NTNU
Norwegian University of
Science and Technology

Consumer ROV injection molding shell/frame design

Gøran Jensen Borkamo

Mechanical Engineering
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Supervisor: Martin Steinert, IPM
Co-supervisor: Heikki Sjöman, IPM

Norwegian University of Science and Technology
Department of Engineering Design and Materials

THE NORWEGIAN UNIVERSITY
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AND MATERIALS

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STUD.TECHN. GØRAN BORKAMO

Consumer ROV injection molding shell/frame design

This master thesis will include

- Re-design the next generation BluEye ROV shell/frame optimized for an efficient and economical manufacturing in an assembly line perspective. (polymer prototypes)
- Experiment and prototype in order to find the most feasible prototype production method.
- Map out favorable polymers for prototyping with injection molding.
- Add-on: if feasible, look into the requirements for manufacturing of watertight containers.

Factors to take into consideration are:

- Quantity of 100-200 ROV units.
- A construction designed to withstand the hydrostatic pressure at 100 meters under water.
- Total costs for shell/frame construction <2000£.

Formal requirements:

Three weeks after start of the thesis work, an A3 sheet illustrating the work is to be handed in. A template for this presentation is available on the IPM's web site under the menu "Masteroppgave" (https://www.ntnu.edu/web/ipm/master-thesis). This sheet should be updated one week before the master's thesis is submitted.

Risk assessment of experimental activities shall always be performed. Experimental work defined in the problem description shall be planed and risk assessed up-front and within 3 weeks after receiving the problem text. Any specific experimental activities which are not properly covered by the general risk assessment shall be particularly assessed before performing the experimental work. Risk assessments should be signed by the supervisor and copies shall be included in the appendix of the thesis.

The thesis should include the signed problem text, and be written as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents, etc. During preparation of the text, the candidate should make efforts to create a well arranged and well written report. To ease the evaluation of the thesis, it is important to cross-reference text, tables and figures. For evaluation of the work a thorough discussion of results is appreciated.

The thesis shall be submitted electronically via DAIM, NTNU's system for Digital Archiving and Submission of Master's theses.

Contact persons:

At the department	: Martin Steinert, Heikki Sjöman
From the industry	: Erik Dyrkoren (BluEye)

Torgeir Welo
Head of Division

Martin Steinert
Professor/Supervisor

NTNU
Norges teknisk-naturvitenskapelige universitet
Institutt for produktutvikling og materialer

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Abstract

This document describes the process and the outcome of a master project conducted at the Department of Engineering Design and Materials at the Norwegian University of Science and Technology in the spring of 2016. The purpose of the project was to explore the possibilities for the production of a small series of prototypes and conduct an experiment to find the most favorable method for Blueye to manufacture their prototypes in the future.

This paper starts with a brief introduction and explains the background for the thesis. Furthermore, the paper continues with Chapter 2 where the methods used to solve the task are described; design thinking and Wayfaring. Chapter 3 is dedicated to understand the current situation through knowledge gained by design thinking. Through empathizing with Blueye and an injection molding manufacturer, it was discovered that due to the expensive tools concerning injection molding, there is a need to acquire knowledge about more favorable prototype methods. This could possibly reduce the prototype's time to market and reduce cost of production of a future 0-series.

Furthermore, the theoretical background are established for the experiment and for the wayfaring model, which is an early-phase product development methodology. The method is based on a broad, short sprint approach and not "following a fixed plan". An experiment on how to prototype with injection molding, 3D printing, castings with 2-component resin and milling were performed. Testing was angled experimentally, by allowing findings revealed through testing, determine the road ahead. It was quickly revealed that rapid tooling had potential in the form of small scale casting production, various molding materials was therefore tested. To take this concept further, there was performed a basic finite element analysis to document the effect of favorable geometric structures according to guidelines for molding and casting.

This task is relevant to readers interested in the following topics:

- Rapid prototyping
- Comparison of various prototype methods
- Wayfaring model
- Design of casting parts for prototyping
- Finite element analysis of ABS plastic

Sammendrag

Dette dokumentet beskriver prosessen og resultatet av et masterprosjekt utført ved Institutt for Produktutvikling og Materialer ved Norges Teknisk-Naturvitenskapelige Universitet våren 2016. Hensikten med prosjektet var å utforske mulighetene for produksjon av en liten serie like prototyper og utføre et eksperiment for å finne den mest gunstige metoden for Blueye til å produsere sine fremtidige prototyper.

Dokumentet starter med å gi en introduksjon og forklarer deretter bakgrunnen for oppgaven. Videre tar dokumentet for seg kapittel 2 hvor metodene brukt for å løse oppgaven er beskrevet; desing thinking og wayfaring. Kapittel 3 er dedikert til å forstå dagens situasjon basert på kunnskapen som ble tilegnet gjennom design thinking. Gjennom empathizing med Blueye og en sprøytestøpeprodusent, ble det oppdaget at på grunn av kostbare verktøy til sprøytestøping, er det et behov for å tilegne seg kunnskap om mer gunstige prototypemetoder. Dette skulle ønskelig redusere protypenes tid til marked og redusere kostnadene ved produksjon av en fremtidig 0-serie.

Videre blir den teoretiske bakgrunnen lagt for eksperimentet, samt for wayfaring-modellen som er en tidligfase produktutviklingsmetodologi. Metoden baserer seg på å ikke følge en låst plan, men å ha en bred, «short sprint» tilnærming. Det ble forsøkt på hvordan å prototype ulike produksjonsmetoder; injeksjonsstøping, 3D-printing, støpning med 2-komponent og fresing. Testingen ble vinklet eksperimentelt gjennom å la funn avdekket gjennom testingen styre valgene videre. Det ble raskt avdekket at rapid tooling hadde potensiale i form av støpning i småskala, ulike formmaterialer ble derfor testet. For å ta dette konseptet videre ble det gjennomført en enkel finite element analyse for å dokumentere effekten av fordelaktige geometriske strukturer i henhold til støpning.

Denne oppgaven er relevant for lesere interessert i følgende temaer:

- Rapid prototyping
- Sammenligning av ulike prototypemetoder
- Wayfaring-modellen
- Design av støpedeler til prototyping
- Finite element analysis av ABS-plastikk

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Introduction

Background

As described in the premaster thesis (Borkamo & Lødemel, 2015) the main aim for Blueye Robotics is to expand the use of remotely operated underwater vehicles (hereafter called ROV) in the private consumer market. This thesis aims to meet the requirements in order to manufacture ROV prototypes with high-end quality at low cost in the fastest possible way. Such vehicles are common in deepwater industries such as oil and gas exploration, geotechnical investigations and telecommunications since the early 80s. The many opportunities ROV technology offers the private consumer market are underrated, because potential users do not have the opportunity to buy a high quality ROV in an affordable price range. There is also a lack of knowledge about ROVs as an underwater tool.

Through technological advances, the world has become more accessible and new possibilities have become available. Yet the ocean is still mostly unexplored. The ocean is mostly unreachable to most divers at depths below 30m and science relies on remotely operated tools or manned submersibles to access deep waters (Ludvigsen, 2010). In addition, simple tasks such as inspecting underneath a docked ship is performed by a diver, which is time consuming, impractible and might be costly. Using a ROV opens a completely new dimension in those areas. Underwater vehicles are advantageous for fast access to the water and give access to exploring the ocean in new ways.

ROVs has existed for years, but mainly expensive ones for the industry. Price limits the market and the narrow market further limits the exploration of the ocean. There are some ROVs in more affordable price ranges. However, these models are very limited. It is therefore desirable to develop a solid, simple and user-friendly ROV aimed towards the private consumer market.

Objectives

The aim for this thesis is to:

- Re-design the next generation Blueye ROV shell/frame optimized for an efficient and economical manufacturing in an assembly line perspective.
- Experiment and prototype in order to find the most feasible prototype production method.
- Map out favourable polymers for prototyping with injection moulding.

- Add-on: if feasible, look into the requirements for manufacturing of watertight containers.

The research done for this paper will not cover all possible situations, but covers the logic way for me to get quick access to new and important experience. In order to be able to further develop the production for the new easy-to-use low-cost consumer ROV.

The purpose of this paper is to achieve insight in an efficient and economical manufacturing method for the future prototype- and 0-series models from Blueye. In order to help them make future design decisions faster and cheaper.

This paper is organized and separated in nine chapters to help the reader trough the thesis. As a human centered-designer the task has been solved open minded. Chapter 1 therefore guides the reader through the methodology used for this thesis. Design thinking is a method for practical, creative resolution of problems and creation of solutions that embraces the values of human centered design. After gaining insight into the minds of users and Blueye, I have applied a wayfaring mindset for exploring different production methods. Therefore, chapter 2 is dedicated to give the reader an overview to the current situation. Chapter 3 includes theory required to give understanding of the thesis. After acquiring some insight into the current situation at Blueye and their potential users, the project went in a wayfaring direction. Wayfaring is a mindset inspired by “The Hunter-Gatherer Model”, which is based on having a broad approach with rapid learning cycles. Chapter 4 includes experimental testing of production methods based on findings through the testing. The prototypes are after the experimental test benchmarked against each other to determine what process is favorable. In the end, an updated version of the re-designed shell is presented, where the gain of rib structures are verified.

Chapter 1 Tools and Methodology

As an early phase development project, the focus was on discovering a production method suited for Blueye's next ROV. To avoid locking onto my own and Blueye's biases towards the design of the product an open-minded approach to the project was necessary. Manufacturing a product correctly when you do not have the sufficient background data could be problematic. It may turn out costly and perhaps impossible to change the design if new data is introduced at a late stage of the project. From the course *TMM4245 - Fuzzy Front End* (spring 2015), a technique introduced, *design thinking*, were applied in the start of this project. The model that was followed is *An Introduction to Design Thinking - Process Guide*, by Plattner (2010). In addition, molding and casting were unfamiliar areas, the thesis was therefore chosen to be solved with a wayfaring and design thinking mindset.

1.1 What is Empathizing?

The method starts with getting to know the consumer through empathy. Empathy is the midpoint of a human-centered design process. The work in this phase is done in order to understand the user for whom the product is designed for, within the framework of the design challenge. It is up to the designer to understand how the user does things and why. As well as discovering the user's physical and emotional needs, what the user thinks about the problem and the solution, and what is meaningful to the user. However, other people influence how the solution should be designed, for example the manufacturer. In order to empathize, the "Stanford Introduction to design thinking" suggests three stages: observe, engage and immerse.

Observing - Connecting with the users and watching their behavior in a specific context. Observing can be a powerful tool that makes it possible to see things from another perspective.

Engaging - Interacting with the user during the conversation. Sometimes people's perceptions of what they think they are doing is not the same as what they actually do. By engaging the user, it is possible to identify needs and insights that the user was not even aware of. These insights give you direction to create innovative solutions.

Immersing - Putting yourself in the same situation that the user experiences. This allows you to understand his situation.

The main tool used for this process is structureless interviews to make them more like a conversation. I have through my work interviewed some potential users as well as Blueye and an injection molding company named Lycro. The interviews have been used to validate design selections and as a supplement for Blueye to understand the design criteria for the future production models. However, it is difficult to generalize interview data. Results are therefore not used directly, but only to verify other research and findings.

1.2 What is Wayfaring?

Instead of following a fixed plan approach, wayfaring is described as an exploration journey to discover innovative ideas. The wayfaring model is founded on "The Hunter-Gatherer Model" by Steinert and Leifer (2012) and Ingold (2007). The Hunter-Gatherer Model is based on aiming for the last known location of the prey. The hunters are able to occasionally shift their target coordinates, or even change the prey targeted.

Going from the hunt to a project, this means that the project is divided into short legs with a focus on building and testing to gather needed knowledge to head for a new destination.

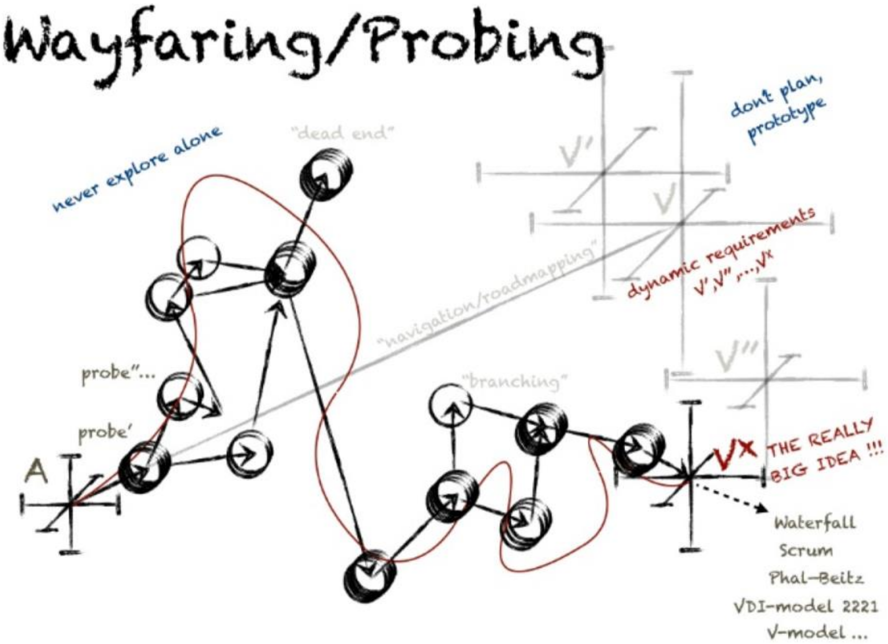

Figure 1 - Wayfaring retrieved from Gerstenberg et al. (2015).

Later, Gerstenberg et al (2015) have further developed the wayfaring model as an early concept creation methodology for product development projects with a high degree of innovation. The idea behind the model is that one cannot predict and target the perfect solution to a new problem, as we do not have empirical evidence for the outcome of which has yet to be done. The methodology as depicted in figure 1 can be divided in four main aspects:

Probing – exploring new ideas by means of design, building and testing low-resolution prototypes, to fail early as new discoveries are made, and to enable abductive learning. The method is depicted in figure 2 below.

Merging interdisciplinary - Creating interlaced knowledge by including all disciplines at the start for finding various dependencies.

Speed - Timeframe based on short sprints to maximize number of iterations and opens for agility as new discoveries are made.

Agility - Letting the discoveries shape the outcome of the next step in the in the development process.

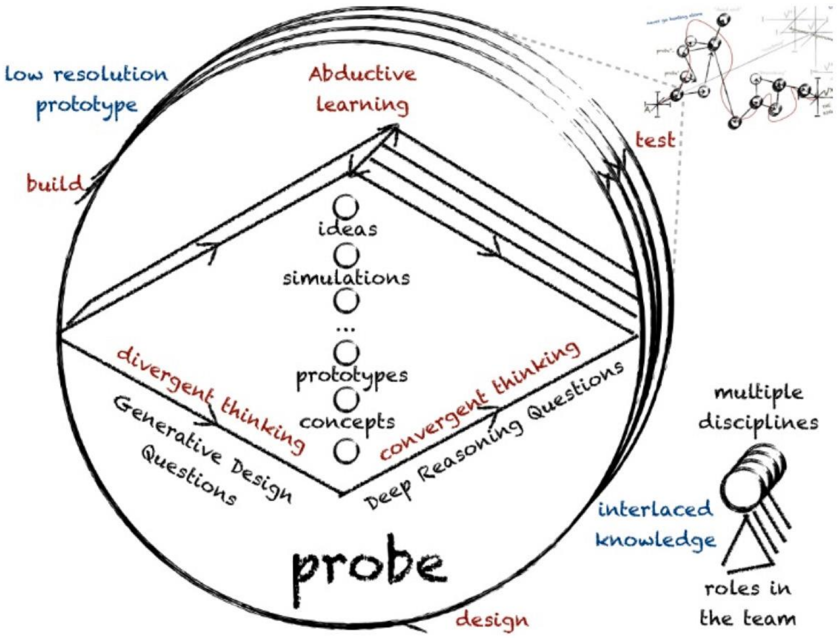

Figure 2 - Probing retrieved from Gerstenberg et al. (2015).

There may be some concerns using wayfaring. Because the research is conducted alone, it is easy to favor personal biases, and make choices without discussing the consequences of choice. To avoid this, I have attempted to reflect over the choices made and discussed this with people with relevant expertise. In addition, in a wayfaring project where the researcher has little experience, it might be hard to narrow project down. Therefore, I have tried to set natural limitations where it is possible.

1.3 Prototype

A prototype is an early stage model, or release of a product built to acquire knowledge by creating models showing either functions or looks (Blackwell & Manar, 2015). Prototypes has become an essential part of a product development process (Soares & Rebelo, 2012). Ulrich and Eppinger (2012) distinguishes between prototypes used for learning and prototypes used for validation. Furthermore, the purpose of a prototype should always be to answer a question. For example, “does it fulfill the requirements?” or “will it work?”. Further, the report defines a prototype as “An approximation of the product along one or more dimensions of interest”. Meaning their definition of a prototype cover both non-physical and physical models including; sketches, mathematical models and simulations, mechanisms, mock-ups, section of the product, and preproduction ready versions of the product (Elverum & Welo, 2015). As opposed, Beaudouin-Lafon and Mackay (2003) define a prototype as “(...) a tangible artifact, not an abstract description that requires interpretation.” The report looks at how one takes an idea and into the physical world. Therefore, anything taking a physical form can be a prototype (Bootcamp Bootleg, 2010).

Generally, prototypes will diverge from the final product in three fundamental ways:

Materials – Production ready products may require manufacturing processes involving high cost materials for achieving desired quality and quantity as cheap and as little time consuming as possible. In general, this is not practical for prototyping. Instead, engineers attempt to substitute the material with other materials, which have properties that enables the prototype to simulate the intended function or form. (Elverum & Welo, 2015)

Processes – It is often required expensive and time-consuming tooling to manufacture a custom design. Designing a prototype is often a compromise by using cheaper materials fabricated with simpler processes, such as 3D printing in polymers and manual cutting and bonding in plywood. The processes are often characterized as inefficient or substandard technology sources for manufacturing. Lim and Stoltermann (2008) states that the benefit with a prototype is its incompleteness. This allows the designer to examine the strengths and weaknesses of an idea, without manufacturing the final product.

Fidelity - Final production designs often require extensive preparation to secure high volume manufacturing detail and precision. In general, such fidelity (or resolution) is unnecessary for prototypes as changes to the design is to be expected. Fidelity is used for describing the level of details in a prototype, or how close the prototype resembles the final product (Elverum &

Welo, 2015). On the contrary, McCurdy et al. (2006) defines fidelity as the level of richness and functionality of the prototype. McCurdy also reveal the use of mixed fidelity, combining low- and high fidelity of the prototype**,** but only one fidelity is acted upon at a time (Coyette et al., 2007). Meaning that the mobile phone has high fidelity in terms of outer looks, but low fidelity in terms of user interface as shown in figure 3**.** Often prototypes are created using very limited resolution compared to the final product to being a tool for discussion. It is important knowing how to design with a proper resolution in order to obtain reliable feedback without consuming too much time. Research has shown how too high or too low prototype fidelity can prevent the audience from generating useful feedback (Houde & Hill 1997). An example of a lower fidelity prototyping technique is paper prototype, also seen in figure 3. These are often used to confirm design decisions before more expensive and time-consuming processes are initiated (Medero, 2007).

Figure 3 - Paper prototype. Retrieved from *www.april-steed.com*

Chapter 2 Understanding the Client

2.1 Who is Blueye Robotics

Blueye Robotics is a newly established company that originated from NTNU AMOS. Blueye aims to make underwater exploration possible for everyone with user friendly and supreme underwater drones that let you discover and learn about the world hidden below the surface! The company consists of a competent core team that works closely with NTNU professors, as well as master- and PhD-students. The entrepreneur team is passionate about the ocean and wants Blueye's drones to provide users worldwide the opportunity to explore the ocean where they live. Blueye is located in the inspiring environment of Gløshaugen Innovation Center along with several NTNU start-up businesses (Dyrkoren, 2015). The idea with the startup is to become the market leader in a relatively new and unexplored market. For years, the ROV market has mainly been for the industry, due to the poor usability and the sky-high purchase prices. Blueye now see an opportunity to conquer this market with its ROVs.

The Blueye product development model is still under progress. Blueye is currently working on their second prototypes and soon going for their first 0-series prototype that will be sold within a closed group for further, more rapid testing. The aim is to learn even faster and get knowledge about a more commercial production process.

As well as being a ROV maker, Blueye also wants to be a solution for saving the planet. Through 2016 they can be found in multiple articles and at conferences explaining how their product could help discovering the damages caused by plastic pollution in the ocean. Mechanical Design Engineer, Rune Hansen, says that the products in the future will be manufactured with a focus on the environment. He tells that Blueye are looking on alternative materials for the buoyancy elements, such as recycled polyethylene terephthalate (PET) from empty bottles. They will design their future models with a focus on recycling, meaning using as little glue and other permanent bonding processes as possible.

2.2 Product Development at Blueye

As a relatively newly established company still working on prototypes, Blueye has not yet focused on design for manufacturing. However, Rune Hansen at Blueye says that they will be designing the first release model for injection molding. According to production engineer Ståle Sve Rian at Lycro, companies that are developing new products do not understand the limitations of injection molding. Therefore, they are using a lot of time re-designing their models in collaboration with Lycro. Rune Hansen has design experience from Microplast AS. In addition, Blueye are cooperating on the design with EGGS Design, a multidisciplinary design consultancy housing Scandinavia's widest design competence. Rune Hansen further reveal that necessary expertise will be hired if needed.

