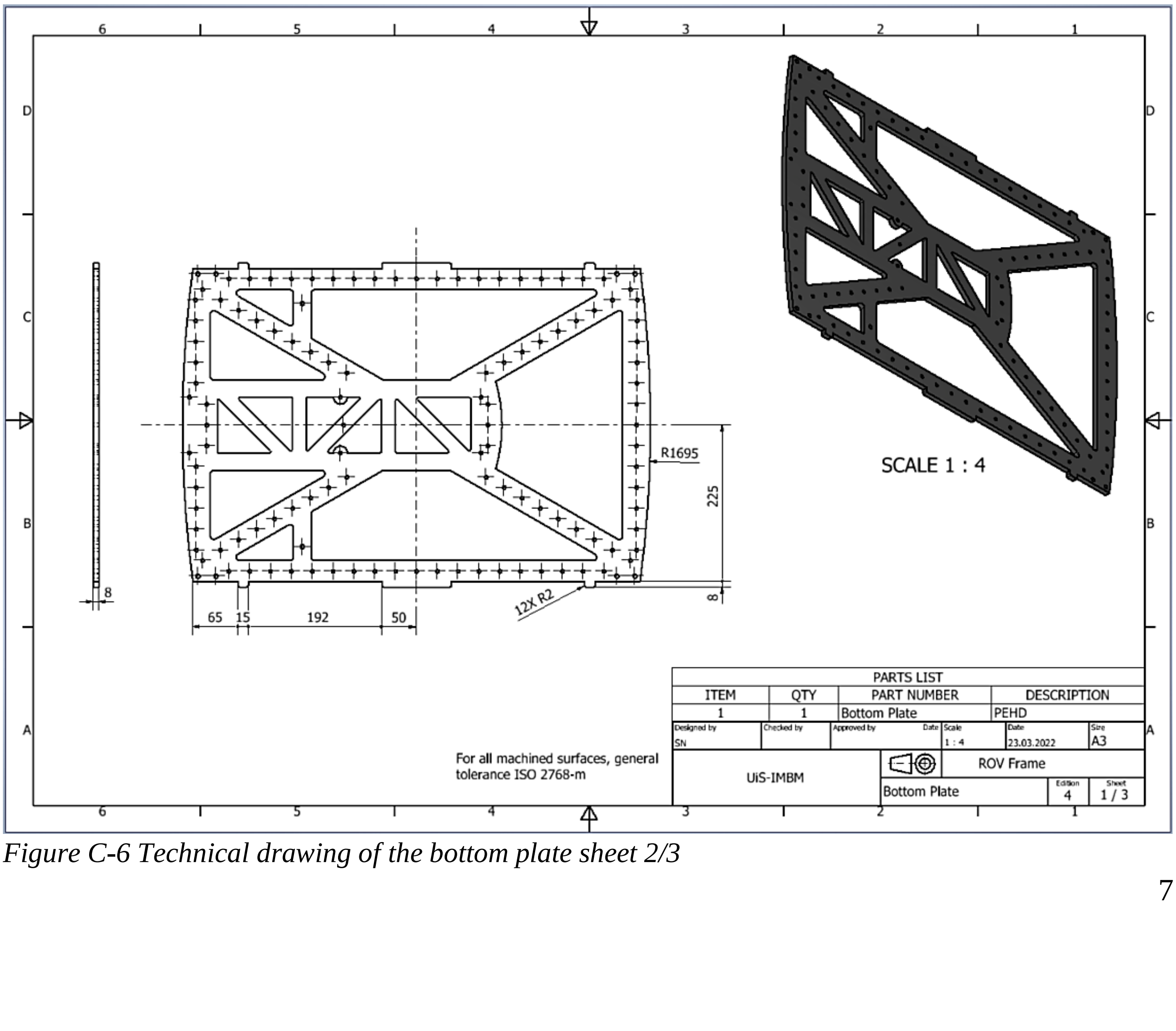


Figure C-6 Technical drawing of the bottom plate sheet 2/3

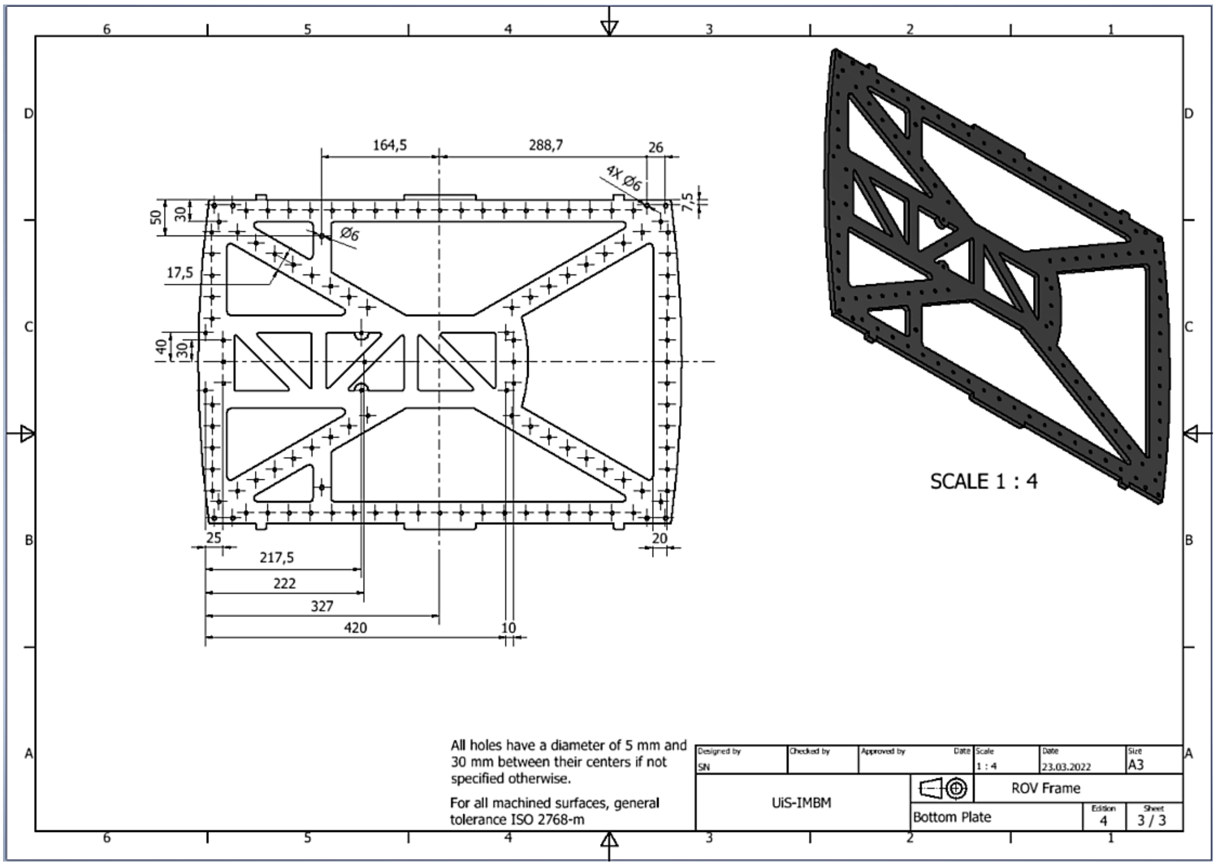


Figure C-7 Technical drawing of the bottom plate sheet 3/3

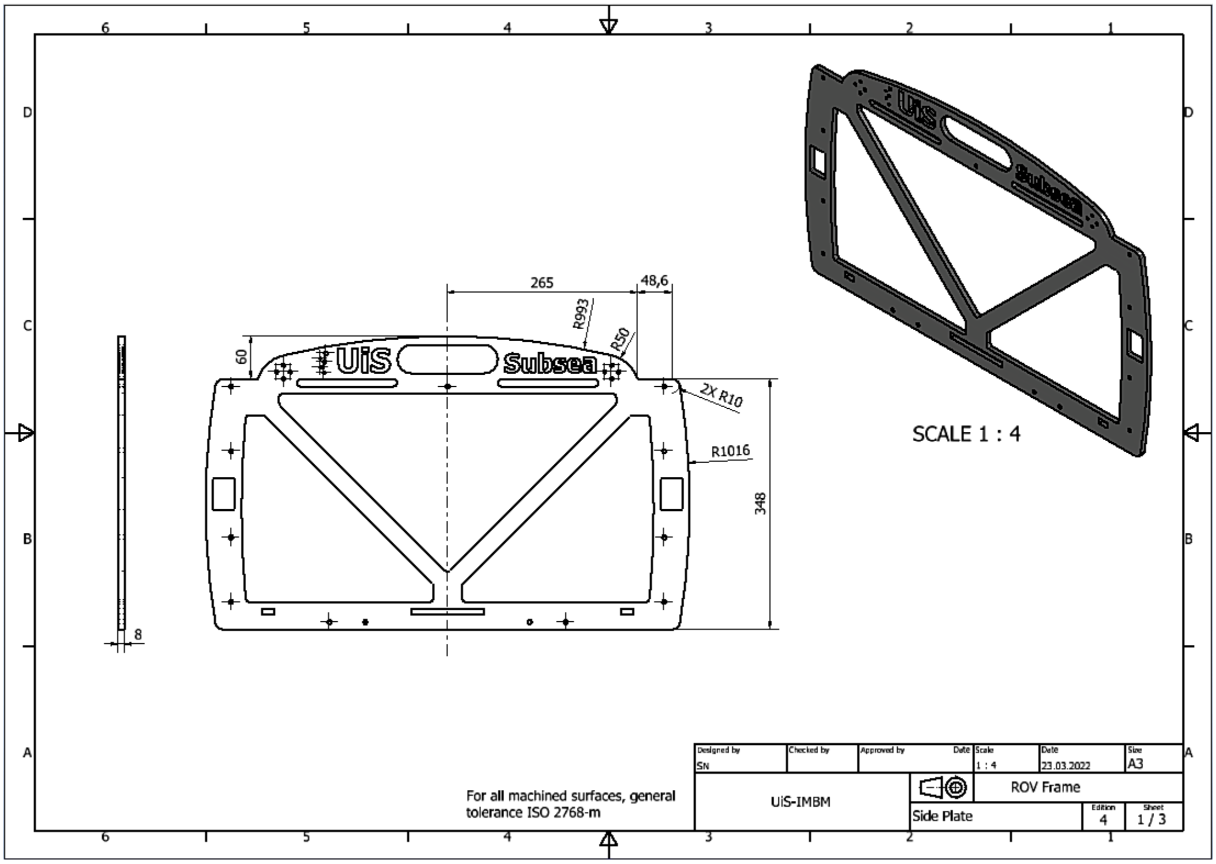


Figure C-8 Technical drawing of the side plate sheet 1/3

