CHALMERS

Greenland Paddle in Carbon Fiber With a Split

Master's Thesis in Product Development

MUSTAFA BAYSAL

Department of Product and Production Development
Division of Product Development

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2011

MASTER OF SCIENCE THESIS

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ABSTRACT

Greenland paddling is a challenging sports as most of the outdoors sports are and the paddlers demand more and more specialized and advanced equipment in order to facilitate their experience and to be able to take the challenge.

The demand for advanced equipment in Greenland Paddling led to the introduction of paddles made up of carbon fiber which give a great advantage of lightweight and strength. On the other hand, the length of a paddle combined with the mobility demand of the paddlers created the need for a detachable paddle. The purpose of this study is to develop a detachable version of an already existing carbon fiber paddle developed by *Escape Outdoors* located in Gothenburg.

In the development process of this product, the first step was to investigate the market for competitive products and market opportunities in order to develop a background on the objective. The next step was to identify the requirement specification with a focus on the users/customers. Then multiple concepts were developed and evaluated using the tools provided by product development methodology. Selection of a final concept was followed by strain and stress calculations for the plastic snap fit and design for the final product.

Contents

Foreword

This is a report of a master thesis at the *Department of Product and Production Development* at Chalmers University of Technology. The work has been done for *Escape Outdoors* located in Gothenburg, Sweden.

I'd like to thank to my examiner Lars Lindkvist for his guidance and supervision and Andreas Dagman for his help in the project.

I'd also like to thank Sara Wagner and Peter Kane from *Escape Outdoors* and Erik Kullgren from *Elitcomposit* for sharing their expertise, creativity and contributions on the project.

Finally, my gratitude goes to my friend and colleague Çağlar Kurtuluş for his valuable opposition at my thesis presentation, his friendship and support during the project.

Gothenburg June 2010

Mustafa Baysal

1 Introduction

This master thesis has been carried out for *Escape Outdoors* located in Västra Frölunda, Gothenburg. The problem has been proposed to the department of Product Development by the company and it has been designated as a master thesis subject. In this section, the background of the company, the problem and the aim of the project will be described. The product development methodology used for the project will be exhibited in this chapter as well.

1.1 Background

Escape Outdoors is a company located in Västra Frölunda, Gothenburg since 1999. The activities of the company are mainly based on sea kayaking, caving, skating and other outdoor activities. They give courses, organize events and sell equipment to their customers throughout the year. Taking inspiration from the country of origin, Greenland, much of products and paddling technique is developed. The shape and technique of Greenland paddles has created more and more interest among paddlers all around the world.

Hence, *Escape Outdoors* is planning to provide their customers with more Greenland kayaking experience and they are introducing a Greenland paddle made up of *carbon fiber reinforced polymer* (CFRP) for their customers. The advantages brought by having the traditional Greenland paddle made of CGRP are eliminating the dependence on good quality wood and carving skills, bringing the advantage of mass production and having an identical product with a stable quality once the perfect paddle design has been established. For the sake of simplicity, CFRP will be mentioned as carbon fiber shortly.

1.2 Problem description

One needs to have lots of gear to be able to do sea kayaking, but the two most important equipments needed for sea kayaking are the paddle and the kayak itself. Most of the time, the equipment needs to be either transported or stored close to sea since not everyone lives by the sea. Besides, most of the people prefer not to own the equipment but rent it from companies like *Escape Outdoors*.

When it comes to paddling technique and performance, the paddle has a significant impact on the performance of the kayaker. Especially the unique shape of each paddle might vary significantly from paddle to paddle. There are many parameters affecting this variation on a Greenland paddle. These parameters are basically; the length of the loom, the cross section of the loom (grip), the deviating thickness and width of the blades, the length of the paddle and eventually the weight.

While there are so many parameters affecting the performance, the users most of the time can have their own paddle even though they do not own a kayak. Therefore, the paddle needs to be transported but the Greenland paddles can be very hard to transport because of their length exceeding two meters. A regular Greenland paddle with a length of 2.2 meters is nearly impossible to fit in a regular trunk or to bring inside a public transport like bus, metro or tram. There are detachable paddles of other types and having the carbon fiber Greenland paddle detachable as well is crucial.

1.3 Aim

The aim of this project is to investigate the needs of the user and design a mechanism that allows the carbon fiber Greenland paddle to fold, split or become as small as possible in any other means to give the user a better degree of freedom. The final product should allow the users to be able to travel with their paddles more flexibly. On the other hand, the product should be light, stiff, salt water resistant and durable to sustain many years. *Escape Outdoors* has already developed a one piece carbon fiber paddle which weight about 500 grams and the expected outcome of the project is to have a detachable variant of this model which will not require the manufacturing of a separate carbon fiber mold. More detailed specifications will be identified during the study.

1.4 Delimitations

This master thesis is a part of a project named "*Black Light Paddles*" which is owned by Sara Wagner from *Escape Outdoors*. The project includes the design, manufacturing and marketing of a Greenland paddle made of carbon fiber. The shape, design and manufacturing of the paddle itself are not in the context of this thesis work. The shapes of the blades are well defined through experience and there will be no optimization or other means of change in the form of the blades. The scope did only include the middle grip section of the paddle.

The final design will be a variant of the single piece, non detachable version. Nevertheless, the development of the paddle itself has been monitored throughout the process to be able to have the best understanding of the product.

Since the product is planned to be manufactured with a number of around 50 for the first year, the development will not be focused on mass production practices. The focus will rather be on tough performance requirements. Manufacturing of the carbon fiber paddle is outsourced from *Elitcomposit* since *Escape Outdoors* has no manufacturing capability. Manufacturing of the joint will be outsourced as well. Therefore, the design of the joint will be done as close as possible to the manufacturing stage but a detailed planning for manufacturing will not be done.

After some literature research and a meeting with the paddle manufacturer (Erik Kullgren from *Elitcomposit Ab*), it has been understood that carbon is likely to cause galvanic corrosion while in contact with engineering metals such as aluminum, steel, titanium, etc[1]. It is possible to avoid the corrosion by coating the metal insert by some nonconductive material (i.e. PET sheet) but, the process includes cost, risk of failure and it brings restrictions for both the use and the design. Therefore, concepts that will require to be made of metals are preferably avoided during the concept development process.

2 Theory

In this section, some information about Greenland paddling will be given in order to create a better understanding of the use of the product. Also, some more information about the carbon fiber manufacturing, polymer materials and injection molded part design will be given as it is related to the final outcome of the project.

2.1 Greenland paddling

It would not be wrong to say that all modern sea kayaks heritage, to a greater or lesser degree, from old Inuit kayaks which have existed around the arctic region for many centuries. These traditional kayaks were made of wood and skin and the main material for the paddles were the drift woods that they found in the sea. These Inuit kayakers from Greenland have developed very advanced kayaking techniques and it has been the main guideline for the modern local kayaking practices all around the world. The combination of these techniques and refined equipments let Inuit paddlers resist even the toughest conditions.

It should also be noted that it is not possible to say that there is only one proper kayaking technique or type of equipment such as paddle, kayak, etc. The technique and the equipment derive from region to region and each region has its own local environmental and traditional constrains [2].

2.1.1 The paddle

Greenland paddling has become very popular not only because of its authentic status. Thanks to its narrow blades, it's less vulnerable to strong winds and easier to roll with and there are different types of traditional shapes (Figure 1). The narrow blades are considered as an advantage because it brings less failure risk for the muscles during day-long trips as compared to "*euroblade*" type wide-blade paddles as seen in Figure 2.

