This master thesis project was performed in collaboration with

**Alten**
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Design and Prototyping of a Waterproof Probe Enclosure

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Abstract

This 30 credits master thesis was a project which marked the last part of the Industrial Design Engineering masters’ program at Royal Institute of Technology (KTH), Stockholm. The thesis was conducted at Alten Sverige in Kista, Stockholm during spring 2015. The report describes a product development project with the aim of developing and producing a prototype for a waterproof enclosure of a probe which has high demands on sealing capability as well as durability against other external interference such as vibrations, impacts and weather.

A theoretical study was made in the beginning of the project within the fields of seal design, eco-design, materials and manufacturing. The study led to deeper knowledge in the areas and formed a base for the development. The product and its use was mapped and design requirements for the enclosure were determined. Several design concepts were developed, both from the point of aesthetics and different functions using methods such as brainstorming, 6-3-5 Brainwriting, Build To Think and a morphological matrix. The concepts were evaluated and selected by using a decision making matrix. A final concept was selected and developed further, which resulted in a hamburger structured enclosure with an o-ring sealing. The probe is attached to the target object by using mounting tape. A concept for a snap-fit attachment was also developed. In order to find the most suitable process and material for the final prototype several rapid prototyping processes and materials were tested. The iterative prototype process was a key part of the development of the concept. The final prototype consists of a rotational milled base part with a vacuum formed cover. 3D printed tests for the snap-fit attachment was made. Different test cases and real life scenarios were put forward and provided basis for the testing and evaluation of the prototype. As the tests showed mainly positive results, the project was successfully conducted.
Sammanfattning


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# Abbreviations

<table>
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<th>Definition</th>
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<tr>
<td>DFE</td>
<td>Design For Environment</td>
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<tr>
<td>LCA</td>
<td>Life Cycle Assessment</td>
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<td>AM</td>
<td>Additive Manufacturing</td>
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<td>DFM</td>
<td>Design for Manufacturing/Manufacturability</td>
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<td>DFA</td>
<td>Design for Assemble</td>
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<tr>
<td>CFRP</td>
<td>Carbon Fiber Reinforced Polymers</td>
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<td>CAD</td>
<td>Computer-Aided Design</td>
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<tr>
<td>RIM</td>
<td>Reaction Injection Molding</td>
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<td>RP</td>
<td>Rapid Prototyping</td>
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<tr>
<td>FDM</td>
<td>Fused Deposition Modeling</td>
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<td>SLA</td>
<td>Stereolithography</td>
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<td>SLS</td>
<td>Selective Laser Sintering</td>
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<td>3DP</td>
<td>3D Printing</td>
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<td>STL</td>
<td>StereoLithography</td>
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<td>CT</td>
<td>Computer Tomography</td>
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<tr>
<td>MRI</td>
<td>Magnetic Resonance Imaging</td>
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<td>EDM</td>
<td>Electronic Discharge Machining</td>
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<tr>
<td>CNC</td>
<td>Computer Numerical Control</td>
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<td>CAM</td>
<td>Computer Aided Manufacturing</td>
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<tr>
<td>MMP</td>
<td>Micro Machining Process</td>
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<td>HCM</td>
<td>Hot Cutter Machining</td>
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<td>RPD</td>
<td>Rapid Product Development</td>
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Introduction

Background, problem statement and method used are here briefly presented to give an overview of the project and its aim. Also delimitations and validation is discussed.

1.1 Background

This project was conducted by two students from KTH as a master thesis within product development and was carried out at Alten Sverige, in Stockholm. An in-house team at Alten, called MAKEMAKE, developed electronics and software for a small probe as a part of a research project.

The use and application for the probe was, due to the research project, classified but with a simplified explanation it can be described as a device that is attached to different objects, referred to "target objects" in this report, and measures for example movements. It then sends the data wirelessly to external devices where the user can interpret the information. The probe will be used in an outdoor environment and must therefore cope with harsh environments such as cold, hot, wet, salty, etc. However, the enclosure design itself is not classified and this is what this thesis is focused on.

This master thesis is based upon the development process and design of an enclosure for the probe, with the aim to design a fully functional prototype of the product. The probe enclosure also needs an attachment solution for making it possible to mount it on the surfaces of the target objects.

The stakeholders in this project refers to the group of people at Alten who has been a part of the development of the probe, first and foremost the project owner (the supervisor at Alten) and the team MAKEMAKE.
1.1.1 Problem Statement

The probe will be used in an outdoor environment and therefore needs an enclosure which will protect the electronic components from environmental factors such as water, vibrations and impacts.

The task is to design a waterproof enclosure for the probe where the goal is to obtain a sealing ability of IP67. The IP (International Protection Marking) standard refers to a system for classifying the degrees of ingress protection provided by the enclosures of electrical equipment. The label numbers are linked to the difficulty of test that the product should pass. The first number indicates how well an enclosure is protected against ingestion of solid foreign objects and access to hazardous parts, such as electrical components. The second number indicates the level of protection against harmful ingestion of liquids.

The outdoor use will also expose the probe enclosure to salt, UV, impacts, temperature differences etc. Material choice is therefore an important aspect in this project, in order to make the enclosure durable. The probe will measure factors from its environment and send the data wirelessly to external devices and the material must therefore be compatible with the wireless system so that signals are not blocked.

Another factor to consider is how to supply the probe with power and how to integrate the power source in the design. The probe also needs a solution for making it possible to mount it on the target object without affecting the surface. The width should not exceed the target objects width, which is about 40 mm. The dimensions for the length and height are a little bit more flexible but should not exceed 80 mm in length and 60 mm in height.

The stakeholders at Alten have expressed a desire for a clean design that gives a hi-tech impression and an active and sporty form. The interaction is primarily conducted through an external device, such as smart phone or tablet, where the user can interpret the data which has been recorded. However, it should be possible to see some basic information on the probe, for example if it is activated and is sending data.

A functional prototype should be delivered in order to make real use tests in the future.

To sum up, the task was to develop a waterproof enclosure with an attachment solution to mount it on the target objects. Additionally also deliver a functional prototype.
1.2 Method

The product development process of this Master Thesis contains six major stages: 
*Prestudy, Insights, Concept Generation, Concept Evaluation, Concept Development* with an iterative *Prototype Development Process* and finally *Evaluation*.

At the start of the project a theoretical prestudy was made in order to understand the problem and to gather knowledge about seal design, design for environment, materials and manufacturing. Also a market research was conducted to get ideas and inspiration of different solutions and processes used in similar products today.

In the Insight stage, the knowledge gathered during the prestudy was compiled and discussed. The product and its’ use were determined using a Storyboarding method and by defining *Use Case* and *Scenarios*. This resulted in a specification of requirements which was used to set criteria for the concept generation.

To simplify the process of generating ideas and solutions, several supporting methods were used as a resource during the Concept Generation stage, such as *mindmapping*, *brainstorming*, *Brainwriting (6-3-5)*, *Build to think* and a *Morphological matrix*. These methods encourage creativity and help the designers to "think outside the box" in order to generate as many ideas as possible. These ideas are later compiled into concepts which are evaluated based on the requirements put forward. In order to ensure that no important factors were forgotten and that the concepts were evaluated objectively a method called *Decision Making Matrix* was used. The result from the evaluation was presented and discussed with pros and cons regarding the different ideas and solutions. Two interesting concepts emerged and were prototyped for further investigation. The two prototypes were discussed with the supervisor and the MAKEMAKE team and a final concept was chosen.

The chosen concept was further developed with more details into a complete concept. The Concept Development stage was mainly based on an iterative prototype development process. The concept was designed, prototyped, evaluated and redefined until a satisfying concept, a final prototype, was produced. Several materials and rapid prototyping processes were used and tested, evaluated and selected based on the requirements of the design.

To ensure that the function of the enclosure fulfilled the requirement, the prototype was tested and evaluated according to the test guidelines for the given IP - classification and real life test scenarios.

At the end of the project, the final product and the project itself were evaluated and ideas for future work and improvements were suggested.
1.3 Delimitations

Time was a limitation since the thesis had to be conducted within a time period of twenty weeks.

The development process was dependent on the progress of the MAKEMAKE team regarding the determination of the electronics that was to fit into the enclosure.

The goal was to deliver a functional prototype of the enclosure which made it necessary to adapt the design to a manufacturing thinking. Materials and manufacturing processes used for producing the prototype were limited depending on the access and costs of materials, machinery, equipment etc.

Market research and customer involvement was not given focus during the development process since the application and the real user of the probe was not known by the designers. Instead the supervisor, who was considered as the stakeholder and user, was continuously involved during the development.

1.3.1 Validation

The project is validated based on Master Thesis requirements for a high grade, set by KTH, see Appendix A. Also the judgement by stakeholders at Alten about how their requests and wishes about the final report and prototype were met, is included.

The prototype was tested according to the guidelines for the given IP classification in order to ensure the function of the enclosure. An additional test was made in order to validate the design, based on the use case and real life scenarios determined for the product.
Theory

In this chapter, the theory from the projects prestudy is presented. Relevant research for the development of the product was made in the fields of seal design, eco-design, materials, manufacturing processes and prototyping. The aim with the prestudy was to gain an understanding of what is the latest research, to deepen the knowledge within the fields, gain a strong base for decision making during the development and inspire for new ideas in the project. These studies where carried out during the first month of the project and had a great impact on the characteristics of the whole project.

2.1 Ecodesign

With the technology’s advancement, life has become more comfortable and simple in many ways. It’s made communication and travel more available and affordable which in turn has led to globalization. Companies can reach bigger markets and consumption is increasing. Products that once required skilled craftsmen to be produced can now easily be mass-produced with new technology and manufacturing processes and distributed all around the world. On the other hand, the growing consumption and production have a more or less strong connection to environmental impacts such as pollution, global warming, resource depletion and emissions [3].

Environmental issues have been given more and more attention and there has been a growing interest in environmental questions in the last decades [32]. The growing collective awareness of the environment and how the everyday life of humans affects it also reflects in how the customer chooses its products. Ecodesigned products provide greater satisfaction to consumers, who are increasingly environmentally conscious and aware of the value of recycling [44], [52] and the quest for sustainability is starting to change the competitive scenery, forcing industries to change their view on processes, businesses, technologies and products. Therefore, in order to enable potential buyers and staying competitive, environmental protection and
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sustainability for the society has become an important strategy within several industries and companies. Not only is there a growing market pull for sustainable products, there are also many mandatory regulations from governments [39].

Through ecodesign, companies can create and develop products and services which help to achieve a sustainable society. The principles of ecodesign are especially important to implement early in the design process where there is still a lot of design freedom. According to the European Commission "More than 80 % of the environmental impact of a product is determined at the design stage" [8]. Figure 2.1 represent a simplified model of a product development process focusing on the relationship between design freedom and the knowledge of the new product.

![Figure 2.1: Design freedom and knowledge in a product development process](image)

In the beginning when nothing is determined and there is little design restrictions, design freedom is high. As the product develops, more decisions are made and restrictions are established, but at the cost of design freedom. Once major decisions are made, only small changes or a re-design is possible. Sustainable solutions often demand radical changes and re-think of product systems and are therefore dependent on what is determined early in the design phase. It is therefore important that an ecodesign mindset is there from the beginning.

Not only does ecodesign enhance the company’s image as 'eco-friendly', it also provides more flexibility to adapt to new regulations and stay competitive on the market. In a research, where the sustainability initiatives of 30 large corporations where studied, sustainability is a source of technical and organizational innovations [39].

It is tempting to simply adapt to the lowest environmental standards and regulations for as long as possible but by setting sustainability as a goal today and try to adapt to the most strict rules, early movers will get a first mover advantage and the chance to develop competences that the competitors will find a hard time to match. An example is the company Hewlett-Packard which early in the 90s realized that the government would one day proscribe lead solders as lead is toxic. They then started to experiment with alternatives and in 2006 the company had developed a solution; solders made out of a mix of copper, silver and tin as well as a solution for managing the problems of tarnishing and oxidation during the soldering process. Hence they were able to meet the European Union’s Restrictions which took effect
Another example of how a global company can save money by aiming to achieve the most strict global standards, is due to the variation of regulations from country to country, companies that adapts to the lowest standard need to manage logistics, production, resources etc. for each market and country. If a single norm is used, which is the most strict, they can optimize their supply chain worldwide and thereby save money. Focusing on design for environment and being thrifty about material, energy and other resources used in the products life also lowers costs as companies end up reducing the inputs which they are using. It can generate additional gains from better products or enables companies to create new businesses.

When developing a product which will only be produced in a small batch, like this probe, the environmental impact may not be of such significance. One can argue that its impact will only be "a drop in the ocean". However, it is never unnecessary to have a Design for Environment mindset in product development. If for example the probe works as intended and the prototype gives a satisfying result, it may be taken into development for a bigger market and produced in bigger series. All of a sudden, DFE becomes increasingly important and with that mindset already implemented early in the design process, there may not be any need for radical design changes later on. It can also serve as an inspiration or as an educational product when similar products are being developed.

2.1.1 Guidelines and tools

Below are some examples of guidelines and tools regarding design for environment presented.

Functional Profile
In order to effectively ecodesign a product it is important to have a clear view of what the product will do and how it will affect the environment during its’ use. The functional profile is used for creating an understanding of the product that is being developed by evaluating the products function and the essential properties.

It consists of a functional description, which represent the main function of the product, and a set of functional categories, which represent the secondary functions. It helps to clarify the focus and responsibility areas for the product early in the design process.

The functional description describes, often in one sentence, the most important function of the product as well as its primary user. It is mainly used to clarify and remind the designer of the main purpose and task of the product. However, customers rarely base their decision of which product to buy on just the main function. Other factors such as aesthetics, price, ergonomics etc. are often the properties that affect the satisfaction of the costumer’s desire. The functional categories represent properties which have an important impact in how well the product work and sell.
10 Golden Rules
The 10 golden rules [34] are guidelines which are a good starting point in the product development process. Which guidelines to use and how to apply them, depends on the product designed, some designers might only have a specific use for a few of them.

The 10 golden rules are presented in Figure 2.2 and are described in more detail below.

**1. TOXIC**
Do not use, or avoid, toxic substances

**2. PRODUCTION RESOURCE**
Minimize resource and energy consumption in the production and transportation phase.

**3. ENERGY**
Minimize resource and energy consumption in the usage phase.

**4. UPGRADES & REPAIRS**
Prepare the product for upgrades and repairs

**5. OPTIMIZE PRODUCT LIFETIME**
Optimize the product to have a long lifetime. This is especially important for active products

**6. OPTIMIZE WEIGHT**
Minimize weight by using high quality materials and structural features without compromising the function

**7. PROTECT**
Protect the product from dirt, corrosion and wear by using better materials, surface treatments etc.

**8. INFORMATION**
Provide information to simplify upgrading, recycling, repairing etc.

**9. MATERIAL HYGIENE**
Avoid material mix to simplify recycling and streamline the extraction of materials

**10. STRUCTURE**
Use as few joining elements as possible, such as adhesive, for easier disassemble.

*Figure 2.2: The 10 Golden Rules*

**GR1** - Do not use, or avoid, toxic substances. If toxic substances are use they should be in a closed system.

**GR2** - Minimize resource and energy consumption in the production and transportation phase. Audit the procedures and routines to limit the use.

**GR3** - Minimize resource and energy consumption in the usage phase. This is particularly important for active products that have their most environmental impact during this phase. Understand how the product will be used in order to create as much efficiency in the consumption as possible.

**GR4** - Promote and create a plan for how the product can be repaired and updated. This is particularly important for system products.

**GR5** - Optimize the product to have a long lifetime. This is especially important for active product as they are creating most environmental impact during the usage phase. However, products that expect to have a short use-time should not be designed to have a long physical life because that would be an inefficient use of materials and resources.

**GR6** - Use structural features and minimize the weight by using high quality materials without compromising with the requirements needed for the product, such as
impact strength and flexibility.

GR7 - Protect the product from dirt, corrosion and wear by using better materials, surface treatments etc. This will also contribute to a longer lifetime for the product.

GR8 - Prepare and provide information to simplify upgrading, recycling, repairing, for example through labeling, modularization and manuals.

GR9 - Promote material hygiene and avoid material mix to simplify recycling and streamline the extraction of materials. Avoid for example alloys and use as few parts as possible.

GR10 - Use as few joining elements as possible for easier disassemble.

Material Hygiene

Material hygiene (MH) is referring to the management of materials throughout the lifecycle of a product. The goal of material hygiene is about optimizing the use of materials and that, as far as possible keep the material in the eco-cycle. After the use phase it is of great interest to have the recycled material at as high value as possible and therefore a high level of material hygiene means a high level of effectiveness.

Material hygiene is based upon a few aspects, some contradict each other, and therefore it is important to view them as a whole when designing a product, and not seek to achieve each aspect separately. Depending on the product that is being designed, there is a break even balance point.

1. Purity of fractions - Prices for material, due to demand, are growing faster than the extraction rate of virgin materials. In order to be less dependent on virgin materials a lot of focus is directed to recycling. One of the most important aspects of material hygiene is therefore the purity. Material with higher purity is more valuable in the recycling phase. With higher purity in the recycled material less virgin material needs to be added.

2. Material mix - This aspect implies to reduce the amount of parts and materials used in the design and in this way keep the design as simple as possible. The amount of different material used in a design has a direct connection to the possibility of extracting clean fractions during the recycling phase. On the other hand, it is better to use several materials which are easy to separate than having two materials inseparably as for example in an alloy.

It is becoming less expensive to recycle than to process new raw material but if one material contains another or if the materials are difficult to separate the expenses increase. The emphasis lies in avoiding alloys and design the product for an easy disassemble into components made of a single material [52].

3. Product structure - If the product is designed with many details in a total disorder with no clear separating boarders it could complicate the recycling. Strive for structure clarity with few details and where it is easy to detect the border between different parts.
4. **Fragmenting properties** - It is preferred, especially from a material hygiene point of view, to separately extract valuable components and materials, for example WEEE (Waste Electrical and Electronic Equipment).

5. **Integrating components** - One way to reduce the material mix is to integrate parts that have the same material or through integration create clear sorting borders. It does not mean having few parts with many materials because then the purpose of material hygiene is lost.