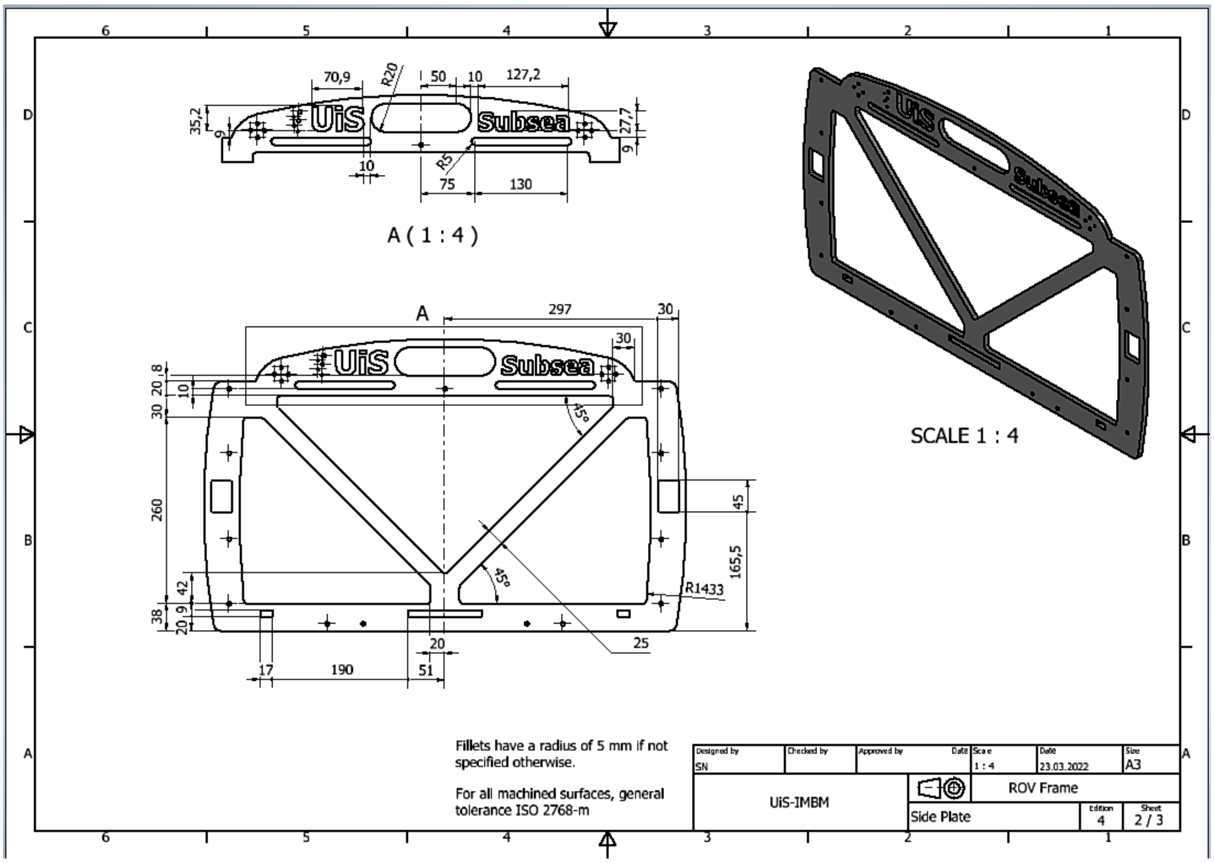


Figure C-9 Technical drawing of the side plate sheet 2/3

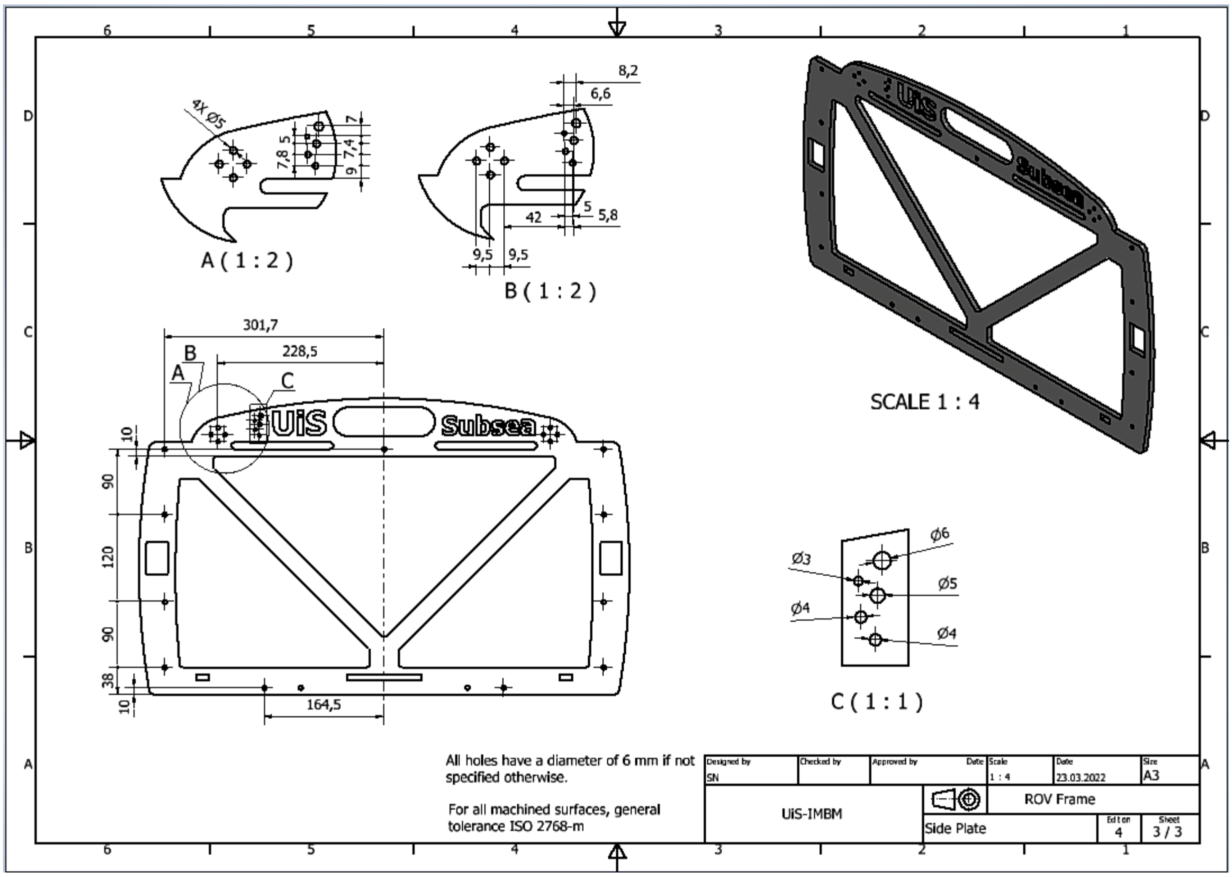


Figure C-10 Technical drawing of the side plate sheet 3/3

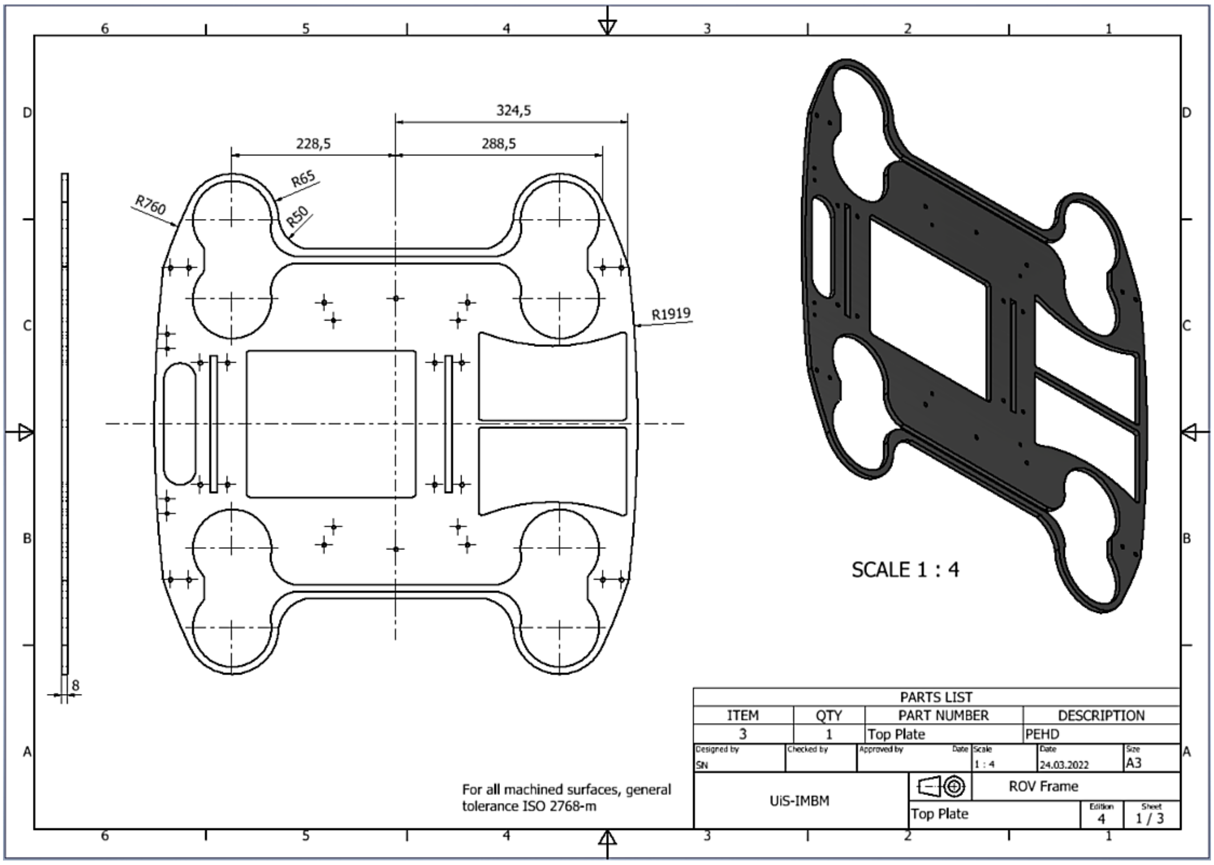


Figure C-11 Technical drawing of the top plate sheet 1/3