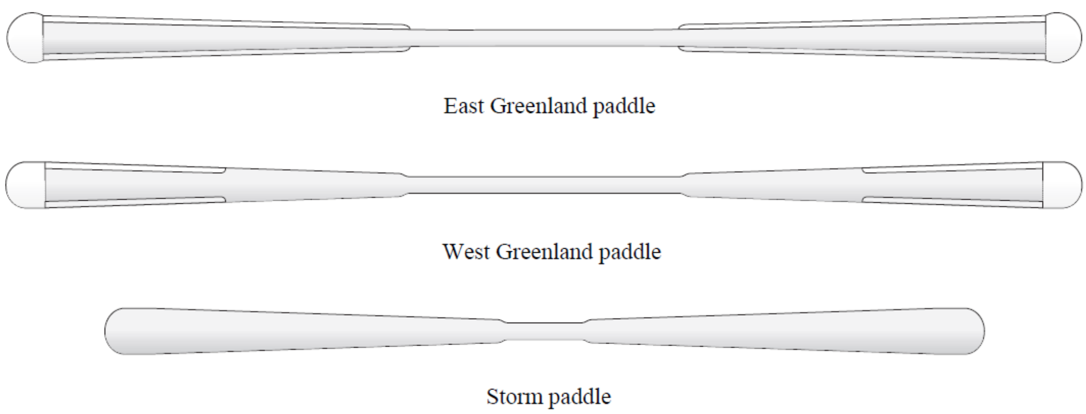

Figure 1: Traditional Greenland paddles

Figure 2: A user with a 'euroblade' paddle.

The blades are long and narrow, tapering towards the loom. The cross section of the blade is almost like a wing. The thinner it is in the end part, the better it is because it has an advantage when the blade enters the water. The width of the paddle is narrow because it is to be grasped by the paddler. The paddler slides the hands on the paddle and can grip the paddle from either the loom or the blade part. Thus, the connection between the loom and the blade should be as smooth as possible to let the grabbing hands to slide over and this connection is called "*shoulder*". The loom has an oval grip to let the paddler has the most comfortable use of the paddle. The length of the loom is to be between 1/4 and 1/3 of the paddle length [2]. The length of a paddle is dependent on the user and it can be calculated as "*an arm span and the distance from the elbow to the wrist*" [2]. As you can see in the Figure 1, the loom is shorter in a "*storm*" paddle while the blades are the same length. This type of paddle is for stormy conditions where the paddler will have to use the blade grip more often. The edges are traditionally made up of whale bones and the amount of bone usage differs from region to region. Most of the modern wooden paddles are made up of only wood.

2.1.2 Carbon fiber Greenland paddle

A carbon fiber paddle has the same outside geometry as the traditional wooden version. The difference is that it is made up of carbon fiber and that is hollow. The thin carbon fiber shell gives all the strength and integrity to the structure. However, the inside of the paddle could be filled with light density foam to have a better feeling during the use in terms of weight, noise and vibration.

There are different methods to manufacture a carbon fiber paddle in the market. As the paddle is symmetrical both from the loom section and within the blades, it is possible to manufacture four (or two) identical parts and join them together by using solvents or adhesives. Another method, which *Escape* *outdoors*' paddles are made by, is using a long tubular carbon net to mold the carbon fiber composite. This method has a better result by making it possible to have a blade with smaller thickness. See Figure 3 for these paddles.

Figure 3: Carbon fiber paddles from Escape Outdoors

2.1.3 Paddling technique

There are many different kayaking techniques but it is possible to divide them into two different categories, namely *"forward stroke techniques"* and *"capsize recovery strokes"*. The strokes are described below due to their relation to the project in terms of the handling of the paddle [4].

Forward stroke is the stroke when the paddler is cruising in forward direction. The main techniques for this type of strokes are *"long distance forward stroke" (Figure 4)*, *"sliding stroke"* and *"sprint stroke"*. In both *long distance forward stroke* and *sprint stroke* the hands of the paddler are located on the edges of the loom right next to the shoulder part and the difference comes by how the blades are stroked in the water.

Figure 4: Long distance forward stroke

In *sliding stroke,* one hand grasps the paddle from the tip of the blade and the other one right next to the middle of the loom. At the next stroke, the hand on the blade slides through the loom and meets the other hand while the other hand slides to the other tip. This type of stroke is better to do with the shorter paddle which is the *storm paddle*. Figure 5 is depicting a sliding stroke.

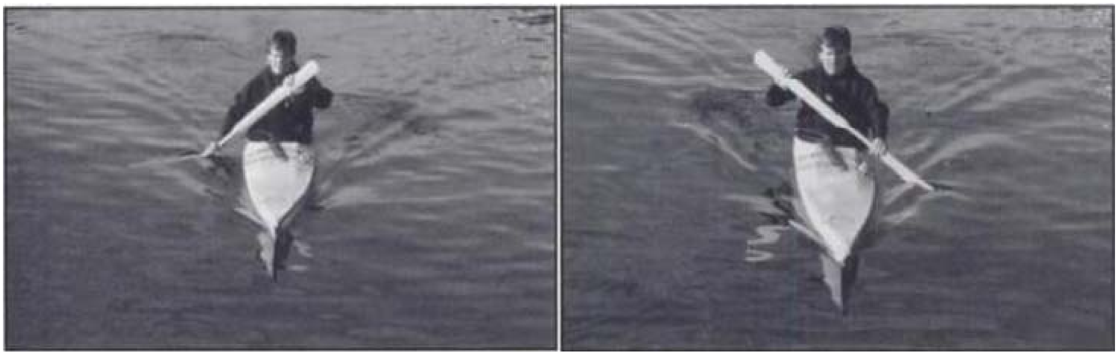

Figure 5: Sliding stroke [5]

The other group of strokes called "*capsize recovery strokes*" is the stroke techniques that are used when the paddler needs to get out of the water if the kayak is turned upside down (capsized) because of strong wind, waves, etc. This type of stroke is very critical for the safety of the paddler and making this sort of strokes are a subject of a challenge in the kayaking world. Kayakers train these strokes to test their abilities, strength and condition. Even though there are many different types of *recovery strokes* the handling of the paddle is similar. One hand being on the tip of the blade, other hand is on the loom, located close to the *shoulder* of the same blade. See Figure 6 for *recovery stroke*.

Figure 6: Recovery stroke

Besides all these techniques, rope gymnastics are another major thing that paddlers do to train themselves in terms of balance and strength. You can see a paddler executing rope training in Figure 7 below.

Figure 7: Rope training [3]

2.2 Carbon fiber reinforced plastic (CFRP)

CFRP is a composite material with extremely high *relative strength,* which means that it's a very light and strong material. It is used widely in the high performance demanding applications such as aerospace industry, racing industry, sports equipments, sailing, etc. This is because of its high relative strength and low thermal expansion [6]. CFRP is often recalled with the name of its filament material, i.e. "carbon fiber", in the market.

A composite is composed of a filler and matrix. In CFRP, the filler is very tiny fibers composed of neatly aligned carbon atoms and crystals. These carbon fibers have extremely high tensile strength along the fiber direction. Carbon fiber can be commercially found as a thin fabric. A picture of a carbon fiber woven is depicted in Figure 8 below. While the carbon fiber is the filler, the polymer matrix could be epoxy, polyester, nylon, vinyl ester, etc. but the most common material for the matrix is epoxy.