6. **Identification** - Identification is an important aspect when it comes to managing waste and recycling. There is a different need for the amount and format of information depending on who is responsible for the recycling of the product. For example, if those who assemble the product are also the once recycling it, there might be a less need of information than if a person with no or little connection to the product is managing the recycling. In the latter case, clear markings, labels, scrapping manuals etc. is possibly needed. Particularly if the design contains toxic or valuable materials, it is essential to have sufficient and necessary information in order to obtain maximum economic return.

The SPI Resign Identification Code is an example of labelling used for plastics to identify the polymer type. The codes can be viewed in Figure 2.3, and are a set of symbols developed by the Society of the Plastic Industry (SPI) in 1988. They are used to make an efficient separation and the code is used internationally.

7. **Housekeeping with scarce or toxic resources** - Materials and resources that are rare, toxic, valuable etc. are especially important to, through monitoring and documenting, secure in the life. By reducing and housekeeping with these materials in products, it can in many cases lower the costs.

8. **Weight** - Depending on the product, a light weight or a heavy weight is preferred. A lower weight can lower energy consumption for products that moves and when transported. An optimization of the cars weight to be as low as possible generates for example efficiency in fuel consumptions. On the other hand, adding material to a product can lengthen its lifetime, which is preferred for products that generate the most environmental impact during the user phase. Using steel instead of a composite material will increase the weight but is significantly easier to recycle and adding isolation material might also lower energy consumptions.

Once again it is up to the designers to balance the different guidelines of DFE based on the products desired functions, requirements, properties etc. in order to find a break-even point. However, the mindset of *10 Golden Principals* and *Material Hygiene* is to:
• Use as few materials as possible.
• Keep the material fractions apart as much as possible.
• Label each major fraction in the product and in the CAD model.
• List all factions by type, amount and position.
• Outline the boundaries of major fraction in the product and in the CAD model.
• Arrange separating points for important material modules.
• A good reason for adding another material in the product must exist.

**Life Cycle Assessment**

Life cycle assessment (LCA) is a “cradle-to-grave” approach for evaluating how a product, service, industry etc. affects the environment. According to the article Danni Chang [10] “life cycle assessment is an important tool to assist in ensuring proper sustainability through assessing the environmental impacts of product designs”, “cradle-to-grave” means that the whole life of the product is assessed, from the extracting of raw materials to the end of life phase when all materials are returned to earth.

The LCA consists of four phases: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation.

*Goal and scope definition* – Here the product, the process, methods and activities, limitations and assumptions are defined and described as well as a definition of the context in which the LCA is going to be performed and its boundaries.

*Inventory analysis* – The products lifecycle is compiled in an analysis where the usage of resources, such as energy and materials, are identified and quantified as well as environmental releases, such as emissions and disposals. The products lifecycle is divided into five stages; material, manufacturing, transport, use and disposal, see Figure 2.4, where all the stages are assessed interdependent about their environmental impact.

*Impact assessment* – assess the potential human and ecological effect of the different factors identified in the inventory analysis.

*Interpretation* – The results from the inventory analysis and the impact assessment are evaluated to select the preferred product, process or service.

The LCA tool can help designers and engineers in the decision making of selecting the products, services, processes etc. that generate the least impact on the environment. However, the result from a LCA does not reflect cost effectiveness or the products performance. Therefore should the result be used as an input to a more comprehensive decision making process.

A LCA analysis may however be more suitable to perform when re-designing or improving an existing product because it requires many inputs and details which may not have been completely determined when a new product is being developed. On
the contrary, it is in the beginning of a design process when there is greatest potential for disruptive innovation. Uncertainties can instead be filled with assumptions and the further along the development process a product moves, the more accurate will those assumptions get. Also if possible, a reference product can be used which is similar to the new product. The LCA can even be used for comparing different concepts in order to see which concepts generate the smallest environmental impact.

2.2 Seal Design

The most important function for the casing is that it safely encloses the electronics. Since it will be used in an outdoor environment the probe may be exposed to water, humidity, salts etc. which can cause corrosion but most importantly, it can cause severe damage to the electronics.

Waterproofing electric components in a harsh environment is both art and a science. According to the book Maskin Element [42], how the seal really works is not fully understood. There is little theory about its function, despite great efforts have been made to understand it. There is however a lot of experience in sealing design which comes predominantly from empirical tests.

Waterproof is an ambiguous term with many names; water resistant, submersible, watertight, water repellent, sealed – but what does it mean? In most cases, these are just marketing terms and companies have a tendency to use them quite freely. The Ingress Protection (IP) rating is a standard developed by the European Committee for Electro Technical Standardization to specify the environmental protection an enclosure provides. It normally has two numbers; (1) Protection from solid objects
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and materials, (2) Protection from liquids. The IP rating is described more in Section 3.2.1. Effective sealing for high IP ratings tend to add both cost and size, so it is important to choose the right sealing requirement. In either way, the design team should be prepared to meet a decent level of complexity in both design and testing, in order to hit performance requirements and for the product to be competitive on the market.

Designing reliable sealing solutions in the context of manufacturing constraints in the real world, is inevitably a challenge. According to Andrew Weiman [54] from Bressler Group, a company with over forty years within the business, the goal is to keep it simple through simplifying geometry and mechanical elements, simple parting lines and part interfaces in order to develop a robust design.

The most common sealing solution are o-rings and gaskets, due to that it is easy to use, easy to manufacture, effective and it requires little space. However, there are also more complex solutions that can make an effective seal. Here, experience really matters and especially the understanding of which possible and applicable processes there are and their limitations and benefits.

Some examples of other types of sealing options apart from o-rings and gaskets are insert moulding, over moulded elastomerics, welding such as ultrasonic and hotplate welding, double-sided foam tape and adhesives. Welding methods are for example used to create hermetic sealed enclosures. A hermetic seal has the quality of being airtight and the electronic components are then enclosed in a box which often is laser welded. The housing is commonly filled with Nitrogen in order to prevent corrosion and connectors have glass sealings. This type of enclosure is often difficult to disassemble, which makes it problematic to carry out services and upgrades to its components. Also, the problematic disassemble might make it more difficult to recycle in the end of life phase. Completely sealing of something might not always be the best solution. It is a good idea to make a way for air to travel in and out of the enclosure. Otherwise, the device might explode due to air pressure changes.

Also, all mechanical seals leak to some extent. There is always a mass flow rate across the face of mechanical seals [4]. The water vapor can start to condense on the electric components and therefore it is favorable to give it a chance to get out.

It is important to clearly understand the use of the product and also whether it will be produced in a high or low volume when deciding which solution to use.

2.2.1 Different types of seals

Seals are used in a big variety of application areas and depending on its purpose they have different requirements on sealing performance. Some examples of common use for sealing are:
Function

- A bearing is often provided with a lubricant intended for its whole life. The lubricant must therefore stay in the bearing.

- The engine in a submersible pump cannot be exposed to water, which puts high demands on the sealing design.

- In electrical units, water is strictly forbidden and therefore must all entries be sealed against water ingress.

Cleanliness

- In medical equipment, seals are important for preventing infections etc.

- In the food industry, seals have an important role of preventing substances, such as lubricants from the machines etc., to end up in the food.

Toxic and dangerous substances

- In industries working with chemical and toxic substances and gases, it is important that these substances are well contained.

All of these application areas place different demands on the sealing, from absolute sealing performance to where some leakage is tolerated. With higher sealing performance comes often more friction, which in turn leads to wear and power losses.

There are different types of seals and they are divided in different categories. The most common ones are:

- Non-contact, such as gap or dry seals, or contact seals, such as wet seals

- Static or dynamic

- Radial or axial

Shorter descriptions of the different categorizations are described below.

Non-contact seal
Non-contact seals form a narrow gap between the stationary seal lip and the rotating component. Since there is no contact, there is also almost no friction, resulting in no wear hence the seal becomes well suited for high temperatures and high speeds. The gap can be designed axially, radially or in combination, simple or complex like a labyrinth. The tortuous path help to prevent leakage and a typical use for this type of seals is when there is a rotational motion. The rotation can be used to create a centrifugal motion which helps to keep the fluids from passing through the passages.

Contact seals
A contact seal is generally a reliable solution but its effectiveness depends on many different factors, such as:

- Material choice

- Contact pressure
• Seal design
• Surface finishes
• Condition of the seal lip
• Presence of lubricant

The most commonly used contact seals are gaskets and o-rings and they are categorized as static or dynamic depending on if the surfaces are moving or not.

**Static seals**
Static seals are used between stationary surfaces and the most commonly used types are gaskets and O-rings. A static seal is usually categorized as axial or radial, depending on from which direction the squeeze is applied on the cross section. The effectiveness of the seal depends on the deformation.

The static axial seal and the gasket are compressed on both the top and the bottom of the cross section and are usually mounted in face (flange) type applications. Due to the non-existent extrusion gap there are fewer design steps and easier to control the tolerances. Therefore tend axial seals to be easier to design.

The static radial seal is squeezed between the inner and outer surfaces of the O-ring and are commonly used in cap and plug applications.

When an O–ring is exposed to either external or internal pressure the seal should always be placed against the low pressure side of the groove, see Figure 2.5. In this way, the seal is already in the right place as an outcome of the pressure.

![Figure 2.5: O-ring location depending on the direction of the pressure](image)

**Dynamic seals**
Seals which are used where there is reciprocating, rotating, sliding or oscillating motion are called dynamic seals. This type is commonly used in machine components that are moving relative to each other. There is a large range of different seal designs depending on its application and how the two surfaces move relative to each other. Some examples are:

• Pneumatic Seals
• Oscillating Seals
• Reciprocating Seals
• Seat Seals
• Rotary Seals

The performance of a dynamic seal can be affected by a variety of factors due to operating environment. Some examples are seal swell in fluids, lubrication, thermal cycling, pressure, squeeze, friction and surface finish. These factors are often related to each other and it is therefore important to consider all of them in the design solution. For example, if an O-ring is exposed to excessive running friction due to continuously moving applications, the heat which is being generated can cause swelling and in return cause even more heat that leads to seal extrusion and failure. Depending on the seal design and material choice, different seals have been given different speed limits.

2.2.2 Sealing solutions for the probe

Below are the sealing solutions which were considered to have most potential for the probe enclosure. Gaskets and O-rings are the most commonly used sealing solution for this kind of applications.

Gaskets
A gasket is a type of mechanical seal which can be categorized in different ways, for example by function, application or material. This type of sealing is often used for preventing leakage in pipes but also have many other applications such as reducing vibrations. Soft gaskets can for example be mounted between mechanical elements and thereby prevent the transmission of vibrations. Elastomer gaskets are usually produced from rubber or silicone and are custom moulded to fit perfectly with the application and the flange geometry. This makes elastomer gaskets a good seal solution when the flange design has a rectangular or more advanced geometry. An example of a gasket design for an enclosure is shown in Figure 2.6 below.

![Figure 2.6: Two examples of gasket designs](image)

To custom mould a specific design requires however a tool for moulding, which makes it an expensive component if only a few will be produced. Another, more cheaper, way is to die cut or water jet cut the shape out from a sheet. An example of a gasket installed in an application can be viewed in Figure 2.7.

O-rings
The o-ring is one of the most widely known and common type of seal used today, due to its easy use and requires little space. It is used in a large variety of applications
and in industries and is often the first type of seal being considered. The o-ring is basically a toroid generally molded from an elastomer, but it can also take a large variety of shapes and cross section designs.

The seal fits into a groove or gland in one of the mating parts to keep it in place and as the parts come together the o-ring is compressed, see Figure 2.8. Unlike plastic and metal parts which are probably failing if deformed, an o-ring and most other elastomer seals have to be deformed to function properly. The opposite sides of the seal is squeezed between the cavity of the two parts where the o-ring is mounted, resulting in a zero clearance within the gland. This gives an effective sealing which is blocking liquids and gases from passing through. When the pressure is released, the o-ring almost completely returns to its original shape. This is especially true for elastomers because of their ability to “remember”.

Other sealing solutions
Another commonly used sealing solution used for products today are elastomeric overmold cases. Not only does it form a continuous gasket solution but it also helps to protect the device when dropped and it can include buttons etc. These solutions are however more suitable for mass production products as the case needs to be moulded and is therefore expensive.

Gasket dispensing is a method where viscous fluid is extruded along a desired path. The fluid is then cures and forms an elastomeric seal. The dispensing process can be done automatically and it facilitates troublesome handling and placing of cut
Chapter 2. Theory

There are many different types of seals for different situations and a correct selection is crucial for the product’s performance and lifetime. Therefore, must engineers and designers involve the seal thinking early in the design and development process to save both money and time. There are four major areas which are important to consider in order to find the right material and seal type; Operating environment, Mechanical Factors, Materials and Manufacturing.

Operating Environment

The first step is to define the operating conditions. Will it be used in static or dynamic situations? What kind of environment? Will it be exposed to chemicals? Is the sealing solution supposed to seal out water and or dust? If it contains electronic equipment, does it need to be able to seal for electromagnetic interference (EMI). A clear and defined list of specification of requirements is needed as well as a full understanding of the environment it will operate in.

Operating conditions include parameters such as vibrations, pressures, temperature as well as their variations. If a material that otherwise would work sufficient for a system is exposed to thermal cycling or pressure spikes, this could unfavourably affect the performance.

Also, for sealing applications in areas such as food and pharmacy industry, careful analysis of environmental or regulatory issues is important. If for example there are any regulations or standards that forbids different specific materials in the application the product is being designed for. For example in the food and pharmacy industry, the product may need to be approved by the FDA (Food and Drug Administration) and then there are specific requirements to consider. Another example is when a fireproof material is mandatory.

Mechanical Factors

Mechanical factors refer to aspects such as gasket compression limits, gasket thickness, housing rigidity etc. Housing rigidity has a major impact on what type of seal to use. Fragile materials such as plastic, glass and fibre-reinforced plastic needs for example a seal material that seals with low locking force. Housings made out of plastic or thin metal can for example bow or flex under high load and therefore a seal with softer material is desired to reduce compression forces. Metal flanges used for high pressure application on the other hand needs a high bolt load. The amount of joint elements, their material and applied load needs to be taken in consideration. The spacing between fasteners is a central part of the seals performance. If they are too far apart the mating surfaces can bow or flex which can result in a leaking seal. More tightening does not always mean a better sealing performance. Seal compression limits are therefore important to consider, otherwise the seal may fail due to over tightening.

Uniform shapes are simpler to seal than complex designs. Circle shapes are consid-
ered the most simple shape i.e. since o-rings and flat circular gaskets are standard and they are easy to manufacture. Sealing gets more troublesome when the shape is not uniform and when parts doesn’t meet up. A common reason for sealing failure is due to surfaces not being uniform, resulting in a gap which doesn’t get sealed no matter how hard the parts are compressed.

**Material**

There are materials and different combinations to choose from and therefore, selecting the most appropriate is challenging. Interesting material properties are durometer hardness, polymer cellularity and compression force deflection. Durometer hardness is the materials hardness and is normally measured on the Shore A scale for solid materials. The standard o-rings have a hardness around 70-90 Shore A but different hardneses are available from around 10 - 90 Shore A.

*Cellularity* refers to whether the material is solid or if the cells of the polymer are open or closed to each other. Closed-cell foams and solid materials do not absorb fluids while open-cell foams tend to absorb fluids.

*Compression force deflection* (CFD) is expressed in pounds per square inch (psi) at a given percentage deflection and is a measurement of firmness.

Nature of the media and chemical compatibility refers to the importance that the gasket material fits well with the surrounding materials and media. Is it a liquid, a gas or maybe both? Is it chemically compatible with the media? Will the gasket for example be exposed to salts or chemicals? Concentrations and pH must be taken in consideration. The gasket itself cannot contaminate or be harmful for the surrounding environment. It might even be necessary to perform laboratory test to assure the compatibility if the gasket is to be used in critical applications. Plasticizers and UV-resistance are other interesting factors to consider.

**Manufacturing**

Managing manufacturability is also important to consider early in the design process. The most common manufacturing techniques for gaskets and o-rings are injection molding. Gaskets can also be produced using high speed die cutting, water jet cutting, material lamination and roll slitting. Which type of process depends on which type of application the seal will be used in and also the production quantity. Injection molding requires for example tools and therefore can it be expensive if just a small series is going to be produced. For smaller series water jet cutting is a better option but then there are also other design boundaries.

### 2.2.4 Dimensioning of the seal and its groove

Through consultation with the two companies Trelleborg Sealing Solution and Mec-Move guidelines for dimensioning seal and groove was given:

- The seals thickness should be 70% of the grooves width.
- The seal should be compressed about 25% and therefore should the depth of the groove be 75% of the seals thickness.
• The seal should stretch about 1-2%, which means an o-rings diameter should be slightly smaller than the diameter of the groove.

2.2.5 Installation

Once the right gasket has been selected for the application, proper installation is just as important for the seal performance. This is one of the most common reasons why a seal leaks. The following seal installation actions are some examples of what to consider:

• Inspect the gasket for visual defects and damage.
• Inspect the gasket surfaces for scratches, cracks, corrosion etc.
• Clean contact surfaces.
• Use new screws, bolts, nuts etc. in order to meet the quality standards needed for the application.
• Lubricate all thread contact areas and nut facings.
• Make sure the flanges are aligning.
2.3 Materials

Two of the most important aspects when designing a product are knowledge in what material and manufacturing process will suit the design of the product best. The “right” choice of materials for a product is not only materials with the right mechanical properties but also materials which reflect the products personality and design attributes. With the selection of materials the selection of manufacturing processes follows naturally and nowadays products are often designed with manufacturing in mind already from the start.

2.3.1 Material Science and Engineering

The basic concept of material science is the investigation of the relationship that exists between the structure and properties of different materials. Material engineering on the other hand is the designing and engineering of these structures of materials to produce desired properties [55]. The main focus in this study was on plastic materials, mainly because of requirements on the operating conditions of the probe and the manufacturing of prototypes.

Structure

To understand material you have to start looking at a very small perspective on the structure and the arrangement of the materials internal components. The structure of materials relates to atomic structure, nanostructure micro structure and macro structure all which contributes to different properties of the material. For example from electrical and magnetical at a small scale to mechanical properties like corrosion resistance and visible properties like surface structure and finishing at a larger scale.