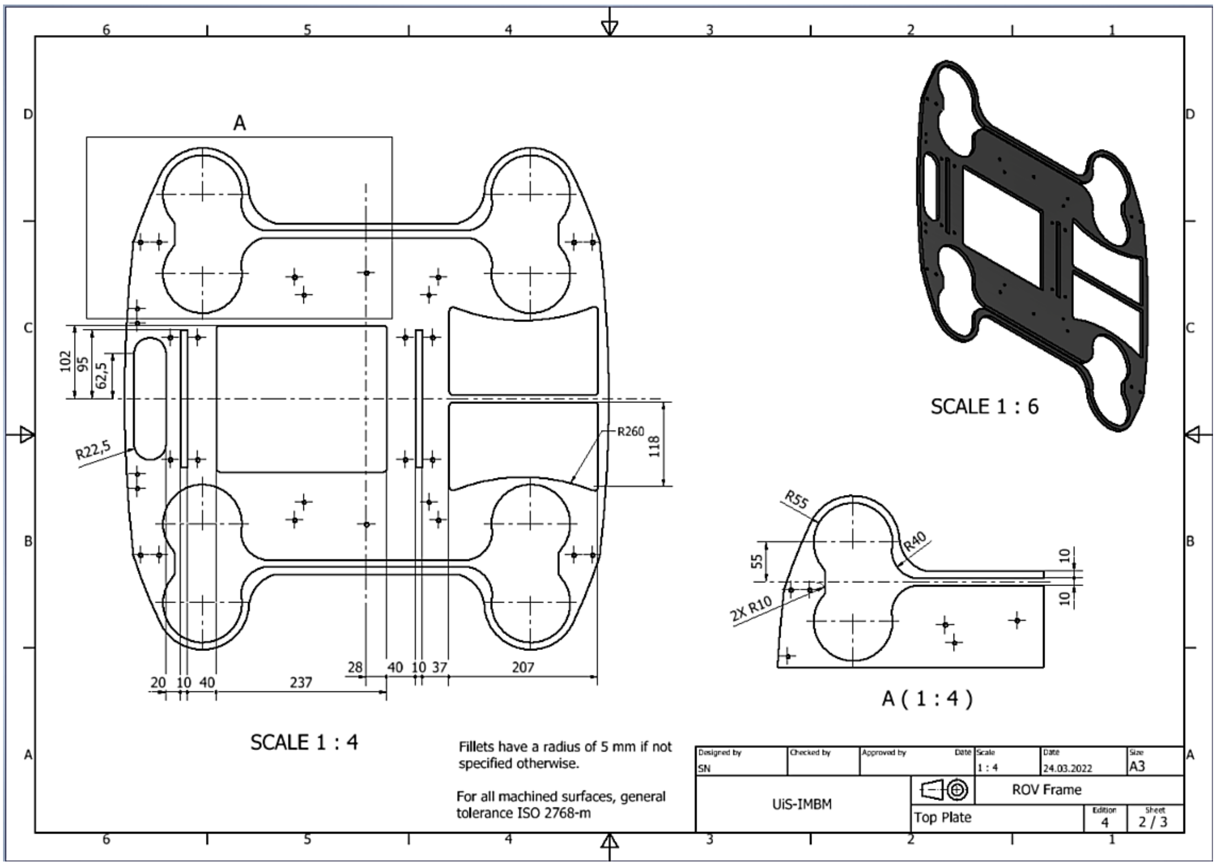


Figure C-12 Technical drawing of the top plate sheet 2/3

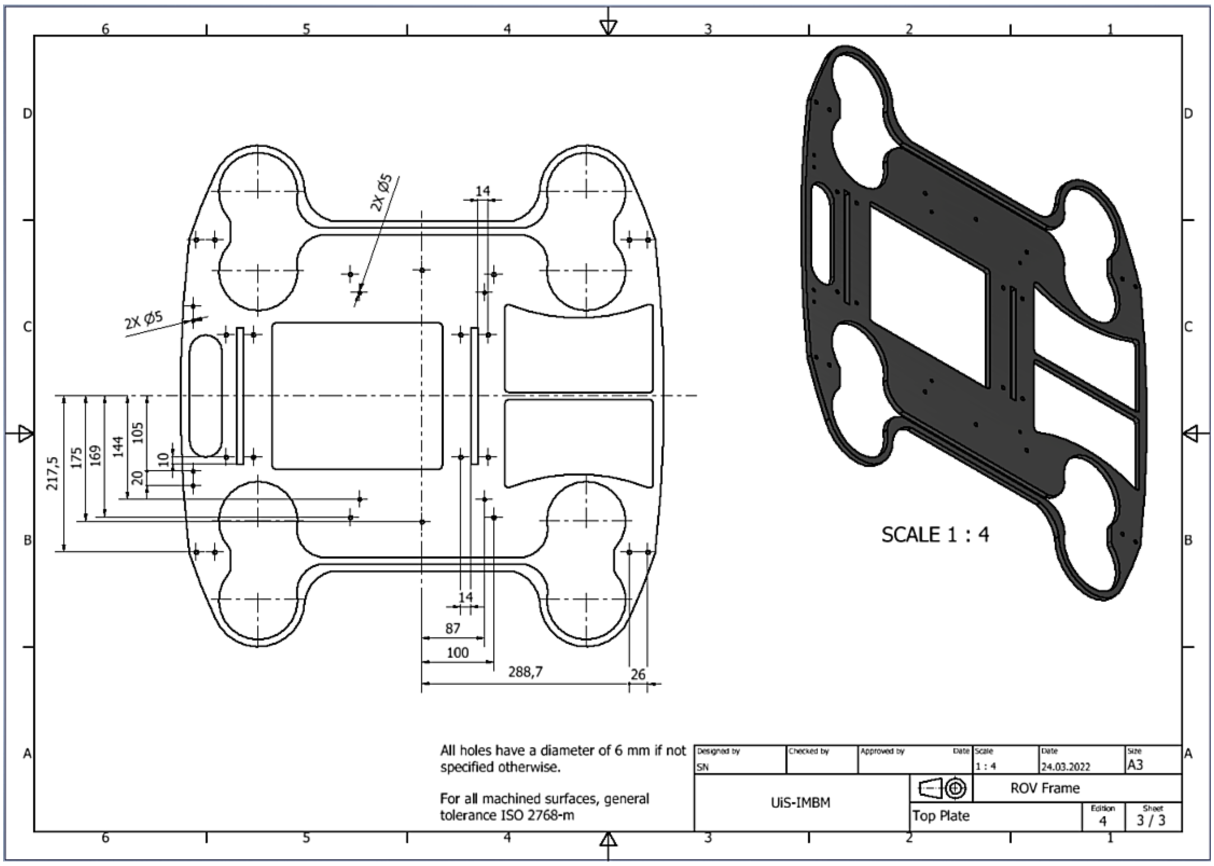


Figure C-13 Technical drawing of the top plate sheet 3/3

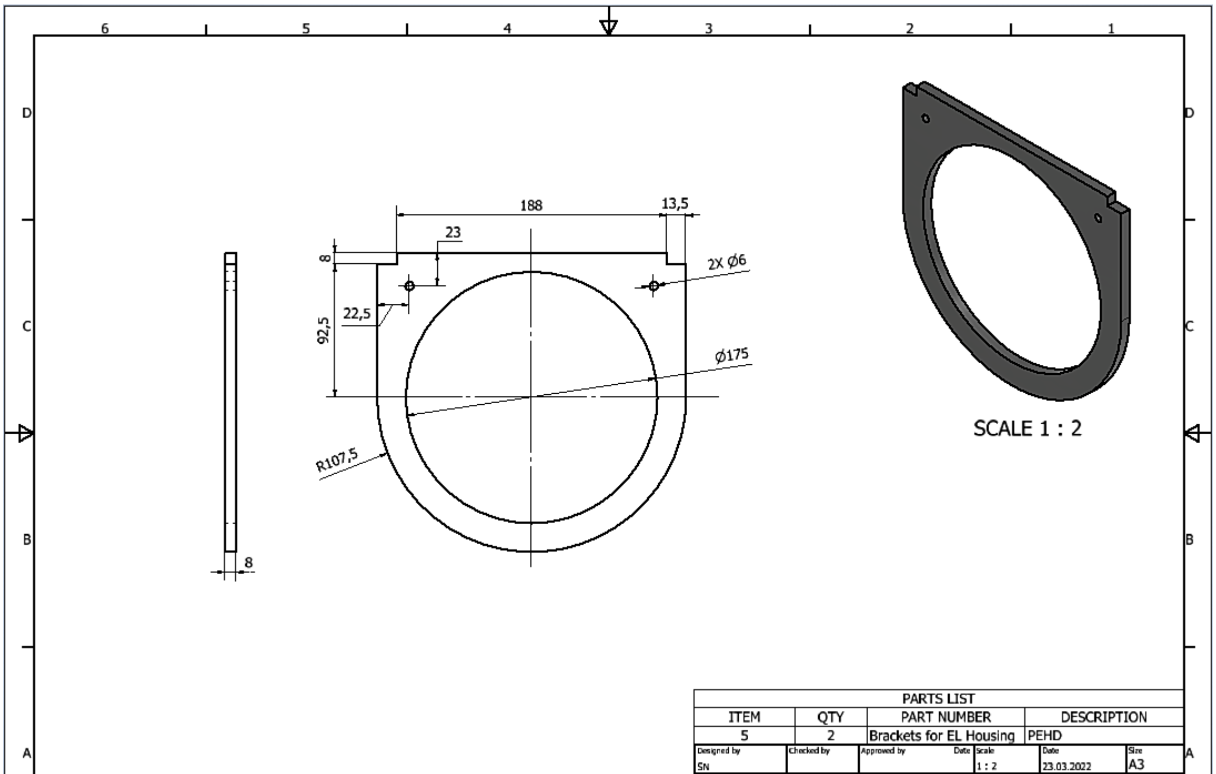


Figure C-14 Technical drawing of the bracket for el housing