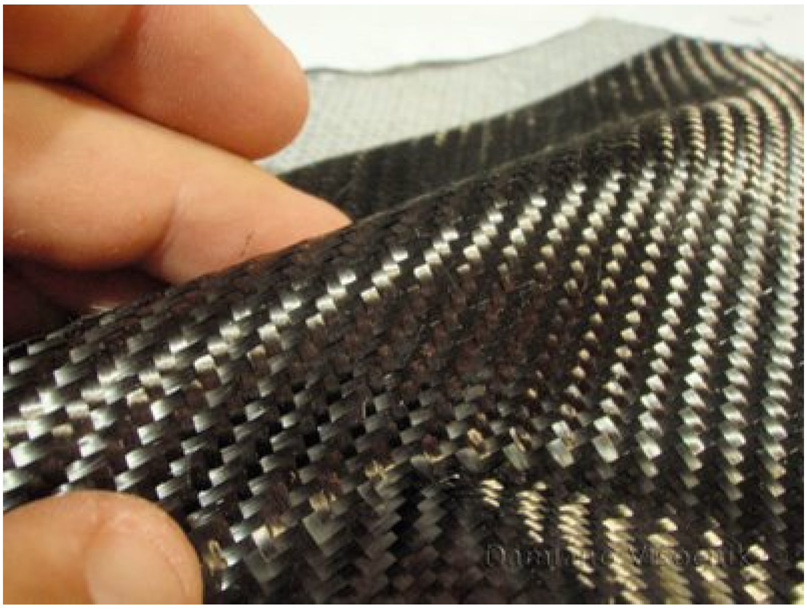

Figure 8: Carbon fiber woven

The process of making CFRP parts depends on the part geometry, desired mechanical properties, scale of manufacturing (unit/day), price, etc. The basic process is as follows; a mold which will give its shape to the part is made up of various materials such as fiberglass, aluminum, etc. Then, some release agent and resin is applied to the molding surface and the carbon fiber fabric is put in to the shape of the mold by applying more liquid resin.

This process might be repeated to gain more layers depending on the desired strength of the composite. In some applications, fiberglass might also be applied together with the carbon fiber. After applying the desired number of layers and material, the mold is vacuumed by using a vacuum bag or a counter mold. The vacuum is very crucial in order not to have any air bubbles and extra resin at the surface or between the layers. Some trapped air might cause serious esthetic and structural defects on the final product. As the last process, the pressurized/vacuumed part is heat treated in the oven to have the final product [7].

2.3 Plastic part design guidelines

In this section, some guidelines to be followed while designing plastic parts will be shortly summarized from the related literature. Since the final result is an injection molded *"snap fit"* part, the emphasis will be on that type of products. Plastic part design as a whole is beyond the coverage of this thesis but the following sources have been used as guidance and are strongly recommended to be read before starting a plastic part design.

- *Joining of Plastics: Handbook for Designers and Engineers, Jordan Rotheiser87]*

- *Engineering Polymers – Part and Mold Design – A Design Guideline, Bayer Corporation[9]*

The chart in Appendix 1 summarizes the plastic design guidelines visually.

2.3.1 Avoiding part distortions:

Having the plastic parts not fitting properly is a common problem and the most common reason to this problem is the part distortions that occur after molding the part. However, it is possible to minimize these defects by following simple design guidelines.

The very basic reason to this problem is the improper cooling of the part. The cooling of the part should be uniform all around the part. The very basic precaution to be taken against non uniform cooling is to avoid "thickness variations greater than 25%". This rule applies more to thermoplastics that have high post molding shrinkage rates. However, reinforced plastics get less affected from this phenomenon [8].

2.3.2 Inside corner stress:

Avoiding non uniform wall thicknesses is not the only concern while designing a plastic part. Sharp inside corners also have high contribution to high level stress concentrations. Figure 9 describes how the inside radii affects the stress concentration on the corner section of a snap fit cantilever.

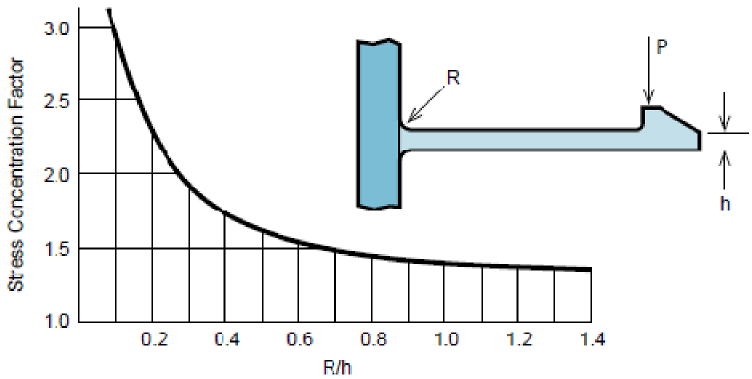

Figure 9: Inside radii effect in a snap fit cantilever [9]

Besides, coherent to the uniform wall thickness rule, inside and outside radii should be compatible so that the uniformity is kept.

2.3.3 Draft (Locking effect):

A molded part needs to be ejected from the mold and the surfaces tend to stick to the mold surface. Moreover, there is a post molding shrinkage which can make the part harder to eject from the mold. The part will eventually be able to eject from the mold but it will take time to wait for the part to cool down so that it withstands the ejection force. This adds up cost to the process since the molding cycle per piece becomes longer. This problem shows itself especially when there are ribs because ribs create extra contact surface. The guidelines to avoid locking effect are; give a minimum of 0.5 degrees of draft angle, the distance between two ribs should not to be less than twice of the wall thickness and ribs should not be so thick that they would result in mold shrinkage, cavity and shape distortion [9]. Figure 10 illustrates common draft guidelines.

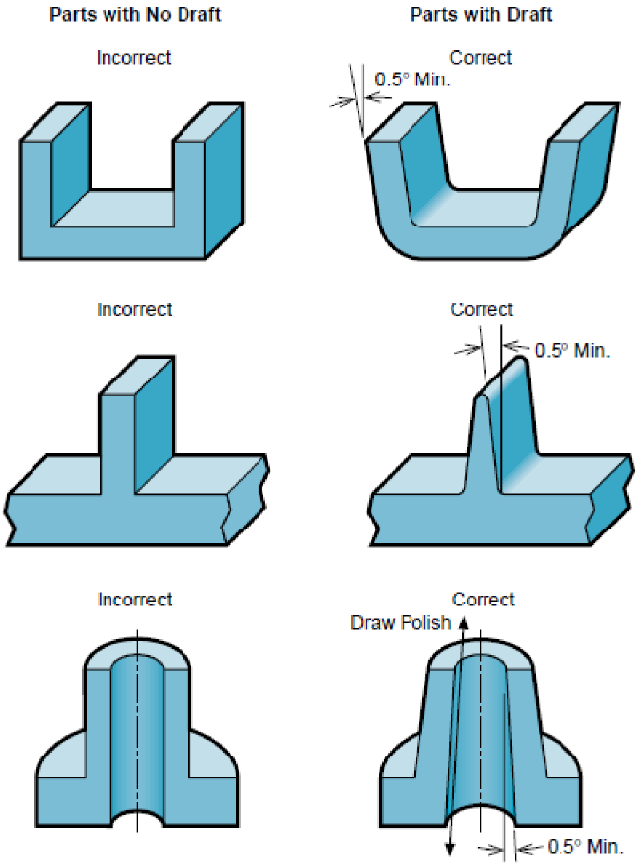

Figure 10: Common draft guidelines [9]

2.3.4 Shrinkage:

A molded plastic part of course expands and contract due to temperature changes like all other materials in the nature. When this occurs after the part is ejected from the mold, it is called *"post molding shrinkage"*. Even though the part reaches the room temperature, this shrinkage does continue sometimes and it might take from two hours to a week depending on the type of the material molded. The basic guideline in this matter is to *"wait 24 hours before performing any machining operations more precise then edge or gate trimming" [8].* This principle applies for assemblies as well, but in some cases the shrinkage might be an advantage like if the part is a female fitment so that the part shrinks to grab the male fitment [8].

The dimensional calculations against the post molding shrinkage are often made by the mold designer but it is wise if these guidelines are taken into consideration by the part designer as well [8].

3 Methodology

There are many methods and different approaches in the product development process. Product development tools from various sources[10,11,12] has been used in different stages of the process and each one has been described in this section.

3.1 Pre study

At this first stage of the project the main idea is to get to know the problem and the market through literature search and benchmarking.

3.1.1 Literature study

The literature study is conducted in order to collect information about a topic, theory, phenomena or any information regarding the problem. Having the correct information when it is needed is crucial during a development process. The sources of literature search could be internet, printed literature or expert consultancy. Even though the literature search is the initial step of a development process, it is also dispersed throughout the whole development effort.