Properties

Different materials possess a lot of different properties. A property could be said to be a material characteristic in terms of how it reacts and the scale of response to a specific event like subjection to force or heat [55]. It could be the scale of deformation, heat conductivity, optical aspects etc. Properties of materials can be grouped into mechanical, electrical, thermal, magnetic, optical, and also deteriorative. The performance of materials could be said to be the function of its properties [55].

For the limitation of this study and by previous experience based on the specification of requirements for the probe the most interesting material to consider are polymers (plastics) but also metals and composites was also considered. The classification of materials is shown in Figure 2.9

Polymers

Polymers include plastic and rubber materials. The difference between plastics and polymers are that plastics are made up of long chain polymers, it have polymeric structure, polymers in turn are made out of smaller fragments known as monomers that are joined together in a long chain, it have monomer structure.
Many plastics are semi-organic and extracted from oil or petroleum. This means that they are made out of organic compounds based on carbon, hydrogen etc. The main characteristics of plastics are that they often have low densities and have high stiffness and strengths per mass unit. Polymers also differ in the arrangement of molecular chains, thermoplastics are for example either amorphous or semicrystalline. Amorphous polymer has in its natural form a glass like, transparent appearance and can be thermoformed. Semicrystalline polymers have a regular structure and are because of the intermolecular forces often stronger, but may shatter like a for example a plastic cup. PET is an example of a material which occurs in both states, Figure 2.10.

There are two main types of plastics, thermoplastics and thermosettings. The main differences are that thermoplastics can be melted and do not undergo chemical change while solidify. Examples of the most common thermoplastics are, Polypropylene (PP, for example food containers ), Polyethylene (PE, for example plastic bags), Polyvinyl chloride (PVC, plastic pipes). Thermosets on the other hand have cross-linked polymer chains, which gives them better strength and chemical stability. But because of the cross-linking they can only be melted, take shape and solidified once
and hence they are really hard to recycle and a lot of used thermosets are just scrapped. However new research has showed that is possible to synthesis thermoset which are possible to recycle through different reactions [19].

Figure 2.11 displays the main principle of thermoplastics and thermosets.

Figure 2.11: Thermoplastic and termoset structure

Metals
Metals are material made out of a metallic element and often also a small amount of a nonmetallic element such carbon (C) or oxygen (O). The atoms are closely packed together and arranged in an orderly and structured manner. Metals are often stiff, strong, ductile, resistance to fracture and used in many structural applications they are also good conductor for heat and electricity and if containing iron also magnetic.

Metals are arranged in ferrous, such as steel and cast iron and nonferrous such as aluminium and cooper. The differences are that the nonferrous do not include iron, in some cases just a small amount, they are often more expensive and are often of lower weight.

Composites
A composite is as the name proposes composed of two (or more) individual materials. The design goal of a composite is to combine the best characteristics of the internal components and achieve a new material with better properties than the single materials. Most composites consists of different combinations of polymers, ceramics and metals. Example of composites are fiberglass (for example boat hulls) and carbon fiber reinforced polymers (CFRP, for example parts of sports cars). CFRP is stiff and strong and possess properties like high toughness and high temperature resistance, better than for example metals like steel and aluminium, but they are much more expensive and very hard to recycle. Often composites are shredded and used as filling material at its 'end of life'.

Thermoplastic composites are a quite new type of interesting composites where both the fibers and sheet are composed of thermoplastics such as Polypropylene (PP). This enables it to have almost as good properties as carbon fiber, not shatter at impact as carbon fiber can and at the same time it makes it recyclable [46].

The stress-strain diagram describes some properties of materials and gives an idea of how materials behave while being stretch until they break Figure 2.12.
Today there is a trend that engineers are attempting to integrate environmental considerations directly into material selection processes, in order to respond to an increased awareness to protect the environment. Environmental responsibility is constantly increasing in importance to both consumers and industry. Sustainability is a topic of today and the future. It’s become very important to regard a product’s whole life cycle from "cradle to grave". Hence bioplastics which are made from resources that are renewable are great ways of improving the impact a product has on the environment.

Although normal materials still are a more economical choice than bio materials there is a steady and growing demand after these types of materials as society’s current views on environmental responsibility increases. Especially bioplastics containing starch and, or cellulose fibers are right now going into a bright future [1]. An example of this type of plastic is Polylactic acid (PLA) which is a transparent plastic with similar characteristics as PET or PE but produced from corn or dextrose.

**Additives**

Another important aspect when dealing with especially plastic characteristics and sustainability is additives. In almost all commercial plastics the polymers are mixed with monomeric ingredients to improve their processing and end-use performance. The most common types of additives are reinforcing fibers, plasticizers, colorants, fillers, coupling agents, stabilizers, processing aids like lubricants and flame retardants. These additives are essential to get the desired plastic characteristics and properties but also pose a problem from an environmental standpoint because they are often strong chemicals. Therefore it’s of great importance to consider the desired characteristics the materials should have and evaluate which additives to use from both theses and from an environmental aspect [6].
2.3.2 Material Personality

The choice of materials is not only important from an engineering standpoint, there is much more involved and to think about before making the final selection. The success of a product is achieved through a mixture of different aspects, mainly technical and industrial design which together creates “product character” [5]. Product character is the way material and processes are used to provide functionality, usability and satisfaction, see Figure 2.13.

![Figure 2.13: Product character](image)

Product personality refers to the set of personality characteristics that people use to describe a specific product and to distinguish it from other products [21]. Materials in a product impact the personality in many ways. Starting from the three main points of interest when discussing materials; fabrication, application and appreciation [13]. With appreciation as a base this plays a major role in how well the product is received and adapted by the market. Hence the selection of the right material is not only depending on technical and functional aspects but on aspects such as look, sense, sound, smell etc. as well. These aspects together with association and perception create the products personality, Figure 2.14.

![Figure 2.14: Product personality](image)

Product personality is determined by how a product looks, the things it brings to mind and how it is perceived by the user. Hence materials selection has a huge
influence on the aesthetics, associations and perceptions. Materials have even before being shaped into products a character of their own. Form, color, texture etc. are important aspects of the materials which need to be considered when making the selection. The materials in a product must reflect the personality one wish to create for the product and this physiological aspect can be critical in the success of a product.

An example of material personality is wood which have a tactile experience, featuring a distinctive surface texture, patterns, color and feel. It’s considered warmer than many other materials and seemingly gentler, giving some products a friendlier look and feel. In contrast, metals appear cold, sterile and precise. Machined metal seems durable and robust. Designers can use metal in products to suggest a high level of engineering and indicate technological superiority. Meanwhile, plastics are much warmer than metals, more disposable and can be used to give a product a bright or even cheerful personality [5]. Because of this, different products even belonging to the same brand, can be described to have diverse personalities. Product personality can also have consequences for the users interaction with the product and help users to anticipate how to interact with a product [50].

All in all this is summed up to the "product personality design process" which includes three main phases of analysis, translation and application. Thus, properly used materials helps to create personality, affecting both form and function. Through careful selection, designers can impart aesthetics, associations and perceptions as well as enhance product performance [24].

2.3.3 Material Selection and Ranking

When designing a product it’s essential to select materials very carefully. Not only technical aspects should be considered because materials also play a major part in the user-product interaction. Materials can be said to form the products interface to the user and it influences the sense of quality, the interaction, product personality and using of the product like ergonomic features. Selecting materials for products could be said to be “the process of specifying materials while considering many aspects to create products that fulfill both high technical and high user-interaction standards” [15].

Figure 2.15 displays the product development life cycle and it is clear that material selection is important in almost all of these steps.

As there are an almost countless number of materials and methods of processing these and almost as many factors that affect the materials and the selection, cost, performance, safety, risk, aesthetics, environmental impact, recyclability etc. It is important to have a clear picture of the criteria and demand of the product and rank the importance of these before looking into what materials that could be used. A selection of the material for a product is based on the limiting properties such as; general properties, for example density and price, mechanical properties, thermal properties, electrical properties, optical properties, eco- properties and environmen-
A lot of research has been done in methods of selecting and ranking suitable material for a product based on the specification of properties.

The main basic factors to look at when selecting material are; material properties, what is the expected performance from the material, material cost and availability, processing and the effect the material and processing has on the environment. It can be concluded that the use of the appropriate material and design for a product has a profound impact on carbon emissions. [23].

There are also intangible aspects of choosing materials, like the psychological factors mentioned in the chapter above.

The design of a product can be narrowed down to three main steps, functionality, usability and satisfaction. In all of these steps materials play a major role and materials also play a role in product function. Materials are selected to satisfy the technical requirements of a design or in some cases, to enable a design with greater functionality.

To select a material four basic steps are often used, displayed in Figure 2.16.

1. Translation
   Function: What does the component do?
   Objective: What essentials conditions must be met?
   Constraints: What is to be maximized or minimized?
   Free Variables: Identify which design variables are free?
2. Screening
   Methods to evaluate large range of materials
   Material Bar Charts
   Material Property Chart (density vs. Young’s Modulus)
   Screen on Constraints
   Rank on Objectives
3. Ranking
   What if multiple materials remain after screening?
Rank on Objectives
Objectives define performance metrics
4. Seek documentation
Select, then verify with any supporting materials

This is the most basic way of selecting material, but there are a lot of new variables and methods developed. The hardest part of these four steps is how you evaluate the materials and what methods to use.

The best way is to start by identifying a set of all possible material alternatives then remove all alternatives that not fit the specification of criteria from this set. One painless alternative is to use CES EduPack which is a software-based package developed by Michael Ashby and Granta Design. In CES EduPack plots can be made for material properties which gives a good overview of the different material groups. Figure 2.17 shows a plot based on Youngs Modulus (GPa) against density (kg/m^3).

In the software many mechanical and variables such as price and manufacturability can be inserted and the program sorts out the ones which do not fit the specifications. This is an effective and easy way to select materials but as there are other demands on materials like the ones discussed above just relying on this program is often not enough.

One other important factor that play an important role when selecting material is the volume of production, for example plastics are inexpensive in large scale production but in small volume productions they can be an extremely expensive, due to high tooling costs.

In the end the final selection often comes down to a compromise between technical and economic factors hence the choice of material cannot be made without consideration of necessary manufacturing processes like forming, welding, etc. and this factors also rely on material properties.
2.4 Manufacturing Processes

A whole thesis and more could be based on manufacturing processes of materials hence in this chapter only a short review of the most relevant processes for the manufacturing of plastics, with focus on the probe will be presented. Processes for metals and composites are not presented hence many processes are similar. Also some extra techniques will be studied for gaining better knowledge and as inspiration.

Advancements in technology have had great impact on manufacturing processes and these advancements have enabled companies to produce products faster, cheaper and with better quality. The technologies have gone so far that it enables processes where raw materials turn directly into the finished products in the same machine from CAD-drawings.

Plastics
The production and manufacturing of plastic products can be roughly divided into four categories [55]:

1. Acquiring the raw material or monomer
2. Synthesizing the basic polymer
3. Compounding the polymer into a material that can be used for fabrication
4. Molding or shaping the plastic into its final form

When plastic materials are created they may not have all of the desired properties
for the desired use. Therefore different additives are often mixed into the plastic during the manufacturing process. Additives help to improve mechanical, physical, visual and chemical properties.

The method used to form the final plastic material depends on whether the material is thermoplastic or thermosetting. If thermoplastic the material melts while being heated and can be easily formed. Thermosets on the other hand can only melt and solidify once.

Polymeric materials are often fabricated under pressure at high temperature. Thermoplastics are formed above their glass transition temperatures, if amorphous, or above their melting temperatures, if semicrystalline, Figure 2.18.

![Figure 2.18: States of plastics during heating](image)

The most interesting manufacturing processes for plastics, mainly for mass production are;

Injection Molding – Used to produce three-dimensional parts of high quality and great reproducibility. It is mainly used for thermoplastics such as PP, ABS and PC but some thermosets and elastomers are also processed by this method. In injection molding plastic material is pushed through a heating chamber by an extruder screw in which the material is melted. At the end of the extruder the molten plastic is forced at high pressure into a closed mold. Once the plastic cools to a solid, the mold opens and the finished product is ejected, Figure 2.19.

![Figure 2.19: The main principle of injection molding](image)

Thermoforming - Film of thermoplastic are heated, when the film is soft it’s pulled by vacuum or pushed by pressure over a mold or pressed with a plug into a mold.
The finished parts are cut from the sheet and the scrap sheet material recycled for manufacture of new sheet. Reminds a lot of vacuum forming. Figure 2.20.

![Diagram of Thermoforming Process](image)

**Figure 2.20:** The main principle of thermoforming

Compression Molding – In this process a piece of plastic is placed into a mold and then a second mold or plug is applied to squeeze the plastic into the desired shape. It works for both thermoplastics and thermoset and is a relatively cheap method. Figure 2.21.

![Diagram of Compression Molding Process](image)

**Figure 2.21:** The main principle of compression molding

Blow Molding - A chilled mold is clamped around a tube and compressed air is then blown into the tube to form the tube to the interior of the mold and to solidify the stretched tube. An advantage of this is the ability to produce hollow shapes without having to join two or more separately injection molded parts. Another blow molding technique is to first injection mold and a preform which afterwards is heated and pressed up against a mold by air pressure. PET bottles are as example formed made like this, Figure 2.22.

![Diagram of Blow Molding Process](image)

**Figure 2.22:** The main principle of blow molding

Die Casting - One of the oldest manufacturing methods. Casting is often done by just pouring liquid plastic resins or other molten material into a mold containing the desired shape of the product, Figure 2.23.

![Diagram of Die Casting Process](image)

**Figure 2.23:** The main principle of die casting

### 2.4.1 Design for Manufacturability

The expression design for manufacturability is nothing new but might be of greater importance than ever before as products, materials and processes are becoming
more and more advanced and there is also a demand to get product out on the market as fast as possible. It started when manufacturing processes enabled mass production and it became more common that design engineers and people working in the manufacturing industry collaborated with the aim to optimize quality, speed and costs of the manufacturing of the products.

The factors which are needed to consider when designing includes, not only functionality, but also to optimize cost, delivery, quality, reliability, ease of assembly, testability, ease of service, shipping, human factors, styling, safety, customization, expandability, and various regulatory and environmental factors.

By the time a product has been designed, only 8 % of the total product budget has been spent and by that time, the design has determined 80 % of the cost of the product [2]. So the design determines the manufacturability which determines a significant part of the introduction and production cost of the product.

There are two basic guidelines for DFM;

1. Design simplification - means reducing the number of parts and features of the product whenever possible. A simpler product is easier to make, costs less, and gives us higher quality.

2. Design standardization - refers to the use of common and interchangeable parts. By using interchangeable parts a greater variety of products can be made with less inventory, significantly lower costs and with greater flexibility.

Besides using software for DFM, such as different expansions to for example Solid-works etc. it is also important to have knowledge in manufacturing methods and how they work, what materials and shapes they can handle, and how the structure of the product can be built to ensure stability etc.
The importance of integrating sustainability with manufacturing and design is also increasing in popularity, along with the need to use appropriate tools, like Design for Environment (DFE) and Life Cycle Assessment (LCA). Along with competitiveness, profitability and productivity, environmental stewardship and sustainability are likely to prove increasingly important for manufacturing in the future and is setting the main priorities for advancing manufacturing operations and technologies. Although economics may still dominate at the expense of sustainability [49].

2.4.2 Selection of Manufacturing Process

So how do you choose the right manufacturing process for your product? Having the right knowledge in different material, processes and design it should be quite straightforward.

The main factors that influence the selection of a manufacturing process are: quantity of parts required, complexity (shape size, features), material, quality of part, cost of manufacturing, availability (lead time and delivery schedule). It’s also important to consider how the product will be assembled, if there is low volume perhaps manual assembly is the best from economical standpoints and for high volume perhaps automated assembly is better. For a medium volume, based on labor costs, technical requirements etc. robotic assembly may be an option [2].

There is a close interdependence between material selection and process selection. This is based on the product specification, material class, number of parts, size, shape, minimum thickness, surface finish, tolerance. Is also important to know what the objective is with the process, to minimize cost, maximize quality, minimize time etc.

Manufacturing processes is also a very important aspect to the design and product personality [6]. For example shaping which gives the product its form, joining which gets parts together and surfacing which gives textures, finishes and coatings for protection and decoration. Surfacing can enhance the visual and tactile qualities of products and can so contribute to the ergonomics, aesthetics and perceptions of products [6].

Joining too can be used expressively. In product design joints can be used as a mode of expression. Deliberately highlighted joints are used as decorative motives, sometimes to emphasize the function of the product, sometimes as a way of creating associations. Surface finish too, in the same way, carries messages [5].

There are also important aspects in the energy the machining consumes that’s important to consider when making an LCA of a product [9]. Life Cycle Energy analysis could also be done on processes and material to get this information. The resulting output represents the sum of all energy inputs into the product in the form of a minimum to maximum value [37].

Often is also relevant to rank options based on their cost. The cost must be reached in a way which is applicable to all the options and should be appropriate to any
shape made of any material and by any process [16].

2.4.3 Rapid Prototyping

Hence the above suggested manufacturing processes mainly are to be considered for mass production there is a need to address the fact that the main purpose of the project is to first deliver a functional prototype. With the help of Rapid Prototyping (RP) techniques small scale production can be made for a relatively cheap cost. Rapid prototyping is used for quick fabrication of product models or parts direct from a CAD model. It’s not only used for the manufacturing of prototypes but with today’s technology it could also be used to manufacture real and complex parts. The main types of prototypes and their purpose are illustrated in Figure 2.24.

![Image of different types of prototypes](image)

**Figure 2.24:** *Graph of different types of prototypes*

Development and use of rapid prototyping has expanded greatly the last years. The prototyping development process is illustrated in Figure 2.25.

![Image of prototyping development process](image)

**Figure 2.25:** *The prototyping development process*

Rapid prototyping processes take many forms. Here the four main types of processes: additive, subtractive and casting and rapid injection molding will be presented. An overview is displayed in Figure 2.26.
Additive

In Additive Manufacturing (AM), also known as 3D printing, digital 3D design data is used to build up a component layer by layer using a range of different materials; plastics, metals and composite may be used. Some of the most popular processes are presented below.