Because the company still is in an initial phase, there is no direct design practice. Today they are using prototypes to learn about their product and trying to design their prototypes closer towards a manufactural design. The side covers of the Blueye ROV are today manufactured by milling polymer blocks. Further, complex features are glued on to make a solid model. This is a manufacturing method that is time consuming, costly and not viable when manufacturing larger quantities of parts. Being a company going for mass production in the future Blueye is, with their polymer frame, most likely to use injection molding for manufacturing.

After empathizing with Blueye there was possible to see what they actually wanted to achieve with this thesis. Two main aspects were uncovered. Firstly, they wanted to reduce time to market, meaning discovering ways of learning faster from the prototype towards the final product. Secondly, to reduce 0-series costs, meaning finding a cheaper way of prototyping smaller batches of identical prototypes.

2.3 Visit to Lycro AS

In the start of the master's thesis I contacted Lycro AS, a company working with production of injection molded plastic parts and production of tools involved in injection molding. The purpose of the visit was to get an introduction to how production with injection molding is performed. I was welcomed by Production engineer Ståle Sve Rian (Figure 4) who gave me a tour in the manufacturing department. Lycro's headquartered and factory for the production of molded plastic parts are located in Leksvik, Trøndelag. They have extensive expertise in all domains concerning injection molding.

Figure 4 - Production Engineer Ståle Sve Rian

The challenge concerning injection molding is the high cost of the tooling. Normally, companies like Blueye have their tooling designed and manufactured by suppliers such as Lycro. Rian informs that the tools are designed and constructed by their project engineers in Norway together with the customers in accordance with European standards and requirements and customer specifications. The tools are then manufactured in their factory in Dongguang, China, ensuring cost-effective production. The price can very well be more than a million Norwegian kroner for complex tools. Further Rian elaborates that after the tool is manufactured very few modifications are favorable without shipping the tool back to China. Such as modification of hole diameters and change in rib thickness. This design re-loops causes delays and extra costs due to manual labor, and ultimately be avoided. Therefore, good preparation and extensive expertise are beneficial in terms of keeping the costs as low as possible.

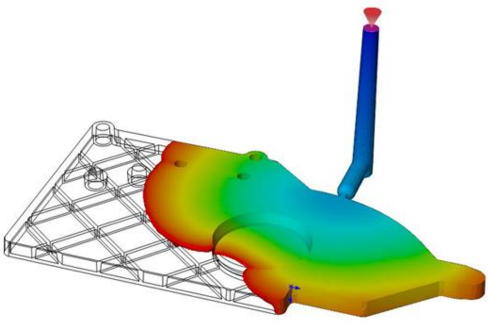

Figure 5 - Filling from injection molding. Retriever from http://www.solidsmack.com/

Lycro offers a service where they simulate the injection molding process using simulation named SolidWorks Plastics. A simulation software embedded in the computer aided engineering (hereafter called CAD) software SolidWorks (See figure 5). The simulation helps to determine problems such as where to put the inlet gates and how the polymer melt freezes. At Lycro they have experience that the simulation does not always represent reality, but generally gives a good indication.

With new products, it is normal to run a 0-series before the production tool is manufactured. These 0-series are made from a complete replica tool using low-cost prototype material, typically aluminum or silicone. Ståle Sve Rian discloses that this is done to tune the different process parameters before the tooling steel tool are manufactured. Starprototype has stated that a silicone (polyurethane) mold is ideal for making up to 50 functional duplicates of the master part ("Polyurethane-casting", 2016). In addition, Honda has built a deck tray for the Honda Accord in an high quality aluminum tool, and has since 2007 passed roughly 500,000 cycles ("Why Aluminum Tooling Makes Sense for High-Volume Automotive Parts", 2016).

At Lycro they are manufacturing products in several different materials, from simple polypropylene to glass filled grilamid. Sve Rian mentioned that there are infinitely many materials with different material properties, which can be used in injection molding, all dependent on the customer demands and wishes.

All injection-molded plastic parts are produced at Lycro's own factory in Leksvik, Norway. They have a fleet of 22 automated injection molding machines with a closing pressure of between 45 and 1500 tons, and can produce plastic components with a weight of 1.0 grams to 10.5 kg. However, Ståle Sve Rian explains that the injection pressure typically can range from 400-700 bars. He further explains that the pressure serves three purposes. First, the pressure fill the cavity with molten plastic, and makes sure that it solidifies simultaneously. Further, the pressure gets rid of the air trapped inside the cavity before it fills every cavity caused by shrinkage of the material. Rian explains that cooling and filling after shrinkage takes up over 50% of the cycle time. The cycle times of a typical thin wall structure varies from 2-6 seconds, but can be up to 30 seconds on large, complex products.

2.4 Potential Users

There were five main interview objects, from a potential user group. Common for all was that they wanted stability rather than speed for the ROV. It was clear that the live experience was the most important aspect. Quality and functions were preferred over looks. For the first 0-series, it is therefore not as important with surface finish. In addition, the ROV should be easy to use in terms of transport, maneuverability and needed maintenance. Which coincides with Blueye's wishes to avoid permanent bonding for their parts. Two of the interviewees also had personal experience with ROVs. Tips in terms of problems with ROV usage were collected. It was pointed out that the ROV's surface will be worn, which indicates that there is no need for a perfect surface finish for the pre-production 0-series. Interview summaries can be read in Appendix A.

Chapter 3 Theoretical background

3.1 Rapid tooling

Rapid tooling labels any mold-making process that can fabricate tools quickly and with minimum manual labor. Rapid tooling is based on tool-making approaches that apply additive manufacturing- (hereafter called AM), subtractive- , and pattern-based processes. Further, these molds can be applied in different types of applications, from injection molding to casting operations. The advantage with rapid prototyping is the saving of time and cost. According to Ulreich (1992), Westinghouse Electric Co. manufactured prototypes, in 1988, using stereolithography (3D printing technology) for $2,700 in ten days, instead of $3,600 in ten weeks with their usual prototype manufacturing routine.

Rapid tooling can be applied in two different forms, indirect rapid tooling and direct rapid tooling.

Indirect rapid tooling include pattern-based methods where the tool is casted from a master part that depicts the part to be molded ("Rapid Tooling Guide", 2016). A conventional approach is to create the master part by 3D printing.

Direct rapid tooling is when the mold, mold inserts, or other components are rapidly prototyped as a tool, to reduce time, cost and to achieve agility in the prototype phase. Generally, the tool is machined in a less expensive and softer material than tool steel. Usually this provides sufficient quality when producing a small batch of parts (Karapatis & van Griethuysen, 1998).

3.2 What is injection molding?

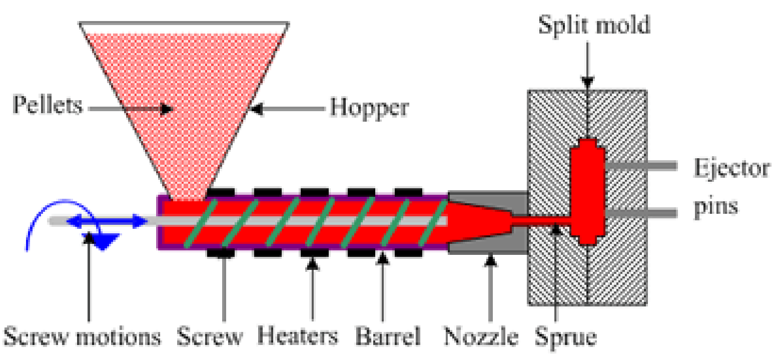

Figure 6 - Principals of an injection molding facility. Retrieved from http://www.veejayplastic.com/

Injection molding is a manufacturing process (seen in figure 6) where the desired material, in this case a polymer, is fed into a heated cylinder containing a reciprocating screw, where the granules are melted and mixed ("Part and Mold Design", 2000). The screw then builds up pressure before it pushes the melted granules forward into a mold cavity, where part cools and solidifies into the configuration of the cavity (Todd, Allen & Alting, 1994). After solidification, the part is ejected from the cavity using ejector pins (Groover, 2011). The ejector pins leaves ejector marks on the surface of the component, which in some cases must be hidden. Injection molding is typically a quick-cycle process. The method can produce large quantities of parts, offer good part-to-part repeatability with relatively tight tolerances ("Plastic Injection Molding Tolerances Guide", 2016). Because of the high investment cost associated with injection molding, the manufacturing process is best suited for mass production.

3.3 Rotocasting

Rotocasting is a manufacturing process where a self-curing resin is poured into a mold containing a cavity. The mold is then gently rotated, usually around two perpendicular axes as depicted in figure 7. This causes the material to disperse and stick to the walls inside the mold, shaping after the geometry of the cavity (Todd, Allen & Alting, 1994). In order to maintain a uniform thickness throughout the part, the mold continues to spin around the perpendicular axes at all times during curing to avoid sagging and deformation. The process offers a design advantage over other molding processes. With proper design, parts assembled from numerous pieces can be molded as one part. In addition, due to less tooling required, the mold can be put into production quicker than alternative molding processes, eliminating high fabrication costs.

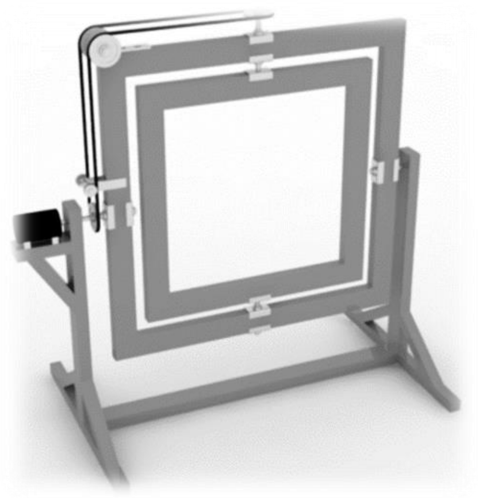

Figure 7 - Frame for rotating molds when curing, designed in SolidWorks

3.4 Vacuum Casting

Vacuum casting is a high quality production method, as depicted in figure 8, favorable when producing a small quantity of production quality parts. Vacuum casting is a based on casting silicone around a master part ("Vacuum Casting", 2016). The master part is often manufactured using AM processes or with computer numerical control-technology (hereafter called CNC) to ensure a production quality finish to the surface. After the casting, the silicone cube is split in two halves, and the master part is removed. This cavity is then injected with the favorable casting material. A vacuum is then applied to the silicone mold, which effectively pulls the material into any corners inside the mold. A company called Materialise recommend that up to 20 parts can be made before retooling is required. As opposed to Starprototype, stating that vacuum casting is ideal for making up to 50 functional duplicates of the master part. However, the drawback is that this process requires substantial manual labor.

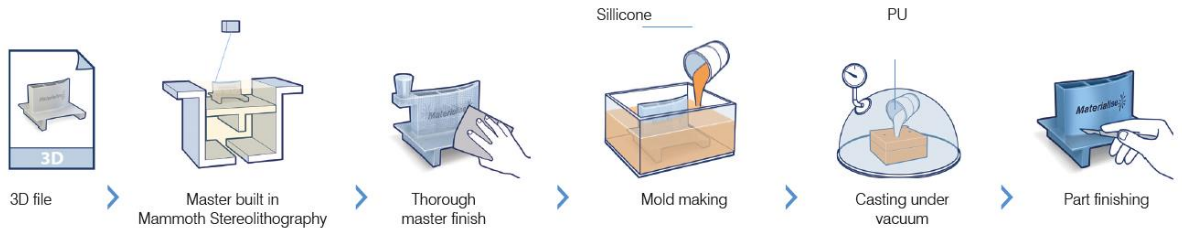

Figure 8 - Vacuum casting process. Retrived from Materialise (2016).

3.5 Design for production – Casting and molding

Design for production in the world of casting and molding is the theory of designing products so that they can be manufactured in the most effective way. However, using molds as tools leaves the designer to limited variations of geometry.

3.5.1 Wall thickness

The thickness of the walls highly influences several key properties, including mechanical performance, moldability, cosmetics, feel, and costs. Generally, the optimal thickness is a sense of balance between opposing properties, such as cosmetics versus stiffness or durability versus cost.

The use of uniform thickness (see figure 9) allow the mold cavity to fill more easily since the melted polymer does not have to be forced through varying restrictions as it fills. Generally, for injection molding, wall thickness varies from structures down to 0.05mm and up to 4mm ("Injection molding design guideline", 2016). Some parts are made up to the critical thickness point, which is around 5mm in room temperature for polycarbonate. Critical thickness is where the structures loses impact strength ("Part and Mold Design", 2000). Self-curing resins for castings tolerates higher thickness, but due to material costs, weight and strength it is generally not favorable.

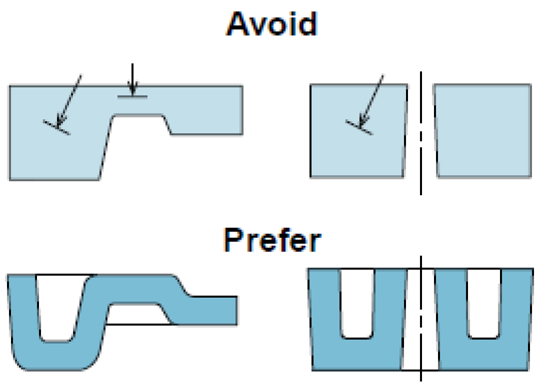

Figure 9 - Uniform wall thickness. Retrieved from Part and Mold Design (2016)

3.5.2 Draft angles

Draft ease the removal of the part from the mold. Providing angles on product features such as walls, bosses and ribs that are parallel to the direction of release is important. Especially where the molds are straight pull only (depicted in figure 10). A smaller draft angle increases the chance of defects on the part during ejection from the mold. Typical draft angles are from two to five degrees ("Injection-Molding Part Radiusing and Draft Guidelines", 2016), but designing products with draft angels down to half a degree is possible ("Part and Mold Design", 2016).

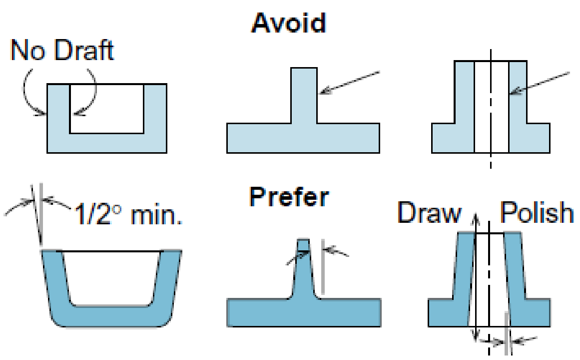

Figure 10 - Draft angles. Retrieved from Part and Mold Design (2016)

3.5.3 Undercuts

Some design features, because of the partition of the mold, place parts of the mold in the way of the ejecting part, called "undercuts" (depicted in figure 11). In some cases, the part can flex enough to release from the mold during ejection, depending upon the undercut's shape and depth and the resin's elasticity (Turner, Adomatias & Boik, 1973). Normally, an external side core is used to shape the undercuts. This lets the part eject freely from the mold. However, generally it is favorable to design parts without undercuts due to less complexity and costs.

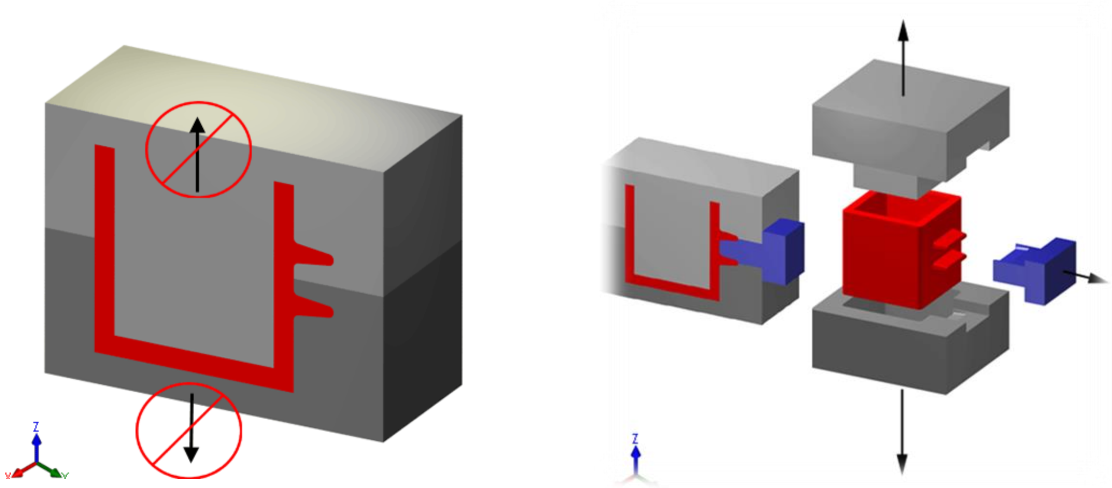

Figure 11 - Undercuts. Retrieved from http://www.custompartnet.com/

3.6 Sink marks

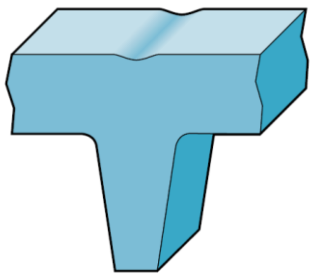

Figure 12 - Sink Marks. Depicted from Part and Mold Design (2016)

Dealing with shrinkage there is one major concern regarding the design. As the polymer melt solidifies in the cavity, areas with higher thickness will contract more than areas with lower thickness and cause sink marks, as depicted in figure 12 (“Part and Mold Design”, 2016). Production engineer at Lycro, Ståle Sve Rian, explains that in order to avoid sink marks in features such as ribs, the maximum thickness cannot exceed 0.7 times the thickness of the wall. As the molten polymer contracts more in the thicker areas it introduces stress concentrations (“Fundametals of molding”, 2016).

Besides these design considerations, several process parameters affect the quality of the manufactured part. Inlet location, curing time, corner design, holes and rib structures are some of the other concerns. In addition, for injection molding input pressure, flow rate, weld line, melt temperature and mold temperature can give significantly changes in the outcome.

3.7 Milling

Milling is a material removal process (Brown & Sharpe, 1914) to create a range of different features to create a part by feeding the workpiece into a rotary cutter, as depicted in figure 13. It covers a wide range of different machines working on models from small individual parts to large, heavy-duty assemblies. Milling is the most conventional process for making industrial molds. These machines can be computer aided (often called CNC mill) and fabricate parts with high quality tolerances. Milling is favorable when fabricating asymmetric parts with several features, such as holes, slots and three-dimensional surface contours. Parts that are fabricated completely through milling often include components that are used in limited quantities and for some prototypes.

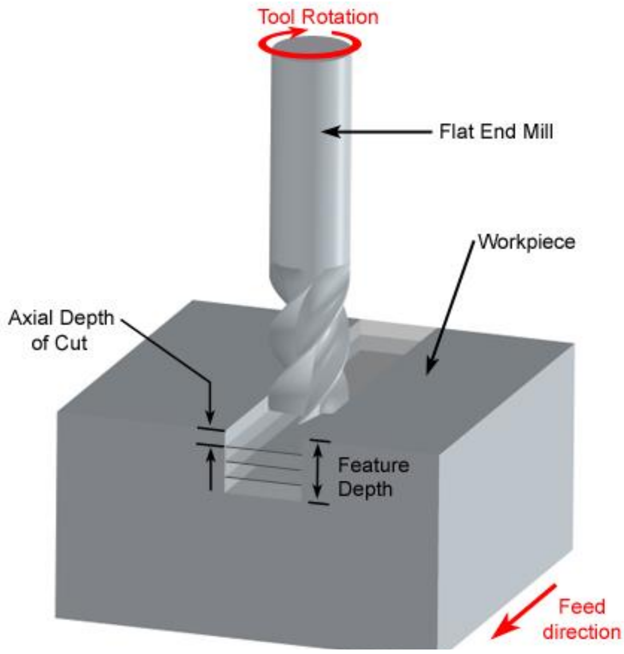

Figure 13 - Milling process. Retrieved from http://www.custompartnet.com

When milling there are four major cutting parameters that determines the quality and manufacturing time of the milled product ("Milling", 2016).

Cutting feed - The distance that the cutting tool advances trough the workpiece during one revolution of the spindle.

Cutting speed - The speed of the workpiece relative to the cutting tool during a cut, normally measured in surface meters per minute.

Spindle speed - The rotational speed of the cutting tool in revolutions per minute.

Axial depth of cut - The depth of each cut along its axis of the workpiece. A tall axial cut depth will require a low feed rate, or else it will result in overload of the cutting machine and reduce the tool life.

In addition, other factors as the use of rough cutting in the start and the amount of finishing cut to get the desired surface finish will affect the quality manufacturing time.

3.8 3D printing?

The creation of 3D objects can be achieved using AM processes. Multiple layers of material are computer aided to create a part. Each of these layers can be seen as a sliced horizontal cross-section of the part.

There are several different types of AM processes, all characterized by how each process creates each layer. The most common technique for early stage prototyping is fused filament fabrication (hereafter called FFF) as depicted in figure 14 (Turner & Gold, 2015). The technique includes extruding a thermoplastic material through a heated nozzle to create a part layer by layer (Crump, 1989). A roller then guides filament into a liquefier. The liquefier is at a temperature above the filament's melting point to let the material flow freely through the nozzle. The filament then cools and solidifies after reaching the build platform. Once a layer is complete, the part is lowered with the thickness of a layer and the making of the next layer begins. If needed, a secondary sacrificial material can be deposed as a support construction for overhanging geometries ("Adding and Modifying Support Structures", 2016). In addition to FFF, there are several other common AM processes. Typical, using an ultraviolet laser to solidify a photosensitive polymer (Stereolithography), selectively jetting a binder into a polymeric powder (Polyjetting) or using a laser to melt polymeric powder (Laser Sintering).