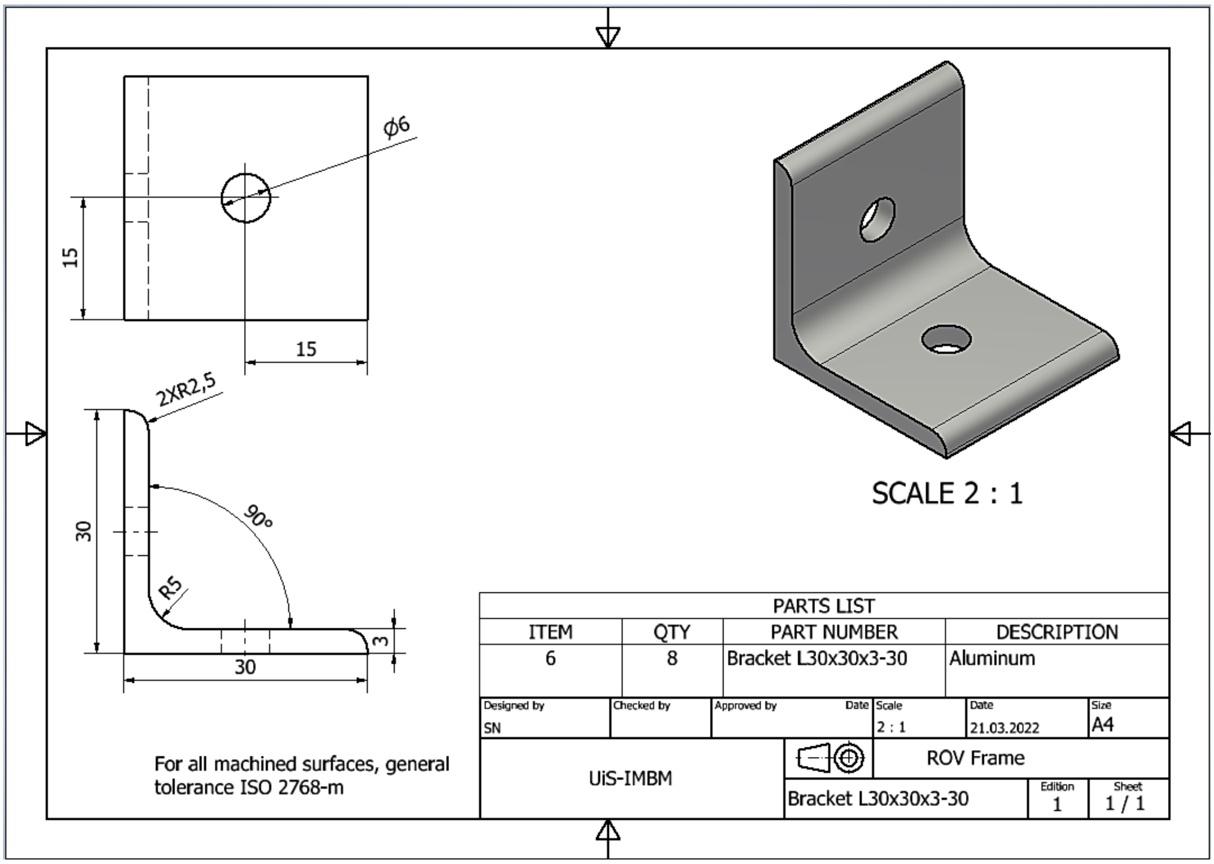


Figure C-15 Technical drawing of the bracket L30x30x3-30

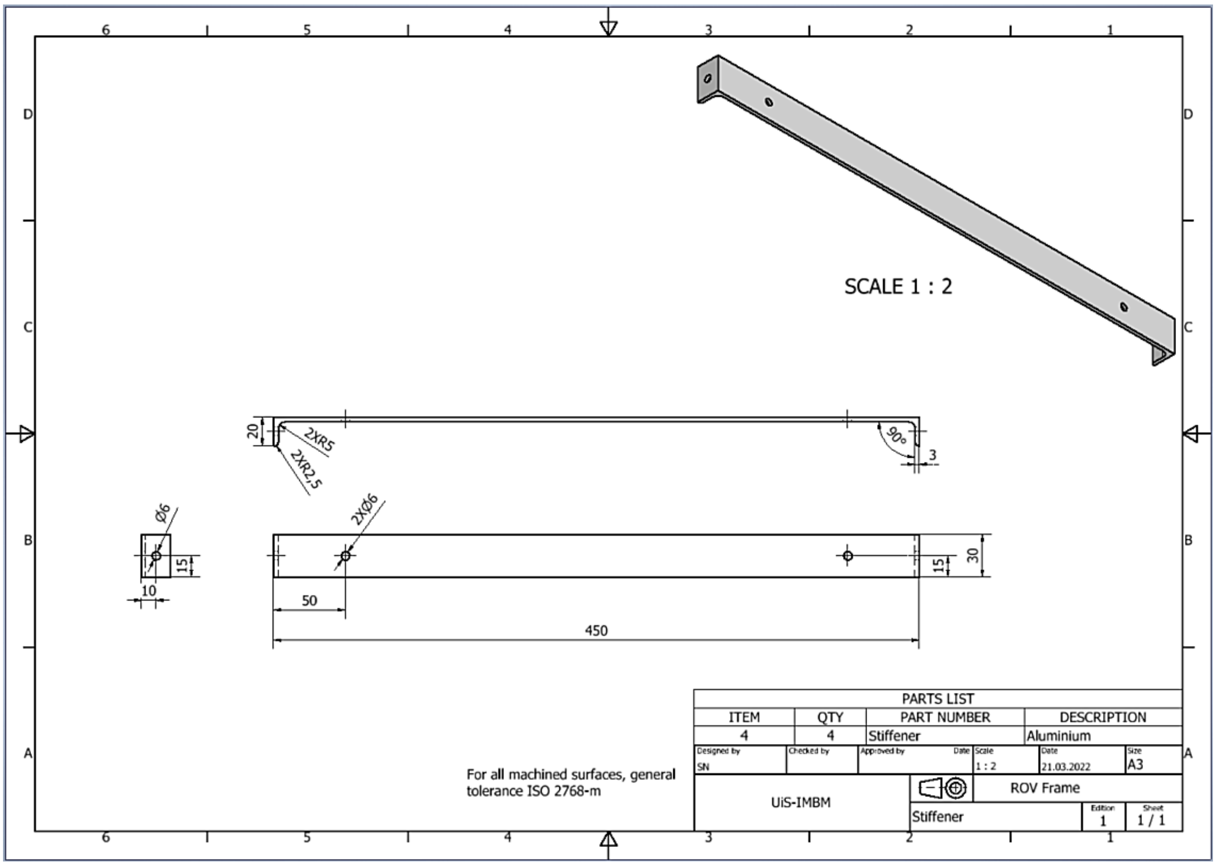
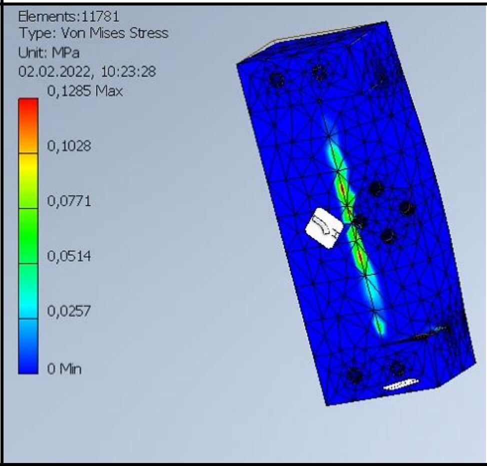
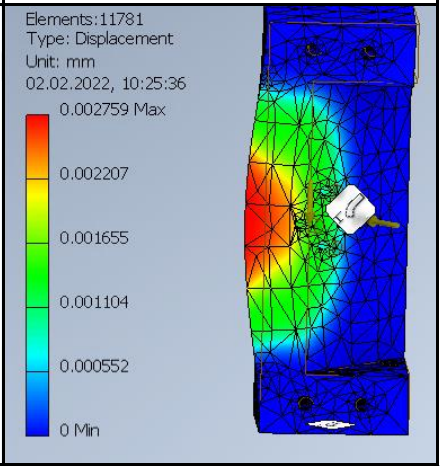
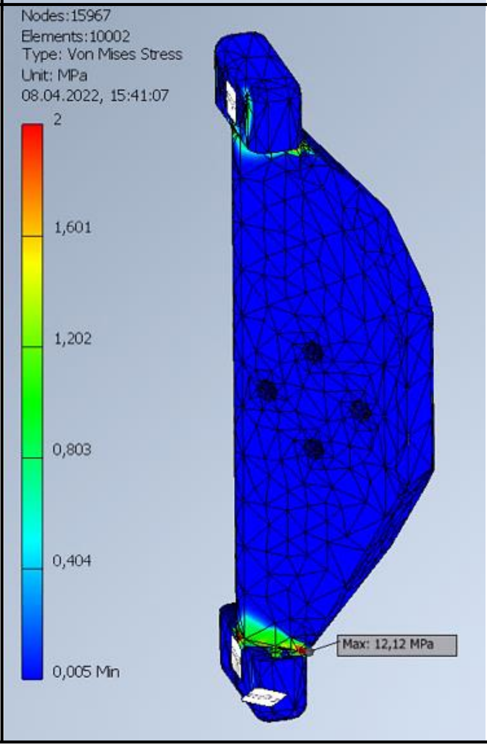
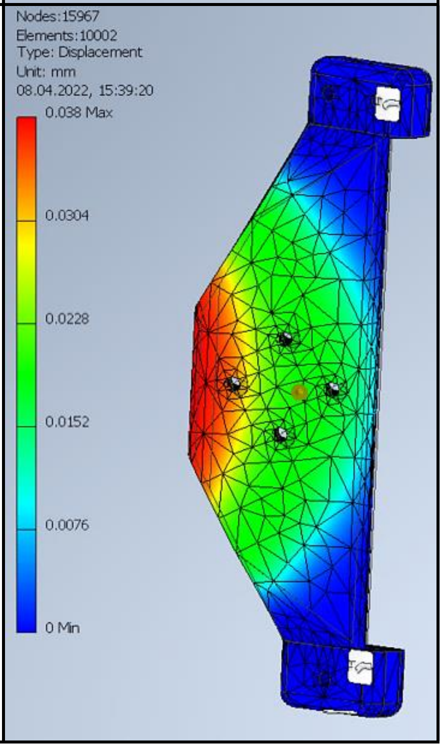