**Stereolithography (SLA)** - Uses a laser to cure thin layers in a container of liquid UV-sensitive photopolymer. Model resolution can be modified by changing laser "spot size" and layer thickness. Smaller spot size and layer thickness increase resolution, and also increase build time and cost. Methods where one whole layer is projected and solidify the surface at once is also a new and fast method. SLA models can be post-processed for varying levels of finish. One disadvantage is that the material is thermoset so recycling is very hard. Figure 2.27.

![Figure 2.27: The main principle of stereolithography](image)

**Fused Deposition Modeling (FDM)** - Creates models layer by layer using a thermoplastic extrusion process. While the surface finish of FDM models is generally rougher than that of models produced using SLA, the end product is typically more robust. FDM is considered ideal for applications where functional prototypes do not require high-quality visual surfaces 2.28.
Selective Laser Sintering (SLS) - In selective laser sintering, models are created by adhering layers of laser-cured resin powder to a moveable platform using a tracing laser. The SLS process can use a variety of polymer powders that can approximate the performance of thermoplastics after sintering. SLS parts can often be machined following the process, and features such as living hinges can be incorporated into the parts. Figure 2.29.

3DP - This involves building a model in a container filled with powder of either starch or plaster based material. An inkjet printer head shuttles applies a small amount of binder to form a layer. Upon application of the binder, a new layer of powder is swept over the prior layer with the application of more binder. Figure 2.30

Applying additive processes to low volume production is often referred to as "direct digital manufacturing". This enables low volume production without tooling investment, or the constraints on design for higher volume manufacture via tooling.
However one drawback in most additive methods is that the layer upon layer creates a structure in the part which can enable liquids to ingress into it. Hence to be waterproof most of the additive produced parts needs to be post-processed and surface treated after printing.

Typical errors in AM are stair stepping error due to slicing (staircase effect), Figure 2.31, cylindricity error and flatness or straightness error. These can be reduced by part orientation and layer thickness. A deeper study was made in the use of additive manufacturing as manufacturing process and is presented later on.

Subtractive and Casting Processes
Subtractive and casting processes are similar to the standard manufacturing processes, some examples are;

*CNC Machining* - produce finished parts from a variety of materials, including plastic, aluminium, magnesium, titanium and steel, by cutting parts from blocks of the desired material. CNC machining is generally the most accurate prototyping process but has greater design constraints than additive processes. CNC also has higher cost and lead time than additive processes [18]. The simplest type is illustrated in Figure 2.32.

*Urethane Casting* – A process that is sometimes used for creating multiple models using a single master model as a base. The master model is typically built using SLA or Polyjet process and is finished and textured to simulate the final product. Silicone rubber is poured over the part, and when cured, the master model is removed, leaving a core and cavity capable of producing up to 25 copies of the original. The mold is then injected with a liquid urethane thermoset resin that can be custom colored, resulting in parts that are production like in appearance, and can be used for fit and function evaluation or testing. In some cases machined acetal or ABS molds
are used to create multiple urethane elastomer parts in a wide range of quality and hardness.

**Rapid Injection Molding Processes**

*Reaction Injecting Molding (RIM)* – Uses thermosetting polymers which requires a curing reaction to occur within the mold. Two parts of the polymer are mixed together. The mixture is then injected into the mold under high pressure using an impinging mixer. The mixture is allowed to sit in the mold long enough for it to expand and cure. Figure 2.33.

![Figure 2.33](image)

*Figure 2.33: The main principle of rapid injection molding*

To make the tools for injection molding techniques like CNC Machined Rapid Tooling is used, usually in aluminium or soft steel. But conventional mold building techniques can be applied to rapid tooling to allow more advanced geometry than allowed by CNC machined rapid tooling, while still delivering shorter lead times than production tooling. Electronic Discharge Machining (EDM) is used to better match the tooling with the design. Rapid tooling also allows the use of more advanced, durable materials such as hardened steel. Undercuts are usually formed with automated slides, and advanced gating techniques may be used. An advanced conventional rapid tooling approach provides a low cavitation rapid tool built to similar standards that may be applied to higher cavitation, higher volume production tools later in the development process.

Another important method for prototyping is vacuum forming which is a simplified version of thermoforming, where a sheet of plastic is heated to a forming temperature, stretched onto a single-surface mold, and forced against the mold by a vacuum. Figure 2.34.

![Figure 2.34](image)

*Figure 2.34: The main principle of vacuum forming*

A comparison between the different processes are presented in Table 2.1
2.4.4 Additive Manufacturing as Manufacturing Process

Many traditional and established manufacturing processes are far from efficient. Processes such as die casting and investment casting require large amounts of raw materials to be heated, melted and held in a molten state for many hours before solidification. Other processes such as CNC machining, electrical discharge machining and water jet cutting, require cutting fluids, dielectrics and chemicals that are often manufactured from mineral oils, petrochemicals or simply large quantities of water. Some AM processes on the other hand appears to be more sustainable, as they do not use water or cutting fluids, oils or dielectrics. Also, they only use energy when they are processing materials from raw state into part geometry.

All AM processes starts with 3D data often generated using CAD software or from none contact laser scanning, Computer Tomography (CT), Magnetic Resonance Imaging (MRI) or through mathematical modelling software. The 3D data is then translated into a standard data exchange format called STL, which is used by all AM machines. Once the STL file is imported into the proprietary software used to control the AM process, it is translated into the most suitable build orientation. The build orientation has a number of effects on the quality, cost and the delivery time of AM parts.

Once the optimal orientation has been established, automated software is then used to slice the STL file into discrete digital layers of data. The digital layer thickness corresponds exactly to the thickness of the build layer used in the AM processes. Slice data is then fed into the AM machine starting with the bottom layer of data first. The basic process is illustrated in Figure 2.35.

![Figure 2.35: The main steps of additive manufacturing](image_url)

The main advantage gained by using AM compared to conventional subtractive
method is its capability to produce parts which have high shape complexity, different material composition, hierarchical complexity and functionality complexity. Besides, to be able to utilize fully the abilities of AM, specific design tools are needed. For example, the part orientation must be optimally defined before fabrication by AM. Aspects to optimize in the choice of the orientation include the minimization of the surface roughness, build time, need of supports, and the increase of the part stability in building process. Despite all these considerations the part is considered as a single component. AM can also directly fabricate assemblies, such as mechanical joints. In this type of part, the most important feature is the assembly. As such, orientation consideration should mainly focus on these features and not necessarily the whole part. A proposed method is to orient a product considering all components as a functional assembly [20]. Also a two-step solution for the multi-part orientation optimization problem is possible [57]. A lot of software for 3D printing suggests the orientation automatically but this must be considered carefully before accepting.

Additive manufacturing is showing a lot of potential in many different fields for example architecture services, footwear manufacturing, aerospace engineering, automotive engineering and even medical such as organs [41]. However there are still some disadvantages to AM such as poor surface quality, physical properties, the limited accuracy of the machines, questionable repeatability, both between machine tools but also between parts built by the same machine and that the processes work with only a limited set of available materials. But hence AM is relatively new and increasing in popularity in a very rapid pace there’s a lot of research going on in optimizing this manufacturing method.

Materials
Plastic is the most common material in today’s printers. This mainly is a result of the low cost and the low melting points of the materials hence making the design of the machines easier and cheaper. The most used plastic is Acrylonitrile Butadiene Styrene (ABS) and is currently found in almost half of the machines especially FDM. ABS has good strength, flexibility and temperature resistance and it can also be welded. Polyamide (nylon) is another popular material often used in SLS-printing. It’s strong and flexible and can be polished and dyed. In SLA and Polyjet processes a photopolymer resin is used which creates the possibility to make transparent objects. Multicolor is another example of a material brand used that can print color objects directly.

In new research there is constantly a demand for manufacturing lighter functional parts or parts with improved functional properties. For example light-weight metal matrix composites have been developed to build 3D parts having high mechanical properties and low density. Polymer matrix composites have also been developed for SLS and FDM technologies [51].

Carbon fiber 3D printing are a new method which deposits layers of unidirectional composite in a defined orientation that can be specified by layer into a blend of thermoplastics matrix which hardens during printing.

Environmental Impact
Claims have been made about the environmental benefits of 3D printing. It’s believed that it can be a new process of sustainable production and consumption. 3D printing might change how items are manufactured in the future and also where we manufacture them. A common believe is that 3D printing eliminates material waste, for example FDM machines not using support material is an example of this but other 3D printers can produce as much as 43 % material waste [28].

Some positive environmental effects of a successful AM process chain could however be; minimizing raw material consumption, decreasing material waste streams, optimizing supply chain configuration and minimizing transportation, enabling remanufacture and product restoration, enabling topologically optimized product manufacture, increasing product efficiency through design optimization, enabling parts consolidation and reducing assembly operations, minimizing stockholding etc.

A green material for 3D printing is PLA bioplastic; it’s commonly used and has lower printer energy use as well as lower embodied impacts than ABS plastic [14]. Salt, sugar and starch is also example of materials which also enable low-energy printing processes, because they rely on chemical adhesion as opposed to melting plastic or curing photopolymers with UV light.

AM service providers with demand-varying customers could also increase service performance to maximize use of production equipment with resulting positive environmental effect [38]. Using AM to fabricate metal parts also opens the possibility for reducing material usage that could enable overall reduction in cost and greenhouse gas emissions related to manufacturing [22]. In SLS a multi-step optimization method enables it to be more energy effective considering factors such as surface finishing for minimizing material waste, laser processing and overall energy consumption [53].

**Post Processing and Waterproofing**
The resolution of additive manufacturing methods is still a major disadvantage when compared to other manufacturing techniques. Hence produced parts are often in need of post processing [31].

There are various methods to improve the surface finish of parts manufactured by AM depending on the requirements. Besides the conventional methods there’s also research in chemical treatment and Laser micro machining. Some methods are displayed in Table 2.2.

<table>
<thead>
<tr>
<th>Conventional</th>
<th>Non-conventional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibratory bowl abrasion / abrasive blast</td>
<td>Ultrasonic abrasion</td>
</tr>
<tr>
<td>Vibratory grinding</td>
<td>Chemical post-processing treatment</td>
</tr>
<tr>
<td>Hot cutter machining (HCM)</td>
<td>Electrochemical polishing</td>
</tr>
<tr>
<td>Optical polish</td>
<td>Electroplating</td>
</tr>
<tr>
<td>CNC</td>
<td>Laser micro machining</td>
</tr>
<tr>
<td>Micro machining process (MMP)</td>
<td></td>
</tr>
<tr>
<td>Epoxy resin filling / painting</td>
<td></td>
</tr>
</tbody>
</table>

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41
Surface roughness could also be controlled by process parameter and the arrangement of components in the buildup chamber with heat accumulation [27].

As a result of the layer-by-layer deposition characteristics of additive manufacturing processes, fabricated parts exhibit limiting qualities such as porosity. Hence often a sealant is needed in and on the material to make it waterproof. There are many methods to seal an FDM part and many characteristics to consider when choosing the best approach. Cost, time, geometry maximum part size, viscosity, maximum pressure, chemical resistance and temperature sensitivity etc. [30]. For example the material can be sealed by exposing the surface to a vaporized smoothing agent. Epoxy coating is a method where a two-part epoxy is brushed onto the part in small sections. This method does not require an investment in equipment, and the end result is ideal for harsh operating conditions. Epoxy infiltration is a method where parts are immersed in epoxy resin and a vacuum is drawn to infiltrate the epoxy into the part. In addition to a vacuum chamber, an oven is needed to pre-heat and cure the epoxy. Painting and filling is another alternative but with lower protection.

Business Potential and the Future

Rapid prototyping and additive manufacturing can enable the displacement or elimination of many traditional manufacturing processes both in product and software development. In product development, rapid prototyping can eliminate unnecessary features and failures at early stages of the process. This could help to immensely reduce development and testing times. Today there is also a growing need for faster time-to-market and this is also a major driver for market growth in the area of RP according to a 2015 report from TechNavio [48]. Rapid prototyping equipment can help to improve the efficiency and effectiveness of the product development in the manufacturing process and considering the current competitive business environment of today, more and more companies are in the need of a shorter product development processes. Rapid prototyping equipment can help companies to reduce their lead time by reducing product design time, shortening the production planning process and reducing times spent on design changes and hence also reducing costs [11]. Hence the integration of additive manufacturing and rapid prototyping in the product development process save both time and costs. Steps of the normal product development process can be moved too an earlier stage and this saves time. The rapid prototyping model compared to the traditional product development process is displayed in Figure 2.36.

Some other steps of the product development process which could be removed with additive and rapid manufacturing is for example detailed drawings which could be removed as the processes will utilizes CAD data directly to produce the parts. As the processes and materials improve, it’s now also possible to use prototype machines for final production. Also time and costs for tool manufacturing for injection molding can be greatly reduced [35].

However a drawback of today’s AM technology it that it still lacks the ability for high speed production and is therefore more expensive compared to processes such as injection molding, though for small batches it’s already a much more economical
choice. The break-even point hence depends upon the quantity being printed, see Figure 2.37.

Additive manufacturing may also impact a significant number of the categories for lean manufacturing. For example, additive manufacturing may reduce the need for large inventory, which is a significant cost in manufacturing. Reducing inventory frees up capital and reduces expenses. In-house prototyping helps save time when a design requires multiple prototype generations. Many first prototypes uncover shortcomings in a design, triggering a second-generation prototype. Addressing different design problems can lead to two, three, or even more design iterations. Saving time on each prototype generation can amount to a significant reduction in the overall design process [33]. All in all it can be said that the rapid prototyping process can be used to replace the ordinary product development process and instead create a more iterative product development process.

The conclusion of this is called 'Rapid Product Development' and it’s a growing trend for innovative design. Rapid prototyping, reverse and concurrent engineering, virtual prototyping, simulation and rapid tooling are improving fast, enabling inexpensive ways to create products directly from the computer and might already be
changing the product development processes as it is known today.
Product Development Process

The development of the enclosure was carried out parallel with the development of the electronic architecture and the software which was going to be integrated into the probe. The team developing the electronics, called MAKEMAKE, was working according to scrum [56], which made the development of the enclosure having to adapt to an agile process where the objective could somewhat change during the project time. However, the thesis project followed a planned product development process, visualized as in Figure 3.1. It contains six major stages: Prestudy, Insights, Concept Generation, Concept Evaluation, Concept Development with an iterative Prototype Development Process and finally Evaluation. The work and the methods used in each step are described separately in following sections. The methodology is inspired and based upon The Mechanical Design Process by Ullman [52].

![Figure 3.1: The Product Development Process of the Master Thesis](image)

3.1 Prestudy

Based on the problem statement provided by Alten, a prestudy was made within four areas; seal design, ecodesign, materials, manufacturing processes and rapid prototyping, which were regarded as useful and valuable inputs into the project.
A prestudy of seal design was made in order to gain understanding about challenges and to find out guidelines regarding sealing design. Ecodesign, called Design for Environment, was considered a relevant aspect as there is a growing collective awareness of environmental issues, both among consumers and companies who put more attention in developing products which contribute to a sustainable future and society. It is important to involve an ecodesign mindset early in the design process when there is still a lot of design freedom. Since one of the main goals was to develop a functional prototype, the areas of materials science, manufacturing processes and rapid prototyping were explored in order to find suitable materials and processes which could be used. The theory from the prestudy is presented in Chapter 2.

### 3.2 Insights

During this phase the result from the prestudy was discussed among the designers and was compiled in a number of guidelines and wishes for the development of the product. Also the use of the probe was more clearly determined and defined in this stage through discussions with the supervisor and the MAKEMAKE team. This helped to set up a more detailed and updated design specification with requirements for the design.

**Ecodesign**

From the guidelines and principles gathered during the ecodesign prestudy, some were considered more relevant and possible to apply in the development of the enclosure. These are discussed below and were translated into requirements for the design specification.

Since this probe is a first version prototype the enclosure should be designed to facilitate testing, repairing, upgrading and changing of components. In other words, give the enclosure a simple and flexible design so that changes can easily be made. A hamburger structure was considered to be a good option as it may simplify manufacturing and assembly as well as giving an easy access to the different components. Other structure designs can however be interesting to consider during the idea generation.

The enclosure should be easy to disassemble so that electrical components can easily be removed and sorted in the end of life phase of the product. The design should consist of as few parts as possible and with clear sorting borders with high separability to facilitate the recycling process. The amount of joining elements should also be as few as possible and without adhesives and laminating dissimilar materials. The weight should be optimized, both through design and through the choice of material.

The amount of different materials should be limited and rare, toxic and valuable materials should be avoided. The materials should however be good enough to protect the product from corrosion, wear, dirt etc. in order to optimize the lifetime of the product. The materials used in the design should be labeled to facilitate the recycling process.
There were also some guidelines which were considered not to be applicable in the development of the enclosure but nevertheless should be considered in the development of the electronics and the overall product. For example, to minimize the energy consumption in the usage phase through optimizing electronic components and routing electrical wiring for easy removal.

Guidelines like optimizing manufacturing processes and transportation to minimize resources and energy consumption, was considered not applicable in this project due to budget limitations and due to the limitation of process availability.

**Seal Design**

With the ecodesign mindset discussed above, where sealing solutions such as hermetic enclosure, welding and adhesives are excluded in order to make it possible to open the enclosure when upgrading, repairing and changing components. O-rings or gaskets are commonly used in this kind of seal applications and was considered an interesting solution. It is relatively cheap but yet an effective solution and therefore also a practical solution to deal with when developing different prototypes. Since the parts of the enclosure will not move relative to each other, a static seal is needed. It can be either radial or axial depending on how the parts will be assembled to each other.

**Material and Manufacturing**

The most valuable insights from the material and manufacturing study was a greater knowledge about how materials and manufacturing processes works and how they can be applied in different scenarios. Also the combination of material selection and manufacturing process and the integration of environmental aspects in the selection of materials and process. The study suggests that additive manufacturing could be a potential manufacturing process for real products and applications but it is still a quite young method and there are some uncertainties in how it will perform. A lot of knowledge in different prototyping processes and methods to use when developing and evaluating the prototype was gathered and a decision to try and use additive manufacturing to produce the prototype.