Figure 14 – FFF-machine, Ultimaker 2.

3.9 Release agent

A release agent is a chemical used to prevent other materials from bonding to surfaces. They have become an integral part of many manufacturing processes. ("Release Agent", 2016) They are often necessary, but generally used to improve productivity, extend tool life, improve surface quality and reduce number of defects.

Chapter 4 Experimental setup

The purpose of the experiment was to achieve insight in an efficient and economical manufacturing method for the future prototypes and 0-series from Blueye. To help designing a proper model for the experiment, a CAD software called SolidWorks was used. The thought was to prototype the same model in different manufacturing methods, this to reduce parameters in terms of difference in complexity in geometries for different parts. Designing in CAD software eases the process going from one machine to another without much effort.

4.1 The model

The first generation Blueye prototype was made by milling of plastic and gluing them together. The focus for the prototype was getting it into water instead of production effective design. Many advanced design features that were nearly impossible to manufacture revealed this design flaw. The model chosen to use in the setup is the side cover of Blueye's ROV (model depicted in figure 15). The model was re-designed and optimized for molding and casting production, meaning design features as draft angles, wall thickness and undercuts had to be taken into consideration.

Figure 15 - Blueye ROV

A medium fidelity prototype was designed with less features (such as brackets and attachment points). The model was scaled down with 38% from the original model, leaving dimension of 105 mm x 115 mm x 28mm (l x w x h), in order to adapt to the tools available at Trollabs. The side cover is re-designed symmetrical so that the same part can be used on both sides of the ROV. This to reduce the number of molds required (to reduce time and cost), and will also give an indication of how good the parts fit after casting/molding. Features such as space for a vertical thruster and space for a front compartment was added.

The wall thickness was set to 3mm for the entire part, approximately a 1:1 scale of Blueye’s model, to create a representative result. This is a massive thickness, especially concerning injection molding (as mentioned in theory). Designing ribs to achieve the same stiffness should be taken into consideration. However, the model was held simple to get results in terms of repetitive surface quality.

One the most critical features for the model was the slip angle. The minimum draft was set to 1.5 degrees on the top and bottom of the part as depicted in figure 16. Less than 2 degrees, which is the minimum standard. However, this is just on a limiting area. The side of the part runs down from 1.5 degrees to 90 degrees in the bottom. Therefore, the part should be ideal to eject from the mold.

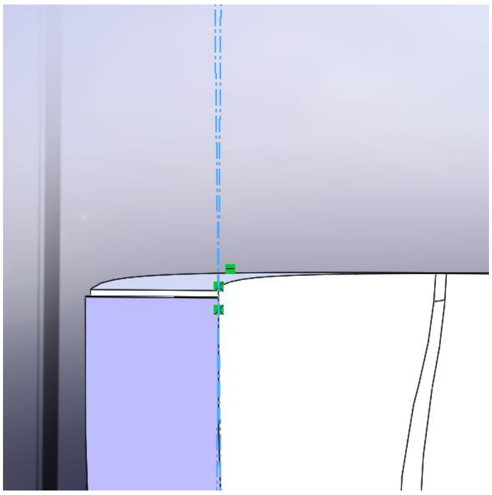

Figure 16 - Designing draft angles

The final model is depicted in figure 17. A low fidelity prototype of Blueye's side cover with the main focus of being moldable.

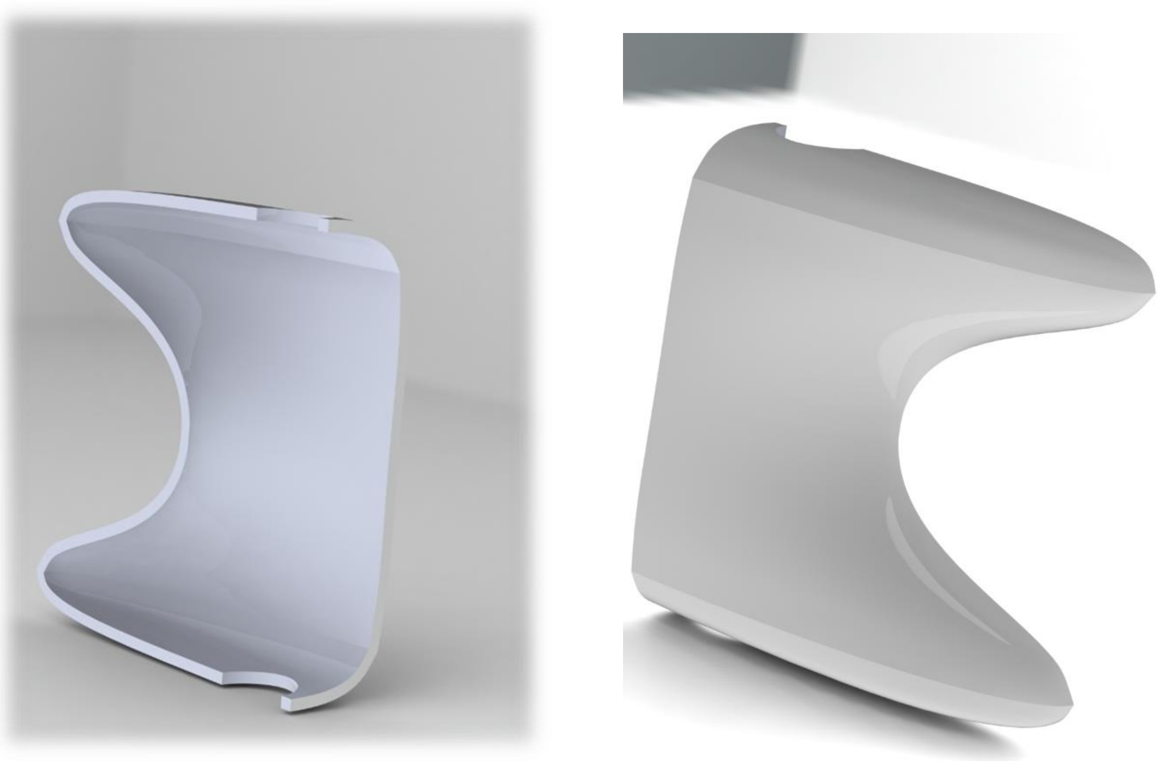

Figure 17 - Prototype side cover

4.2 The tools

To create the prototypes, several tools were to be used.

Injection molder – The injection molder that was used in the project was designed and constructed by Øystein Bjelland, as a part of his pre-master's thesis. The molder is a simple version of an injection molder, only heating up the granules in a chamber before manual injected to the mold. The whole system was temperature controlled using an Arduino to achieve the preferred temperature. The injection molder is shown in figure 18**.** (A setup like this can be constructed for around 20.000 NOK depending on tools available).

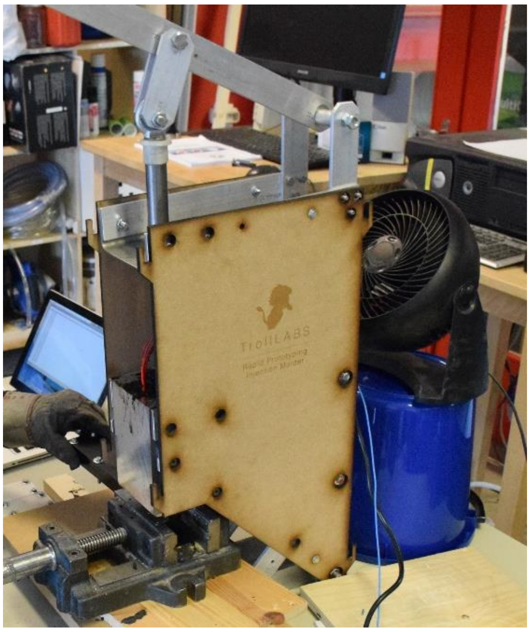
Figure 18 - DIY Injection molder

Mill - MDX-540 is a 3-axis benchtop CNC machine for fast, accurate prototyping. An accurate rapid prototype machine with easy setup and with a price less than half that of most additive systems (approx. 200.000 NOK). It was the main tool to fabricate the wood and foam molds, as well as it was used to manufacture the master part for the vacuum casting.

3D printer – The Ultimaker 2 is a fused filament fabrication printer that was used to print the prototypes throughout the thesis, both molds and some side covers. The printer (cost approx. 20.000 NOK) is designed to make high quality prints for rapid prototyping to a relatively low price.

4.3 Materials

Materials were held to a minimum to reduce the number of parameters for the testing. As discovered at Lycro, materials is not the problem concerning the manufacturing process, the tool is. In consultation with Blueye, it was agreed to not dig deeper into materials. As a wayfaring experiment, the discoveries concerning the diversity of materials led to focusing even more to the production methods.

For the molds, a 2x6" wood profile (spruce) was bought as well as a foam material having a density of 300 kg/m3. In addition, a mold printed in polylactic acid (hereafter called PLA) and a silicone mold was to be prototyped. The silicone was a 2-component silicone resin, called Smooth-on Mold Max 20.

For the injection molder polypropylene granules (hereafter called PP) was used, due to its high tensile strength and elongation. For the casting, a 2-component epoxy resin called Easyflow 120 was chosen to be used. This on the basis of the manufacturer's description in terms of flexibility, castability and fast curing time.

Furthermore, nylon was used to make the master part for the silicone mold, as well as two extra side covers for the ROV as a comparison to the other manufacturing methods. In addition there was printed some side covers in PLA with the Ultimaker.

4.4 The tooling

The prototype tool was designed after the model using SolidWorks tool "Cavity". This tool shapes a negative part after the surface lines of a part. Both the bottom and top mold were based on using this tool. The inlet hole was set to be on the top mold. Only leaving gate marks on the inside of the side cover. The hole was located almost in the bottom of the mold**.** Four holes were put in every corner of the molds, these intended to compress the molds together using bolts. The first version of the molds and an assembly of these can be seen in figure 19**,** figure 20 and figure 21**.** The tool was designed in different versions of material and surface quality.

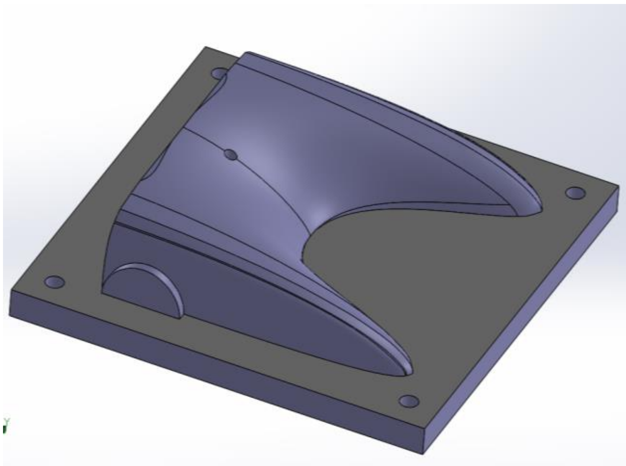

Figure 19 - Top mold

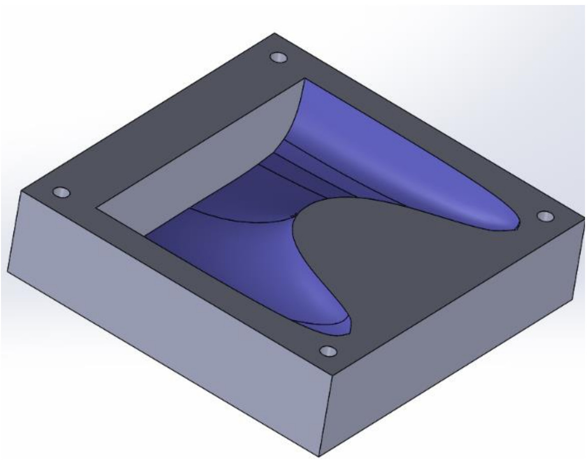

Figure 20 - Bottom mold

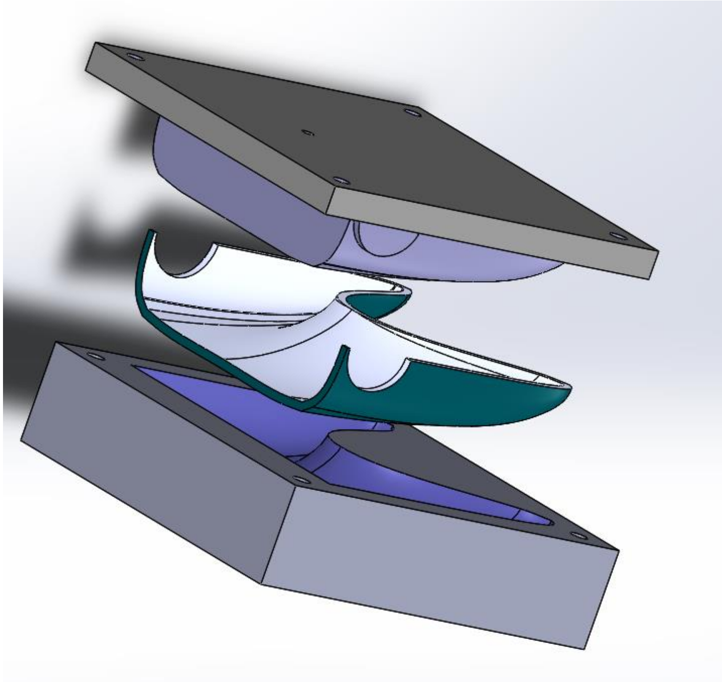

Figure 21 - Assembly of molds with casted part

Chapter 5 Testing

As a wayfaring experiment, serendipity findings might occur. Therefore, the prototypes were manufactured in several batches to have the agility to let the findings and results control the next steps in the project.

5.1 Production of the tooling

After the design was set, the molds were manufactured. Four similar wood molds was made in the CNC mill as depicted in figure 22, as well as a foam mold. For all molds, the 6mm straight rotary cutter was used to get a rough and fast cut, to minimize production time. Additionally, a 4 mm ball rotary cutter was used for smoothing of the surface in the end to get the desired surface finish.

Figure 22 - Milling of wood mold

The problem concerning cutting in spruce are the long chips that not necessarily loosen from the workpiece. No matter what was done to the cutting parameters, the long chips were unavoidable. This resulted in manual labor in terms of removing the chips from the mold from time to another. Some sections of the surface was also partly damaged as a result of the chips that did not release perfectly.

Another problem concerning milling in an inhomogeneous material, such as woodwork, is that it is hard to optimize the milling parameters. Only having a 400W DC motor, the mill struggled and went into safety mode when hitting branches. This resulted in a complete shutdown before it was possible to resume the milling. The outcome was to reduce the feed rate and the axial cutting depth, resulting in longer machining time.

For the homogenous foam material, it was easier to tune the cutting parameters to optimize cutting time and surface finish. Using the lighter, homogenous foam was much easier and faster to manufacture than the rough wood. The chips was just like dust particles, and there was no need to monitor the milling process continuously. This resulted in a smoother surface finish, ideal for molding/casting.

A 3D printed mold was also on the agenda. Using only 20% fill density to make the structure for reducing production time and material usage. The makers of the Ultimaker has stated that 20-30% fill density is the ideal density for most structures. However, the process is very time consuming in comparison with milling. On the other hand, there is no need for monitoring of the process, and can easily be done at nighttime. The surface finish of the mold has signs after each layer from the manufacturing, not giving a proper surface quality, which may lead the model to stick to the mold when casting/molding (depicted in figure 23)

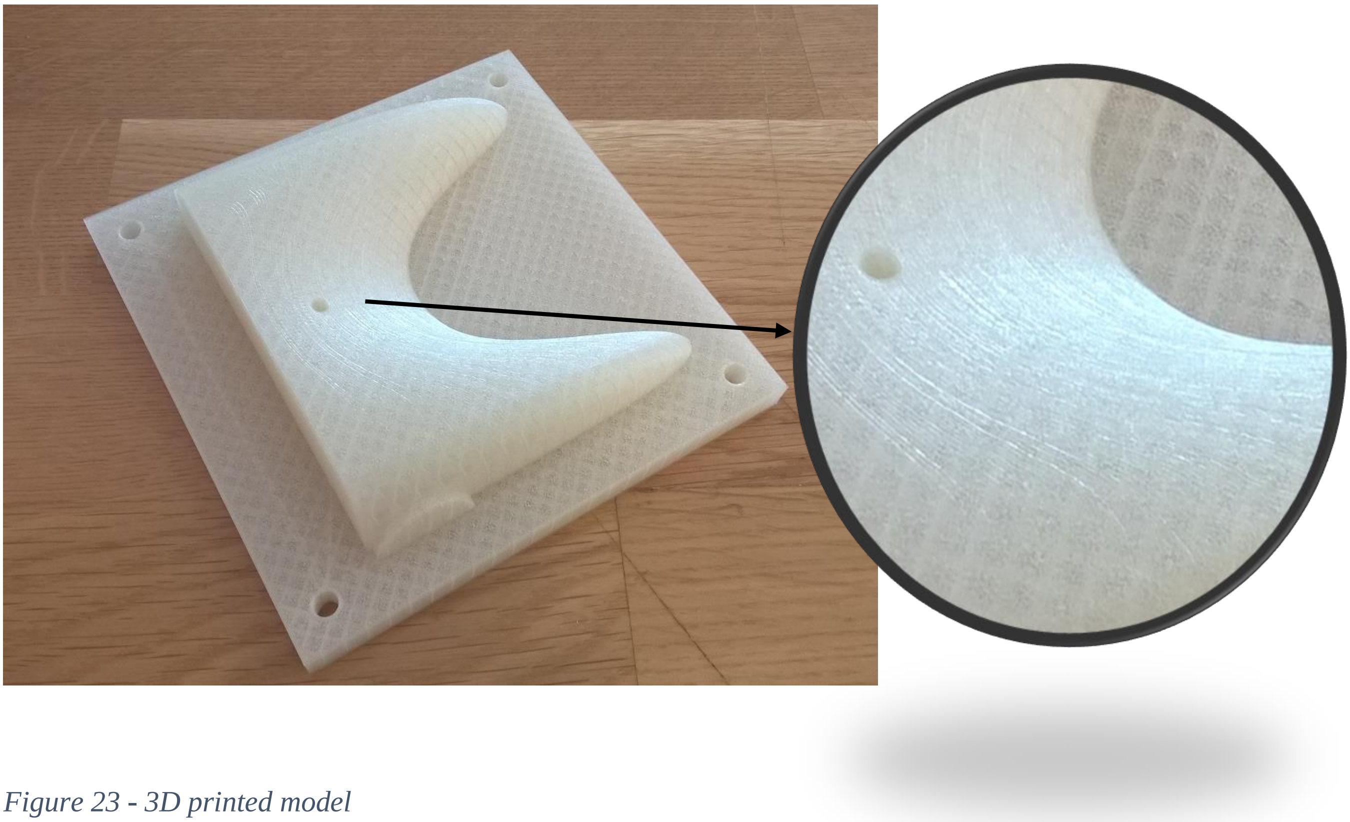

Figure 23 - 3D printed model

At last, there was to be made a silicone mold. The mold was made using a 2-component silicone epoxy resin called Mold Max 20. The silicone resin is stated to “produce the finest detail from a variety of industrial parts including reproducing prototypes”. To produce the mold, a master part had to be made. The master part was fabricated in nylon using the mill, being a true copy of the CAD-model (seen in figure 24). The master part was then put into a watertight container designed in SolidWorks and manufactured using a laser cutter and a glue gun. The 3D-model of the container can be seen in figure 25 on the next page. Furthermore, the master part was put into the container, and sealed with wax on the underneath to make the bottom mold. The silicone had to be mixed with epoxy hardener in 1:10 ratio before it was poured over the master part in the container. After 24 hours curing the bottom mold was completed**.** The model had some air bubbles trapped inside the top of the mold. However, the side of the silicone facing the part to be casted was smooth and has no traces of trapped air bubbles or other defects (depicted in series of images in figure 26 on next page**)**. The same procedure was followed for the top mold. Unfortunately the mixture never solidified 100%. The top mold was therefore useless. Not having enough material for another top mold lead to testing with just the bottom mold. This would anyway give an indication of moldability, repetitive quality and surface finish.

Figure 24 - Nylon model

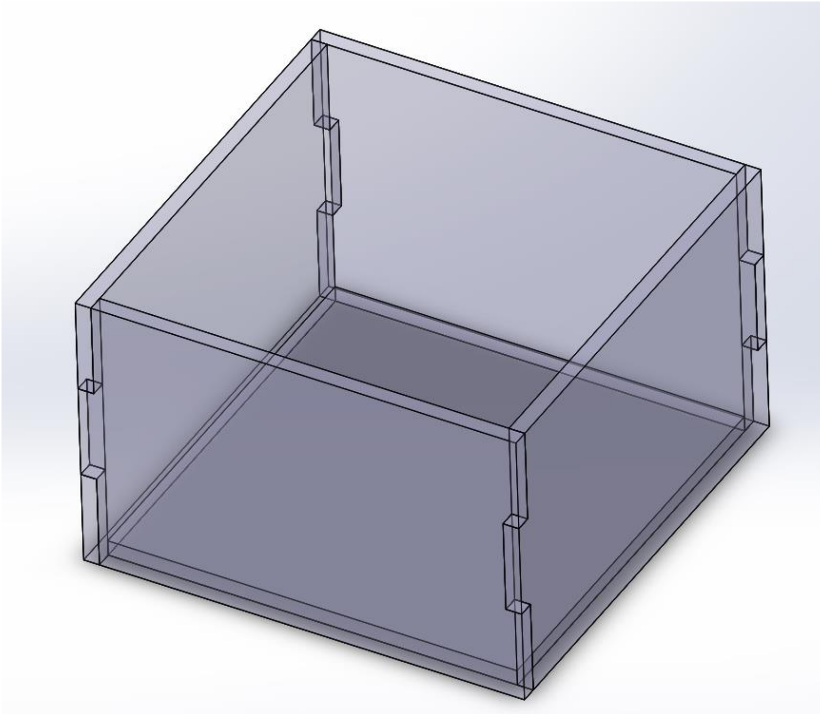

Figure 25 - Silicone casting box

Figure 26 - Image series of casting of silicone mold

5.2 Results mold making

Through the process of mold making there have been several findings, in terms of manufacturing time, surface quality and material selection. The results are compared relative to each other and not manufacturing standards. It was clear that the lighter, homogenous foam material was much easier to mill than the rough spruce with many branches. Table 1 is presenting the results from the manufacturing process. In addition to the mold manufacturing, the table contains information regarding surface treatment based on findings declared in chapter *5.4 Casting*. The foam mold along with the wood- epoxy mold represented the best surface quality after manufacturing.