Figure C-16 Technical drawing of the stiffener

Appendix D: FEA of Thruster Bracket Revisions

Revision	Von Mises	Displacement
1		
2		

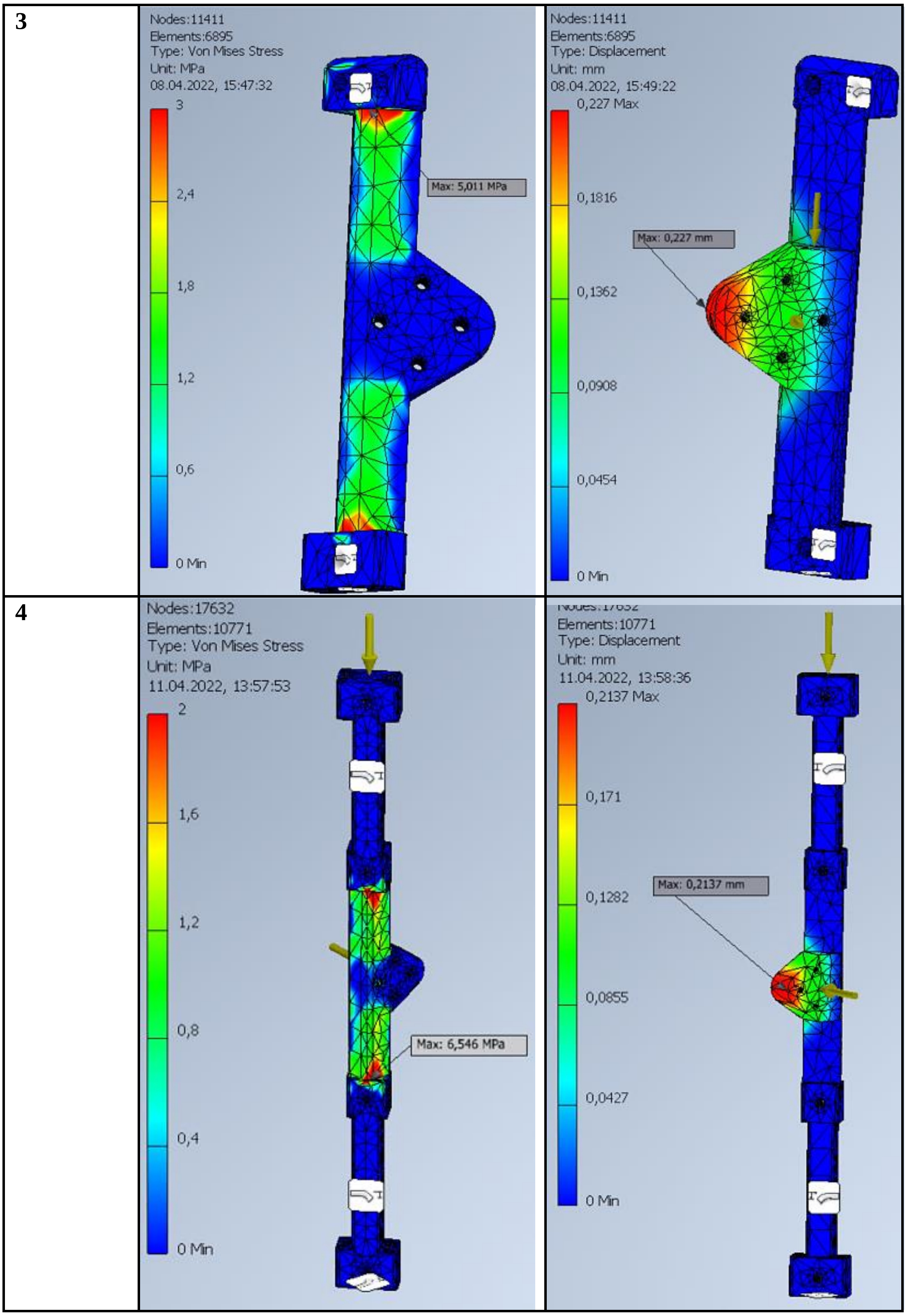
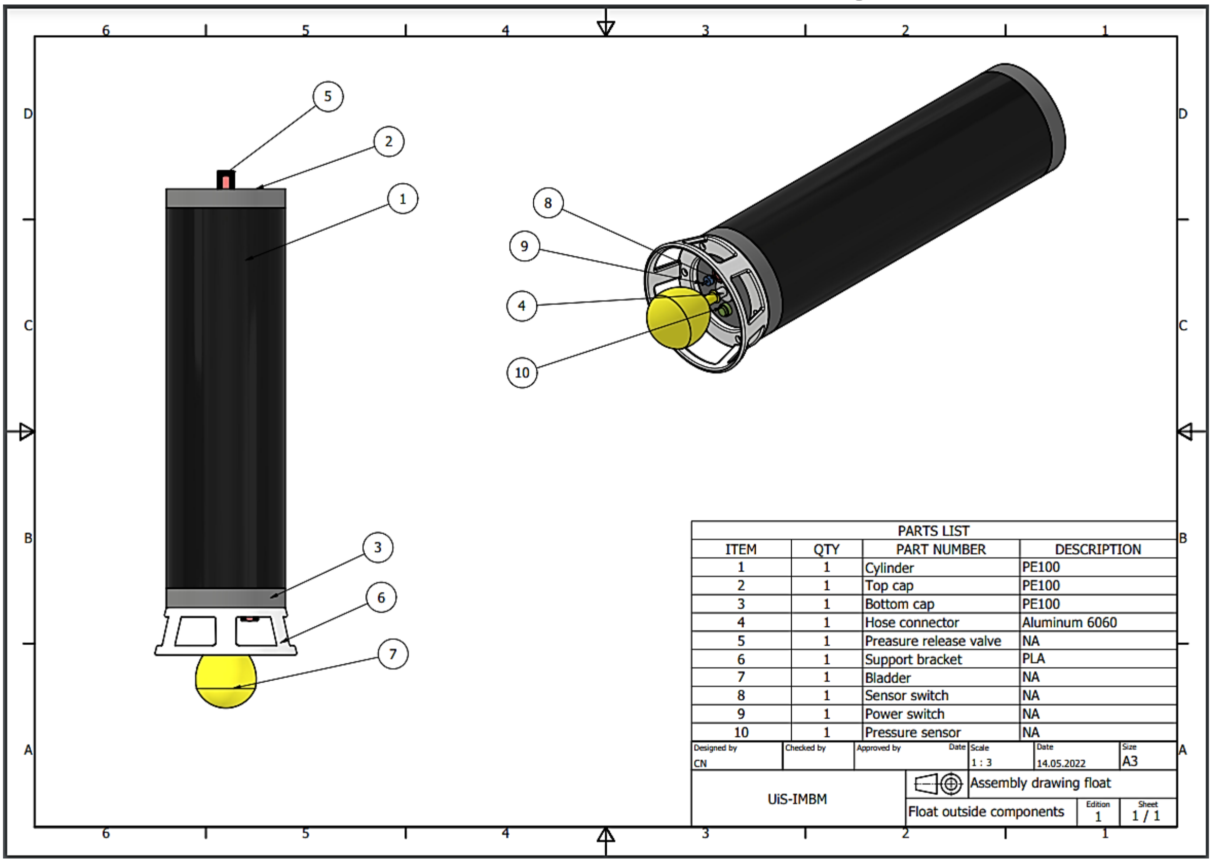