The most suitable materials for this project are plastics mostly because of the freedom of design, the possible shaping processes and possibilities to make prototypes in small quantities. But also metals could be considered suitable hence this left out composites from the equation, also because it is time consuming and rather expensive to produce parts in these materials. Material advantages and disadvantages were compiled into Table 3.1.

Balancing the advantages and disadvantages of plastics and metals against each other led to the selection of plastics as the main material to be used both for the prototype and for mass production. One of the main reasons was also that an enclosure made in metal could block the wireless transmitting or require more complex electronics. Other factors for limiting the material choice to plastic were costs, design and manufacturing freedom, weight and corrosion resistance. Also deeper knowledge and inspiration in how to select the right type of material for a product was made; from mechanical properties and environmental factors to the impact of the design. Design rules for plastics were also considered. For mass production it was important
**Table 3.1: Plastic and metal comparison**

<table>
<thead>
<tr>
<th>Plastic</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advantages</td>
<td>Disadvantages</td>
</tr>
<tr>
<td>Lightweight</td>
<td>Non-renewable resources</td>
</tr>
<tr>
<td>Economical</td>
<td>Deformation under load</td>
</tr>
<tr>
<td>Mouldability and design freedom</td>
<td>Low heat resistant and poor ductility</td>
</tr>
<tr>
<td>Colours and finish</td>
<td>Combustibility</td>
</tr>
<tr>
<td>Good strength and toughness</td>
<td>Loses mechanical properties</td>
</tr>
<tr>
<td>Corrosion resistant</td>
<td>Flexible</td>
</tr>
<tr>
<td>Low thermal expansion</td>
<td>Not biodegradable</td>
</tr>
<tr>
<td>Good water resistance</td>
<td>Raw materials costs and effects</td>
</tr>
<tr>
<td>Recyclable</td>
<td>Polymeric particles in water</td>
</tr>
<tr>
<td>Durability</td>
<td>Additives</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Metal</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Advantages</td>
<td>Disadvantages</td>
</tr>
<tr>
<td>Recyclable</td>
<td>Heavyweight</td>
</tr>
<tr>
<td>Relatively cheap</td>
<td>Corrosion</td>
</tr>
<tr>
<td>Strength and stiffness</td>
<td>High density</td>
</tr>
<tr>
<td>Easy machining and design freedom</td>
<td>Prototyping</td>
</tr>
<tr>
<td>Reflect quality</td>
<td>Hard to form</td>
</tr>
<tr>
<td>Temperature resistance</td>
<td>Colour options</td>
</tr>
<tr>
<td>Mechanical properties</td>
<td>Expensive to extract</td>
</tr>
<tr>
<td>Durability</td>
<td>Expensive to repair</td>
</tr>
<tr>
<td>Non-toxic</td>
<td>Chroming</td>
</tr>
<tr>
<td>Good sealing tolerances</td>
<td>Oxidation</td>
</tr>
</tbody>
</table>

to gain knowledge in what could be suitable processes for different materials and how the design could be optimized for the manufacturing process.

### 3.2.1 Product Requirements

A method called storyboarding was used and “Use Case” and “Use Scenarios” were determined in order to fully understand the life of the product being developed. These were used as an additional aid to support the creation of requirements for the design.
Storyboarding
A storyboard is a user or product story diagram where sketches are made to illustrate how a user or product would move through time, how it will interact with different events etc. Not only does the sketch reduce memory loading, it also stimulates design thinking through various stimuli such as words and images. [43]. An overview of the life of the probe was compiled, which can be found in Appendix C. It provided an understanding about the life of the product and its’ use.

Use case and scenarios
Use case and scenarios helps to put focus on specific product features. The use case and scenarios might change with time during the product development as the product matures and an understanding of how the product will work and who the actual user will be. Therefore it could be said to be a “living” document which is necessary to come back to and update during the process. Validation and testing of the product is done trying to replicate the scenarios and real life usage as well as possible. The use case and scenarios were determined through discussion with the supervisor and was defined as:

"An enclosure for an electronic unit is used in an outdoor environment where it is attachable to an object in such a way that it does not affect the objects surface or fall of while the object is in movement. The enclosure must also protect the electronics against water, dust and similar natural environmental factors."

A scenario is a specific event, within the use case, which is likely to happen during the use of the product. The scenarios were used for determining appropriate testing methods for validating the prototypes. Four scenarios were determined and can be viewed in Figure 3.2.

SPECIFICATION OF REQUIREMENTS
The use case and the scenarios were translated into requirements. A compilation of the requirements can be found in Appendix B. The different requirements have been graded according to its importance on a scale from one to three, where number one requirements are the most important. In this way, in case some contradicts each other, it is defined which requirements are more flexible and can be compromised. The main goal with this project was to develop and prototype a waterproof enclosure for outdoor use. The requirements regarding its sealing capability against water and dirt and material properties such as corrosion and UV resistance are therefore of most importance.

IP67 which was the target requirement for sealing performance is an international protection marking standard and refers to a system for classifying the degrees of ingress protection provided by the enclosures of electrical equipment. The numbers in the label are linked to which difficulty of test the product should pass. The first number indicates how well an enclosure is protected against ingress of solid foreign objects and access to hazardous parts, such as electrical components. The second number indicates the level of protection against harmful ingestion of liquids. According to SP Sveriges Tekniska Forskningsinstitut [17], IP67 means that the enclosure is totally protected against dust and protected against the effect of immersion at a depth of between 0,15 - 1 m.
3.3 Concept Generation

In order to generate different concepts, several supporting methods were used, individually and in combination, to help the designers to think outside the box and enhance creativity. The methods which were used during the concept generation phase were Mindmapping, Brainstorming, Brainwriting, Build To Think and a Morphological matrix. These are presented individually below.

**Mind Mapping**
Mind mapping is a way to remember, organize, process, and combine information in a creative and effective way. Each thought is recorded in one or two representational key words. Relationships amongst key words are shown by diagramming. Symbols are used to add visual variety and increase memorability. Different colors are used to represent different groups of ideas. It starts by writing a key word that represents
the problem in the center of the page and circle it. Associations and ideas that comes to mind by this word are written around it and connected with lines.

This technique was used to create an overview of which problems is needed to be solved, how they relate to each other and other factors to consider. This was a method to visualize and compile all uncertainties regarding the development of the product. The mind-map can be viewed in Appendix D.

**Brainstorming**

The purpose with the brainstorming method is to generate as many ideas as possible. It does not matter whether the ideas is big or small, possible to implement or useful. There is no evaluation or judgement of the ideas - all ideas are welcome, even silly, impossible or wild ones, because these can generate spinoffs and inspire to other useful ideas [52]. The method was developed for groups but it is also useful for an individual engineer. The benefits with collaboration are that every member contributes with ideas from their point of view which may help to rigger new ideas. If the brainstorm is performed individually, the person can easily fixate him or her selves on one type of solution. However, too many people can generate frustration if each member is not given time to suggest their ideas. It could be a good idea to give all the members a few minutes to generate ideas individually in order to give everyone an equal chance to contribute and to retrieve all the member’s opinions. A brainstorm session should focus on one specific function and therefore should the problem be clearly determined. All ideas should be recorded and it could therefore be useful to appoint someone as secretary or facilitator. However this person is also free to contribute to the idea generation. Usually, many ideas are generated in a brainstorm session and it can be hard to know what to do with all the material. One way to manage all the single ideas is to cluster and relate them to each other. Building patterns and visualizing relations is important for creativity. It enables the members to get an overview instead of focusing on parts.

To facilitate the process, the problem statement was divided into problem themes where at least one brainstorm session was held for each theme. The problem themes were defined as; sealing solutions, attachment solutions, power supply solutions, interface solutions and aesthetic design proposals. Mood boards were used to support and inspire in the sessions.

The brainstorm method returned several times again during the concept development phase to solve structural and design problems that arose. The sessions were mainly conducted by the two designers but the results were presented and discussed with the stakeholders at Alten where they could contribute with ideas and feedback. This was an iterative process until enough material was generated.

**Brainwriting, C-Sketch/6-3-5**

For 6-3-5 and C-sketch six participants are seated around a table, and each silently describes three ideas on a large sheet of paper. The ideas are then passed to another participant who develops the ideas. This exchange goes on for five rounds. For the original 6-3-5 method, ideas are described using only words. In contrast, the C-sketch method permits only sketches. One advantage of C-sketch over 6-3-5 is that sketches are typically ambiguous and one person may misinterpret aspects of
someone else’s sketch, which may lead to new ideas [26]. Often these methods are combined and lead to cases in which group members build on previously generated ideas then brainstorming. The choice of group idea generation usually affects the total quantity of ideas generated as well as the number of high quality concepts generated, but no significant effects for either novelty or variety. But the study also showed that both individual and group interactions are important in the idea generation process. As group members add ideas on others and the overall product solution becomes more complete and improves in quality. Group member’s ideas also spark other members to a greater level of productivity [25]

This method was conducted together with another master student with similar educational background, also conducting a master thesis at Atlen. In this way, getting new ideas from an external person who is not been too close to the project.

**Build to think**

This was a method for physically visualize ideas where simple models were build out of office material such as paper, tape etc. These low fidelity prototypes are made to hold and see the concepts and in this way more easily interact with the ideas than with sketches. Prototypes are a good way to encourage reflection about design aspects. Low fidelity prototypes, such as paper models, are often cheap, fast and easy and is therefore well suited early in the design process.

The design concepts were 3D-modelled and rendered to better visualize shapes, surfaces and other features. It also made it easier to make a fair evaluation as all concepts were presented in a similar way. The design proposals can be viewed in Appendix E. The designs were presented to the supervisor at Atlen and the different forms were discussed. A more square or rectangular shape was considered more appropriate than a round shape, according to how the shape would blend in with the target object when attached.

**Morphological Matrix**

This technique provides a systematic and structured way of generating ideas for each function and features which need to be considered [52] to generate as many solutions as possible for each step. A systematic way of visualize the method is to put the functions in columns and the solutions in rows. The last step is to combine these individual solutions into complete concept designs where all the function requirements have been covered. The method is about choosing one solution from each function and combine them into a single concept.

The morphological matrix, which can be viewed in Appendix F, was used to compile all the material generated during the idea generation methods described above. The different problem themes were put as columns and the solutions in the rows. This provided a good overview to visualize if a problem required more attention. Finally enough material for each theme was generated.

To sum up the idea generation phase; eight seal design concepts were developed, see Figure 3.3, seven attachment solutions, five solutions for how the probe would be supplied with power, six interface ideas and 15 ideas for the exterior aesthetic design, see Appendix E.
3.4 Concept Evaluation

The evaluation was divided into two stages. The first stage was to evaluate the concepts and the solutions with a decision matrix and then merge the solutions with the most potential into overall concepts. These concepts were in the second stage prototyped to get a more tangible perception about the concepts, to feel and hold them. These overall concepts were discussed together with the stakeholder at Alten; the supervisor and the team developing the electronics.

3.4.1 First Stage of Evaluation

All the solutions and concepts generated during the previous phase were evaluated using a decision making matrix to choose which solutions to continue with and use in the further development. This is a simple and effective method for comparing different alternatives. In essence, the concepts are scored in relative to each other in its ability to meet the criteria. This method of comparing ideas and concepts gives an insight of which is the best alternative in an objective way, which can be useful when some concepts or ideas might be favored based on personal opinions.

The first step in the decision matrix method is to state the issue. The issue is not always obvious and therefore important to clarify so that goal is fully understood by the participants. In this project, three matrices were made; one for which power supply solution to use, one for choosing the most suitable design for sealing and one for determine the most appropriate attachment solution.

The next step is to select which alternatives that is to be compared. All the concepts generated were included in the evaluation and presented in a similar level of abstraction. This means that the knowledge about functionality, manufacture ability, structure, technologies needed etc. are fairly the same for all the concepts that are being evaluated, which is important in order to make a just assessment.

The third step is to choose the criteria and determine which basis the concepts are being compared and evaluated. The concepts were in this case compared based on how well they meet the requirements that were set in the beginning of the project. In the matrix for evaluating the designs, the requirements were also categorized as
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general, design for environment, manufacturing and aesthetic design in order to get a better view of how they perform in the different areas. All the criteria were also discussed and clarified so that all the participants had an equal definition about their meaning. For example 'a Hi-Tech design' can have different meanings to different people. Once the criteria have been determined their relative importance were rated, to indicate which are more important and which are less important. They were given a number from 1-5, where 1 is less important and 5 is very important. The concepts were then graded on how well they meet the each criterion. The grading is done one criteria at a time on a scale from 1 – 5, where 1 is a when the concept do not meet the criteria and 5 when it meets the criteria very well.

The result of the evaluation is the value factor. The value factor is the sum of the products of the respective alternative grading and criterion weighting factor. The concept with the highest Value factor and closest to the Ideals Value factor, which is the maximum, should be the best alternative. The value factor was calculated for each requirement category as well as a total.

However, the result from the decision making matrix is just an indication of which concept is the best. Other factors are also of big importance, such as the gut feeling. For example 'Dark horse ideas', i.e ideas which may seem risky and unrewarding but in the end generate a lot of profit, may be rejected and given a low Value factor. One should also consider that if the criteria have not been fully determined or clearly defined, the result can have a misleading outcome. Therefore was the result discussed with the stakeholders at Alten and a decision was taken together.

The result from the matrix showed that 'The Lid' concept and 'The Two Halves' concept were the most promising solutions for the design, the mounting tape was the best attachment solution and supply the probe with the 'USB' concept was the most convenient data connection.

3.4.2 Second Stage of Evaluation

The different concepts solutions and the result of the evaluation were presented and discussed with the supervisor and the MAKEMAKE team. Two concepts emerged which were chosen for further development and evaluation. These were first developed into more clearly defined and detailed concepts, see Figure 3.4. They are similar in their exterior design but have a different inside structure. The next step was to produce a physical model, using rapid prototyping, in order to test their functions and receive a tangible idea of how they look and feel. Due to limited access to the rapid prototyping machines, different methods were used. Concept A was produced using FDM and Concept B using SLA. The rapid prototyping process and the methods used are described in more detail in Section 3.6. The fact that the two concepts where made with different prototyping methods did however not affect the evaluation between the two.
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Figure 3.4: The two concepts that were chosen for further development

Concept A
Concept A is a concept where the electronics is mounted on to a board which slides into an interior cover and fasten with screws. In the end of the board is a lid with a USB connection. An exterior cover is then slided onto the interior part protecting the USB from water etc. Two o-rings are mounted on the outside of the interior cover, giving an effective radial seal. The design of Concept A is visualized in Figure 3.5.

Figure 3.5: Visualization of Concept A

The concept was 3D printed using a FDM method in ABSplus. The printed model together with the assembled o-rings can be seen in Figure 3.6.

The design was robust and expressed a feeling of speed and sportiness with its arced walls. However, the design made it too complex for assembling circuit boards, diodes etc. which would require to be custom made to fit in the cavity. Another problem that was discovered was that the air had no place to go when the exterior cover was assembled, especially when the o-rings were present. A hole was made in one of the short sides for giving the air a way out, which made it possible to assemble the
exterior cover. The hole needs however development in order to make the enclosure waterproof. The o-rings had a good fit and would probably provide an effective seal. However, no test was made in this matter due to the non-waterproof material.

**Concept B**

Concept B is an outcome of the 'Two Halves' design and is basically a box with a cover. The electronics is mounted inside the base and is sealed with the cover and a radial seal mounted on the base wall. The USB is positioned in a countersink on the underside of the base and with a plug to protect it. The concept is visualized in Figure 3.7.

This concept was 3D printed using SLA. The 3D printed model together with an assembled o-ring is visualized in Figure 3.8. Also this design felt robust but from an aesthetic point of view it was regarded as less exciting. The mounting of circuit board and other electronic components were considered more simple for this Concept. The problem with the air getting stuck was also present in this concept but in less severity.

The conclusion of the last stage of the evaluation was that Concept B had most potential of being successful in this project. Concept A had a more interesting design
but was considered too complex to produce a fully functional prototype within the
time limit. It requires a more custom fit architecture of the electronics with smaller
components and would be too time consuming and expensive for the prototype.
However, it is an interesting concept if the product is being further developed for
mass production.

3.5 Concept Development

This stage addresses the development of the concept, which was chosen in the eval-
uation phase, into a final product. There were still several challenges and uncer-
tainties in the design that needed to be solved and determined. These are presented
below.

- Provide a way for air to flow
- Seal Design
- How to attach the product to the target surface
- Selection of manufacturing method and material
- Prevent formation of condensation inside the enclosure
- Interaction design
- Aesthetic design

3.5.1 Air passage

One of the first problems that was discovered with the prototypes of the two concepts
was that it was almost impossible to assemble the exterior cover as the air got
trapped inside and did not have a way to escape. A safe and waterproof way to vent
the air was therefore needed. This would also make the enclosure less vulnerable to
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pressure changes, which may arise for example if the probe is subject to temperature differences, see Appendix H.

Another problem is the condensation which can occur if warm humid air comes into contact with a surface colder than the dew point. If the probe would quickly be cooled, for example because it is submerged in water, the warm air inside the probe may be cooled to a point where it can no longer hold water vapor. When the air reaches its dew point condensation occurs.

These two problems were solved using a Gore-Tex membrane which is a liquid repelling yet breathable textile membrane. The pores between the fibres are 20 000 times smaller than a water droplet, which prevent water to penetrate, but big enough to allow water vapor to pass through. In this way, the membrane is waterproof but permeable to moisture and air. It also helps to prevent condensation within the enclosure as humid air can escape.

The ventilation hole was positioned in the bottom of the base part with a countersink where the membrane was placed. The membrane was fastened with a threaded plug, similar to an inverted screw cap for a bottle. The solution was tested, see Section 3.7, and worked sufficient. However, an o-ring was added to the final solution, between the Gore-Tex membrane and the plug, for an even more reliable sealing. Another option would be to manufacture the threaded plug out of a rubber-like material, making it seal by itself. An exploded view of the air passage solution can be seen in Figure 3.9.