Table 1 - Results mold making

Mold	**Material**	**Manufacturing time (top / Bottom)**	**Surface treatment**	**S.T. Time**	**Result**
Wood #1	Spruce	5 / 4,3 Hours	-	-	Rough surface finish.
Wood #2	Spruce	4,8 / 4 Hours	-	-	Rough surface finish. Warped overnight.
Wood, Benga	Spruce	4,5 / 3,9 Hours	Bengalack	3 Hours	Optimized manufacturing time. Better surface finish than the previous wood molds.
Wood, Epoxy	Spruce	4,5 / 4,1 Hours	West systems 105 Epoxy	12 Hours	Longer manufacturing time on top mold due to many branches in workpiece.

Foam, Epoxy	Foam 300kg/m^3	2,8 / 2,1 Hours	West systems 105 Epoxy	12 Hours	Good finish. Short and easy manufacturing because of homogenous material.
PLA	PLA – filament (20%- filament)	16 / 21 Hours	-	-	Rough finish from the different layers. Long manufacturing time.
Silicone	Mold Max 20	26 / 26	-	-	Top mold did not solidify. Not the best recreation of the master part. Better preparation needed.

5.3 Injection molder

Information gathered from the visit to Lycro and the articles, showed that the need for pressure and heated molds to get desired quality is crucial for injection molding. Øystein Bjelland's home made injection molder had a theoretical max back pressure of 150 bar. Taken friction into consideration, max pressure could even be as low as 50-60 bar, which is lower than recommended for similar products. All shots for the injection molder was performed with the epoxy coated wood mold as depicted in figure 27**.**

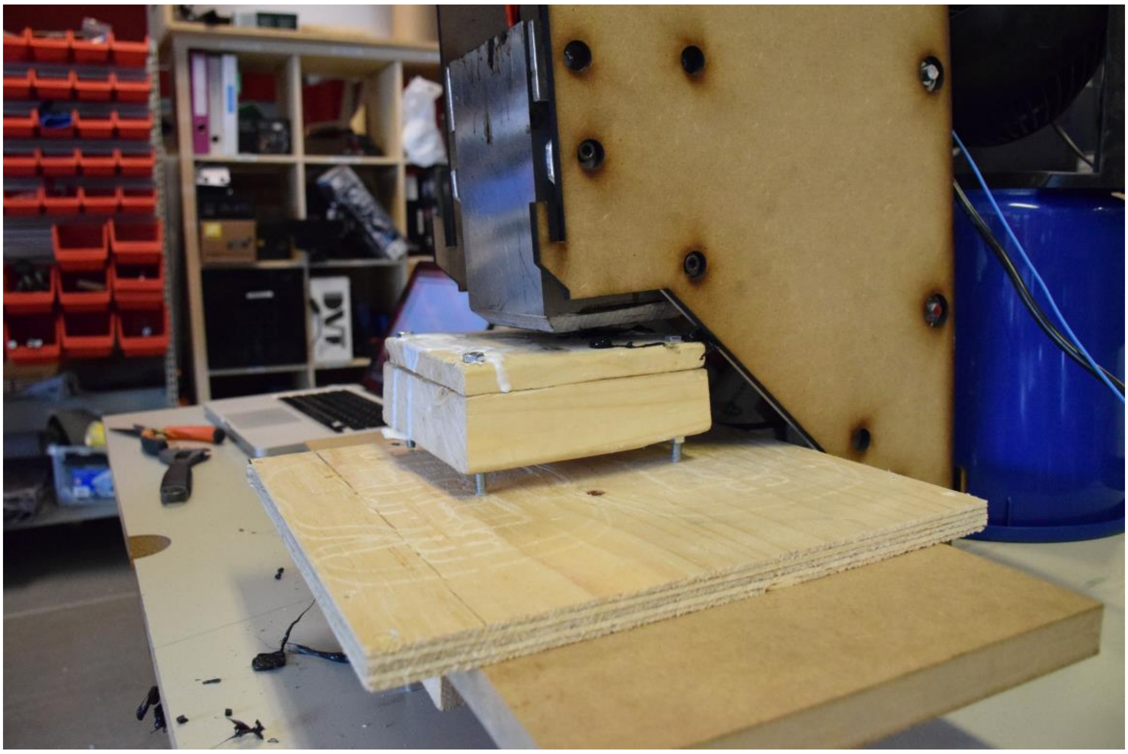

Figure 27 - Test of injection molder

The first shot was not a success at all. Only stuffing the inlet gate before solidifying, there was little information and experience to retrieve. The reason why it stuck in the inlet gate was probably a combination of the molten plastic's low temperature and low pressure. The solution to this was to raise the temperature of the molten plastic from 195 ^{o}C and up to 230 ^{o}C. The second attempt was more successful. The molten plastic shaped after the geometries of the cavity. However, it still did not fill up the cavity completely. The problem was the pressure and the filling time. This time the molds were hard to separate. It seemed like the plastic was stuck to the walls of the mold. It was observed when separating the molds after 20 minutes of solidification, that the plastic was still hot. After succeeding to separate the molds, the result was not as good as expected. Only 50-60% of the volume was filled, and there was almost no contours from the mold's cavity.

Due to findings with the two component resin in the chapter *5.4 Casting* later in this thesis, the mold's surface was treated with an industrial wax, RenLease QV 5110. The wax was brushed on and did cure over night before a third shot with the injection molder was performed. Even with all this adjustments of the parameters, the third shot was not either a successive attempt. Once again, the molten plastic solidified before the cavity was filled. There was simply not enough backpressure to fill the cavity rapid enough before the molten plastic solidified. However, the cavity was a bit more filled than last time, as well as the model had more contours from the walls of the cavity. Shot two and three can be seen in figure 28. It is clearly a progress, but there is still not the quality of a result that is wanted. There is clearly some differences in the surface as well. The surface of the third shot is more faded, probably due to the higher temperature.

Figure 28 - Injection molded parts

Separation of the molds this time was much easier. This time the mold cooled for 1 hour instead of 20 minutes. This lead to more shrinkage of the model which, in combination with the wax, made the model pop out of the mold.

For the fourth shot, temperature had to be even higher to get the cavity completely filled up. In discussion with Øystein Bjelland, the plastic melt was raised to 240 ^{o}C. However, a heater cartridge broke and there was a short-circuiting in the system. Even after a lot of troubleshooting and repair, the injection molder was unable to be repaired. The fourth shot was cancelled.

Despite unsuccessful injection moldings of the model constructed, Øystien Bjelland had a successful model made in the injection molder. The mold was made by a high-end polyjet facility, another 3D printing technology. A picture of the model is depicted in figure 29. The model had a lot better recreation of the walls of the cavity than the tests performed in this thesis.

Figure 29 - Good result with injection molding

In table 2 below, results from the shots are listed. Again, the results are compared relative to each other and does not reflect high-end products.

Table 2 - Results injetion molding

Shot	Material	Mold	Surface Treatment	Temp. ºC	Result
1	PP	Wood, Epoxy	-	195	No result, stuffed inlet gate.
2	PP	Wood, Epoxy	-	230	Not completely filled, bad surface finish.
3	PP	Wood, Epoxy	QV5110	230	Not completely filled, better, but still bad surface finish. Material seemed affec4ted by temperature – “Burn marks”.
4	PP	Wood, Epoxy	QV5110	240	Heaters in the injection molder broke. Shot not performed.
5	PP	Polyjet	QV5110	230	Smooth surface, but affected of the QV5110. Shrinkage after cooling.

5.4 Casting

The casting was performed using a 2-component resin called Easyflow 120. Before pouring the resin into the molds, it was first attempted on a similar material to see how it cured and how it bonded to the material surface. It was first attempted on a plain wood surface (from the spruce) and on a piece of the foam. The test revealed that the resin bonded permanently to both materials. After a quick research, a release agent seemed to be an answer to the problem. An industrial wax, called RenLease QV 5110, was selected as the release agent.

The first casting performed was with the Easyflow 120 resin, and a standard wood mold with no further surface treatment. With only 2 minutes pot life, the resin had to be mixed up quickly before it had to be poured into the mold. The resin was mixed using a plastic cup and a stick. After the resin was poured into the mold, the inlet gate was stuffed with disposable ear plugs to prevent the resin to drain. The mold was then rotated for 5 minutes by hand in both axis (rotocasting), to let the resin stick to walls of the cavity. After 40 minutes of solidifying, it was time to separate the molds. Regardless the force used to separate the molds they were stuck together. The molds were also tried separated using a saw, but with no further success. The molds after several attempts of separating are depicted in figure 30. Despite the failure of the casting, it is clear that the resin has shaped after the walls of the cavity.

Figure 30 - Unsuccessful casting

The stuck molds made it clear that a release agent was needed. However, due to long delivery time, a box of vaseline was bought for further testing. Vaseline was chosen because of the inherent properties of vaseline grease. As previously done, bonding between the wood and foam and the resin was tested. 50% of the surface of the test pieces was coated with vaseline, while the other 50% stayed untreated. The use of vaseline showed a significant promise. Similarly to the previous try, on the untreated area resin was stuck to the mold, while the area covered with vaseline released very easily (shown in figure 31). This confirmed the functionality of the release agent.

Figure 31 - Release agent test

As the vaseline gave good results, another test in a wood mold was performed. This time coated with a layer of vaseline using a brush. The vaseline cured in the mold for 5-6 minutes before resin was poured into the cavity. After curing of the resin, the molds separated easily. At the first look, the resin seemed to have reacted with the vaseline under the curing process. The surface was pebbled and soft, and the material properties itself seemed changed. For example, the model was easier to flex than expected. Vaseline had most likely been mixed with the resin and affected the curing process. There was also distinct traces of brush marks from the vaseline and from the rough wood surface, meaning that the surface quality of the mold was not ideal. The model can be seen in figure 32.

Figure 32 - Casting with vaseline

As a result of the poor surface quality in the molds, research was done to improve the results. Marcus Horn, a student at NTNU that have worked a lot with epoxy, introduced me to West Systems 105 Epoxy resin. An epoxy made to give a smooth and durable surface finish. The epoxy was applied to two different molds, one wood mold and one foam mold (depicted in figure 33). The surface became much smoother, covering especially the rough wood surface. The idea was to give the molds a longer lifetime, through allowing the casting release easier due to the smoother surface and because the surfaces become stronger itself.

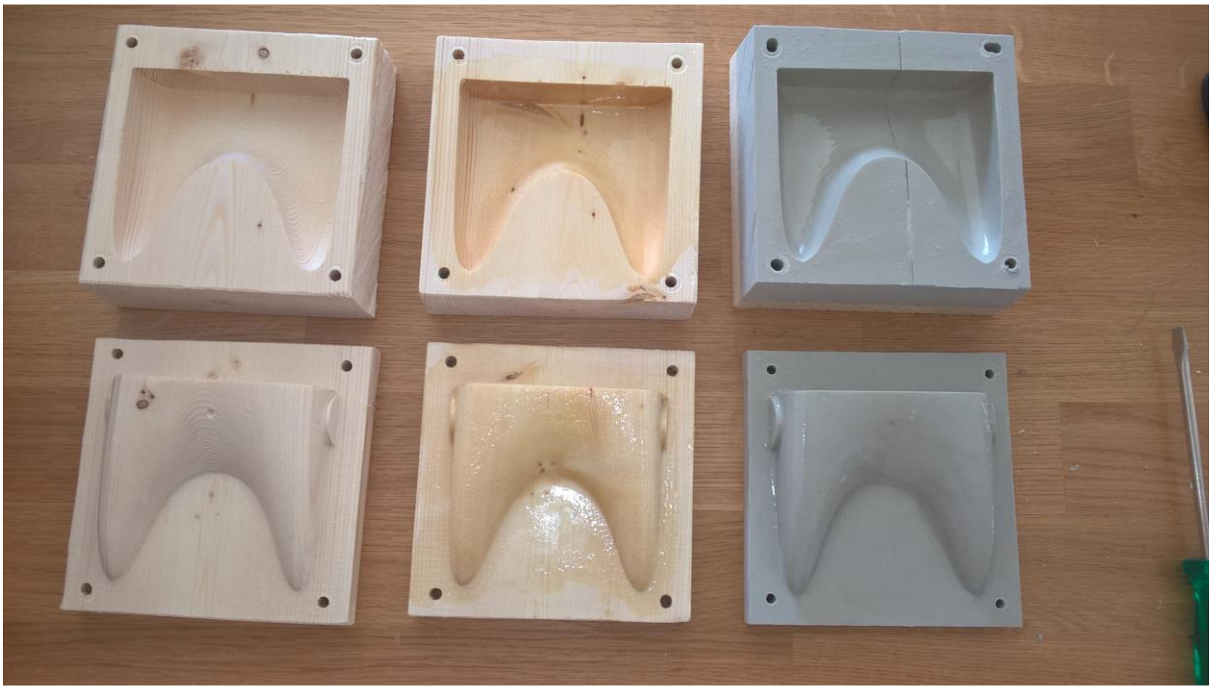

Figure 33 - Surface treatment (wood, wood-epoxy and foam-epoxy)

In addition to the two molds covered by epoxy, an even cheaper surface treatment was tested. Bengalack, a Swedish invented durable paint, was applied to one wood mold. The paint is a bit thicker than regular paint, and provides a hard surface. The paint was applied to the mold in three layers to be sure that the contours from the wood surface were completely covered. The mold is depicted in figure 34.

Figure 34 – Bengalack, surface treatment

After achieving the knowledge from the first castings, later castings were done in larger batches to speed up the testing process. The next batch was done using the wood-benga and the wood-epoxy molds. All these using vaseline as release agent. This time however, the vaseline was brushed on in a thinner layer. In addition, a hair dryer was used to smooth out the brush marks and to cover every corner of the molds. The vaseline also cured over night with the idea that it would not react with the curing process of the resin. However yet again, the castings seemed affected by the vaseline under the curing process. Another finding was that the molds did not completely fill up before the resin started solidifying. Especially the wood-epoxy mold was far away from representing the model. At this stage, the fill gate was at the lowest point of the mold, meaning the resin had to work its way up the model against the gravity. Two new inlet gates, at the highest point, was therefore introduced for all molds, using the gravity to faster fill up the molds. The new inlet gates can be seen in figure 35**.**

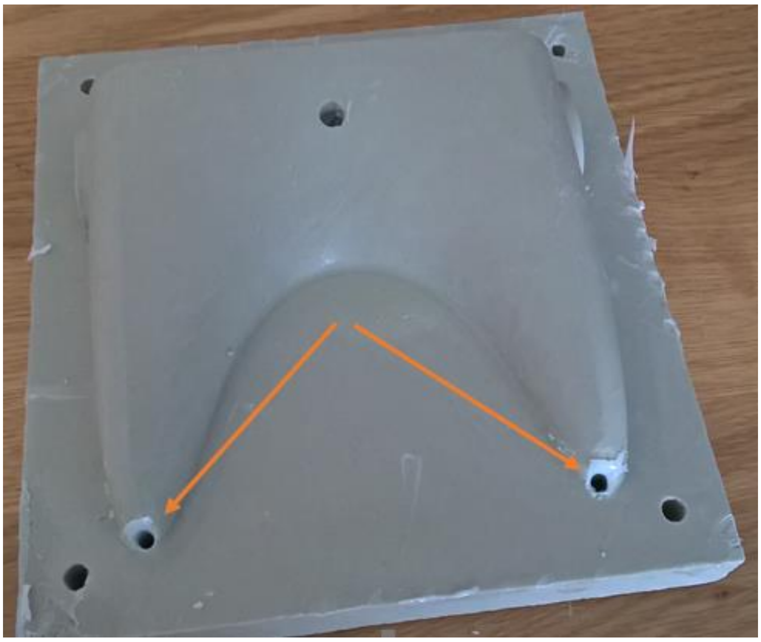

Figure 35 - New inlet gates

To achieve even more volume flow into the molds, sprues made from paper were used for the rest of the castings (depicted in figure 36). In addition, the Renlease QV5110 had arrived to these casting. The next batch of casting was much better. Having completely shaped after the walls of the cavity. Furthermore, the surface quality after swapping from vaseline to a proper release agent had huge improvements. The curing process seemed unaffected by the QV5110, giving the model the material properties listed by the dealer. The first casting with the foam-epoxy was also a huge success. Giving the best results so far, with an almost perfect casting of the mold's

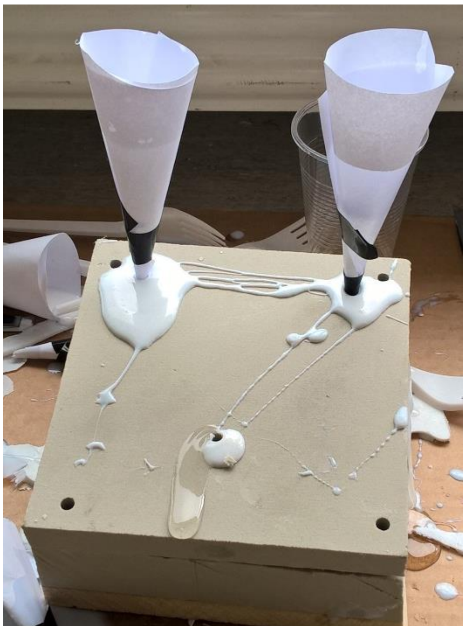

Figure 36 - Paper prototype of sprue

cavity. For this batch two new findings were done. For all castings there is, as expected, excessive material that has to be removed by manual cutting and grinding. Second, the new inlet gates in the end of the mold had tendencies to damage the model when releasing the part from the mold. Both findings are depicted in figure 37 and figure 38**.**

Figure 38 – Excess material

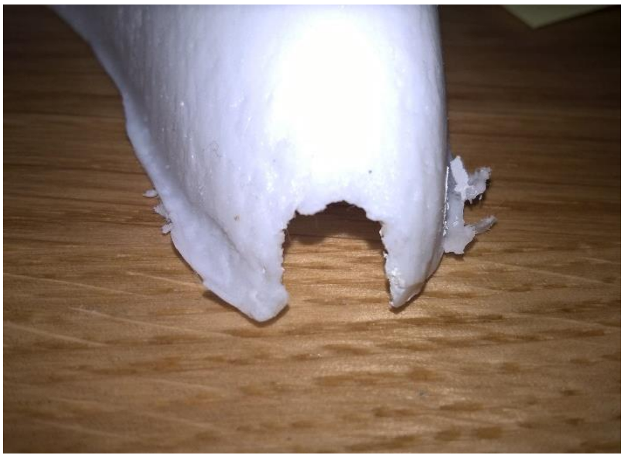

Figure 37 - Damages from ejetion

For the next castings, the release agent solidified overnight, after advice from Marcus Horn. The idea was that the low viscosity wax would smooth out to a more homogenous layer and give an even better surface quality to the castings. The fifth batch was a huge success, achieving the best results yet. For the sixth and seventh batch, the aim was to test wear and repetitive quality of the molds after finding the ideal casting routine. The foam-epoxy mold stood out as the best. In both wear and repetitive quality, making all four castings almost identical. For both wood molds, the results began to be affected of the wear. However, locally it was possible to see potential in both molds.

For the next batches, testing of the silicone- and the polylactic acid-mold was on the agenda. The PLA-mold was prepared the same way as the other molds, using the QV5110 release agent. In accordance with the supplier, there was no need for further surface treatment before casting in the silicone. Separating the part from the silicone mold after curing was as suspected. After the mold was warped back and forth the part popped out. The result was also positive, despite the fact that the casting of the mold itself did not go perfectly. Three more castings were performed with the silicone mold. All these with very positive results, being replicas of each other. For the PLA-mold it did not go well at all. The printed layers started to separate when opening the mold. It seemed like the pebbled surface from the print led to bonding between the resin and the mold. The mold separated in several different layers, meaning that the mold did not have the strength to be separated perpendicular with the layers. Due to this drawback found in 3D printed models no further testing was performed.