3.1.2 Benchmarking

Benchmarking is used to probe the existing products with the same or similar function and to understand the capabilities and specifications of especially the best ones on the market. It is not necessarily an obligation to look for products with exactly the same function or only the best ones. It is sometimes a useful practice to look out for products of completely different use but a slightly similar function to get inspired. The main point is to be able to develop a better background to trigger a creative concept development.

A patent scan could also be included in benchmarking. It might be the situation that an idea has been patented but not implemented on an actual product. Having a final solution which has already been patented is a risk that a development team should try to avoid.

3.1.3 User analysis

The most critical stakeholder of a development project is the user. The literature suggests various methods to capture the ideas, wishes and demands of the user and these methods can give either qualitative or quantitative outputs [10]. Interviews and observations were the most obvious methods used during the project to gather user information in order to create the requirement specification.

3.2 Concept development methods

Concept development is a process which most of the time demands high level of creativity and innovation. There are many approaches to innovative thinking. These approaches are either systematic or random practices. The methods used during this study are described below.

3.2.1 Image board

An image board is a tool to trigger the imagination by having some pictures, sketches, colors, etc., that can represent or be associated with the intended solution, on a poster. Image board can also be called as mood board in the literature. An image board is more like a tool to use during brainstorming or other creative sessions.

3.2.2 Brainstorming

Brainstorming is an activity where all the ideas that might relate to the solution are shouted out. The purpose of brainstorming sessions is to increase the creativity in the project. These sessions need to be done as a group. The quality of the ideas should never be subjected to judgment and quantity is more important than quality during idea creation. It is useful to have someone experienced to lead the session. Even though it is a group activity, the person who leads the session should give some limited individual time to enable the participants to think. Having people from different backgrounds is always a plus for brainstorming.

3.3 Concept elimination

Following the development of concepts, the concepts should be evaluated and a decision of a final concept for further development should be made. This is a very important stage of the development of a product and special care should be given accordingly. The tools listed below are used to do so during this study.

3.3.1 Weighting matrix

Each criterion in the requirement specification has a different importance. Hence, to have a fair judgment of each criterion a *weighting matrix [11]* is used. The criterions to be used for elimination are created by analyzing and deciding the most important criterions in the requirement specification. This decision making requires a fine understanding of the product and the needs of the customer. In a weighting matrix, each criterion is scored against each other and a final weighting score for each criterion is calculated. It should be noted that it is better to use this tool as a group of people rather than an individual.

3.3.2 Kesselring matrix

A *Kesselring Matrix [12]* is a main tool for concept scoring. The criterions retrieved from the weighting matrix are applied in the matrix and each concept is given a score by the group in each criterion in a specified range. Then, the scores are multiplied by their weightings and weighted scores are obtained. The sum of the weighted score gives the final score of each concept and the decision making is straight forward from here since the highest score is the winner one. Depending on the project and the concepts, this elimination process can be repeated or more than one concept can be chosen to go for further development.

4 Development Process

During the development process, the methodology from the book 'Product design and development' [12] was used.

4.1 Requirement specification

Requirement specification has been the very ground of the development effort throughout the whole project. The specifications were carefully prepared in order to not miss any needs and requirements from the users. While defining the requirements both the needs of the customers and the competitive products have been kept in focus. The learning process was dispersed throughout the whole process and the requirement specification was updated continuously. Please see Appendix 2 for the complete requirement specification.

4.1.1 Benchmarking

Primarily, a benchmarking was made to discover the competitive products or products with similar function. The project was in the end, a split design for a tubular carbon fiber structure. After a long search through the internet, the information is merged with the market experience of Escape and the number of similar products found in the market was very limited. While the rest being "*euroblade*" paddles, only one of the products was a carbon fiber Greenland paddle with a split. The split of this paddle was very stiff but it was almost impossible to open it because of the friction caused by the carbon fiber material used for the split. A similar concept is included in the *Kesselring matrix* where the concepts were evaluated against each other.

Luckily, some of the other *euroblade* paddles with splits were available at Escape and we were able to investigate the products to be able to reflect their performance to the requirement specification. In the end, the main goal of the project is to have a product superior to the competitor ones and investigating the competitor products became important at this point.

4.1.2 User study

Besides benchmarking, a study of the user was also made to get the complete requirements specification for the product. Since it was winter, it was not possible to observe the users in real life but fortunately a lot of videos, blogs and other sources of digital materials were available to observe the users and reflect on their needs to the specifications. One should especially go to the webpage of the "*Qajaq USA*" [3] (American chapter of the Greenland kayak association) if any information about kayaking is required. As it has been mentioned before, kayakers are spread all around the world and there is a very strong sharing among each other through internet. Sara Wagner from *Escape Outdoors* was also very helpful with her solid expertise on kayaking. Expert consolidation is always an important source of information and it has been so for this thesis work.

4.1.3 Criteria comments

Many criteria were identified and they were marked as "Wish - W" or "Demand - D" in the requirement specification table. The criteria were grouped according to the different areas of the products life cycle that they are related to. Each group of criteria was briefly described below. Please see Appendix 2 for the complete requirement specification table and Section 4.3 for a discussion on the requirements.

Design

The weight of the whole product is very important for the paddling performance and the total weight should not exceed 650 grams. The product should be resistant to dust, sand, sweet water, saltwater and ice.

Manufacturing

The split design should be in line with the manufacturing of the carbon fiber paddle. The extra cost for the manufactured split should not exceed 1500 SEK.

Transport

Since mobility is a main goal, the final product should be possible to take into an airplane or fit in the car trunk.

Installation

Installation/attachment of the split should be possible by one person and it should not require an extra tool to do so.

Use

The split should not ruin the smoothness of the loom. It should be safe enough that it does not split by accident. The split should be rigid and be resistant to shock which might be caused from dropping the paddle. It should not let water in the paddle so that the paddle could float on the water.

Maintenance

The split should be in line with the 10 years life expectance of the paddle itself and it should be possible to replace the split joint in case of a break down. The split should not require more maintenance than simply rinsing it with fresh water.

4.2 Concept development

As it has been described in the methodology section, brainstorming was the main tool used for concept generation. Since the intended split has a simple function, making a functional decomposition and using a morphological matrix was not viable. One could go to the related literature to learn more about the tools such as functional decomposition a morphological matrix and its benefits for concept development.

Instead, some brainstorming on means of function and means of solution were conducted and some results from the brainstorming sessions can be found in Appendix 3.

The concepts developed as a result of brainstorming sessions are visually depicted and textually described below. The reader should also note that there have been more concepts developed but only the ones that are obviously more promising have been included in the process. All the concepts mainly composed of two plastic parts to be welded in the tubular loom part of the paddle. The welding is intended to be done by adhesives which most of the time give quite good results while bonding most of the polymers with carbon fiber[8].

4.2.1 Concept 1: The Screw

The simplest description of "The Screw" concept would be a screw – nut mechanism. The two plastic parts are connected by the thread on both parts. There is an O-ring placed at the tip of the male part which is intended to help the parts to grab each other more firmly. The O-ring also has the function of creating a certain amount of friction which helps preventing the parts to be unscrewed. Apart from the O-ring, there is a locking mechanism which will lock the two parts on to each other on their final exact position so that the parts are aligned properly with respect to each other. This is a promising concept but the biggest weakness of this part is the risk of failure at the locking mechanism which has to be considerably small for the possible loadings. Figure 11 demonstrates the concept.