![Figure 3.9: Assembly of the Gore-Tex membrane](image)

### 3.5.2 Seal Design

Different sealing solutions were discussed together with two different companies; Trelleborg Sealing Solutions and MecMove. An o-ring seal was considered to be a suitable solution due to being a common, simple and effective method. Another option could be using a gasket in the inside top or in the bottom of the cover. This would however require it to be custom made according to the contour of the sealing surface, which is not preferred when a small amount of prototypes are being
developed since expensive tools is needed for moulding the gasket. A cheaper option could be by water cut a sheet of rubber in the desired shape but then it would be hard to get sufficient tolerances since the gasket would be relatively small.

In the end, an o-ring was chosen as the final seal solution. O-rings can be custom made but there is a big variety of different standard sizes with preferable availability and price. Samples of different o-rings could therefore be delivered with short notice which was an advantage during the prototyping phase and in order to be flexible with the design. In the final design the o-ring is placed in the wall of the base part, see Figure 3.10.

![Figure 3.10: The path for ingressio](image)

The design of the enclosure also creates a slightly difficult path for the water as it has to come in through the gap horizontally and then move vertically up, and passing the seal, to the top and then move horizontally again before it reaches the electronics, see Figure 3.11. The main idea was to avoid having the o-ring directly exposed to the water and sun.

![Figure 3.11: The path for ingressio](image)

The radial seal was considered a better solution then having an axial seal solution, because an axial seal would require some kind of joining elements for pressing the two parts together and compress the seal. By using a radial seal in the wall, the stiffness of the cover creates a pressure around the base part when assembled, which compresses the o-ring. The occurring friction also keeps the cover in place without the need of joining elements. As the cover is assembled, air is pressed out. Then as the Gore-Tex membrane is applied it takes more time for the air to pass through the hole and in this way preventing the cover to detach as vacuum would be created.
Dimensioning of O-ring and Groove

The cross section diameter, \( D_2 \), was chosen to 2.0 mm and according to the guidelines, the o-ring should be compressed 25% which gives a groove depth of \( d = 1.5 \) mm. The contour line of the base part and the groove depth gives an inner circumference of the groove, \( O = 191.65 \) mm, which gives a diameter of \( D_i = 61 \) mm. The o-ring should be stretched 1-2% and therefore an o-ring with a slightly smaller diameter is needed. For perfect fit, the o-ring can be customized but this would require a tool which is based according to the desired shape and therefore an expensive solution for small batch products. Since the purpose of this thesis is to deliver only a few prototypes for testing the products function, standard o-rings are preferred to keep the cost as low as possible. A standard o-ring with the dimensions \( D_2 = 2 \) mm and \( D_i = 60 \) mm was found and used for testing. In addition, the o-ring should be 70% of the groove width and therefore the groove width was determined to \( w = 2.4 \) mm. The dimensions for the o-ring can be viewed in Figure 3.12.

![Figure 3.12: O-ring dimensions](image)

A cross section of the enclosure design with the o-ring and the groove dimensions can be view in Figure 3.13.

An o-ring can be produced in many different hardnesses, the most commonly used are 70 and 90 Shore. Both hardnesses were ordered and examined. Both felt too hard for the enclosure design but since the o-rings had to be custom made if a softer hardness was desired, the 70 Shore was used for the prototypes.

The micro USB connection, used for recharging the battery and for non-wireless transmission, also required a sealing solution. A waterproof USB could be used but they are relatively expensive and the same solution as for the air passage was chosen.

### 3.5.3 Attachment Solution

Different attachment solutions have been generated in parallel with the enclosure solutions. The concept which scored the highest in the decision making matrix was the double sided mounting tape. This tape is widely used as mounting solution for example in the action camera industry, such as GoPro cameras, and has a strong attaching surface which can endure high impact, weather and other external factors. It also doesn’t cause any damage to the surface where it is applied. The tape will
Figure 3.13: Cross section illustration of the enclosure together with the o-ring and its’ corresponding groove dimension

and will help dampen the vibrations from the substrate. Other positive factors are that it is relatively cheap, basically does not require any space at all and it is simple.

However a solution for a snap-fit attachment where also considered to make it easier and faster to remove and attach the probe. If the probe for example would frequently need to be moved between several target objects, a snap-fit could be convenient. It was therefore decided to test a solution where a snap-fit attachment is mounted onto the target object by double sided mounting tape. In this way, several snap-fit attachment could be taped to the different target objects and the probe could easily be moved between them.

3D printing was considered to be the best suitable manufacturing process for a prototype among those available. also due to the complex design and the possibility to print several designs for testing. However since the mechanical properties can vary from print to print as the parts are built up in layers it is hard to predict how the materials will behave. For the prototype the attachment design was made as several concepts and with different dimensions for empirical testing. This showed that the material behaved differently depending on the used process and some measurements needed to be changed. The attachment concept can be viewed in Figure 3.14.
Figure 3.14: Attachment process

The different attachment designs can be viewed in Figure 3.15.

Figure 3.15: Different attachment concepts

3.5.4 Material

Due to the specifications of requirements and availability a plastic material was considered. Metals such as aluminium or magnesium could be alternative choices but due to high demand on corrosion resistance, weight and also price and available manufacturing process to fit the design these materials was not considered suitable. Also one of the most important requirements, that the material needed to let wireless signals through without interference, made metals not a suitable choice. Composites was also not considered, for example carbon fiber, which might be a suitable material for a final product in the future but lacking in availability of high tolerance manufacturing processes and knowledge in these processes. Also price is a limiting factor for these materials.

CES-Edupack was used together with the specification of requirements to screen out materials and make a list of suitable plastic materials, Table 3.2. Mainly the criteria of availability for both material and process and the criteria of tolerating low temperature was a great limiting factor for the plastics leaving out only a couple of suitable candidates. To get the product to reflect the desired purpose, material personality was also considered which also put the demands on the material to reflect quality.
Table 3.2: Material properties

<table>
<thead>
<tr>
<th></th>
<th>Operating Temp. (°C)</th>
<th>Dens. (g/cm³)</th>
<th>Price Fracture toughness</th>
<th>Tensile. Waterabs. UV Hardness Temp. resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Price (SEK/kg) (MPa·m²)</td>
<td>Tensile (MPa) (%) /24h (HV)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC</td>
<td>-73.2-101</td>
<td>1.14-1.21</td>
<td>20.5-32.9</td>
<td>2.1-4.6 66-72.4 0.1 Good 17.7-21.7 Good insulator</td>
</tr>
<tr>
<td>ABS</td>
<td>-73.2-61.9</td>
<td>1.01-1.21</td>
<td>15.9-17.5</td>
<td>1.19-2.29 27.6-55.2 0.3 Poor 5.6-15.3 Good insulator</td>
</tr>
<tr>
<td>PA</td>
<td>-73.2-110</td>
<td>1.12-1.14</td>
<td>26.5-29.2</td>
<td>2.22-5.62 90-165 0.1 Good 25.3-28.4 Good insulator</td>
</tr>
<tr>
<td>PLA</td>
<td>-10(-20)-45</td>
<td>0.91-1.3</td>
<td>16-21</td>
<td>5 45-79 0.1 Good 3.5 Good insulator</td>
</tr>
<tr>
<td>TPE-E</td>
<td>-40-120</td>
<td>0.91-1.3</td>
<td>16-21</td>
<td>5 30 0.7 Good XX Good insulator</td>
</tr>
<tr>
<td>PU</td>
<td>-73.2-649</td>
<td>1.12-1.24</td>
<td>27.29-7.2</td>
<td>1.84-4.97 31-62 XX Good 16.1-22.7 Good insulator</td>
</tr>
<tr>
<td>PP</td>
<td>-40-120</td>
<td>0.89-0.91</td>
<td>13.7-15.6</td>
<td>3.4-5 27.6-41.4 0.008 Poor 6.2-11.2 Good insulator</td>
</tr>
<tr>
<td>Acetal</td>
<td>-73.2-76.9</td>
<td>1.39-1.43</td>
<td>19.2-21.2</td>
<td>1.71-4.2 60-89.6 0.2 Poor 14.6-24.8 Good insulator</td>
</tr>
<tr>
<td>PET</td>
<td>-60(-40)-114</td>
<td>1.38</td>
<td>13.8-15.2</td>
<td>4.5-5.5 55-75 0.16 Good 17-18.7 Good insulator</td>
</tr>
</tbody>
</table>

Availability was a great limiting factor as well, depending on what available prototyping equipment that could be found in the nearby area. The prototyping and selection of process are described in the next chapter. In the end a selection of different materials was made. One for potential mass production, desired quality and requirements and two others for the prototype mainly based on availability, costs and requirements.

The material which met the requirements both from a material properties point of view and also a material personality and eco perspective was polycarbonate (PC). This material is used in several enclosures today which are put under similar conditions. It has great impact and scratch resistance and can be both transparent and coloured. It is also mouldable and suitable for many different manufacturing processes. From an ecodesign perspective it is recyclable and almost all parts of the enclosure could be made out of the same material. The hardness of the material also gives a higher tactile feeling of quality and visually it can be seen that it is a material of high quality.

3.5.5 Interaction Design

The probe needs a basic interface to display some relevant information like mode, battery status (full, low and critical), logging status, warnings, charging status and external connections. All this information could be displayed using different colors and combinations with two LED RGB diodes. Several suggestions of how the diodes would be attached were discussed, for example; drilling holes in the cover and place transparent plastic rods with the diodes mounted on the circuit board in an exact position underneath; assemble the diodes in holders which are glued in drilled holes in the cover; assemble the diodes in a countersinking in the cover part resulting in the diodes shines through the thin wall. The second alternative was chosen as it was considered most practical for the prototype as it was cheap, better access to required parts and had a more flexible assembly operation. Wires could then be deducted from the diodes to the rest of the electronic components instead of being directly mounted on the circuit board. This would require the circuit board to be placed in an exact position in relation to the cover. The diodes were placed on the top surface making it visible for the user while in use, see Figure 3.16.

Several solutions for how to activate the probe was developed through discussions and brainstorming. Some ideas were; using a physical on/off-switch; using a ca-
capacitive touch sensor; using the air passage hole in combination with a resonance sensor. For the latter solution, the user would then press a finger against the hole and a sensor inside the enclosure would react to the resonance change and activate the probe. The solution which was considered to be the best was to activate the probe using a capacitive touch sensor placed on the inside top of the cover. The user then press a finger against the top surface creating a current which activates the probe. In this way an additional hole which needed sealing, as the one a physical power switch would generate, was eliminated. The resonance sensor solutions were considered slightly more complex and there is also a risk that the air hole could be clogged by dirt and water during use, resulting in the probe turning off itself.

3.5.6 Aesthetic Design

A lot of different design concepts where put forward and are displayed in Appendix E. The design and colouring of the probe needed to have focus on reflecting the area of use and quality. Limiting factors to the design were the size of the electronics and the DFM part which put requirements on how the part should be designed for suiting the selected processes and materials. Additive manufacturing gives high design freedom but it was not clear if the materials and processes could fulfill the requirements. Hence the design was made with standard manufacturing processes in mind, like for example injection moulding. The chosen design is symmetric and features curved surfaces on almost all sides which the designers felt gave an aerodynamic and robust impression.

The size is chosen with respect of the electronic components. However, the development of the enclosure was done at a more rapid pace due to the MAKEMAKE team had to give the project a low priority for a while. This lead to the dimensions of the interior components not being determined at the point where the design of the enclosure had to be. An estimated size was then determined so that the enclosure could move on to the next phase. The base part and the cover part are in different colors which gives a clear separation of the parts and a more interesting
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3.6 Prototype Development

A crucial part in the concept development phase was the development and testing of prototypes. The concepts were made in CAD, then produced using rapid prototyping methods in order to verify design solutions, surface and material quality. Design solutions and other features which were not satisfying were improved in the CAD model and then made again for a new validation, making it an iterative process. This was repeated until a satisfactory product was achieved.

Based on material selection and availability a list of suitable processes for the prototypes were put together, Table 3.3.

<table>
<thead>
<tr>
<th>Process/Properties</th>
<th>Economic Batch Size</th>
<th>Availability</th>
<th>Tolerance (mm)</th>
<th>Material Variety</th>
<th>Wall Thickness (mm)</th>
<th>Design Freedom</th>
<th>Layer Thickness (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FDM</td>
<td>1-10</td>
<td>High</td>
<td>0.127-2</td>
<td>High</td>
<td>0.5-100</td>
<td>High</td>
<td>78-330</td>
</tr>
<tr>
<td>SLS</td>
<td>1-100</td>
<td>Medium</td>
<td>0.2-0.8</td>
<td>Medium</td>
<td>0.8-100</td>
<td>High</td>
<td>80-150</td>
</tr>
<tr>
<td>SLA</td>
<td>1-10</td>
<td>High</td>
<td>0.1-2</td>
<td>Low</td>
<td>0.5-100</td>
<td>Medium</td>
<td>25-150</td>
</tr>
<tr>
<td>Vacuum/Thermoforming</td>
<td>10-1·10³</td>
<td>High</td>
<td>0.5-1</td>
<td>Medium</td>
<td>0.1-12</td>
<td>Medium</td>
<td>-</td>
</tr>
<tr>
<td>Milling</td>
<td>1·10⁻⁷</td>
<td>High</td>
<td>0.02-0.5</td>
<td>High</td>
<td>0.2-500</td>
<td>Medium</td>
<td>-</td>
</tr>
<tr>
<td>Injection M.</td>
<td>1·10⁻⁶</td>
<td>Medium</td>
<td>0.07-1</td>
<td>Medium</td>
<td>0.4-6.3</td>
<td>Medium</td>
<td>-</td>
</tr>
<tr>
<td>RIM</td>
<td>100·10⁻⁴</td>
<td>Medium</td>
<td>0.1-4</td>
<td>Low</td>
<td>2-25</td>
<td>Medium</td>
<td>-</td>
</tr>
</tbody>
</table>

Initial Additive Manufacturing Tests

Due to the rather complicated geometry the possibility to 3D print the parts was mostly desired. However before producing the prototype tests had to be done on the different available machines to see if the techniques would meet the specifications of requirements and to be sure if the process was reliable enough to produce a functional prototype.

Different machines and available materials where tested and evaluated based on tolerances, strength of material and waterproofness.

The first step of the tests was to print a couple 50x20 mm samples with different thickness to decide the optimal wall thickness when using the different machines. Stiffness and scratch resistance was also tested by bending, dragging and scratching the pieces just to get a grip on how the material behaved. Waterproofness of the materials was tested by printing half-cubes and filling them with water. The attachment solution was also printed and the snap-fits and their design were evaluated.

Only FDM and SLA machines were tested as they were the only ones available at location. Five different FDM machines and one SLA machine were tested with FDM having more available material options. SLA however showed greater potential in being more waterproof, flexible, less brittle and required less and cheaper post processing. But temperature resistance, mainly to high temperature, of the available
material was less good than some of the FDM materials. The strength of FDM printed parts was greatly dependent on the orientation of the printed part in the machine and hence also the direction of the load, being very brittle if the load was applied perpendicular to the printing direction. This was not the same problem for the SLA parts which had higher resolution and is not based on the method of depositing melted material in thin layers with a nozzle in the same way as FDM, but rather cures larger sections of material directly on top of each layer.

Another consequence of this was smoother surfaces from the SLA while FDM parts got a clear staircase effect in some places where parts had rounded surfaces. FDM parts would require post processing with some epoxy resin or normal filling, grinding and painting to be waterproof and get a smooth surface. While SLA would require mainly painting and perhaps also some filling to get it 100% waterproof and scratch resistant. There is also possible to use colored materials in SLA but theses where not available.

The SLA machine that was tested was a Formlabs machine which has a relatively high resolution with the choice of 0.025 mm, 0.05 mm or 0.1 mm. Although it’s very sensitive to dust and other particles in the air which put high requirements on a clean working area. It’s also important to orient the parts in an angle, which will give the laser a smaller curing area and minimize the risks of defects.

Test prints of all parts were done in the machine. The first tries resulted in parts with small holes and other defects, see Figure 3.17.

![Figure 3.17: Defects on the part printed with the SLA method](image)

This was solved by keeping the machine very clean and orient with an angle of, or above 12 degrees. After the parts are printed they need to be rinsed in isopropyl alcohol (IPA) for about 20 minutes and detached from their support material. Smaller holes could be fixed by curing a small amount of resin over the hole with a laser or in the sun or simply by using some glue. The parts are then wet sanded with
about 800-1200 grit sandpaper to get a smooth surface. Acrylic cleaner on cork board or polishing with a microfiber cloth could be used to obtain a transparent surface.

For economic reasons three other cheaper FDM printers were tested which also used cheaper materials. Ultimaker2 printed in PLA and gave great resolution and quality. A problem was nonetheless that the printer did not have a soluble support material but rather used the print material as support as well. The result of this was that the support material melted into the layers of the part and when removed caused a very rough and irregular surface. When no support material was used the result was that free standing surfaces started to hang down because of that the deposition of material occurred in midair, Figure 3.18.

![Surfaces as a result of the use or nonuse of support material. The black model shows how the support material generated a very rough surface. The white model shows the non use of support material resulted in a sagging surface.](image)

The best ways to avoid or improve this overhang problem is to reduce print speed and temperature, increase cooling or trying to position and orientate the part in such a way that overhang is avoided. Almost the same results came out of the three other machines tested; MakerBot Replicator 2X Experimental 3D Printer, MakerBot Replicator Desktop 3D Printer and WANHAO Duplicator 4S Desktop 3D Printer. These machines used ABS plastic and gave stronger parts but with equal surface quality. For all FDM machines the main problem was to orient the parts in the machine in relation to the direction of the loads the part must endure. Snap-fits could for example not be built flat up since they will break because the fragile bonding between layers.

The main results of the AM tests were that the parts needed a wall thickness of at least 2 mm to be stiff enough. SLA was the most promising process to make the base because it would not need a lot of post processing. Also the attachment showed most promise in the SLA which could have more elastic snap-fits. However the FDM machines had in some cases better tolerances because of some shrinkage of the SLA parts and it was also a cheaper process. But all in all it was shown
that the SLA method had most potential and was considered reliable enough for producing the base part if a 3D print method would be used. The cover part was however too complicated to produce using SLA and all test resulted in holes, due to a too dusty environment, and tolerance problems, due to post shrinking. Because of the hollowness and hence the overhang problem the part could not be oriented in any good way in the FDM printers. The part also became too brittle in the processes.