5.5 Results

As discoveries where done, the models casted improved. The latest models seemed close to identical copies, and shared the same surface finish. An overview of the information from the castings is found in table 3**.**

Table 3 - Results of casting

Batch	**Cast. Nr.**	**Mold**	**Surface Treatment**	**Curing ST.**	**Curing Resin**	**Results**
1	1	Wood	-	-	1 Hour	Bonded completely to the mold, 100% filled
2	2	Wood	Vaseline (thick layer)	0,1 Hour	1 Hour	Slipped easily, but still some wear. Surface affected by vaseline. Torn up around inlet gate.
3	3	Wood, Benga	Vaseline	24 Hours	0,7 Hours	Slipped easily, surface affected by vaseline, not completely filled
3	4	Wood, Epoxy	Vaseline	24 Hours	0,7 Hours	Slipped easily, surface affected by vaseline, not completely filled
4	5	Wood, Benga	QV5110	0,1 Hours	0,5 Hours	Rough finish - contours from woodwork
4	6	Wood, Epoxy	QV5110	0,1 Hours	0,5 Hours	Residues of vaseline probably affected casting. Soft and flexible result.

4	7	Foam, Epoxy	QV5110	0,1 Hours	0,5 Hours	Good result. Almost perfect casting of the cavity.
5	8	Wood, Benga	QV5110	24 Hours	0,5 Hours	Rough finish - contours from woodwork.
5	9	Wood, Epoxy	QV5110	24 Hours	0,5 Hours	Ok surface quality. Good casting of the cavity.
5	10	Foam, Epoxy	QV5110	24 Hours	0,5 Hours	Good result. Perfect casting of the cavity.
6	11	Wood, Benga	QV5110	24 Hours	0,5 Hours	Rough finish, paint starting to loosen from mold. Good casting of the mold.
6	12	Wood, Epoxy	QV5110	24 Hours	0,5 Hours	Ok surface quality. Good casting of the cavity.
6	13	Foam, Epoxy	QV5110	24 Hours	0,5 Hours	Good result. Perfect casting of the cavity.
7	14	Wood, Benga	QV5110	24 Hours	0,5 Hours	Ok surface quality. Casting affected by damaged to the molds
7	15	Wood, Epoxy	QV5110	24 Hours	0,5 Hours	Ok surface quality. Casting affected by damaged to the molds.
7	16	Foam, Epoxy	QV5110	24 Hours	0,5 Hours	Good result. Perfect casting of the cavity.

8	17	Silicone	-	-	0,5 Hours	Result affected by mold, good casting of mold.
8	18	PLA	QV5110	24 Hours	0,5 Hours	Casting destroyed mold.
9	19	Silicone	-	-	0,5 Hours	Result affected by mold, good casting of mold
10	20	Silicone	-	-	0,5 Hours	Result affected by mold, good casting of mold
11	21	Silicone	-	-	0,5 Hours	Result affected by mold, good casting of mold

Depictions of the most important results are in figure 39**,** 40 and 41. Especially, the parts casted in the foam-epoxy mold gave similar results, meaning that they replicated the tool very well. For all castings there were some additional material around where the two molds had met. An amount of manual labor after each casting was therefore required to make the models representable. Damages in the rear are found on many of the models after ejecting them from the molds. This was a result of moving the inlet gates to the highest point of the mold.

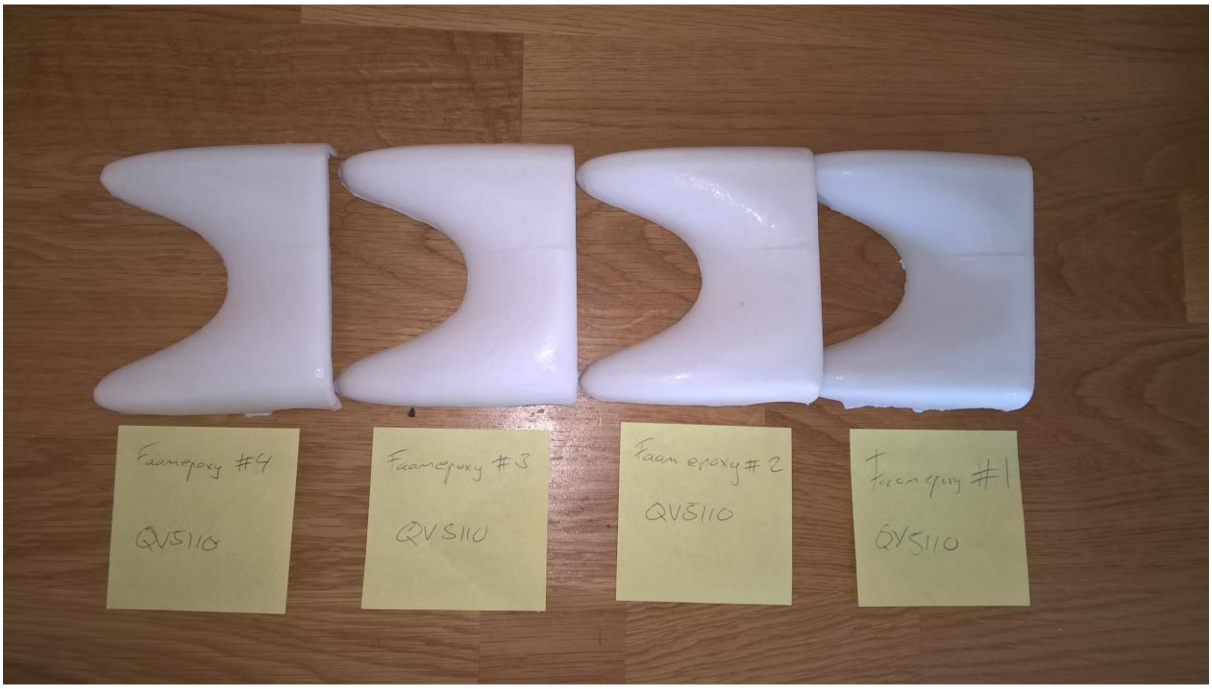

Figure 39- Modeks from foam-epoxy mold

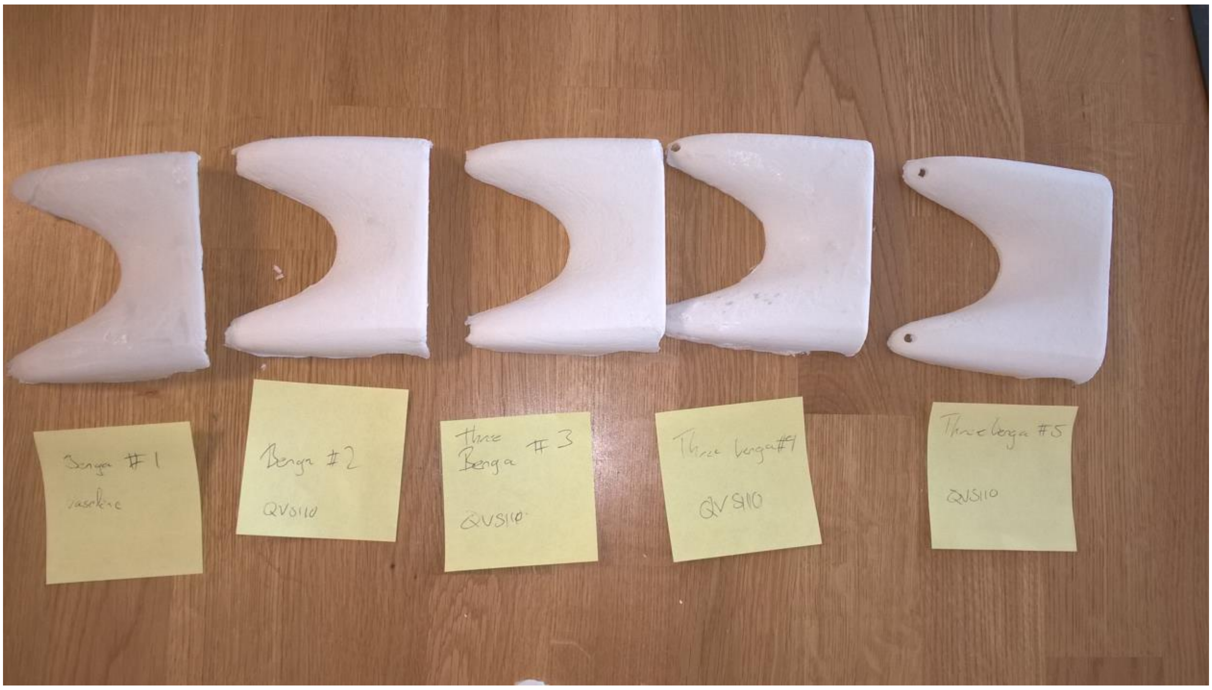

Figure 40 - Models from wood-benga mold

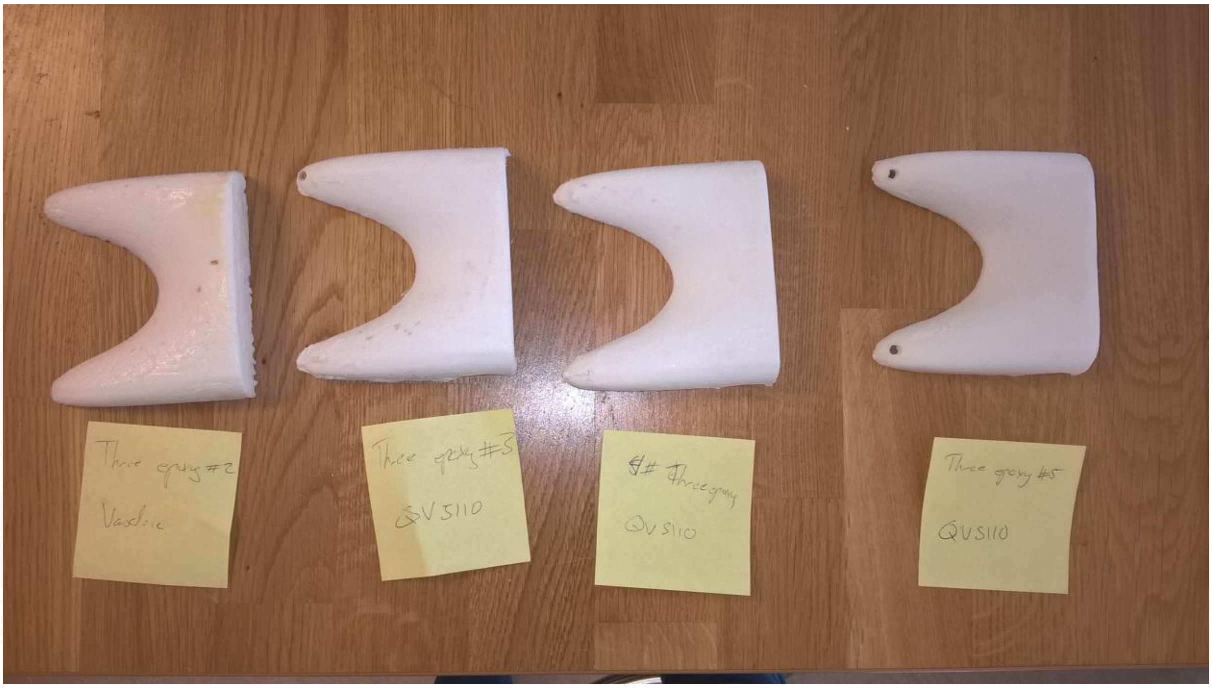

Figure 41 - Models from wood-epoxy mold

In addition to the parts, the molds were examined after the castings. Results experienced concerning the molds are found in table 4**.**

Table 4 - Wear of molds

Mold	**Tolerances**	**Wear**	**Other notes**
Foam, Epoxy	Good	Medium	Foam could have been stronger, easy to damage when ejection of part. Epoxy could have been milled too.
Wood, Epoxy	Medium	Medium	Three warps, epoxy could have been milled too for better tolerances.
Wood, Benga	Bad	High	Paint had to low viscosity to remove contours from the wood. Paint also loosened.
Silicone	Good	Low	Not a perfect casted mold, however, good repetitive quality and good recreation of mold's cavity.
Wood	Bad	High	Bad results overall.

PLA	Medium	Extreme	Did not survive casting. Layers in mold torn apart from each other.

Figure 42 and 43 are depicting some of the wear on the foam-epoxy mold. Most of the wear are from separating the molds using a screwdriver, but there are some major scars in the molds cavity structures. Attempts to smooth the scars were done using the release agent wax.

Figure 42 - Damages after using screwdriver

Figure 43 - Wear of foam-epoxy mold

5.6 Milling

Two models made in the mill were manufactured as a comparison to the molded and casted parts. These models were made in nylon. The purpose was to see how fast the models in nylon could be produced in order to give the same result in terms of quality relative to the castings. The parts were manufactured from two different workpieces, meaning extra calibration and clamping of the workpieces was needed. Considering the mill was merely a 3-axis tool created the need for turning the workpiece upside down in the middle of the manufacturing process to shape all design features (Process seen in figure 44). For both models, the same milling setup was utilized, except that the surface finishing time was reduced. The results from the milling process are presented in table 5**.**

Figure 44 - Milling of prototype

Table 5 - Results of nylon prototypes

Number	Material	Setup time	Manufacturing time	Result
1	Nylon	0,7 Hours	3,20 Hours	True copy of model. Turning of workpiece under manufacturing missed with about 0,5mm.
2	Nylon	0,1 Hours	2,5 Hours	True copy of model.

The results are also depicted in figure 45**.** The had high quality finish with no need for extra manual labor after detaching it from the mill. Some smoothing with sandpaper could be done in order to remove the small chips if desired.

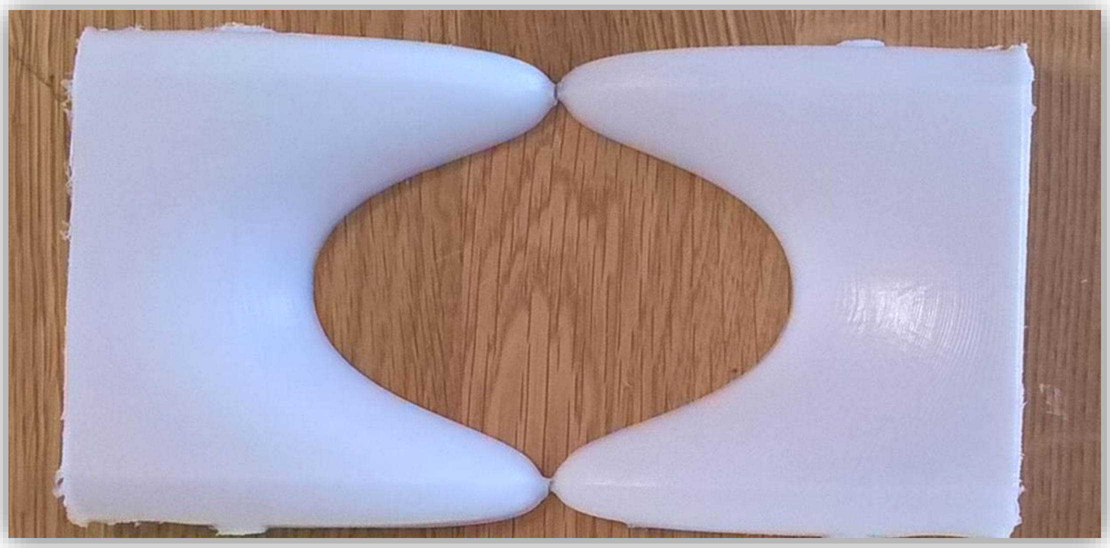

Figure 45 - Nylon prototypes

5.7 3D printing

The last option tested was fused filament fabrication, a 3D-printing technology. The CAD file used was the same as for the mill. The printing was done using 20% fill density, making the structure hollow under the shell. A support structure was added to the program to avoid the overhanging structure to collapse. Three models was printed in two different. The printing process can be seen in figure 46. Further, the results from the 3D printing is presented in table 6.

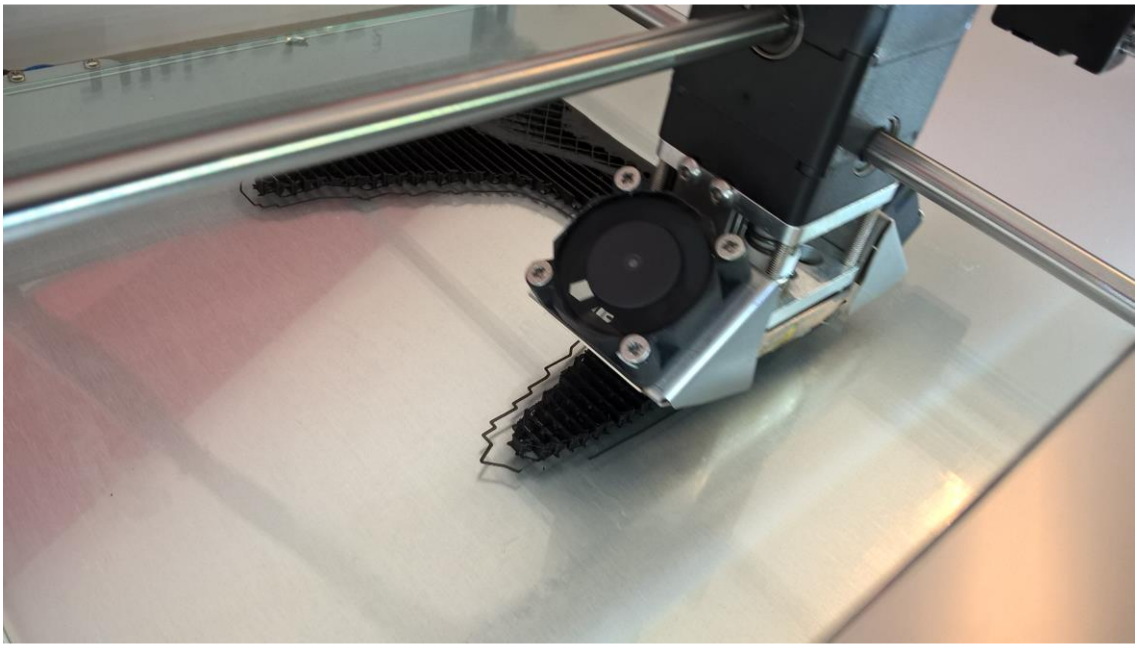

Figure 46 - 3D printing of prototype

Table 6 - Results of printing

Number	Material	Setup time	Manufacturing time	Result
1	PLA	0,2 Hours	7,2 Hours	Copy of model. Rough surface finish. Not homogenous material properties. Hard to remove support structures nicely.
2	PLA	0	7,2 Hours	Copy of model. Rough surface finish. Not homogenous material properties. Hard to remove support structures nicely. Identical to model number 1.
3	PLA	0,1	5,9 Hours	Printing it upside down gives ugly marks by removing the support structure. Inhomogenous material properties.

The printing process is quite slow for larger parts. The advantage is, as earlier mentioned, that it is unessential to monitor the process. For all parts made in the 3D-printer the results affected the manufacturing process itself. Clear defined layers can be seen on the model in figure 47.

The result are also depicted visually in figure 48 below.

Figure 47- Layers from 3D-prrinting

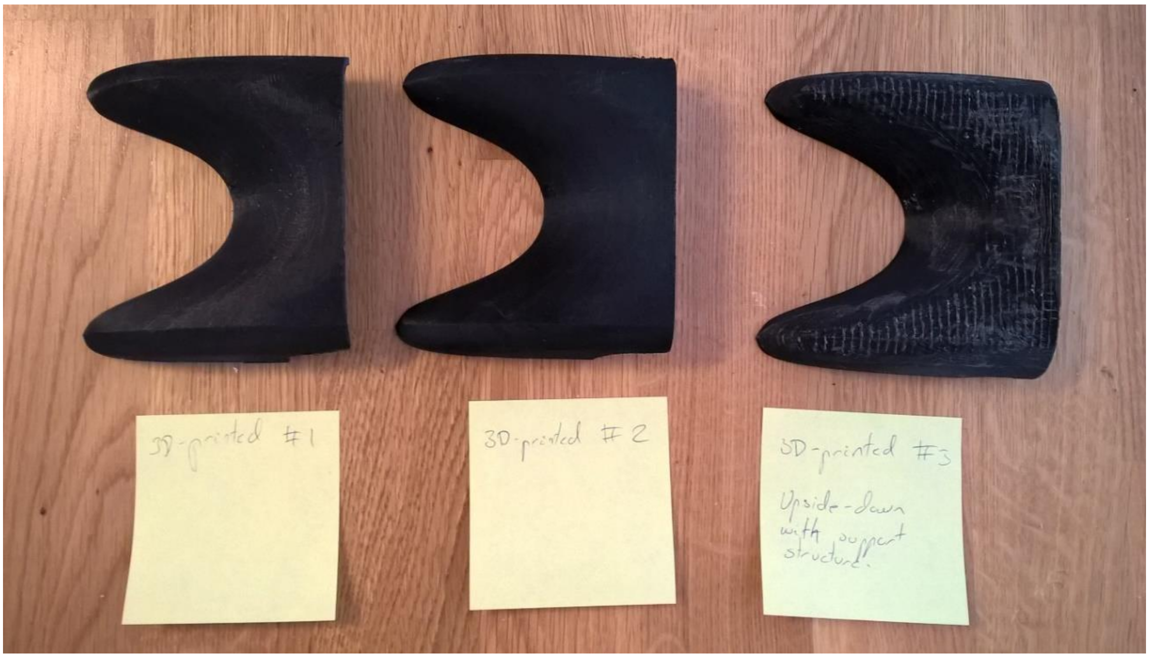

Figure 48 - Results from 3D printing

5.8 Results

Models were compared with each other across the different production methods. It seemed that the rapid prototyping with the foam-epoxy mold and 2-component resin was the best in terms production of a small quantity of parts if not high end tolerances are needed. On the other hand, the silicone showed promising results regarding reproducibility, but the production of the silicone was unsuccessful. Figure 49 shows some of the models and tools used in the thesis.