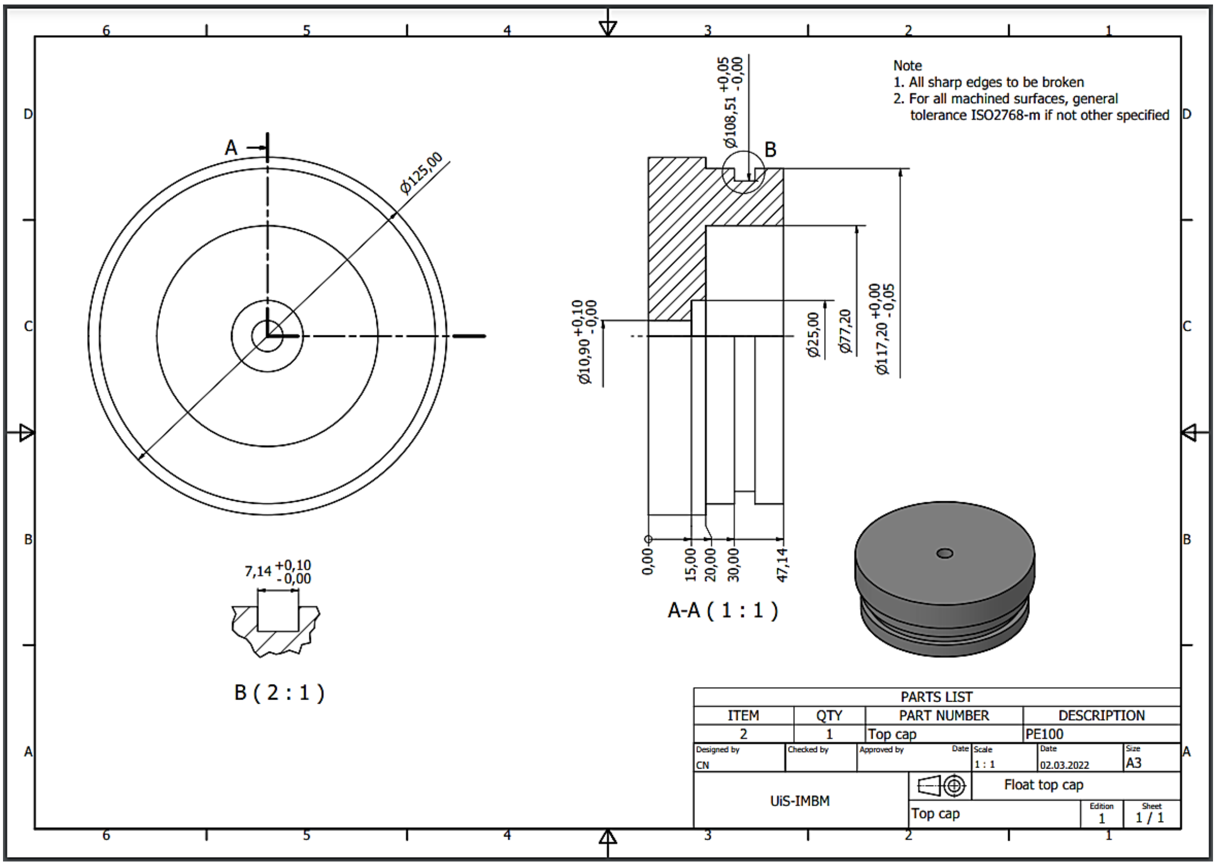
Figure D-1 FEA of the thruster bracket revisions

Appendix E: Technical Drawings Float



PARTS LIST			
ITEM	QTY	PART NUMBER	DESCRIPTION
1	1	Cylinder	PE100
2	1	Top cap	PE100
3	1	Bottom cap	PE100
4	1	Hose connector	Aluminum 6060
5	1	Preasure release valve	NA
6	1	Support bracket	PLA
7	1	Bladder	NA
8	1	Sensor switch	NA
9	1	Power switch	NA
10	1	Pressure sensor	NA