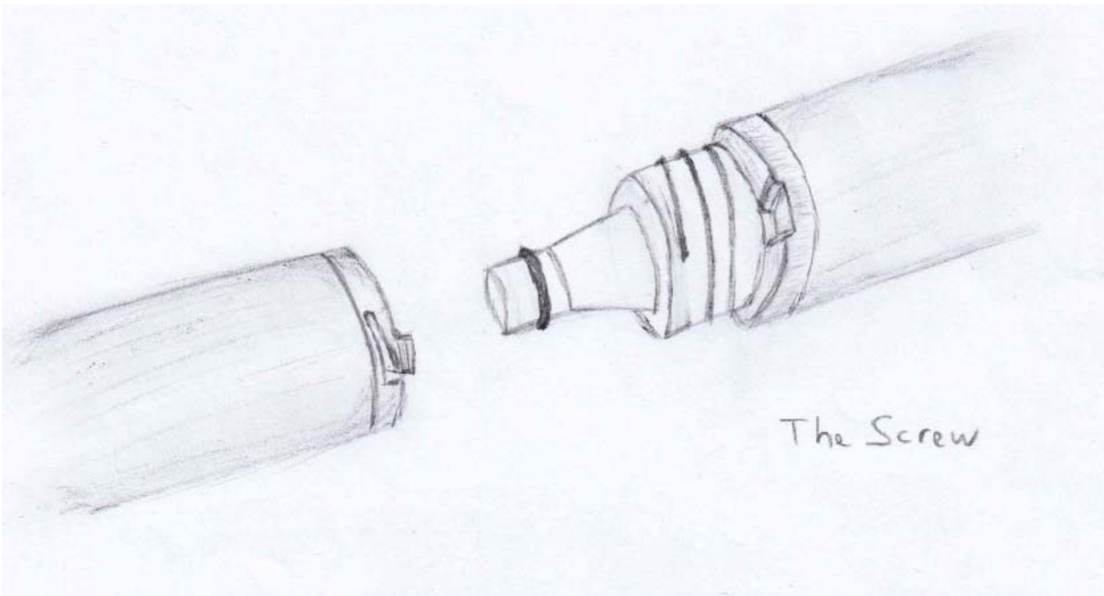

Figure 11: "The Screw" concept

4.2.2 Concept 2: Pin Button

This concept is very similar to the product from *"Superior Kayak & Canoes"* but the difference is in the material used. The product of *Superior* has a split which is made of carbon fiber and the large friction between two parts is a big problem. A split that is made of a proper material should give a better result. The mechanism is simple. Two parts are joined to each other through another tube inside and this tubular connection is fixed against moving along or around the longitudinal axis of the paddle. The pin has a spring mechanism to make it function as a button but having this little pin mechanism with moving parts and possibly metal parts (which might corrode easily) has been considered as a weak point of this concept. Figure 12 depicts the concept below.

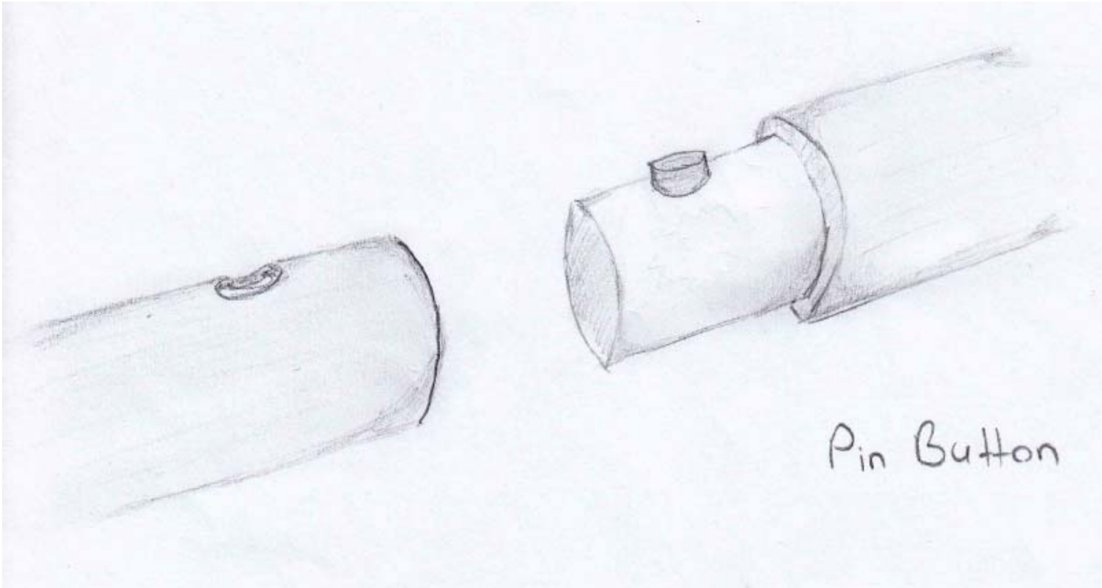

Figure 12: "Pin Button" concept

4.2.3 Concept 3: Padlock

As it can be understood by the name, the "Padlock" concept is inspired from pad locks. The male part is simply plugged in the female part. Inside the female part, there is a mechanism that holds and releases the pad lock edge of the male part. Just like in the screw concept, there's an O-ring which will help to have a better grab between each part. The button is used to release the male part and it is embedded in the loom to have a smooth surface. The weak part of this concept is the moving parts inside and the high risk of these small parts to get broken. See Figure 13 for a sketch of the concept.

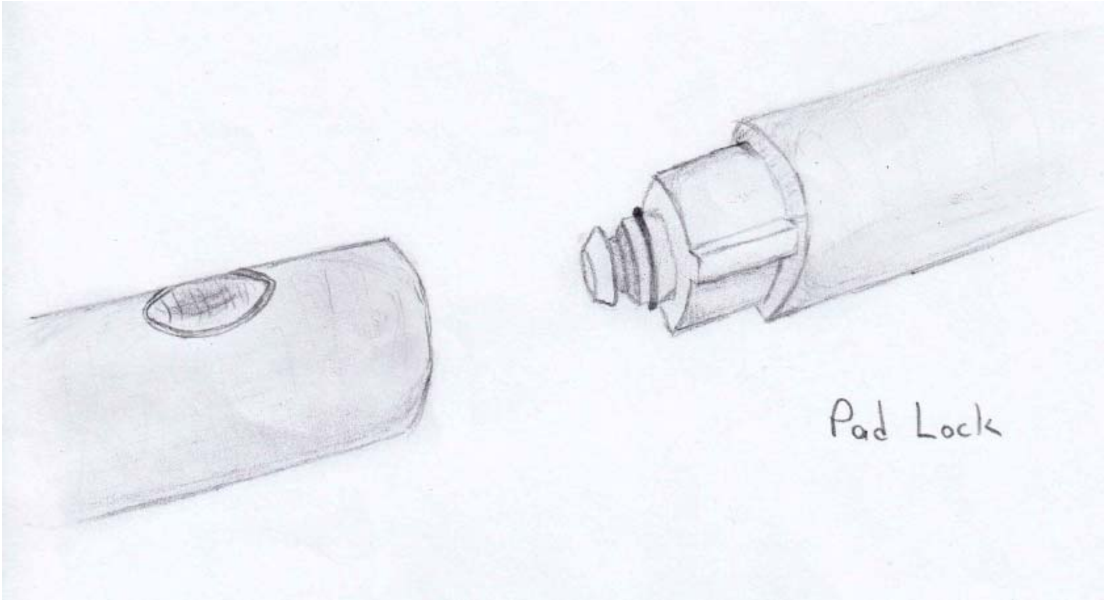

Figure 13: "Padlock" concept

4.2.4 Concept4: Push and Release

As you'll see in Figure 14, this concept is simply a big snap fit mechanism. Snap fits are widely used for joining of plastic parts in the industry. There is a male part with the snap fit cantilevers and a female part which will act like housing inside the loom. The joining operation is simply done by plugging the parts into each other. The strongest side of this concept is that there is no moving part. This concept also has a O-ring to provide a better grab. The weakest part of this concept is that the cantilevers will need to flex frequently and it might create a risk of break down. Careful material selection and calculations are required to prevent any failure with this concept.