However, two other processes were considered to be more optimal to produce the final prototype: milling for the base and vacuum forming for the cover. Vacuum forming is also based on milling as the male mold is milled. As the cover and the base parts requires a clearance fit the tolerances were also easier to control using milling.

The attachment was however best produced by 3D printing due to its' complicated design which would otherwise require injection molding or similar processes, which were not available and would be too expensive.

### 3.6.1 The Base Part

This section describes the final prototyping process for the base part. Several prototyping methods were tested in order to find the most suitable processes among those available at KTH and Alten. Milling was considered the most suitable in order to get a waterproof part with good tolerances.

The process of milling the geometry of the base part is somewhat more advanced and time consuming than the 3D printing process. The main challenge is that it needs to be milled from all sides and in several operations. This required a lot of planning and the final plan was to first mill out the o-ring groove and the bottom contour as well as a rough mill of the exterior shape using a rotary milling process. The next step was to mill the inside of the base but since the part was fastened in that direction, the part had to be removed and milled in another operation and another milling machine. The challenge here was to find a way to position it right in the coordinate system. Even the slightest misplacement could lead to an uneven o-ring groove or skewed walls. The solution to this was to first mill out a fixture based with the bottom outline and then place the model in it. This method was first tested using polystyrene foam, EPS, which is an easy material to work with. The test was successful and the result can be seen Figure 3.19. The left part in the figure is the result of the rotation milling, the middle part is the fixture and the right part is the final part.

There was a slight shift in the coordinate origin between the two operations, resulting in a slightly skewed part, with one wall thicker and one side thinner than planned. This was due to the fixture hole was slightly too big which gave too much space for placement error.

A new version was milled out in the same way but with a better fixture and in the material polyurethane, see Figure 3.20. This time, the result was much better but
still a slight syncing error made the o-ring groove slightly deeper in one side and shallower at the opposite side. The part was post processed with a rasp and sandpaper and sanded until a sufficient result was achieved. For future manufacturing the part needs to be placed in the fixture with better accuracy.

Figure 3.20: *The milling process of the final base part*

The countersink in the bottom, where the USB connection is placed, was manually milled and threaded, see Figure 3.21.

Figure 3.21: *The threaded countersink in the bottom of the base part*

### 3.6.2 The Cover

This section describes the final prototype process for the cover part. Several types of rapid prototyping methods as well as several materials were used for testing
their qualities and tolerances. The first prototyping method that was tested was 3D printing as it is an easy and fast way of verifying functions and design features as well as complex geometries can be made. They were however not waterproof and post processes would be needed which could affect tolerances and shape. Vacuum forming was the next type of rapid prototyping process which was considered suitable. It was more time consuming as molds were needed to be prepared and milled. The result was however much more satisfying than the result of the 3D printing methods and it was chosen as a final process for the cover part. The vacuum forming process is described below.

Vacuum forming is similar to thermoforming, where a sheet of plastic is heated to a point where it is moldable and then pressed onto a surface mold, a so called male mold or positive mold. Suction is then added underneath the male mould, creating vacuum which forces the heated plastic sheet onto the surface of the male mold, where it cools and solidifies in accordance to the male moulds surface, see Figure 3.22. Waste material were cut away and the sides where grinded down to get smooth edges. This technique is quite time consuming and can only make open models with not too complex design, hence only the cover part of the design was manufactured this way, but in the same time is enables waterproof parts with excellent surface finish.

For the prototype, a polystyrene foam, EPS, was used as material for the male mold which is a low density material that enables air to flow through it. Two different types were tested with different densities in order to examine differences in process performance and surface finish.

A first test was made, using the material with the lowest density. It was easy and fast to mill, however only a rough sample of the male mold was milled for this test. The plastic sheet that was used was made out of HIPS (High Impact Polystyrene), with a thickness of 2 mm. The HIPS sheet had a rough a and shiny side and depending on which side facing the male mold different characteristics for the exterior surface could be achieved. The vacuum forming process was executed with a desired result. The porous material enabled the suction to be evenly distributed over the surface making the HIPS sheet taking the exact form of the male mold. The rough side was orientated against the male mold resulting in an excellent exterior surface finish.

Figure 3.22: The vacuum forming process
However, the slightest hole or uneven surface is reflected on final cover part, so for future male molds it is important to mill with a good finish. The material itself is slightly porous and a higher density material will probably generate an even better surface finish. The resulting cover part also had a very good fit to the base part and it was determined to further explore vacuum forming and adapt the cover design for this process. A few design features needed to be improved before the next test, such as adding an extension to the height of the cover mold in order to easier cut the cover part off in a straight and exact angle. Also adding a slight angle, a so called draft angle, on the walls for making the plastic sheet easier to release from the mold. However, due to the relatively soft material the plastic sheet sticks to the surface because it enables the plastic to shrink into it slightly.

A second test was made on the updated design with the improvements mentioned above and using a slightly more dense version of the EPS. A male mold was milled with two cover shapes in order to produce two covers in one operation and in this way also minimize material waste. The result was however not successful, a bridge was created between the parts due to a too slow contraction, see Figure 3.23.

![Figure 3.23: Bridging phenomenon](image)

The slow contraction can depend on several factors. In this case it was probably due to the male EPS material being too dense, preventing enough suction at the surface or because there was too much time between the removal of the heater and the start of the vacuum, making the plastic having time to solidify a little and lose its formability.

The mold was divided into two independent cover molds and the plastic sheet was reheated and reused for the next test. This time, a phenomenon called webbing occurred in the corners, see Figure 3.24. The material around the corner did not have anywhere to go resulting in too much material that was gathered and folded in on itself.

The webbing phenomenon is often a result of excessive draw ratio or poor mold design. To solve this problem, a small block of EPS was placed along the four sides of the cover mold and in this way stretching out the material and minimizing it in the corners. Also the height of the male mold was reduced in order to make the shape easier for the plastic sheet to adapt to. This had a positive effect on the
problem. This test was made using PETG as plastic which gave a transparent cover part with an acceptable fit, suitable for examine how the o-ring is affected when the cover was assembled to the base part.

There was no noticeable difference in the surface finish between the two versions of the EPS material, therefore was the less dense material selected as mold material due to the more even suction it generated over the surface. For the final test the male mold of the cover was redesigned with an increased angle on the extension. In this way making it easier to visualize where the cover part should be cut away from the sheet. A 20 degree angle was grinded in the inner edge to make it easier to press the cover over the o-ring.

### 3.6.3 The Attachment

The attachment solution was tested with different dimensions and prototyped using several 3D printing methods as well as different materials.

![Figure 3.24: Webbing phenomenon](image)

![Figure 3.25: Several test parts for the attachment solution were produced](image)
3.6.4 Additional Parts

Apart from the cover and the base part, the prototype needed some additional parts, such as the plug, Gore-Tex filter and O-rings.

Two plugs were turned out of POM and then threaded. One with a hole through the part, for letting air in to the Gore-Tex membrane, and one without for sealing the USB connection, see Figure 3.26. Test o-rings were provided by Trelleborg Sealing solutions and MecMove in a 70 Shore A hardness and the Gore-Tex membrane was cut out from a piece of Gore-Tex fabric.

![Figure 3.26: The two prototyped plugs. The left one is for the Gore-Tex membrane and the right one is for the USB connection](image)

3.7 Evaluation

The prototypes were tested based on the scenarios stated in Section 3.2.1. Five tests were conducted and are described below.

3.7.1 Test 1 - IPX7

**Source Requirement** - Requirement from Alten

The enclosure is submerged 0.5 m under water for 30 minutes with toilet paper inside the enclosure, see Figure 3.27. The dry paper was scaled before the test to 1.2524 g. After 30 minutes of submersion the paper is visually inspected and scaled for signs of water absorption. The test was conducted in two variants:

- (1) Without the Gore-Tex membrane and a solid thread plug.
- (2) With the Gore-Tex membrane and a threaded plug with a hole though it (no scaling was used due to lack of access to a balance with enough accuracy).

**Pass Criteria**
The conditions of acceptance for IPX7 is met if no water has penetrated the enclosure in such a way that it will affect the safety or operation of the of the product. The
enclosure has passed the test if there is no visual sign of water absorption in paper and the weight has not increased more than 0,1 g.

**Result**
There was no visual sign of water absorption in the paper for test variant (1). The paper was scaled, now with a weight of 1,2672 g, which means an increase of 0,0148 g (1,12%). There was however some water around the USB entrance.

For test variant (2) there was no visual water absorbed by the paper. It was however wet around the Gore-Tex filter, especially around its’ edges. It was assumed that the water around the Gore-Texs’ edge could generate a risk of water intrusion.

**Discussion**
The water which arose in near the USB entrance was probably water that had got stuck in the thread in the bottom plug. As the cover was removed to inspect the inside, vacuum occurred which sucked the water through the thread. Additional tests were made where the plug was unscrewed before removing the cover. This gave a better result. However, at the time and place of the mentioned tests there was no access to a balance with enough accuracy and therefore was the paper only visually inspected which opens up for a more free interpretation of the results.

### 3.7.2 Test 2 - User Environment Waterproof Test

**Source Requirement** - *Use case scenario 2*

One can argue that the IP67 classification is a too strict demand relative to the operating conditions the probe actually will be used in. Use Case Scenario 2 was determined as a likely event during the probes use and a test case, Test 2, was set up that was assumed to represent the scenario. It was conducted as follows:

The enclosure was held under a faucet with running water. The water flow was first measured by measuring the time to fill 1 L. The waterflow was adjusted so 1 L took 10 seconds to fill. The diameter of the nozzle was 20 mm. The enclosure was then held under the running water with 10 s each on the probes six sides, see Figure 3.28. Paper was put inside the enclosure which was visually inspected for water absorption after the test.
Pass Criteria
The conditions of acceptance is met if no visual water or moisture have penetrated the enclosure in such a way that it will affect the safety or operation of the product.

Result
The test was executed successfully with a satisfactory result. No visual water could be found inside the enclosure.

Discussion
The paper was not scaled before and after the test due to lack of access to a balance which could scale with a sufficient accuracy. The paper may have absorbed water which could not be visually inspected. The paper felt dry and there was no visual signs of moisture. This is however an error which should be corrected in further testing.

3.7.3 Test 3 - Enclosure Impact

Source Requirement - Use case scenario 1 and 3
This test represent the events of likely exposures of impacts, for example caused by an accidental drop on a hard surface or if it falls off the target object while in motion. The test was conducted by dropping the enclosure from a height of 1,2 m on each of its’ six sides. After the original planed test, an additional test was also executed were the enclosure was thrown up in the air to a height of about 2,5 m and letting it fall to the hard ground.

Pass Criteria
The enclosure does not open or break.

Result
The enclosure remained intact throughout all tests.

Discussion
The enclosure remained intact showing that the friction force was reliable and no use of screws or other attachments was needed for the cover.
3.7.4 Test 4 - Quality Control of Attachment Solution

**Source Requirement - Use case**
This test represents a simulation of a real use of the probe and the attachment. The snap-fit attachment was attached to the target objects’ surface using the double sided mounting tape. Then the enclosure was attached onto the snap-fit attachment. The target object should then move at a maximum speed of 30 km/h for 20 minutes over a rough surface like asphalt or similar, see Figure 3.30.

**Pass Criteria**
The enclosure does not fall off from the attachment during the test.

**Result**
First of all, the target object never reached a maximum speed, it only reached an average speed of 6-8 km/h. This was due to lack of experience in using the target object. The snap-fit attachment did not sufficiently hold the probe in place. It fell off even at low speeds and hence the prototype was not considered optimal. However only using the mounting tape did work but still, it was not tested at high speeds.

**Discussion**
The failed test is mainly due to the lack of suitable manufacturing processes for snap-fit design. The design was too complex to produce in the same quality as the probe hence it has many weak points. Injection molding could be a suitable process for this type of design as it would give fibre strength in the right direction. Double sided tape did however keep the probe in place.
3.7.5 Test 5 - Attachment Impact

*Source Requirement - Use case*

This test was done to see how well the attachment handles impact. A simulation of a light impact to the side of the probe much like a small hit or similar which are possible scenarios the attachment could be exposed to during use. The critical impact force was tested using a pendulum with a weight of 0.178 g which was released at an angle of 90 degrees from different heights, resulting in different impacts, see Figure 3.31. The chosen start height was based on the assumption that the probe gets an impact which is similar to a light kick to the side.

![Figure 3.31: Visualization of test 4](image)

**Pass Criteria**
The probe does not fall off from its attachment which also remains intact.

**Result**
Four different heights were tested, Table 3.4.

<table>
<thead>
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<th>Height (m)</th>
<th>Pass</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.30</td>
<td>Yes</td>
</tr>
<tr>
<td>0.46</td>
<td>Yes</td>
</tr>
<tr>
<td>0.6</td>
<td>No</td>
</tr>
<tr>
<td>0.8</td>
<td>No</td>
</tr>
</tbody>
</table>

The test did not succeed according to plan and the attachment broke when the weight was released from the height 0.6 m. No further testing could be made.

**Discussion**
The attachment did break hence no more tests could be done. The conclusion was that 3D printing, especially FDM, was not sufficient for snap-fit design. This was most likely because of the layer on layer process on which it build parts. This causes weak points between the layers and it could easily break. The orientation of the layer could be changed but would require more complex printing and might weaken the design in other parts. For a snap-fit design injection molding would be the best suitable manufacturing process. The double sided tape did however on its own withstand a lot higher impacts than required.
The Final Product

The final design of the waterproof enclosure for the probe consists of three main parts; the base, the cover and the attachment, all made in polycarbonate, PC. The design of the product is made with the use area in mind and to fit into its environment. The material and the colors are picked for the same reason and also to give a feeling of quality and performance. PC has good UV, impact and scratch resistance as well as a good temperature durability which will make it look robust and express quality for a long time even though it is a plastic material. PC can be both coloured and transparent, as seen in Figure 4.1.

Figure 4.1: Final design of enclosure
The base part and the cover can be coloured several colour options depending the area of implementation. Colors should be chosen with the customer in mind and depending on in which area it will be used. In this chapter the final concept is presented in two versions. One, which represent a how the cover could look like as a finish product, with a transparent base part. LED lights could then be connected to the base part making it light up, which the designers considered to give a hi-tech expression. The other version is with a base part in blue. Mostly two resemble the prototype which was made in blue polyurethane. The cover was given the colour white to show a neutral and clean color.

The electronics are enclosed in a hamburger structured enclosure with an o-ring sealing where the cover is held in place with friction to the o-ring and the base part, see Figure 4.2. Joining elements such as screws and adhesives have been avoided. In this way, the components inside the enclosure can be accessed if needed, for example in case some components needs to be changed or updated. However, due to the tight fitting between the cover and the base part the cover is somewhat difficult to remove once put in place.

Parts which has been broken can also easily be replaced, which may contribute to a longer lifetime for the product. The sealing solution is radial o-ring which is mounted in the wall of the base part with an exterior cover assembled over it. The o-rings used in the design are made out of Nitrile and with a hardness of 70 Shore A. With this design solution, no additional joining elements, such as screws or snap-fits were required since the friction between the parts hold them together. The enclosure was foremost designed according to DFM since the goal was to provide an enclosure design for a small batch prototype.

![Hamburger structure of the enclosure](image)

**Figure 4.2:** Hamburger structure of the enclosure

The cover is made through vacuum forming from a 2 mm thick PC sheet of material, giving it an excellent surface finish without post processing. The cover was given a draft angle of two degrees to facilitate the loosening from the positive mold. The inner edge has been given a bevel with a 20 degree angle in order to make a
slightly easier assembly over the o-ring, see Figure 4.3. The cover should carefully be assembled to keep the o-ring in the right place.

![Figure 4.3: Illustration of the bevel in the inner edge of the cover](image)

The base is also made out of PC and manufactured through milling. The o-ring groove is located in the base part wall which gives it a complex geometry making the manufacturing having to be done in several operations. If a good surface finish is desired, post processing is required.

The external dimensions for the probe are 4x8x3.2 mm (WxLxH). The dimensions are visualized in Figure 4.4.

A USB connection was added for charging the battery and for transferring data. It is located in the bottom side of the base part and is sealed by a screw plug and a small o-ring. When the product is in use the USB entrance is facing down towards the target object, which makes it impossible for the screw to wind up and accidentally loose. Also the mounting tape will help to prevent this situation.

Also an air passage was positioned in the bottom of the base part in case condensation would occur inside the enclosure and to let air out as the cover is assembled. The hole has a screw plug with an changeable gore-tex filter which let moist air pass through but prevent water from entering the enclosure. The two holes in the bottom of the base part and their corresponding parts, in the assemble order, can be seen in Figure 4.5. The hole for the air passage also prevents the cover to detach from the base as the Gore-Tex membrane slows down the air flow, resulting in a vacuum effect which prevents the cover from sudden detachment.
Chapter 4. The Final Product

Figure 4.4: *External dimensions for the enclosure*

Figure 4.5: *Visualization of the USB connection and the air passage way with their corresponding parts*

The cover contains a touch surface in the middle which turns the probe on through a capacitive touch sensor. The location of the touch sensor is visualized with a slight dimple, big as a thumb, on the top surface. Further description can be provided in an accompanying manual for the device. Two LED lights on the top indicate the status of the probe, for example if it is working correctly and the status for the battery level. In Figure 4.6 different scenarios of indication is visualized.

4.0.6 Attachment

The probe is attached with the help of an attachment part. The attachment itself is attached to the desired surface by two sided mounting tape. The tape does not affect the surface of the object, yet it is strong enough to withstand impacts and vibrations. A concept for an additional attachment was also developed, a snap-fit
solution. The point of this solution was to attach the snap-fit attachment to the target object using the two sided mounting tape. The probe could then be attached and detached and moved between different target objects faster and without the process of add and remove tape after each use. Prototypes were made but the snap-fit solution needs more development.

4.1 Design for Environment

At its end of life the probe is disassembled and the electronics are separated from the enclosure. The enclosure is then recycled as plastic waste. The different parts have been given a label with information regarding material contents which facilitate the recycling process. Also the low amount of different materials simplifies the recycling management. No harmful or rare materials were used in the enclosure design. The design of the enclosure has been made to facilitate replacement and upgrading of parts and components. The material was chosen to achieve the requirements of an outdoor environment and extend the lifetime as long as possible. The design was developed to have a simple structure with a low amount of details in order to create clear separating boarders for the recycling phase but primarily to facilitate the manufacturing.