The results are presented in table 7 below. The purpose is to provide a clear picture of what the various processes are good for, when it is beneficial to use them in terms of geometry, delivery time and size of the batch of parts.

Figure 49 - Overview of the most important prototypes

Table 7 - Benchamrking of manufacturing processes

	Rapid Tooling	Indirect rapid tooling	3D Printing	Injection Molding	Milling
Flexibility design features	Medium – limited by undercuts in mold.	Medium - limited by undercuts in mold. Larger undercuts can be design when using flexible molds.	High – almost all features can be done. FFF bad for overhanging structures. (Other printing methods may be more suitable)	Low – Limited by a complex mold that is made to be automated. Hard to edit if not satisfied.	Medium to high – Limited by axis and the clamping, as well as tools available.
Surface finish and tolerances	Medium - Roughness is the same as mold. Wear over time.	Medium - Roughness is the same as mold. Wear over time.	Low to medium – FFF did not perform any good surface finish. Tolerances are ok.	High[1] – High pressure provides large flexibility on small design features.	High – Provides the desired surface quality. Decided by machining time.
Material properties	Good	Good	Bad – Not homogenous. Weak perpendicular to the layers.	Good when process is optimized.	Perfect – material properties not affected by process.

Setup time and additional manual labor	Short for smaller batches. Long for larger batches. Milling of tooling and removal of excess material from part after each casting.	Medium - manual labor, independent of batch size. One extra step due to the making of the master part.	Minimum	Short for larger batches, long for smaller batches. Time independent of batch size.	Medium for smaller batches long for larger batches. Can be automated.
Delivery time	Short for small batches. Time per part is equal.	Short for small batches. Time per part is equal.	Short for smaller batches. Quickly increasing per unit.	Long	Medium for smaller batches. Quickly increasing per unit.
Price tooling/ machine cost	Dependent on tool material. Low for small batches. However, not economical for large batches due to much	Dependent on tool material. Low for small batches. However, not economical for large batches due to much	Low to medium – dependent on precision of the printer.	High – needing a high quality facility and a supporting mold	Medium

	manual labor.	manual labor.			
Price per part	Medium	Medium	High – Independent of batch size	Low for large batches. High for small batches.	Medium for small batches. High for large batches.

[1] Based on the experience achieved at the visitation to Lycro. Lack of pressure in the injection molder facility available did not replicate these results in my prototyping.

Chapter 6 Increasing fidelity

After the experiment was performed and results were processed the decision fell on to designing a higher fidelity prototype of side cover. This time using more complex features such as ribs and additional draft angels. In addition, since the start of the thesis Blueye had decided to add a lateral thruster to achieve more maneuverability. The model designed can be seen in figure 50 and figure 51.

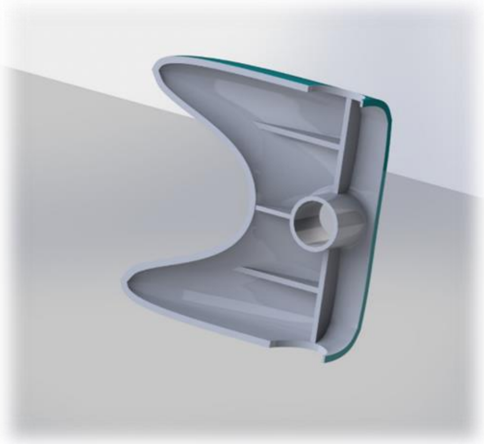

Figure 51 - Bottom side of new model

Figure 50 - Top side of new model

The idea was to examine the effects of using ribs to verify the theory. A brief review of a finite element analysis validating the theory regarding design features was therefore conducted.

6.1 FEA-analysis of geometrical features

Simulation tools can be a part of a design process, reducing the number of expensive prototypes and reducing development cost by minimizing rework and delays. In most cases the mechanical properties of the product is essential. In order to find the balance point between strength and weight a structural finite element analysis (hereafter called FEA) is used as a tool. The finite element analysis is a numerical method for finding approximate solutions to problems of engineering and mathematical physics, where analytical solutions are too complicated, such as in complex geometries, loads, and material properties.

6.1.1 Nodes and elements

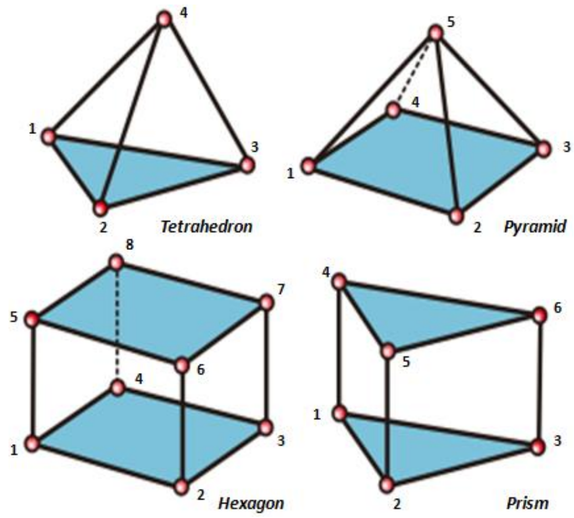

Figure 52 - Types of elements

FEA is normally used as a supplement to computer-aided design. The FEA divides the geometry from the part into a finite number of elements, containing several nodes each element determined by the type of element. A node is a coordinate location where the degrees of freedom (hereafter called DOFs) are defined. The DOFs for this point represent the possible movement, forces and moments that are transferred from one element to the next. Based on the problem, an equation is solved for each node. These equations give an approximated result to the problem ("Nodes and Elements", 2016). There are several types of elements available for the different FEA softwares. It is normally separated between volume elements (3D) and shell elements (2D), where volume elements can be divided into tetrahedral, pyramidal, hexahedral and prismoidal as depicted in figure 52 above. Meanwhile shell elements are divided into triangular and quadrilateral elements ("Finite Element Analysis", 2016).

6.1.2 Mesh

By using a set of elements a mesh is created through the model. The mesh can consist of a single or multiple types of elements depending on the how advanced the model is. Solid elements are favorable for more advanced models, while shell elements are naturally selected for analyzing simple parts, such as sheet metals, trusses and beams. ("Finite Element Analysis", 2016).

Using shell elements is a common way of simplifying geometry because the computational power is a limiting factor in terms of time when doing numerical simulations. However, due to design criteria needed for manufacturing, shell elements will not be a realistic approach for molded and casted geometries. Therefore, volume elements should be used. However, when analyzing mirrored models it is possible to only simulate on a section of the model. This is maybe the best simplification where shell elements is not suitable.

The error for the analysis of any FEA model is directly related to the coarseness of the mesh that is applied. Therefore, it is important to capture geometry to provide enough accuracy. Refining the mesh globally will increase the simulation time due to the significantly larger number of equations to be solved. Therefore, it is more common to refine the mesh locally where we find the highest stress gradients. These are typically located close to sharp edges and holes. Most FEA softwares have a tool that allows for controlling the mesh before solving the simulation.

Based on second moment of area (1) for simple rectangular cross-sections, each 10% increase in wall thickness provides approximately a 33% increase in stiffness. However, increasing wall thickness also adds to weight, cycle time, and material cost. Therefore, it is favorable to use geometric features such as ribs and curves to stiffen the part. These geometric features can add required strength, with little increase in material use.

$$I_x = \frac{wh^3}{12} \tag{1}$$

6.1.3 Linear and non-linear behavior

Some polymers exhibit linear elastic behavior, just like most metals do. This means that relation between stress and strain is linear, as depicted in figure 53. Linear elasticity is the ability of a body to return to its initial state when a loading that does not exceed yield stress is removed. Hooke's law (2) governs this relation:

$$\sigma = E \cdot \varepsilon \tag{2}$$

In contrast, ABS plastic is a non-linear material (in deformational sense). This means that the relation between stresses and strains do not follow Hooke's law entirely. As professor Nils Petter Vedvik said, there no essential difficulties to solve this non-linearity by stepwise functions available in FEA software. However, it can be useful to start with a linear approach. Achieving an approximation to determine the next step in the design process, meaning a faster iterative process.

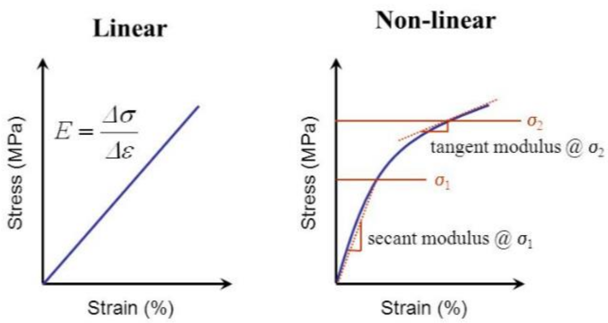

Figure 53 - Relation between stress and strain

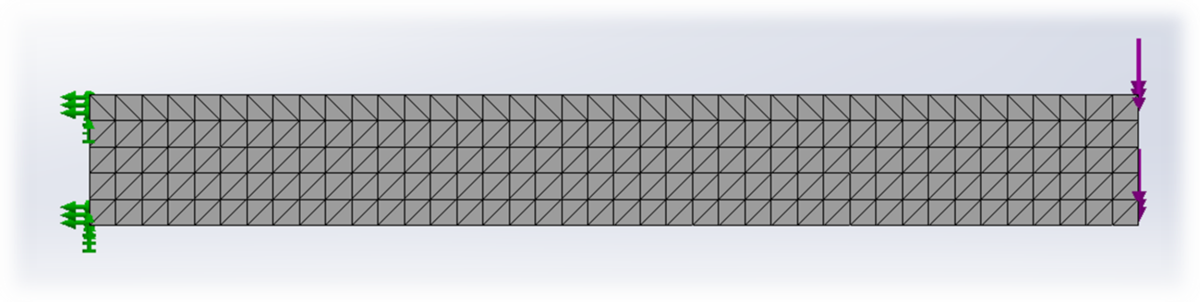

Figure 54 - Boundary conditions beam test

To understand the analysis of linear and non-linear analysis a standard beam test was performed. The beam was designed in dimensions of 200x25x25mm. The only boundary condition set was a complete fixture in one end, as well as a force applied to the other end. Mesh size were set to 5mm tetrahedral mesh. This can be seen in figure 54. The Material applied for the model was ABS with following properties:

Name:	ABS
Tensile strength:	3e+007 N/m^2
Elastic modulus:	2e+009 N/m^2
Yield Strength:	5e+007 N/m^2
Poisson's ratio:	0.394
Mass density:	1020 kg/m^3
Shear modulus:	3.189e+008 N/m^2

The model was put through several tests, both linear and non-linear. Forces between 100N and 2000N were applied to compare the two different approaches. The analysis started out with the largest forces for both the linear and non-linear approach, where graphics from the same tests are depicted in figure 55 and figure 56.

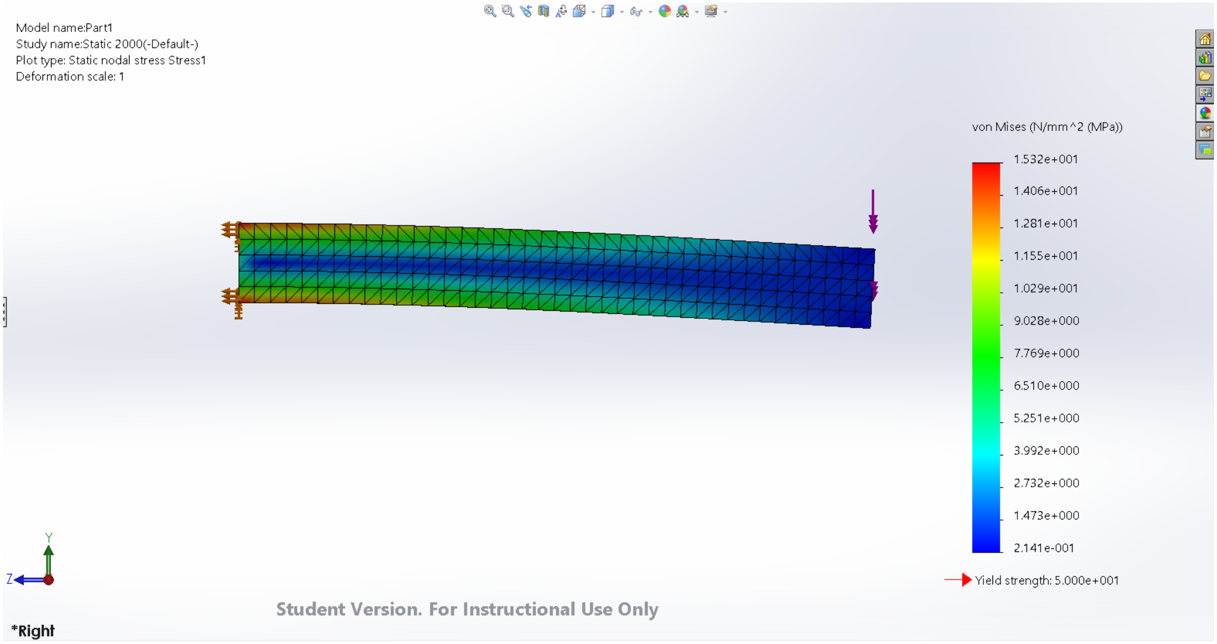

Figure 55 - Linear beam analysis

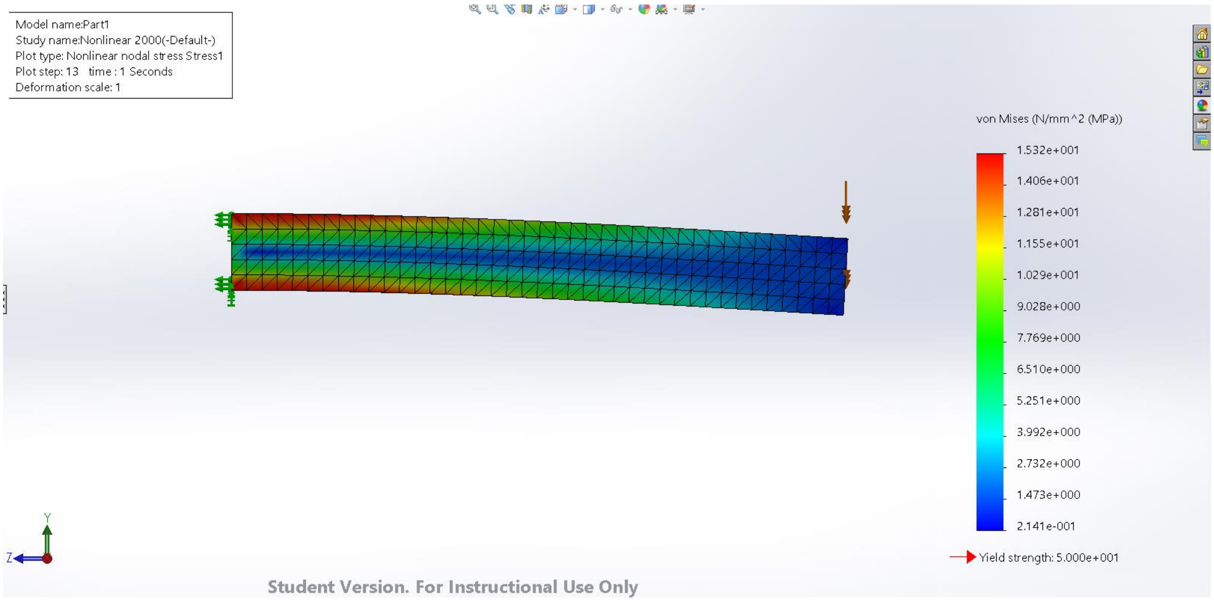

Figure 56 - Non-linear beam analysis

It was interesting to see how different the stress appeared to be distributed. It seemed like the stress had to figure a way to redistribute itself along the cross section so it could someway withstand the load. The linear and non-linear test are compared in figure 57 (done with refined mesh). The test was eventually ran with smaller forces. The results of these tests can be found in the graph in figure 58.

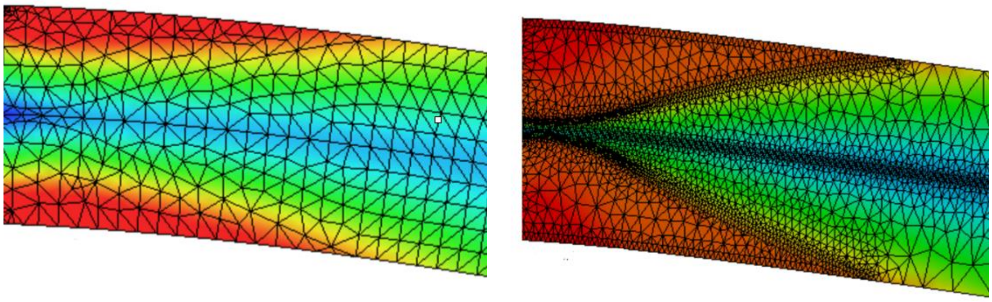

Figure 57 - Stress distribution in critical area. Linear test to the left and non-linear test to the right at 2000N load.

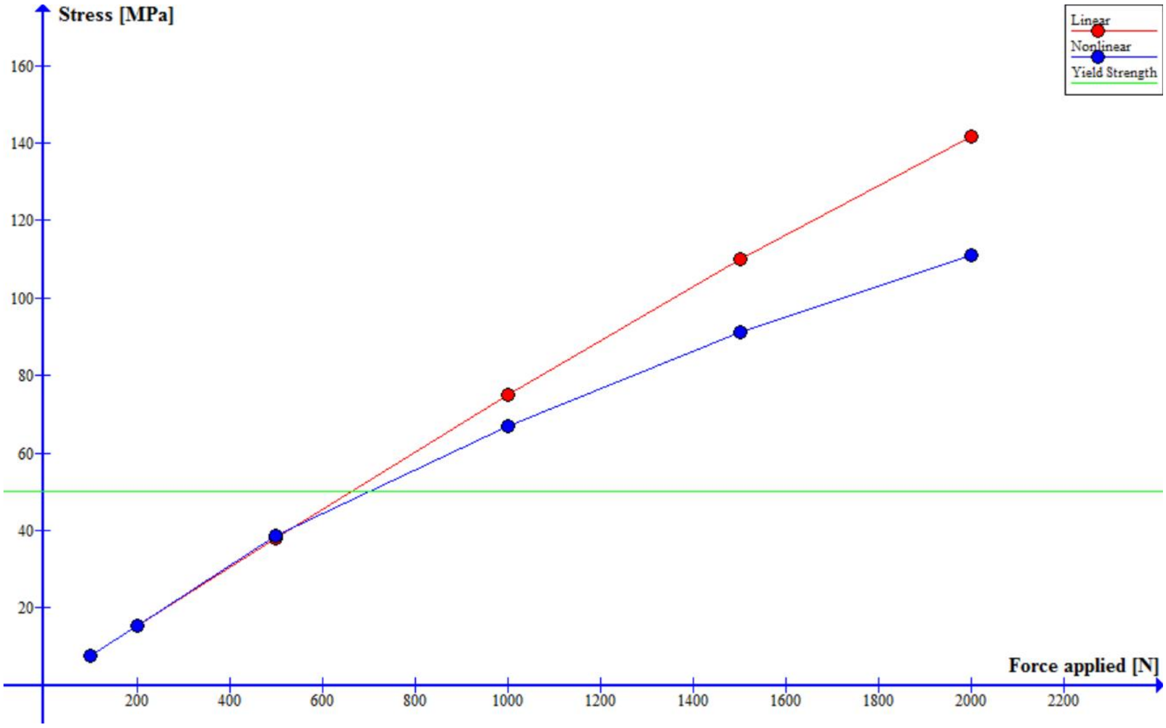

Figure 58 - Linear vs non-linear approach

It appears that differences between the linear and the non-linear approach begin to emerge once the stresses have exceeded the yield strength of the material. It seems like it is necessary to consider non-linear effects if the results exceeds the yield strength to get an accurate result. However, non-linear simulations are much more demanding in terms of computer power and time (about 10 seconds versus approximately 2.5 minutes for the non-linear analysis.) More complex geometries would probably vary even more due to the number of equation to be solved. It should therefore be considered if accurate results have greater value than the number of iterations.

6.2 Blueye side cover

Today Blueye's prototypes contains watertight boxes inside the shells to keep electronics dry, meaning that the outer shell does not need to withstand the hydrostatic pressure from deep waters. Meanwhile in the future, it could be possible that the side shells itself will be watertight. This means that the shell needs to be designed to resist the water pressure on the ROV. To withstand the pressure at 100m depth, the wall thickness has to be very thick if it is design with a homogenous wall thickness. Using design features as ribs and corners can help the model achieve stiffness without having abnormally massive walls.

Because the thesis is more about early prototyping of the parts of Blueye's ROV, the analysis performed is simplified. The idea is to show how to generate stiffness to the side cover and still make it moldable/castable. Therefore, the analysis was tested linear static and compared the different models relative to each other. This was to reduce simulation time, thus increase the number of iterations. The model used in this analysis is based on the same as in the previous chapter.

The model was applied with a hydrostatic pressure 0,4 MPa (depicted in figure 59), which is less than we find at 100m depth. The pressure was lowered because of the downsizing of the model and to achieve more accurate results due to the simplification of using linear static analysis instead of non-linear simulation.