Figure E-1 Technical drawing of the float assembly with parts list



PARTS LIST			
ITEM	QTY	PART NUMBER	DESCRIPTION
2	1	Top cap	PE100

Figure E-2 Technical drawing of the top endcap

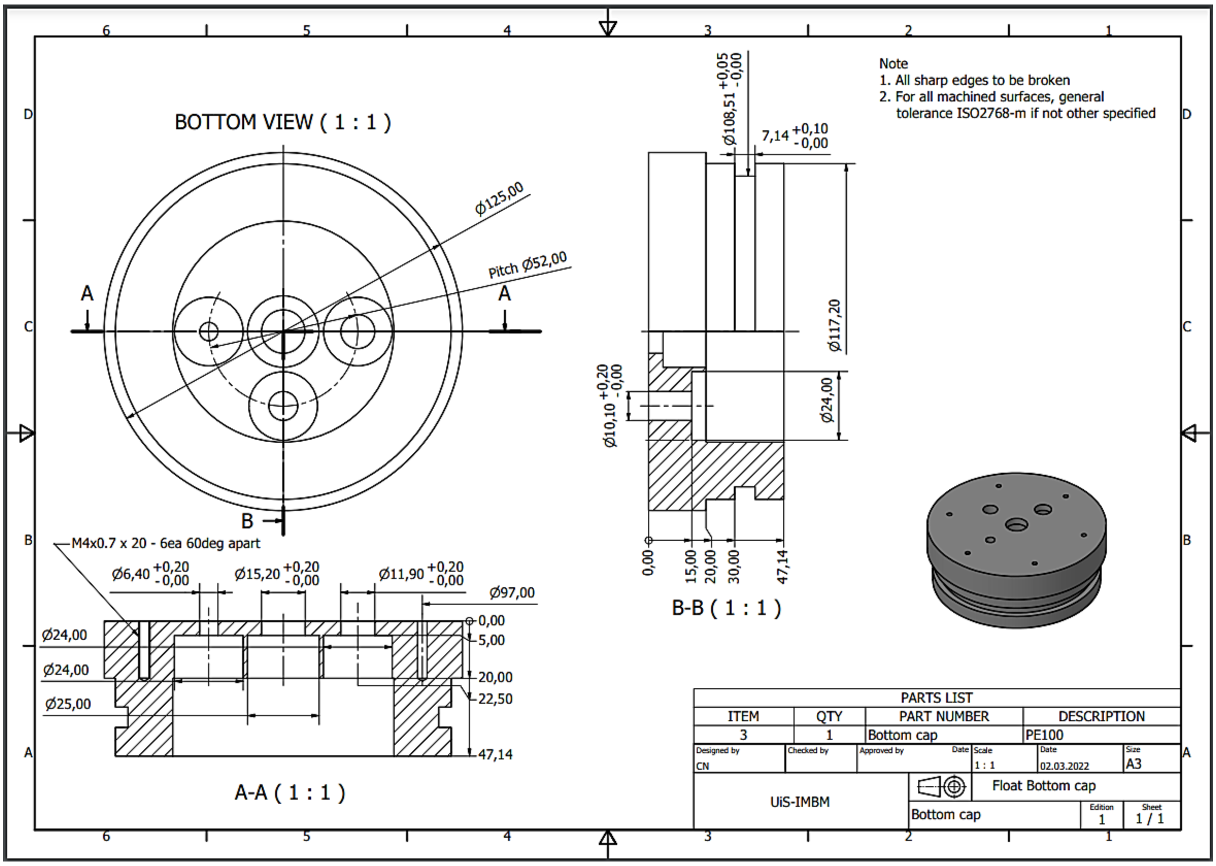


Figure E-3 Technical drawing of the bottom endcap

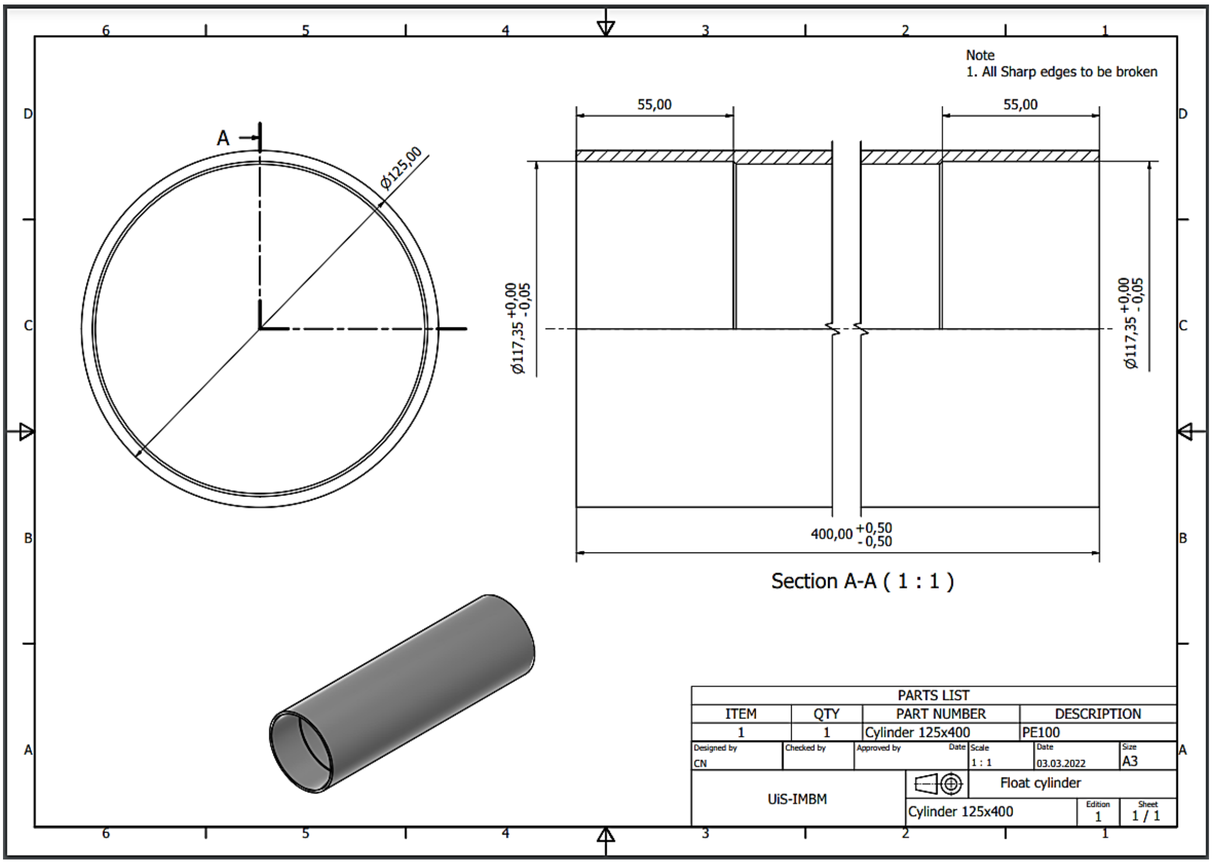


Figure E-4 Technical drawing of the cylinder

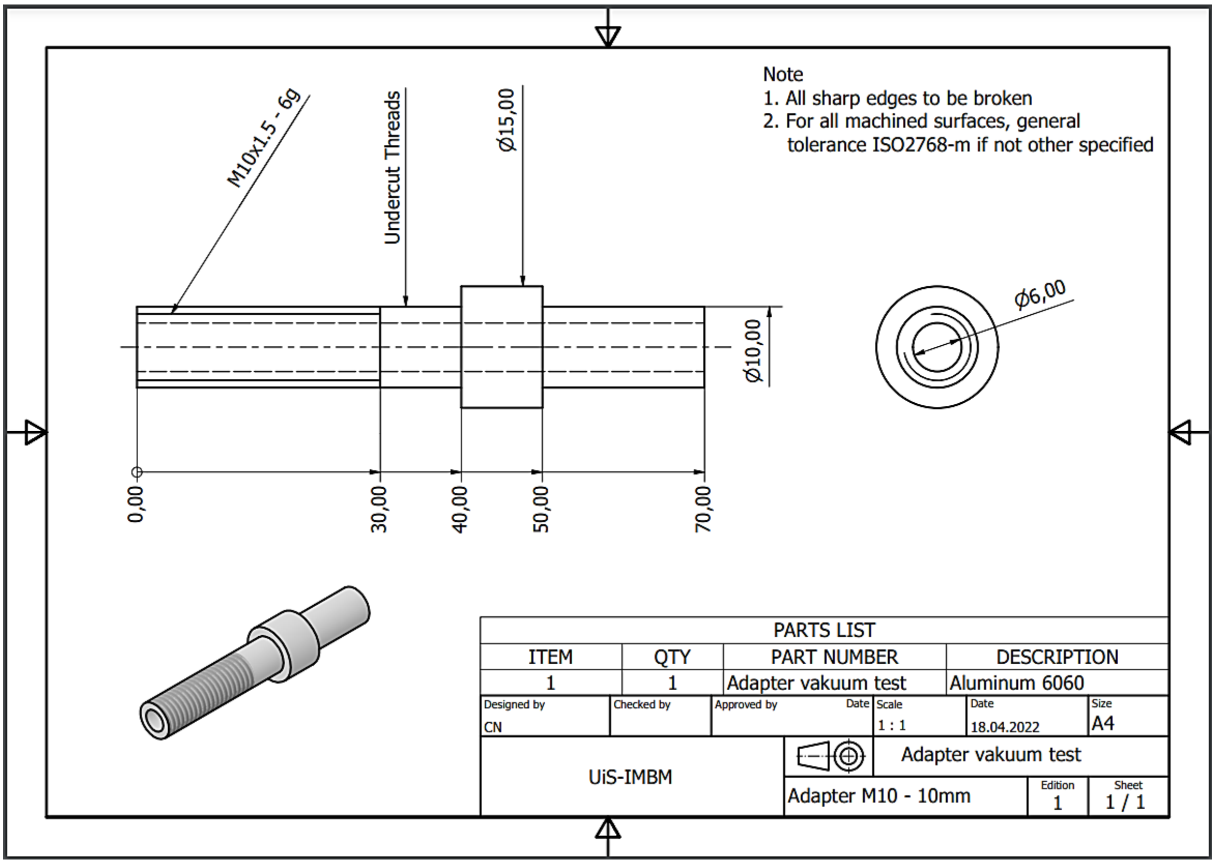


Figure E-5 Technical drawing of the adapter for the vacuum test

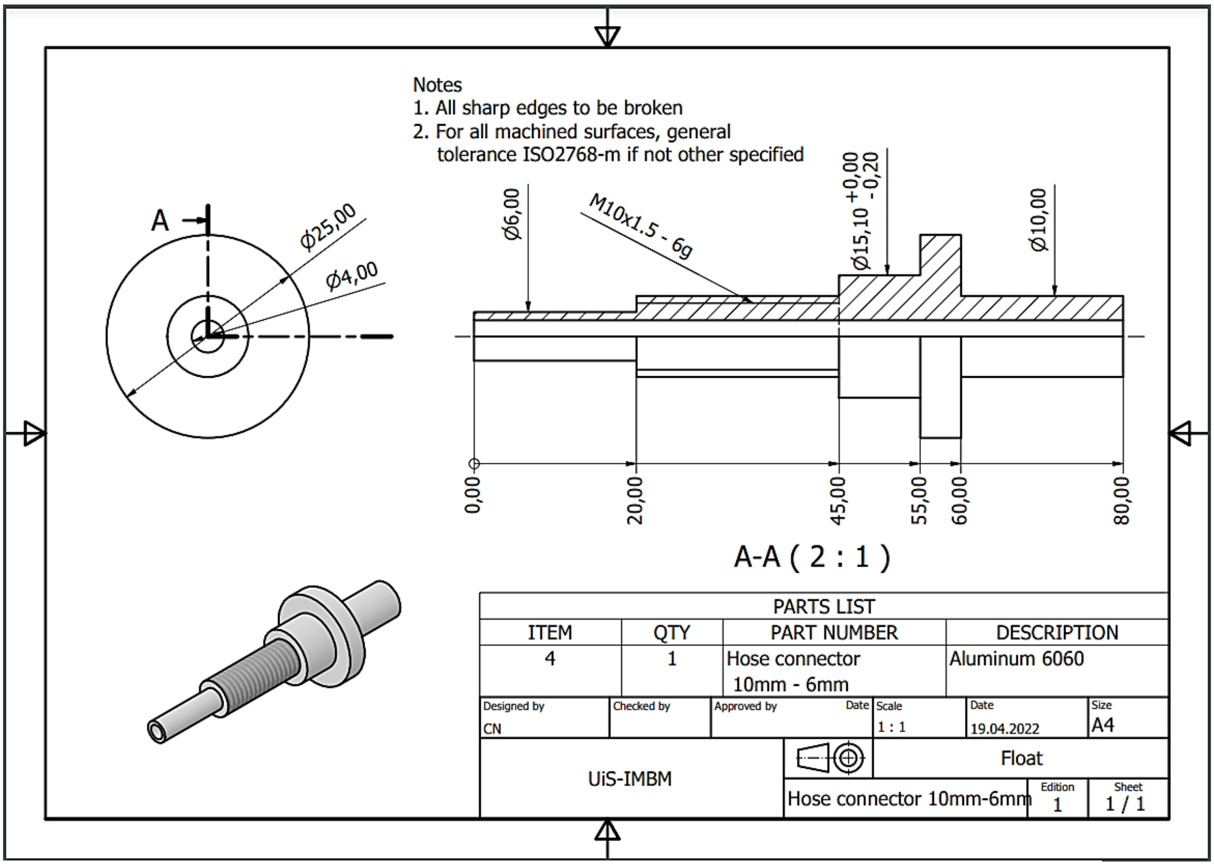
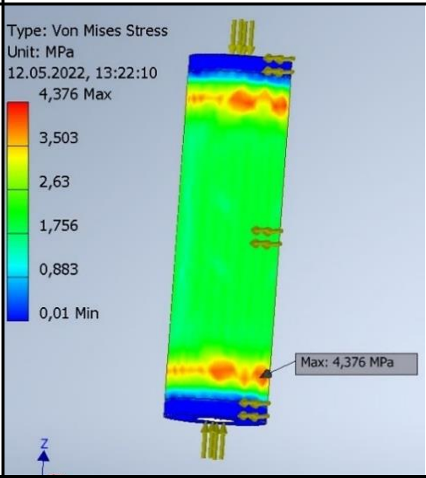
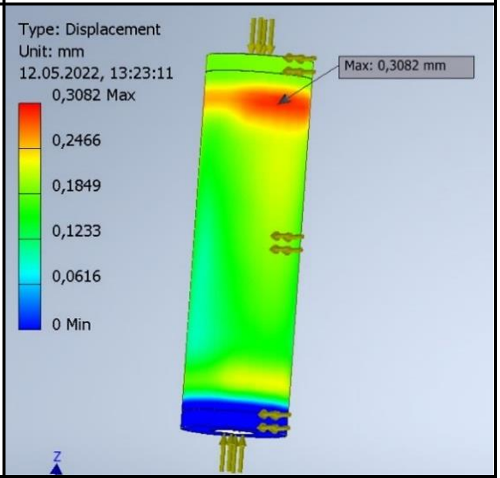
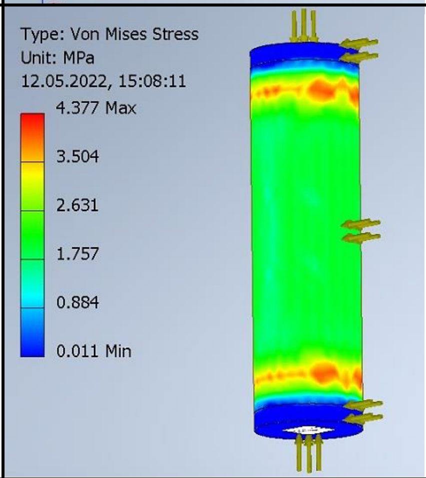
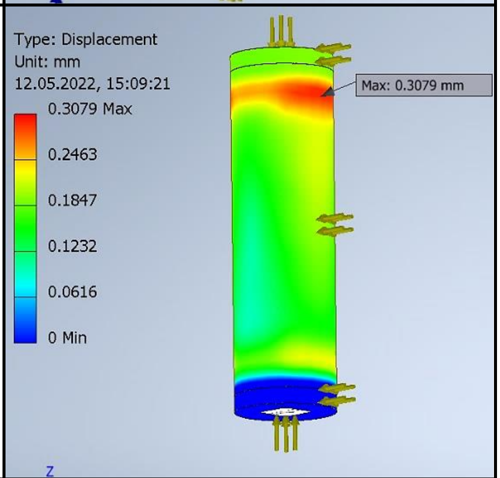