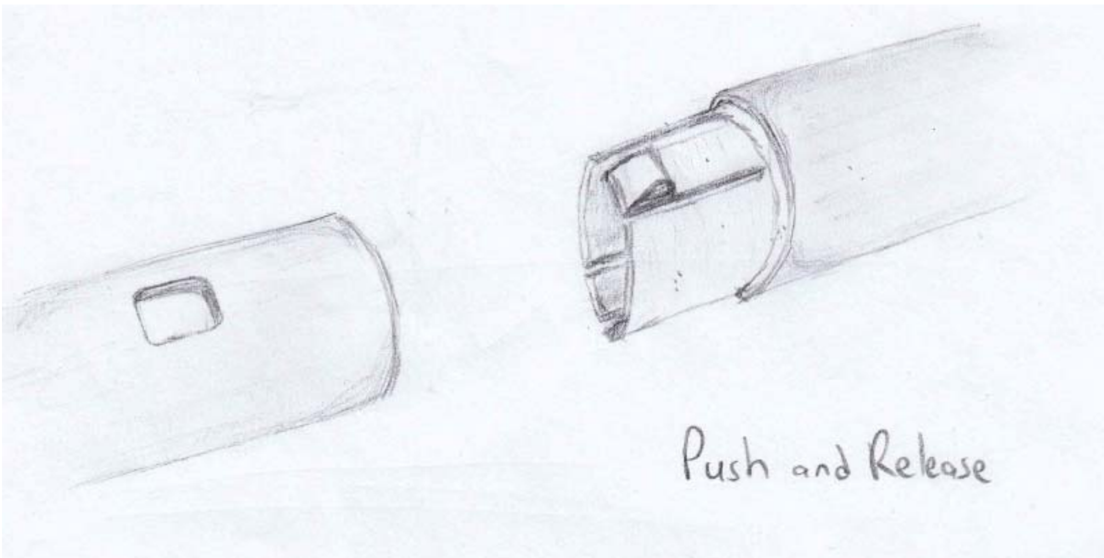

Figure 14: "Push and Release" concept

4.2.5 Concept5: Medicine Jar

This concept is inspired from medicine jars which you need to push before twisting the lid in order to open it. The push and twist mechanism is a way to prevent unintended split of the paddle. Inside the female part there is a guide way to guide the male fitment into place. In the bottom, there's a spring mechanism that helps the locking of the guided part in its place. The user should push the paddle to be able to release from this spring mechanism. This mechanism gives a great advantage with its simple use. The main concern about this concept is the spring part which needs to be made from metal to be able to provide enough push force. The problem of rusting being on one side, the manufacturing of such design would definitely be costly compared to some other concepts. See Figure 15 below.

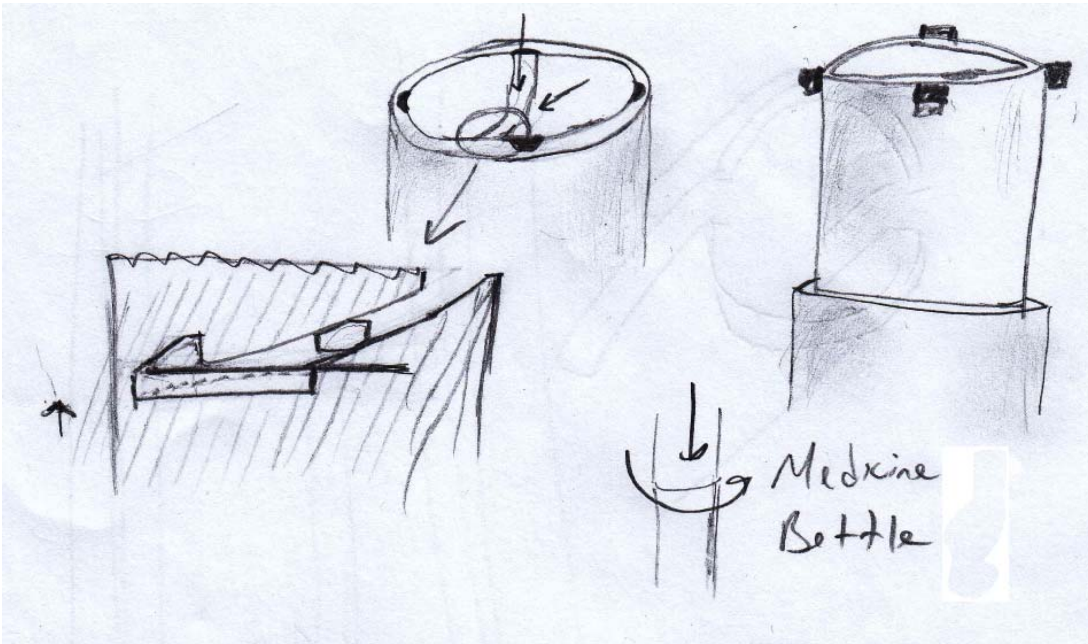

Figure 15: "Medicine Jar" concept

4.2.6 Concept 6: Friction Lock

In this concept (Figure 16), the user simply inserts the fitment in its part and fixes them by pulling the friction ring. The friction ring will press the outer part on the inner part and the friction between two parts will hold the parts together. This concept also gives us the advantage of setting the length of the paddle. Having only one adjustable model compatible for everyone would definitely have an economy of scale. But the main disadvantage about this concept is the loom which is not smooth. Another risk is the possibility of unintended split especially when we concern the wear that will happen after some period of using the mechanism.

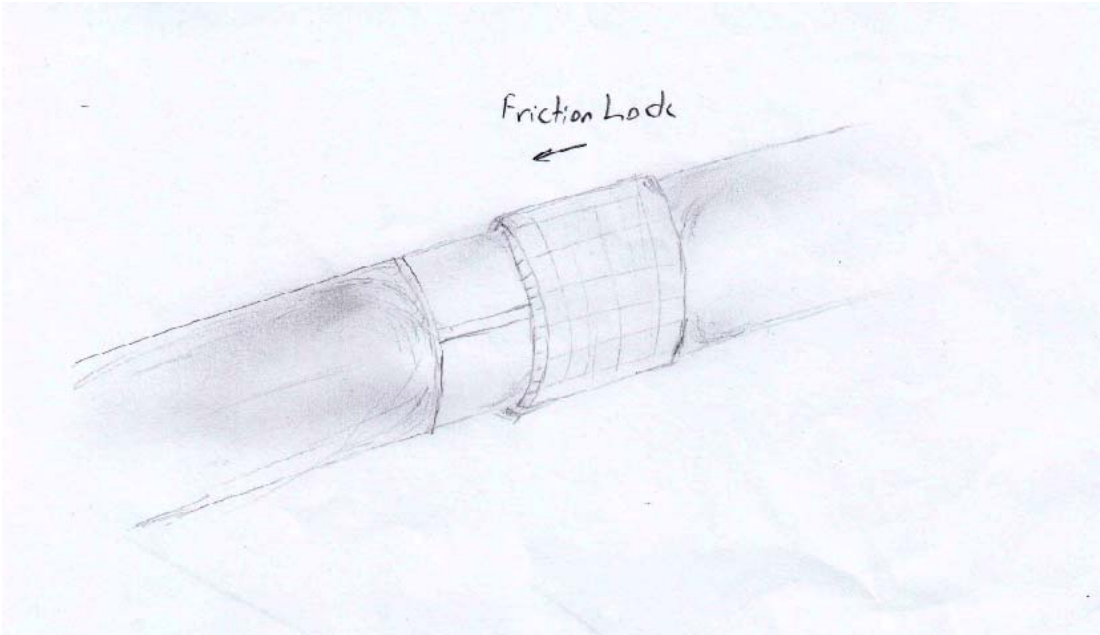

Figure 16: "Friction Lock" concept

4.2.7 Concept 7: Tent Pole

The tent pole concept is inspired by the foldable tent poles with an elastic rope inside the pole. One end of the rope is tied inside the female fitment. The rope goes through inside the male fitment and comes out of a hole at the male part. The user pulls the rope, winds the rope on the male part and jams it into a friction rope lock. During this operation, the user should hold both paddles so that there is a space in between to be able to reach the rope. After locking the rope in its place, the two parts are released and they are attached together by the tension of the rope inside. See Figure 17 below.