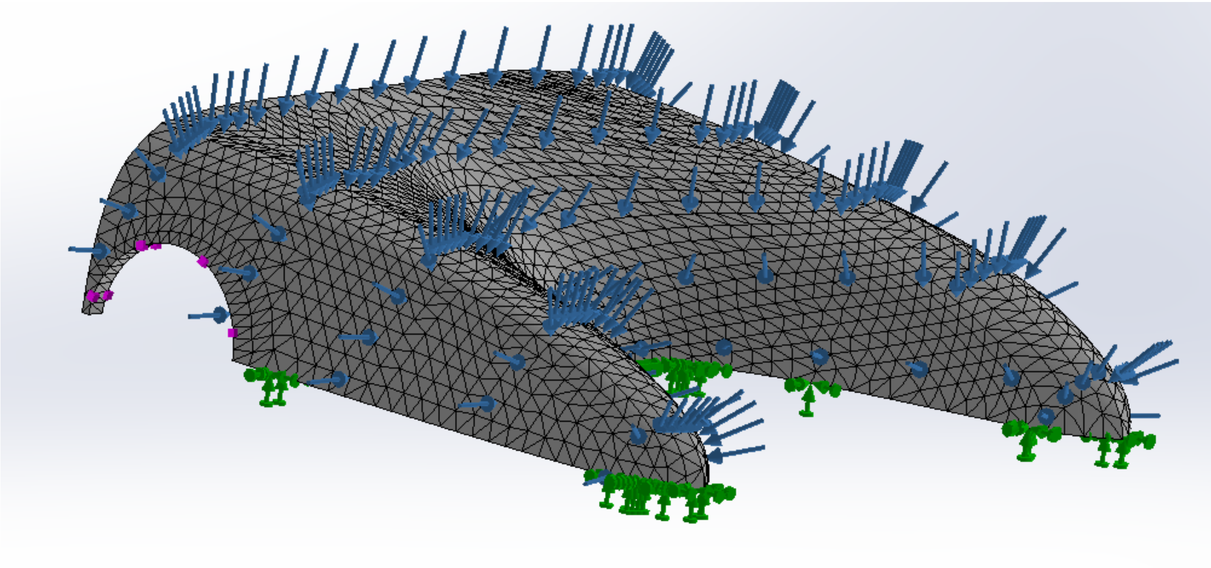

Figure 59 - Boundary conditions in FEA of side cover

Just half the model was simulated to reduce the number of equations to be solved. Normally the shells will lie against each other, meaning that the end of the model have fixed boundaries on opposing sections. The wall thickness is the same as before, 3mm. The mesh is comprised of 2mm tetrahedral elements, but in more complex areas mesh control has been used to set a beneficial mesh size around corners.

Several iterations were made on the use of rib structures to stiffen the shell. The version used in this review is depicted in figure 60. This model has some additional design features, such as rib structure with ribs of 2mm (Max thickness = 3 mm * 0.7 = 2.1 mm). In addition, a tube is added for the lateral thruster, because Blueye has found it necessary to ensure sufficient maneuverability. The ribs and tube are designed with a draft angle of 3 degrees. Besides these changes the shell is the same. Equivalent test conditions were applied to this model as well. The results are clear and can be seen in the paragraph below.

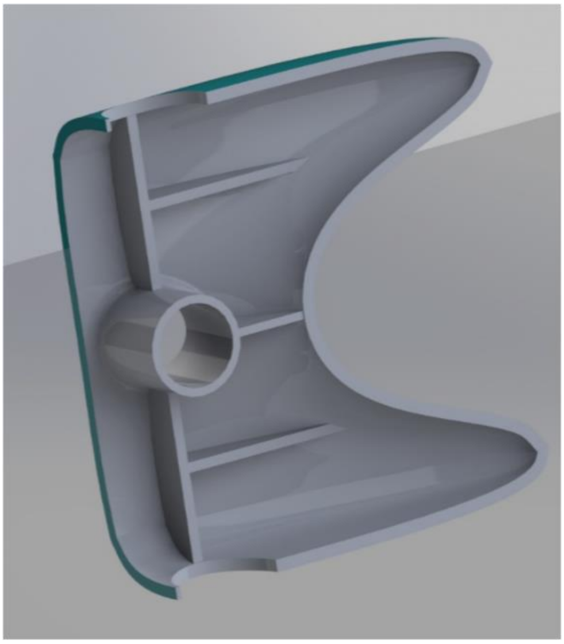

Figure 60 - Side cover with ribs and side thruster

6.3 Results FEA analysis

Considering the stresses, observations show that the stress of the standard model without ribs and the tube (figure 61) are fairly even over the entire surface. In this area the stresses act at around 25-35MPa. The exceptions are higher stresses close to sharp corners and lower around double curved areas such as in the rear end and in the middle of the part.

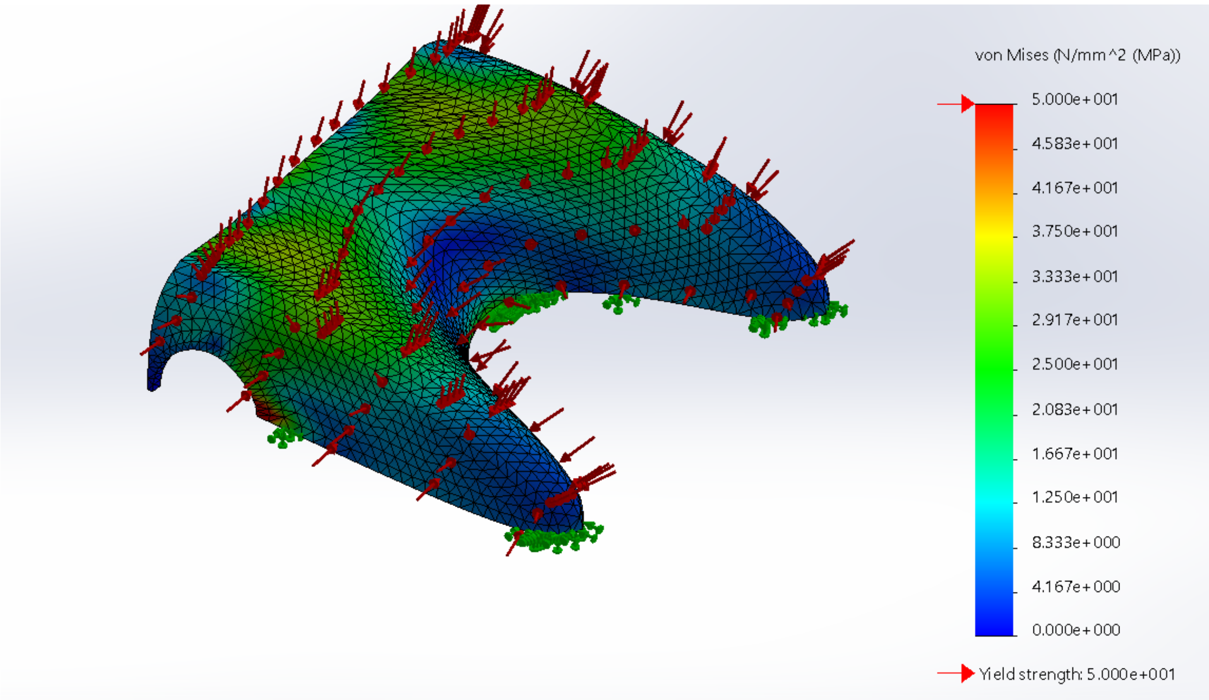

Figure 61 - Stresses standard model

Compared to the model using ribs (depicted in figure 62) the stresses are less evenly distributed over the model due to more complex geometries. However, the stresses are reduced for the most of the model, lying around 5-20MPa.

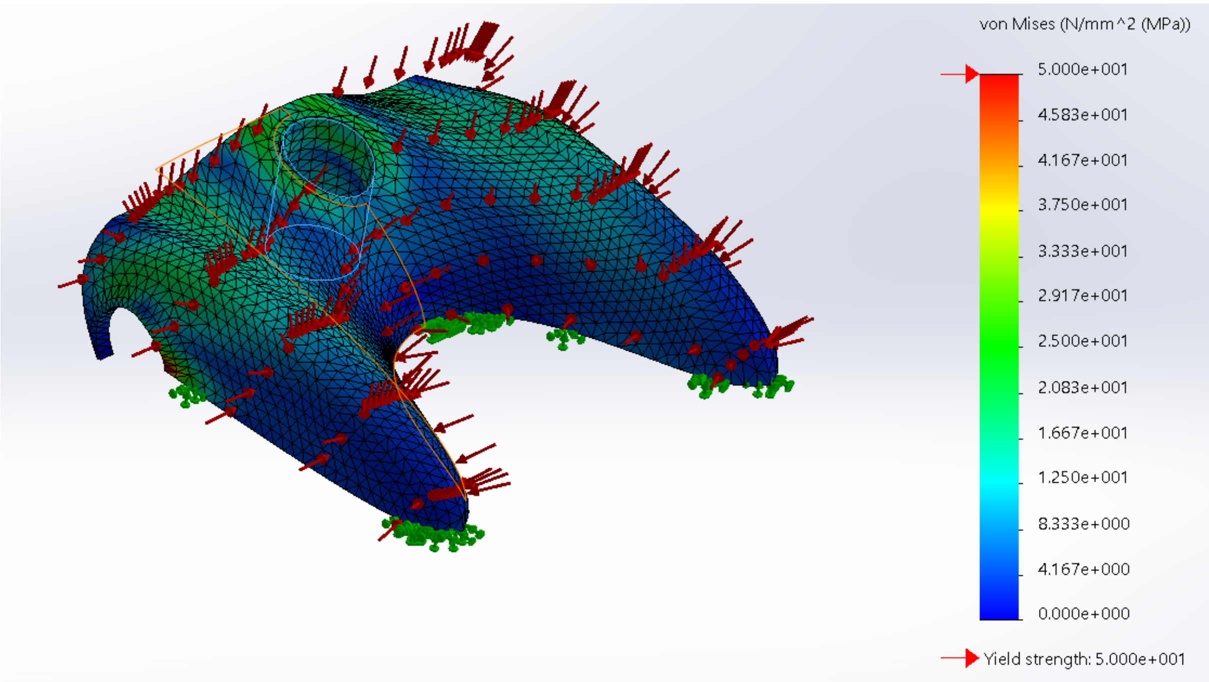

Figure 62 - Stresses rib model

However, the most important effect achieved from the ribs are clearer when looking at the displacement of the models. The simpler model has major displacements, up to 6.3mm (figure 63). Parts of the front surface are also having displacements over 5mm and almost the entire front compartment are having displacements over 2.4mm. These displacements are quite large and can rarely be tolerated.

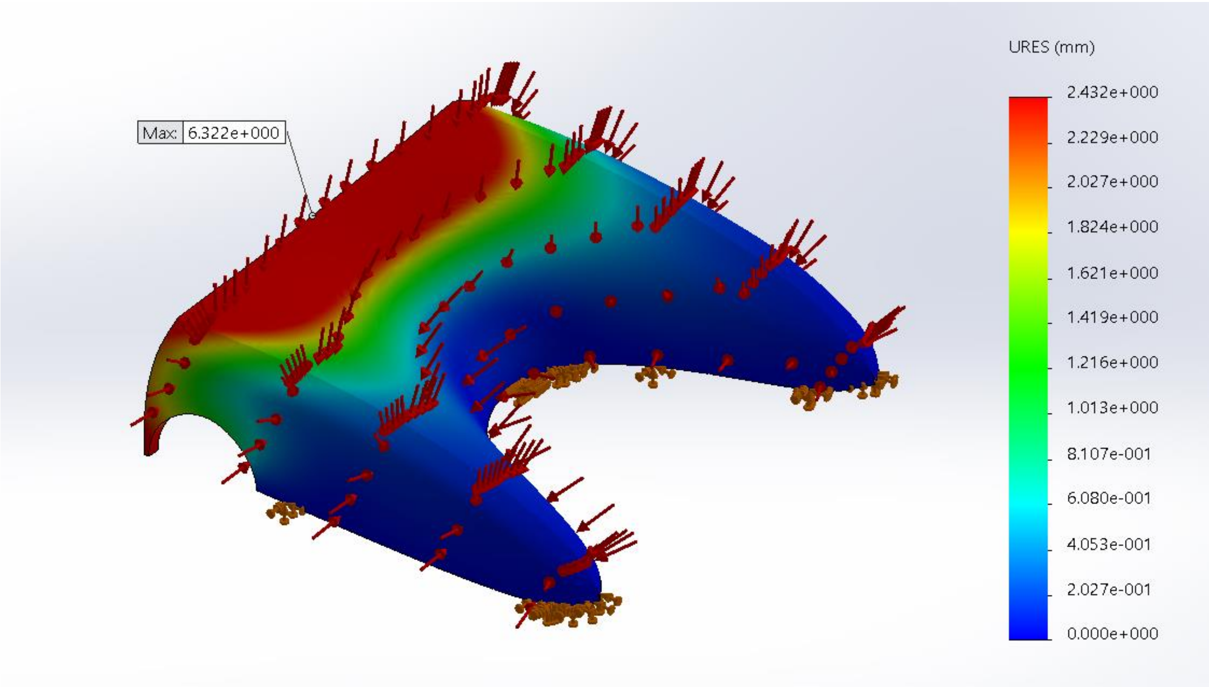

Figure 63 - Dicplacement standard model

On the other hand, the updated model has almost no displacements over 1mm **(**figure 64**)**. From this, it can be argued that the ribs are prevent the deflection. However, some displacements at each end in the front where rib structures are missing, can be observed. Meaning it could be beneficial to design the ribs all the way to the front.

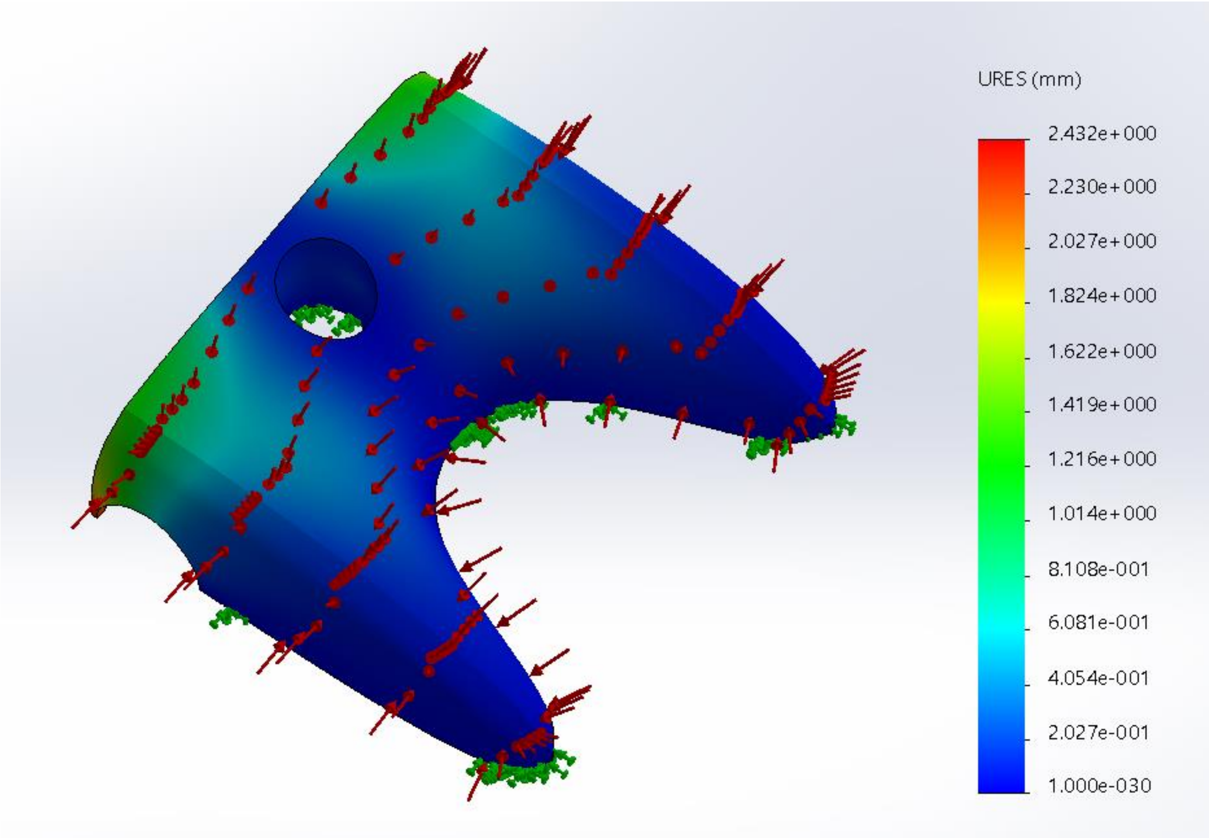

Figure 64 - Displacement rib model

The results show a significant difference in both the stresses and displacement. Thus, it can be concluded that the ribs have a major effect, verifying the theory concerning the use of geometrical features. Furthermore, it can be noted that the tube of the thruster is bracing for the structure. Future attachment points and brackets can therefore advantageously be part of the structure to give the structure additional rigidity against deflection.

Discussion

With almost no prerequisites for injection molding I started the project with an idea that the project would go in the direction of injection molding, resulting in a cheap and simple mold for manufacturing. However, after some research I soon understood that the concept of injection molding was not that simple. To gain extra insight I went to Leksvik to visit an injection molding company named Lycro. By empathizing I experienced that injection molding was more than just filling a cavity with a polymer melt. Firstly, the flow link between the injection molder nozzle and the mold must be air thight, otherwise there will be a pressure drop and polymer melt will flow out. Secondly, a plan must exist on how to eject the molded part from the cavity. Additionally, the part will shrink under cooling, meaning that post-filling is required.

Although I had gained a lot of insight regarding injection molding, I had no practical experience. I therefore re-designed a low fidelity prototype of the Blueye ROV's side cover to be possible to eject from a mold. When wayfaring, serendipity findings might occur. This corresponded well with my experience. While testing the injection molder, I experienced that there were no simple ways of performing injection molding on the kind of geometry I made, without having access to a high-end injection molding facility. However, Øystein Bjelland's part was manufactured with good results in his injection molder. This was probably an effect of using a smaller mold with less geometrical features, which means less pressure needed. *What could be the reason the molds were not completely filled?* A possible reason why the cavity was not completely filled could have been that air was trapped inside the mold. The mold was designed without air gates, because it was assumed that the molds would not be air tight at 50 bars. The attempted solution was to drill two extra small holes in each end of the rear end of the mold to let go of the trapped air. Despite this, lack of pressure and volume flow was a problem.

After the test with the injection molder it soon became clear that a high end injection molder facility was necessary to perform tests with the size and complexity of the molds that I was trying to use. The lack of pressure and the bad usability of the molder was crucial for the bad results. As a wayfaring experiment, the findings made me rethink the problem.

This resulted in the change of attention to explore if the molds itself were ideal to actually make molded/casted parts. The main reason that the choice fell on rapid prototyping with rotocasting was because it in many ways is similar to injection molding in terms of design features and production method. Rapid tooling is more similar to injection molding than milling and will thus provide Blueye useful knowledge about design and opportunities regarding mold making, which in turn could lead to shorter time to market for the model. Milling, as used on todays prototyping, is a completely different manufacturing method. Not much experience is possible to transfer to the final production method which most likely will be injection molding. Although the focus narrowed down to rapid prototyping with the use of rotocasting, additional prototyping methods were performed. All methods were compared to each other. Milling showed its potential to make true copies of the CAD model. However, each sample of the prototype took quite a while to make, meaning that it was not ideal to manufacture larger batches of parts.

The experiment showed early the possibility of rapid tooling in terms of time, cost and agility. Which corresponds with the research of Karapatis, & van Griethuysen (1998). The tooling manufactured almost identical parts, meaning that the tool itself was the limitation of the surface quality and tolerances. Production was done with no cost and short manufacturing time. However, the major concern using these cheap materials as molds was the lifetime. The use of release agents was introduced to the project to provide mold lifetime and easier ejection of parts. In the initial phase vaseline was used as release agent. Despite damaging the material properties of the resin, there were still a lot of useful results in terms of casting technique.

But how should the molds be able mold/cast more than 1-3 passable castings? To provide longer lifetime a surface layer of either epoxy or bengalack was added to the molds. The idea was to make a harder and more durable layer facing the part to be molded/casted. The experiment showed positive results (less wear, despite less release agent used). However, the molds would never survive 100 castings, based on the wear after five castings. Using foam as tool material may be too weak manufacturing hundreds of similar parts, but the method could be useful for smaller parts. If the maximum number of castings are five before additional tooling is required, it is possible to produce 20 small parts in one mold at each casting. This means that one simple and cheap foam mold has the potential to manufacture the 100 parts needed. To achieve even better results, the epoxy (or other material of choice) could be added before the last milling sequence is done. A smoother surface means that there is less surface for the casted part to stick to, which results in less wear. However, the epoxy provided a longer lifetime for the mold. To extend lifetime for the mold, and at the same time keep the costs low, a new layer of epoxy could be applied to the mold before retooling is done. This will reduce the material costs because retooling is much cheaper than making a new tool.

Easy access to a mill or a milling company is therefore advised. It is also possible to look for more durable tool materials. As mentioned in the theory chapter silicone molds are possible to use to manufacture a larger amount of prototypes. The tests performed with the silicone mold showed zero traces of wear after the five castings. However, since I ran out of material a sufficient amount of tests were not performed to verify numbers stated by Materialise (20) and Starprototype (50). If the silicone mold does not perform as desired, the possibility to step up to the level of Honda, using aluminum mold as mentioned in theory chapter, is always there.

When casting, probing revealed several elements to take into consideration before designing the new model. The use of release agent is vital when manufacturing in weak mold materials. However, downsides with the release agents used were discovered. A spray would be preferred. Lubricating the wax on the mold gave an uneven surface with brush marks, which influence the tolerances and surface quality. It is suspected that a spray will provide a thinner and more uniform layer.