4.2 The Final Prototype

The final prototype of the enclosure can be viewed in Figure 4.7. The left image in the figure presents an explosion view of the prototype. The prototype was functioning and the sealed as desired. At the end of the project the software and the electronic components were still not dimensioned and fully developed, resulting in a fully functional prototype could not be delivered. Once the MAKEMAKE team has
determined what needs to be integrated the size of the enclosure needs to be adjust and a final prototype with the electronics inside can be made.

Figure 4.7: The final prototype: exploded to the left and assembled to the right

The base part was milled out from polyurethane and the cover was vacuum formed in HIPS. The threaded plug was turned out from POM. The prototype passed the test for the desired sealing requirement.

4.3 Mass Production Process

For possible mass production classic manufacturing processes are still to be prefered due to their high speed and precision not yet offered by some prototyping processes or standard AM equipment. Also material selection is greatly dependent by process and reverse.

For optimization of the product a polycarbonate (PC) enclosure and attachment made by injection molding is considered to be the most optimal solution if a large quantity of the product will be produced. Injection molding enables high tolerances, speed of production and cost reduction. Vacuum or thermoforming of the cover is also a possibility if the design is not changed. An injection molding technique could enable a more complex design with for example snap-fits or integrated holders for the LEDs. The base part and attachment are designed with injection molding in mind and requires rather simple tools but they can still be optimized, for example the o-ring groove which at its current location can make the tool complicated and expensive. Electronics and electronic attachments could also be integrated reducing the assembly steps radically. Polycarbonate is chosen because of properties like great
impact, scratch, UV and temperature resistance and it also offers both colored and transparent parts making a vast variation of designs possible.
Summary and Discussion

A summary of the work is presented in this section as well as the discovered conclusions of the project. A discussion about the project and its conclusions are also presented together with examples for further work and development of the project.

5.1 Summary

This master thesis has presented the product development process of a waterproof probe enclosure. The initial part of the work focused on a theoretical study in four different fields. This study resulted in deeper knowledge and new additions to the specification of requirements. The requirements was moved into the concept generation phase where two main concepts where selected for further development. Out of the two concepts later one was selected due to complications for manufacturing of the prototype. The selected concept consists of a base part and a cover part which are sealed by an o-ring. The enclosure is then attached to a desired surface by double sided mounting tape and a snap-fit attachment. The concept was then produced using rapid prototyping processes and the design was optimized and improved through an iterative working process. The final prototype was tested by setting up real life scenarios and test standards for IPX7 validation. The prototype finished all the tests to satisfaction except the attachment solution which required further work. Using only mounting tape or a hook and loop fastener was considered to be suitable options.
5.2 Conclusions

From the testing and evaluation of the prototype the main conclusions of the projects is:

- The sealing performance of the enclosure was achieved.
- The enclosure is robust and fulfills requirements on materials and function.
- The enclosure is designed according to ecodesign guidelines and for manufacturing which has laid a good foundation in case of mass production.
- An optimization of the design and additional testing is needed once the electronics have been defined and integrated.
- Mounting tape works but a sufficient snap-fit function was not achieved using 3D printing. Another process should be considered for example injection molding. The attachment also needs design optimization for other types of production.
- Injection molding could be suitable for mass production but the prototyping processes worked sufficiently, although in a slower pace.
- Additive processes in plastics are not yet suitable for a final production of these kinds of products but looking at the pace of development it could soon become a suitable option.
- The result of additive processes in plastics are still hard to predict due to impacts from the environment or settings but it’s still good for visual representation of a product.
- An iterative rapid product development process could be used for optimization of design.

5.3 Discussion

The project had a very broad approach and it was sometimes hard to know the limits of the project.

The work could perhaps have had a better outcome if the electronics, use and the requirements were more specified in the beginning of the project and not during. The electronic components were, even in the end of this master thesis, not specified. Since this was a master thesis, there was a time limit for the project and a decision for dimensions had to be made, before it was known how much space the electronics requires, in order to have time for prototyping the final version and test it. The dimensions for the enclosure had to be determined based on an estimation of how much room was required for the components. The concept for the design works
however as intended, so once the electronics and the circuit board are developed the design can adapt to it.

Due to the agile process the design had to adapt and change many times due to new requirements, size of hardware and specifications that occurred during the project. The agile process was in the beginning unfamiliar to adapt with the more methodical product development process. However, a functional working approach was quickly found. For example, the prototyping process had to be postponed many times, but this time was instead used to experiment and learn the different machines which resulted in a lot of time saved for the production of the final prototype.

Ecodesign did not get too much attentions since it was not a specific requirement from the stakeholders. Several guidelines for ecodesign were nevertheless considered fulfilled. However, an LCA analysis was not made, partly due to more focus was put in rapid prototyping but also too many factors were unknown or uncertain. For example since the electric components were not determined and a battery not dimensioned, the energy usage was not known. It can be more interesting to use the LCA tool once the prototype has been fully tested and if it is considered to be further developed in larger scales.

The sealing solution worked with satisfaction, there are however a few points of potential improvements. First of all, the o-ring that was used had an hardness of 70 Shore, which provided a fully functional sealing, but a slight reduction of hardness could generate an even safer sealing. A hardness of 50 Shore A may provide a better and more even compression of the o-ring and also make it easier to assemble the cover part over the o-ring. An easier compression may also account for possible tolerance errors due to the rapid prototyping process. The 70 Shore A o-ring may have been too hard for the plastic resulting in a fatigue as the cover was removed and assembled several times. On the other hand, the cover should not be assembled and disassembled often.

Another improvement could be to have more rounded corners on the design. At the moment the design of the probe is rather rectangular as a round design was consider not to blend in with the target object as much. Standard o-rings are round but can be applied to rectangular shapes as long as the corners are rounded. However, the more oval the design is the more the o-ring takes its natural shape, resulting in a more efficient seal. With the current design the o-ring got slightly loose along the long sides, even though the o-ring had a smaller inner diameter than the diameter of the o-ring groove. This is probably due to a too rectangular shape with the corners not rounded enough. A solution would be to mould a slightly rectangular o-ring according to the shape of the base part but then again there is the cost for producing a mould tool. It is however not a complex mould and then a 50 Shore material could be used for that mould.

According to the intended use and operating environment of the probe, the IP67 requirement could be considered too high. Effective sealing for high IP ratings tend to add both cost and size, so it is important to choose the right sealing requirement. A more suitable IP rating for the normal use could be for example IP55. However, in extreme case usage, the IP67 rating may be suitable.
The tests could have been conducted with more precise measurements and methods if there was more time and resources available. An full IP6X was for example not tested due to the lack of a required dust chamber. Also more focus was put on making the enclosure waterproof and achieving the IPX7 requirement since this was considered a more important requirement. It is preferred to conduct a real IP67 test in a controlled lab once the final probe is developed with the electronics integrated.

The target object will likely vibrate during use which is important to consider. The attachment design should be designed for achieving a critically damped case and the enclosure designs’ stiffness should be optimized so that the primary frequency originating from the usage does not cause resonance. There was however no data about which the critical frequencies were but it would be interesting to investigate.

DFM is important but also a great limiting factor when it comes to design and freeform, with the help of more advanced AM techniques the gap between designer’s visions and manufacturing requirements could be reduced to make more challenging designs and products. The AM techniques are still rather young but with some more effort and research put into it they could start to compete with traditional processes for real. AM is also hard to predict when it comes to testing. The parts can vary allot even though they are printed in the same way, depending on changes in the environment or just minor settings. Bounding between layers are also hard to predict and the material does not behave in the same way as for example injection molded parts, hence they are not that suitable for snap-fitt designs. The optimal manufacturing process for mass production are still traditional ones for this design but for small batches the prototyping processes used gave great result.

The results of the experiments done could be used as a guide to future prototyping projects and the structure of the thesis as a guide for future product development projects.

Future work includes optimization of the electronics and size of the probe. More expensive material and components, like waterproof connections, could be used if larger scale production is considered. An injection molded attachment could ensure a safer and longer lasting solution for the snap-fits. Rubber parts like small hatches with hinges etc. could be made for a more optimal protection of the USB socket. Inductive charging was considered as an option instead of having any external inlets, and ensure higher waterproofing. Components was bought in for this but was not optimized in time.

The real use for the probe was not known by the master thesis students nor the MAKEMAKE team. This could have a negative effect on the resulting product as more effective and clever design solutions could be developed if the designers have the whole picture. Future design work can be done to make the probe more suitable for other types of use.

Concept A had a perhaps more unique design and if it was possible to custom make the electronic hardware to fit, it would probably be a more interesting solution. It also requires a more advanced manufacturing process and is therefore more suitable.
for mass production as mould tools etc. can be made without resulting in a high cost per product.

5.3.1 Further Work

Suggestions for further development of the probes’ enclosure is presented below.

Once the prototype has been tested and it is validated that the purpose of the product works as intended, an optimization of the circuit board size and electronics is preferred in order to make the probe smaller. A reduction of size, especially the height could make the product more practical. This requires a custom build circuit board which there was no time or resource for at the time of the project.

A better ecodesign can be achieved by performing an LCA analysis. Especially once the electric components have been determined and the energy usage is known for the probe.

A softer material for the o-ring should be tested in order investigate the possibility for better sealing performance.

The USB connection could also be waterproof making the use of the plug unnecessary or a rubber plug could be used, similar to the ones used today on waterproof cameras etc. making it more accessible. These components were however a little too expensive to buy for the prototype or too hard to manufacture by the available equipment. Since the probe will send wireless data to external devices the transferring of data using a USB might be considered unnecessary. Inductive charging could then be integrated in the probe making the USB connection totally unnecessary and eliminate a way in for water.

The attachment could also be optimized. If the probe was smaller and lower a higher attachment could be used like the ones on action cameras which would make the probe safer to use. The attachment as it is done today could require some design changes and it could be a second snap-fit integrated for a safer solution. It could also be better to manufacture it in more reliable material and a better process.

The LED interface could be made in a more interesting way, for example in patterns, a small screen or similar to make the product feel a little more alive.

The probe could be made more optimized for DFM and DFA depending on which process is selected for future development. For example by optimizing it more for injection molding which is a suitable process for the base part.

The design concept A could be considered for a future product. If processes and materials are not a limiting factor as for this project it could perhaps be a more appealing solution. In that case the design needs to be more optimized for manufacturing with regard of for example injection molding. The electronics also needs to be custom design for the enclosure and made more compact. The same attachment solution is possible but the design could be somewhat more optimized. The lid of the enclosure could be made out of rubber giving the lid a sealing function. The
USB-connection could also be waterproof making the main purpose of the part to protect it from dust, dirt etc.

An IP6X test may be of interest to conduct.

The probe, if made smaller, could be made more modularized making it possible to attach it to different objects with for example straps or similar. Preferred material is PC and rubber integrated in the cover to make it more absorbable for impacts.

The probe should be tested with all of its electronic components in its real environment. The electronic attachment inside the probe and on the electronics should be optimized to fit with each other.


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optimization for multi-part production in additive manufacturing. *Journal of
Intelligent Manufacturing*, 2014.
Bibliography
Gradings Criteria

Presented here are the grading criteria from KTH.
Each thesis will be given a grade, A–F, in accordance with KTH-established criteria. All theses will be assessed according to three main criteria outlined below, namely: *Engineering and scientific content; Process; and Presentation.*

To be approved, the thesis must not fail at any of the three assessment criteria.

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<th>Assessment</th>
<th>Process</th>
<th>Engineering and Scientific Content</th>
<th>Presentation</th>
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<tr>
<td><strong>Excellent</strong></td>
<td>Independently plan and carry out the work within the agreed timeframe, show good initiative and be open to coaching and criticism.</td>
<td>Based on the research problem and methodology, show a strong ability to systematically apply engineering and scientific skills such as problem definition, modeling, analysis, development and evaluation in a systematic way.</td>
<td>Establish a well-structured report with an explicit statement of work and results, clear analysis and reasoned argument, using good language skills, plus formal and scientific accuracy.</td>
</tr>
<tr>
<td></td>
<td>Independently identify their needs for new knowledge, and to obtain these skills.</td>
<td>In context to the topic, demonstrate an awareness of social and ethical aspects, including economical, social and ecological sustainable developments.</td>
<td>Good oral presentation skills, with clear arguments and analysis, and the ability to discuss work.</td>
</tr>
<tr>
<td><strong>Good</strong></td>
<td>Plan and execute work within agreed timelines, show initiative and be open to coaching and criticism.</td>
<td>Based on the research problem and methodology, show strong ability to systematically apply engineering and scientific skills as problem definition, modeling, analysis, development and evaluation in a systematic way.</td>
<td>Establish a well-structured report, with an explicit statement of work and results, analysis and argument, as well as good language skills and format, plus formal and scientific accuracy.</td>
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<tr>
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<td>Demonstrate the ability to acquire new skills.</td>
<td>In context to the topic, demonstrate an awareness of social and ethical aspects, including economical, social and ecological sustainable developments.</td>
<td>Show the ability to orally present and discuss the work.</td>
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<tr>
<td><strong>Sufficient</strong></td>
<td>Carry out work within agreed timeframes, show some initiative and be open to coaching and criticism.</td>
<td>Based on the research problem and methodology, show some ability to apply engineering and scientific skills to modeling, analysis, development and evaluation in a systematic way.</td>
<td>Establish a written report with an acceptable structure, formality and language therapy.</td>
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<tr>
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<td>Demonstrate some ability to acquire new skills.</td>
<td>In context to the topic, show some awareness of social and ethical aspects, including economical, social and ecological sustainable developments.</td>
<td>Show a good ability to orally present the work.</td>
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<td>Demonstrate the ability to familiarize themselves with another project and formulate relevant criticism.</td>
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<tr>
<td><strong>Fail</strong></td>
<td>Showing lack of respect for agreements and deadlines, a significant lack of independence, or disregard of the supervisor. Inability or unwillingness to acquire new skills.</td>
<td>Demonstrating major shortcomings in engineering or scientific skills, and/or significant gaps remaining in the methodology, despite requests for corrections.</td>
<td>Important elements lacking in the written report, despite requests for corrections, and/or a substantial inability to orally present and discuss the work.</td>
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Specification of Requirements

Presented here are the design requirements for the probes’ enclosure.
## Specification of requirements

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### Mechanical and material properties

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<td>UV Resistance</td>
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<td>Hardness</td>
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### Ecodesign

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<td>Few materials (or clear sorting boarders)</td>
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<td>Minimize resources/energy consumption in manufacturing</td>
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### Wishes

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<td>Reflect quality and performance in the design</td>
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<td>Shape and colors which fits with the use area</td>
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<td>Attachment without screwing/drilling etc.</td>
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<td>3d printable for easy prototyping</td>
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<td>Avoid toxic substances and material</td>
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<td>Design freedom (material, manufacturing)</td>
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<td>Optimize weight</td>
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<td>Optimize product lifetime</td>
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<td>Easy interface and ergonomics</td>
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<td>Easy to open and charge</td>
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<td>Waterproof connections</td>
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<tr>
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Storyboard

The Storyboard is presented here. It was a method for mapping use and likely events throughout the product's life.
Mindmap

The mindmap is presented here. The purpose was to compile ideas and thoughts about the project and the problem in the beginning of the idea generation.
Concept Designs

The design suggestions developed during the idea generation stage are presented here.
Morphological Matrix

The Morphological Matrix, created for compiling all the solutions, is presented here.
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- **Problem**: Design proposals
- **Solution**: Interface, Power supply, Attachment, Sealing
Decision Making Matrix

The Decision Making Matrices are presented here.
### Appendix G. Decision Making Matrix

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<thead>
<tr>
<th>Criteria</th>
<th>Weight</th>
<th>Alternatives</th>
<th>Design for Environment</th>
<th>Manufacturing</th>
<th>Total Sum</th>
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**Total Sum**

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### Appendix G. Decision Making Matrix

#### Decision Making Matrix - Power Supply Solution

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#### Decision Making Matrix - Attachment Solution

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Pressure Calculations

Pressure changes due to temperature changes are calculated according to the Ideal Gas Law Equation (H.1).

\[ p \cdot v = R \cdot T \]  \hspace{2cm} (H.1)

Where

- \( p \) = absolute pressure (Pa)
- \( v \) = specific volume (\(m^3/(kg\cdot K)\))
- \( R \) = individual gas constant (\(J/(kg\cdot K)\))
- \( T \) = absolute temperature (K)

The probe has to be able to operate in pressure changes caused by temperature changes between -30 - 50°C. It is assumable that the assembly of the probe will be conducted in room temperature, assumed 23°C which leads to a maximum overpressure at a temperature of 50°C.

At the time of assembly, the Ideal Gas equation can be formulated as

\[ R = \frac{p_1 \cdot v_1}{T_1} \]  \hspace{2cm} (H.2)

At the temperature 50°C, the equation can be formulated as

\[ R = \frac{p_2 \cdot v_2}{T_2} \]  \hspace{2cm} (H.3)

Since \( R \) is a constant, the two equations (H.2) and (H.3), can be written as

\[ \frac{p_1 \cdot v_1}{T_1} = \frac{p_2 \cdot v_2}{T_2} \]  \hspace{2cm} (H.4)
Since it is the maximum pressure, $p_2$, which is sought the equation is written as

$$p_2 = \frac{p_1 \cdot v_1 \cdot T_2}{T_1 \cdot v_1} \quad (H.5)$$

and since the volume can be assumed as constant, $v_1 = v_2$ the equation can be simplified to

$$p_2 = \frac{p_1 \cdot T_2}{T_1} \quad (H.6)$$

With $T_2 = 50^{\circ}C$, the room temperature $T_1 = 23^{\circ}C$ and $p_1$ is equal to 1013,25 hPa generates a pressure of

$$p_2 = \frac{p_1 \cdot T_2}{T_1} = \frac{101325 \cdot 323,16}{296,16} = 110562,49 Pa \quad (H.7)$$

This will generate an overpressure of

$$p_2 - p_1 = 110562,49 - 101325 = 9237,49 Pa \approx 0,09 Bar \quad (H.8)$$