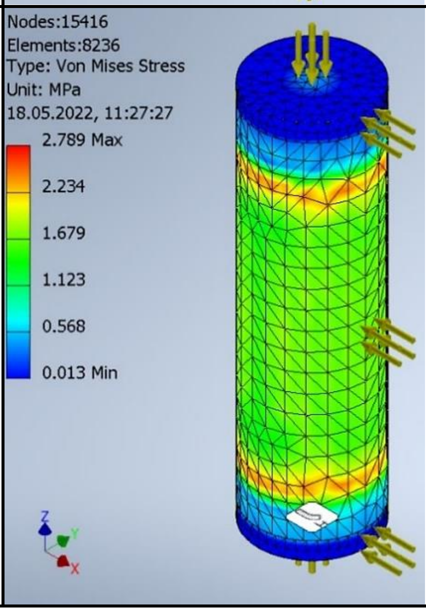
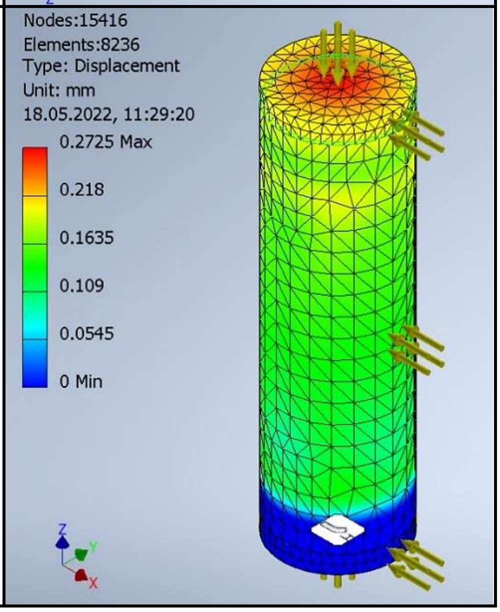
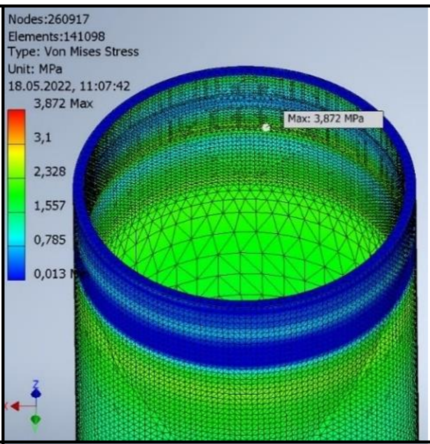


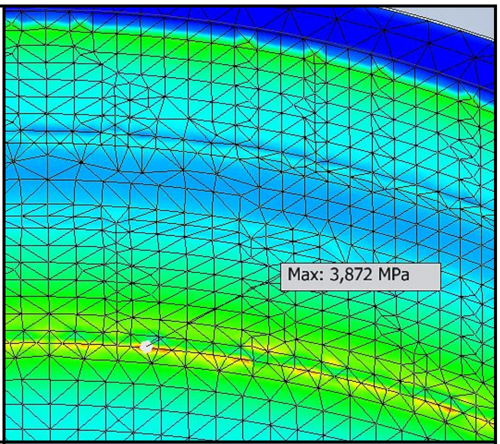
Figure E-6 Technical drawing of the hose connector

Appendix F: FEA Float

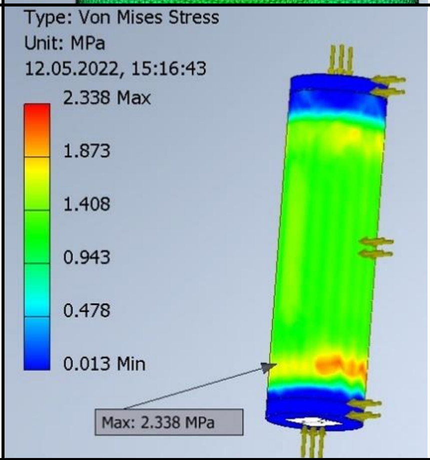
Pipe Size	Von Mises	Displacement
SDR 41 **OD 125** **t=3.1**		
SDR 33 **OD 125** **t=3.9**		
SDR 26 **OD 125** **t=4.8**		

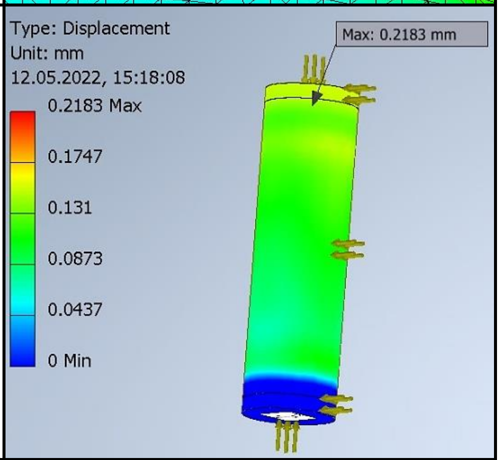
Reduced mesh size



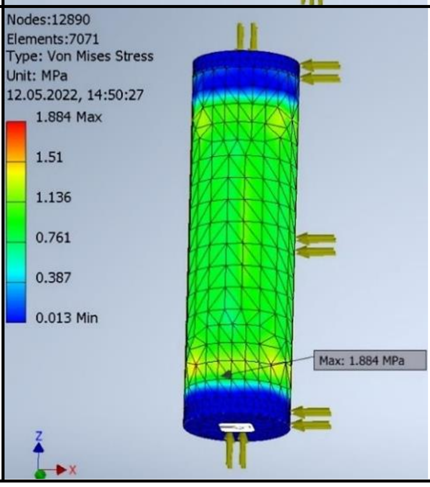


SDR 21
OD 125
t=6





SDR 17
OD 125
t=7.4



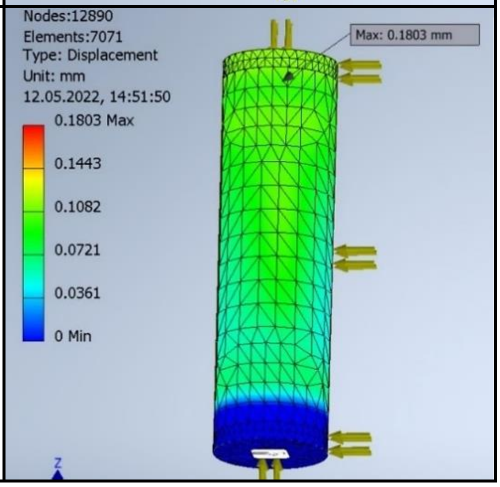


Figure F-1 FEA of the cylinder and endcaps for the different pipe sizes