Another concern was that all the casted models had distorted geometry supposedly due to surface tension in the resin. The big question however is how to achieve better accuracy. More pressure could therefore be desired for geometries that are complex. Instead of applying additional pressure (ex. from an injection molder), suction in terms of vacuum casting can be used. Even though it was not the focus of this thesis, it was mentioned in the theory part of the paper. These additional forces will pull material even closer against the walls of the cavity, which will provide better tolerances to the product.

As Houde & Hill (1997) described in their research, different fidelity on a prototype may be required to generate useful feedback from different audiences. When empathizing with potential users I discovered that the two persons (Jørgen Karlsen and Øystein Borkamo), who were able to hold the rapid tooled prototype themselves, did not show that much interest in it. However, showing the prototype to Rune Hansen at Blueye, the prototypes where used actively through the conversations. Verifying that there is a need for a different fidelity prototype for different audiences.

To validate gains from the use of geometrical structures a FEA-analysis was performed. Both linear and non-linear approaches were tested and compared to the properties of ABS. The results showed a significant difference in both the stress and displacement. Thus, it can be concluded that the ribs had a major effect. Results also revealed that the use of linear analysis could be used to analyze ABS material properties, assuming that the stresses did not exceed the yield point. This was very helpful for achieving a conservative result in a short time, compared to non-linear analysis. This will be beneficial to implement more iterations and eventually end with a non-linear analysis.

What I certainly have discovered is the need for prototypes in the development of new products and the use of new manufacturing methods. By discovering this in an early phase, it could potentially save a large amount of money compared to if it was first discovered at a late stage in the manufacturing process. This corresponds well with the findings done by Soares & Rebelo (2012) of why companies have implemented prototyping as a step in product development. In addition, molding and casting of parts using rapid tooling is a good way to manufacture smaller batches of parts instead of milling which matches the discoveries of Ulreich (1992) in terms of delivery time.

There are some limitations to this study. By not following a specific plan it is hard to distinguish between the procedure and the results gathered throughout the thesis. The short sprint method deals with small changes and miniscule nuances between experiments. It is therefore a quick, but potentially inaccurate. Additionally, the results are not quantified, due to there being no ideal object of comparison. Therefore, the prototypes are only compared relative to each other. I have also been the only one to compare them. Meaning that the results can be biased by emotion. The interviews are lacking in qualitative information. A form could beneficially have been used. Interviewees for this thesis was also in a similar age group, meaning that the results possible came from a very limited audience. The problem regarding taking decisions on my own when wayfaring occurred in one case. When I understood that it was feasible to move the inlet gate to a higher point in the mold to achieve faster filling time I took a rushed decision. Without thinking about the consequences, I automatically drilled two new holes at the highest point of the mold. This resulted in a real struggle to eject the parts from the molds, often resulting in damaging the rear ends of the parts. In retrospect, I see that this decision was taken purely on impulsive emotion without considering scienctific literature. In a team, a decision like this would in greater extent become more thoughtful. Finally, when working with low-cost materials and production methods significant variations in is to be expected from the results.

Conclusion

In this master's thesis the focus points have been to explore the different possibilities regarding prototyping and to give Blueye an introduction to ways of manufacturing a small quantity of similar prototypes. The research method has been a combination of two different methods – Design thinking and wayfaring. During of these methods have been to take notes underway during the interviews, tooling and tests. Findings during the thesis has been generalized into strengths and weaknesses relative to the other processes and the findings has continuously chosen the way forward. The result were based on findings from one company tour at Lycro, five independent interview participants, testing of 33 prototypes (7 split molds, 3 injection molded-, 31 casted-, 2 milled- and 3 3D-printed models). All these prototypes was a re-design of the side cover (shell) of Blueye's prototype, optimized for production methods using molds. The side cover was designed using a CAD software named SolidWorks and further manufactured using five different production methods.

This thesis have contributed to reveal the potential for each process by use of the wayfaring model. This method builds on existing literature as well as adds testing of low fidelity prototyping of 5 commercial processes. It soon turned out that injection molding needed a high-end facility to manufacture prototypes with decent quality in larger sizes. However, an injection molded part by Øystein Bjelland's showed that there are possibilities for simpler injection molder facilities. The result of this became to test the tooling by using a simpler manufacturing method, rapid tooling, which in many ways is similar to injection molding. Discoveries concerning manufacturing of tools, wear of tools and the need for manual labor after processing were explored. Rapid tooling soon showed its potential in terms of flexibility. It was easy, at a low cost, to modify or to make a new tool if manufacturing failed. The total material cost has been under 3.000 NOK. Meaning that there is a possibility to cast low cost parts.

At the end of the project, the side cover was re-designed yet again. This time with higher fidelity, meaning additional features such as ribs and more draft was added. The effects of the features where briefly examined. The results verified the effects of the features as found in several design guidelines for molded and casted products used in this thesis. Through performing both linear- and nonlinear finite element simulations, it was discovered that the linear simulations can provide conservative results in a shorter time, though it fails to render with high accuracy at higher stresses. The non-linear simulations however, can provide more accurate results, are more time consuming and are preferred at higher stresses. The journey in this thesis are illustrated in figure 65.

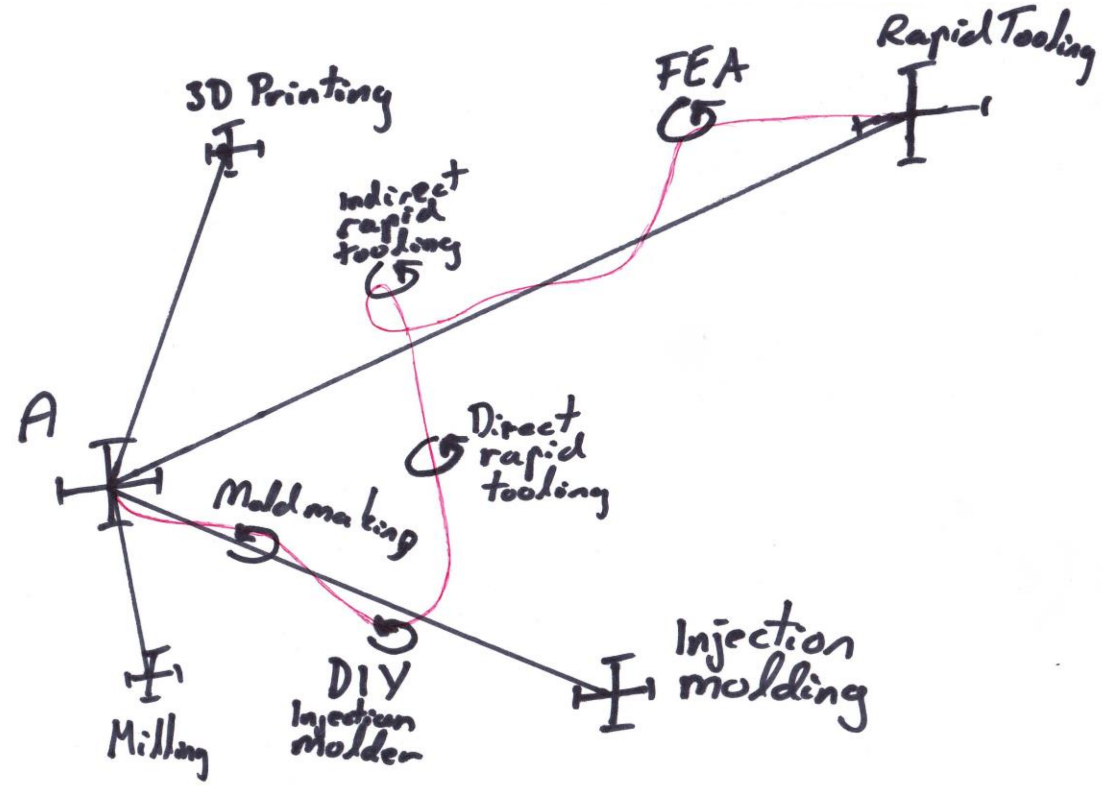

Figure 65 - My journey

The research done in this thesis is important for Blueye to enlighten the possibilities of production methods concerning prototypes and 0-series models. The findings in this research discovered the possibilities of rapid prototyping and low-cost molds, which is much more a similar process to injection molding than milling. This can contribute to faster learning in terms of mold design processes and reduce design time from prototype to final product.

Due to the early findings that materials are not the restrictive factor as well as the agreement with Blueye not to dig deeper into this domain, materials was not explore further. This would be appropriate to go into when material for specific parts to be determined.

As the project developed, there was little indication that it was feasible for the project to point in the direction of watertight containers. Therefore, the add on point in the masters description was not examined.

Suggestion for further work

For further work, there is much more to be discovered in terms of prototyping towards a final product. Especially in terms of rapid tooling. I suggest taking the rapid tooling to a higher fidelity prototype, which provides a design closer to the real model. This means to also take the molds to a higher level in terms of tolerances and material selection. Ranging from more advanced 3D-printing technologies to milling in high quality materials.

In the final phase of the project, I have been in contact with Curtis Stein at Stratasys. He had several suggestions in terms of possibilities to make prototyping molds. He thought the best way to make the molds would be to use a PolyJet process and use the Digital ABS material (digitalABS2). A material they had great success with in terms of rotocasting and vacuum casting. They have actually used that to do some injection molding as well. He roughly estimatet for the mold used in the experiment that it was possible to manufacture between 50 and 100 similar prototypes. Due to little research in this area he could not guarantee success, but many customers have already had success. This is something that actually could fit Blueye perfect. Pricing was around 100$ per mold piece if printed. Another possibility was the use of polyurethane molds in combination with vacuum casting, which is well-tested commercial process.

For the experiment itself, it would be good to find a way to quantify the results. Quantifying the results would ease the process due prototyping in a later stage and comparing it to the previous models. For Blueye this could for example be an impact test or a tolerance test.

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Appendix A - Interviews

Øyvin Sandvik Røhovde is a 29 years old machine-engineer who is taking a master in Global Manufacturing Management on NTNU. He is very fond of his hobbies and dedicates around 20-30 hours each week to them. He is active in the terrain-cycling community and the ski freeride-community. On the side he works on his own ROV-project which is in the start-up phase. Therefore we took us the time to talk with him to get an insight in what the market wants. Øyvin wants a ROV to inspect the ocean floor. Han thinks the three most important factors for a ROV to succeed in today's market is that it had a good quality live video stream, that it can maneuver with high precision and that it has a manipulator.

Øyvin thinks the live video has to be very clear. Especially when you have just arrived at the place where you wish to explore or perform certain tasks. Extra lightning would therefore be nice to have.

It's live entertainment that triggers Øyvin. He wishes to have a good view of what is going around him when he drives. It is especially important with good vision when you are performing tasks with a manipulator.

The maneuvering on the ROV should be good enough to perform simple tasks for the normal human being. It should not be frustrating to drive. It's not the drive to the place which matters, but how stabile and well the maneuvering is when you are performing a specific task. The ROV should go deeper than most divers are able to, so at least 50m deep.

For a price of up to 20 000 NOK the ROV has to do more than only film. A manipulator with either a claw, scissor or screen would be preferred. Also a possibility to store something in the ROV would be nice. This gives new possibilities, like exploring under rocks and doing simple tasks with ropes.

Øyvin does not need a groundbreaking design. He wants a simple design with focus on functionality, battery life and reliability. It is also important that it can be transported by one man and that it fits in a normal sedan.

Name: Jørgen Karlsen
Age: 24 years
Work/school: Employee at Celca
Relevant experience: RC Cars and Drones

- Durability
- Tolerate rough conditions
- Not feel like a toy
- Easy to maintain.
- Look nice when stored
- Optional equipment

Name: Øystein Borkamo
Age: 21 years
Work/school: Employee at NovaSEA
Relevant experience: Salomon industries.

- Durability
- Should dive down to ~60m
- Tolerate rough industrial conditions
- Industrial quality feel
- Easy to clean and maintain.
- One man job
- Function over looks

Name: Bjørnar Fugeløy
Age: 25 years
Work/school: Mechanical Engineering at NTNU
Relevant experience: 1 year at Schlumberger.

- Should do simple tasks in the water surface such as clamping a rope, inspecting boats.
- Should and down to ~60m
- Minimum 1 hour battery capacity.
- Speed is not important, stability is.
- Exploring the abyss.
- Should not brake easy.
- Easy to clean and maintain.
- Should fit into a normal sedan.
- Driving it should be easy for the regular man.
- Easy to charge on different electrical sources.

Name: Joakim Skjefstad
Age: 28
Work/school: CTO at CosyTech/Cybernetics at NTNU
Relevant experience: Diving and used ROVs before.

- Gets a rush from diving, being places no-one has been before, moving in every direction and being in a place not meant for humans.
- Would like a ROV with a 360 camera and connected to VR-googles to get the same rush.
- Important that the ROV is stable and with a good camera so that it can be used to film divers.
- Would be nice if you could control the ROV from under water.

Appendix B - Risk Assessment Analysis

NTNU / HMS	Kartlegging av risikofylt aktivitet	Utarbeidet av	Nummer	Dato
		HMS-avd.	HMSRV2601	22.03.2011
		Godkjent av		Erstatter
		Rektor		01.12.2006

Enhet: Department of Engineering Design and Materials **Dato:** 03.02.16

Linjeleder:

Deltakere ved kartleggingen (m/ funksjon): Martin Steinert, veilleder. Heikki Sjöman, veilleder. Gøran Borkamo, student. Eirik Lødemel, student.
(Ansv. veileder, student, evt. medveiledere, evt. andre m. kompetanse)

Kort beskrivelse av hovedaktivitet/hovedprosess: Designe og videreutvikle ideen om en teknologisk ROV til privatmarkedet.

Er oppgaven rent teoretisk? (JA/NEI): NEI *«JA» betyr at veileder innestår for at oppgaven ikke inneholder noen aktiviteter som krever risikovurdering. Dersom «JA»: Beskriv kort aktiviteteten i kartleggingskjemaet under. Risikovurdering trenger ikke å fylles ut.*

Signaturer: *Ansvarlig veileder: Martin Steinert* *Student: Gøran Borkamo*

ID nr.	Aktivitet/prosess	Ansvarlig	Eksisterende dokumentasjon	Eksisterende sikringstiltak	Lov, forskrift o.l.	Kommentar
1	Bruk av trollLABS workshop.	GB & EL		Brannslukkningsapparat, brannalarm		
1a	3-D printing.	GB & EL	Maskinens brukermanual			
1b	Bruk av lim(og andre sammenføyningsmidler)	GB & EL	Sikkerhetsdatablad og produktets brukermanual.	Sikkerhetsdatablad		
1c	Bruk av laserkutter	GB & EL	Maskinens brukermanual			
2	Bruk av IPM's verksted(skal vi i det hele tatt bruke selve verkstedet)	GB & EL				
2a	Dreiing	GB & EL	Maskinens brukermanual			

2b	Fresing	GB & EL	Maskinens brukermanual			
2c	Skjæreverktøy	GB & EL	Maskinens brukermanual			
3	Testing på havet	GB & EL		Flytevest	Sjøloven	
4	Arbeid utført av andre	Ukjent				

Enhet: **Dato:**

Linjeleder:

Deltakere ved kartleggingen (m/ funksjon):
(Ansv. Veileder, student, evt. medveiledere, evt. andre m. kompetanse)

Risikovurderingen gjelder hovedaktivitet: Masteroppgave student xx. Tittel på oppgaven.

Signaturer: *Ansvarlig veileder:* *Student:*

ID nr	Aktivitet fra kartleggings-skjemaet	Mulig uønsket hendelse/ belastning	Vurdering av sannsyn-lighet (1-5)	Vurdering av konsekvens: Menneske (A-E)	Ytre miljø (A-E)	Øk/ materiell (A-E)	Om-dømme (A-E)	Risiko-Verdi (menn-eske)	Kommentarer/status Forslag til tiltak
1	Bruk av TrollLABS workshop								
1a-1	3-D printing.	Ødelegge printeren	2	A	A	C	A	2A	Opplæring i bruk av maskin.
1a-2		Innhalering av printermateriale	5	A	A	A	A	5A	Ikke stå lenge nærme printeren mens den arbeider.
1a-3		Brannskade	3	B	A	A	A	3B	Opplæring i bruk av maskin. Unngå kontakt med utstyr under printing.
1b-1	Bruk av lim(og andre sammenføyingsmidler)	Eksponering øye	2	B	A	A	A	2B	Vernebriller.
1b-2		Eksponering hud	3	A	A	A	A	3A	Sikkerhetsdatablad tilgjengelig

1b-3		Eksponering åndedrett	3	A	A	A	A	3A	Sikkerhetsdatablad tilgjengelig. Arbeide i godt ventilert område.
1c-1	Bruk av laserkutter	Brann	2	B	A	D	C	2B	Opplæring i bruk av maskin. Ha brannslukkningsutstyr tilgjengelig.
1c-2		Øyeskade	2	D	A	A	A	2D	Opplæring i bruk av maskin. Ha på øyevern.
1c-3		Brannskade	3	B	A	A	A	3B	Opplæring i bruk av maskin.
2a-1	Dreiing	Flygende spon/gjenstander	3	C	A	A	B	3C	Opplæring i bruk av maskin.
2a-2		Ødelagt maskineri	2	A	A	C	A	2A	Opplæring i bruk av maskin.
2b-1	Fresing	Flygende spon/gjenstander	3	C	A	A	B	3C	Opplæring i bruk av maskin.
2b-2		Ødelagt maskineri	2	A	A	C	A	2A	Opplæring i bruk av maskin.
2b-3		Liten kuttskade	5	A	A	A	A	5A	Opplæring i bruk av maskin. Verneutstyr
2b-4		Stor kuttskade	1	D	A	A	A	1D	Opplæring i bruk av maskin. Ikke arbeide alene.
2c-1	Skjæreverktøy	Liten kuttskade	5	A	A	A	A	1A	Opplæring i bruk av maskin. Verneutstyr.
2c-2		Stor kuttskade	1	D	A	A	A	1D	Opplæring i bruk av maskin. Verneutstyr.

3-1	Bruk av sammenføynngsmidler	Eksponering øyet	2	D	A	A	B	2D	Bruk øyevern, ha datablad tilgjengelig.
3-2		Eksponering hud	4	A	A	A	A	4A	Bruk hansker, ha datablad tilgjengelig.
3-3		Eksponering åndedrett	4	A	A	A	A	4A	Bruk åndedretsvern/ god ventilasjon. Ha datablad tilgjengelig.
4	Tilstedeværelse ved arbeid utført av andre.	Se andres risikovurdering om sikkerhet betviles.	3	C	C	C	C	3C	Hold et øye med hva som foregår rundt deg.

Sannsynlighet vurderes etter følgende kriterier:

Svært liten 1	Liten 2	Middels 3	Stor 4	Svært stor 5
1 gang pr 50 år eller sjeldnere	1 gang pr 10 år eller sjeldnere	1 gang pr år eller sjeldnere	1 gang pr måned eller sjeldnere	Skjer ukentlig

Konsekvens vurderes etter følgende kriterier:

Gradering	Menneske	Ytre miljø Vann, jord og luft	Øk/materiell	Omdømme
E Svært Alvorlig	Død	Svært langvarig og ikke reversibel skade	Drifts- eller aktivitetsstans >1 år.	Troverdighet og respekt betydelig og varig svekket
D Alvorlig	Alvorlig personskade. Mulig uførhet.	Langvarig skade. Lang restitusjonstid	Driftsstans > ½ år Aktivitetsstans i opp til 1 år	Troverdighet og respekt betydelig svekket
C Moderat	Alvorlig personskade.	Mindre skade og lang restitusjonstid	Drifts- eller aktivitetsstans < 1 mnd	Troverdighet og respekt svekket
B Liten	Skade som krever medisinsk behandling	Mindre skade og kort restitusjonstid	Drifts- eller aktivitetsstans < 1uke	Negativ påvirkning på troverdighet og respekt

A **Svært liten**	Skade som krever førstehjelp	Ubetydelig skade og kort restitusjonstid	Drifts- eller aktivitetsstans < 1dag	Liten påvirkning på troverdighet og respekt

Risikoverdi = Sannsynlighet x Konsekvens
Beregn risikoverdi for Menneske. Enheten vurderer selv om de i tillegg vil beregne risikoverdi for Ytre miljø, Økonomi/materiell og Omdømme. I så fall beregnes disse hver for seg.

Til kolonnen "Kommentarer/status, forslag til forebyggende og korrigerende tiltak":
Tiltak kan påvirke både sannsynlighet og konsekvens. Prioriter tiltak som kan forhindre at hendelsen inntreffer, dvs. sannsynlighetsreduserende tiltak foran skjerpet beredskap, dvs. konsekvensreduserende tiltak.

MATRISE FOR RISIKOVURDERINGER ved NTNU

KONSEKVENS	Svært alvorlig	E1	E2	E3	E4	E5
	Alvorlig	D1	D2	D3	D4	D5
	Moderat	C1	C2	C3	C4	C5
	Liten	B1	B2	B3	B4	B5
	Svært liten	A1	A2	A3	A4	A5
		Svært liten	Liten	Middels	Stor	Svært stor
		SANNSYNLIGHET				

Prinsipp over akseptkriterium. Forklaring av fargene som er brukt i risikomatrisen.

Farge	Beskrivelse
Rød	Uakseptabel risiko. Tiltak skal gjennomføres for å redusere risikoen.
Gul	Vurderingsområde. Tiltak skal vurderes.
Grønn	Akseptabel risiko. Tiltak kan vurderes ut fra andre hensyn.