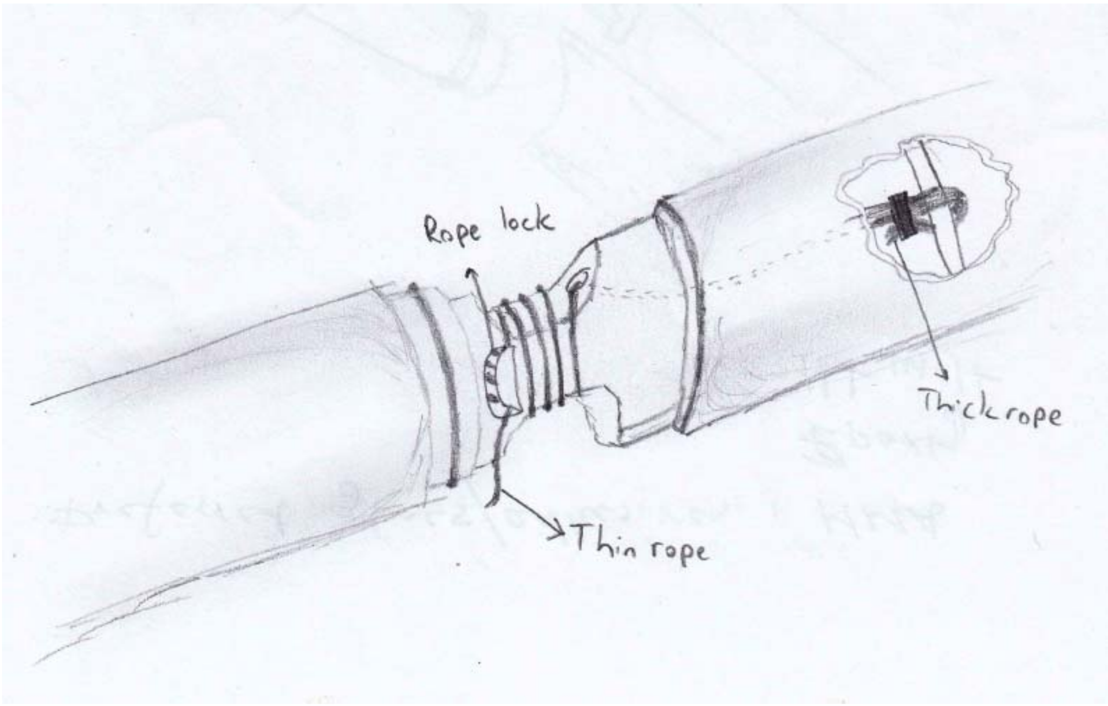

Figure 17: "Tent Pole" concept

There is also an O-ring which will function as a circular snap fit. The O-ring is supposed to prevent the parts from getting unattached easily. The best thing about this concept is that the kayakers are accustomed to use ropes and this operation might enhance the product familiarization for them. However, the possibility of such operation needs to be investigated on a prototype and the reliability and long lasting of the rope is a matter of question.

4.3 Concept elimination

Selecting the concept that fulfills the requirements the most was a critical part of the project. To do this challenging task, a "*Kesselring matrix*" was used. There were many requirements defined in the requirement specification and there was an important need to narrow them down to some criteria to be used for evaluation. Besides, the influence of each criterion was different and a "*weighting matrix*" was constructed to define this importance levels respectively.

The evaluation criteria chosen from the requirement specification and their weights are listed at the Table 1. The weights of each criterion we calculated by using the *weighting matrix* (Table 2) which will be described in this section.

Table 1: Weighting criteria

Weighting Criteria	% Weight
Dependability	10.98
Manufacturability	10.61
Durability	9.85
Smooth loom	9.85
Maintenance	9.85
Sand proof	9.47
Saltwater proof	9.47
Easy installation	9.47
Life time	7.95
Tool-free installation	5.30
Cost	4.17
Weight	3.03
Total	100

Most of the criteria listed above are very clear but some of them needs some interpretation to not cause any confusion. The "durability" criterion is if any of the parts defined by the concept can get broken by an impact or so.

“Dependability” criteria should be taken as, if the design was robust or involved the risk of unwanted split ups. The rest of the criteria are straightforward and easy to understand.

The *weighting matrix* that you see in Table 2 was helpful to understand the importance of each criterion. In the *weighting matrix*, each criterion were compared against each other and graded from 0 to 1. 0 meant that the evaluated criterion has no importance related to the criterion that it was being compared against, while 1 meant the opposite and 0.25, 0.5, and 0.75 were the given marks according to importance level. The weightings were decided as a group at *Escape Outdoors*. Finally, the weighting scores were concluded and the weight of each criterion was calculated as percentage. As you see in Table 2, “dependability” is the most important criterion while weight is the least important.

Table 2: Weighting matrix

Weighting Criterias	Weight	Durability	Sand proof	Saltwater proof	Manufacturability	Cost	Easy installation	Tool-free installation	Smooth loom	Dependability	Life time	Maintenance	Sum	% Weight
Weight	-	0.25	0	0	0.5	0.75	0	0.25	0	0	0.25	0	2	3.03%
Durability	0.75	-	0.5	0.5	0.75	0.75	0.5	0.75	0.5	0.5	0.5	0.5	6.5	9.85%
Sand proof	1	0.5	-	0.5	0.25	0.75	0.5	0.75	0.5	0.5	0.5	0.5	6.25	9.47%
Saltwater proof	1	0.5	0.5	-	0.25	0.75	0.5	0.75	0.5	0.5	0.5	0.5	6.25	9.47%
Manufacturability	0.5	0.25	0.75	0.75	-	0.75	0.75	1	0.5	0.5	0.5	0.75	7	10.61%
Cost	0.25	0.25	0.25	0.25	0.25	-	0.25	0.25	0.25	0	0.25	0.5	2.75	4.17%
Easy installation	1	0.5	0.5	0.5	0.25	0.75	-	0.75	0.5	0.25	0.75	0.5	6.25	9.47%
Tool-free installation	0.75	0.25	0.25	0.25	0	0.75	0.25	-	0.25	0.25	0.25	0.25	3.5	5.30%
Smooth loom	1	0.5	0.5	0.5	0.5	0.75	0.5	0.75	-	0.25	0.75	0.5	6.5	9.85%
Dependability	1	0.5	0.5	0.5	0.5	1	0.75	0.75	0.5	-	0.75	0.5	7.25	10.98%
Life time	0.75	0.5	0.5	0.5	0.5	0.75	0.25	0.75	0.25	0.25	-	0.25	5.25	7.95%
Maintenance	1	0.5	0.5	0.5	0.25	0.5	0.75	0.75	0.5	0.5	0.75	-	6.5	9.85%
													66	100.00%

After retrieving the weight of each criterion, the concepts were graded regarding to each criterion and the grades were put in the *Kesselring matrix*. All the criteria were put on the left hand side on the matrix and the concepts on the columns. For each concept, a grade from 1 to 5 was given depending on their performance on the matter. The grades were multiplied with their criterion weights and a final weighted score was obtained. The sum of all the weighted scores gave the total score for each concept. An imaginary concept was also created which is called the “*ideal concept*” which fulfills all the requirements to the full. While the *ideal concept* had a score of 500, the “push and release” concept became the winning concept with a score of 447.73 and was selected as the final concept for further development. Please see Appendix 4 for the complete *Kesselring matrix*.

4.4 Final Concept

Following the selection of the "push and release" concept as the final concept, further development of the concept were made. First, a preliminary design was made to be able to do some judgments about the material selection. Next, the material selection process was initiated. While selecting the material, the material selection guidelines from Ashby [6] were followed. The guidelines use are the ones defined for *deflection-limited design* and *spring of minimum volume* and the guidelines explained further in section 4.4.2. After the selection of the proper material, the final design was made. While designing the part, the plastic part design guidelines from Bayer [13] and Rotheiser [8] were used.

4.4.1 Design

The final design consists of two parts which are called "female fitment" and "male fitment". As you see in Figure 18, the male fitment embodies four cantilever snap fits with circular cross sections. The snap fits are extending from a support body which has an O-ring on it. The function of this body is to have a solid structure that is the foundation structure of the joint. It is not very obvious from Figure 18 but the shape of the support body is not exactly circular but oval in order to constrain the joint and prevent it from twisting around itself. The axial rotation could also be avoided by further geometrical constraints if necessary. The O-ring, which is simply a ring of an elastomeric material, has the function of avoiding the wobbly grab of the joint.

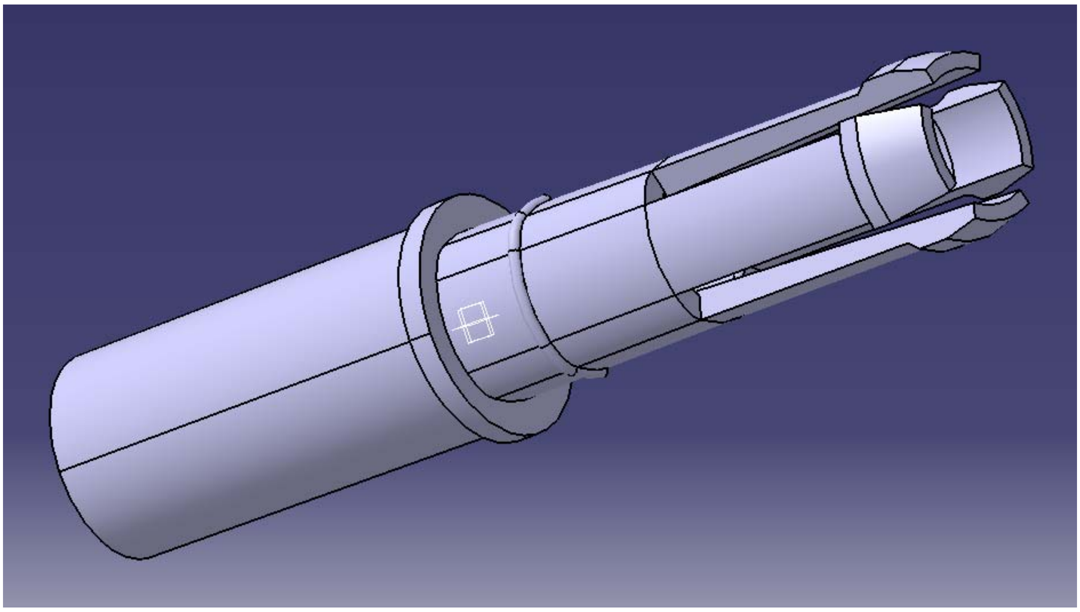

Figure 18: Male fitment

The snap fits that are located facing each other are identical, so there are two different snap fit types on the part. The snap fit which has 90 degrees of slope on its one side (Figure 19) is the type of snaps that can be reached from outside the loom surface. The user is supposed to push these cantilevers to be able to release the joint. The other two snap fits with 20 degrees of slope on their backs are the ones that can't be seen or reached from outside the assembly (Figure 20). These two snap fits require a pull force to let the mechanism to split up. The bigger the slope, the larger the pull force required to split up.

Given the geometry, another important thing about the design is about the plastic part design guidelines. The thicknesses, fillets and the draft angles for the walls are designed within the limits of the guidelines given by the related literature which has been described in the theory section already.

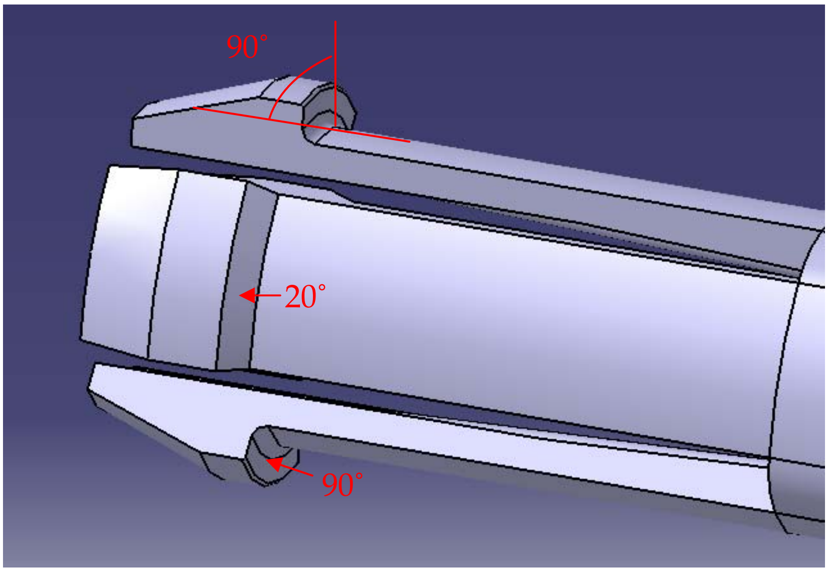

Figure 19: Cantilever with 90 degrees slope

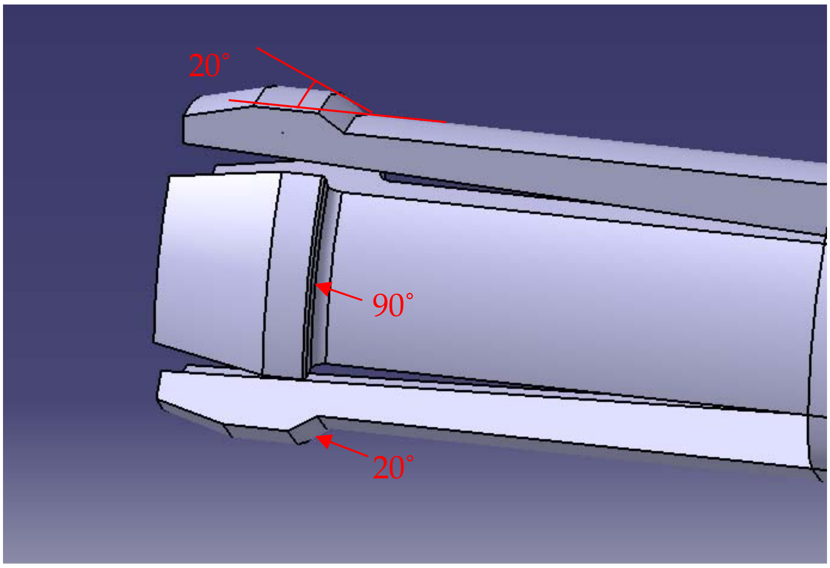

Figure 20: Cantilever with 20 degrees slope

Please see the Appendix 5 for some more snapshots of the design.

4.4.2 Material selection

The material selection was one of the most important parts of the design process. During the process, the first filtering of materials were made by using Ashby diagrams and then after having a narrowed down family of materials, a software from LANXESS (Bayer) named "Campus 5.2" were used to find the final material.

When it comes to snap fit design, the design is a *"deflection-limited design"* and a proper material that will allow the required deflection without a failure needs to be chosen [6]. On the other hand, a snap fit cantilever is sort of a spring and the chosen material should be able to *"store the maximum elastic energy per volume" [6].*

While choosing material for a *deflection-limited design*, Ashby suggests that the materials above the *index line* M_3 shown in Figure 21 are the proper materials. The calculation of the *index line* is done through failure strain calculation at equation (4.1). It has been seen that glass fiber reinforced polymers (GFRP) and such polymers as ABS, PA, PP and PC are suitable candidates for the job.

Failure strain:

$$\varepsilon_f = \frac{C}{\sqrt{\pi a_c}} \frac{K_{1C}}{E} \qquad (4.1)$$

ε_f: $Strain\ at\ failure$

C: $Geometry\ dependant\ constant$

K_{1C}: $Plane - strain\ fracture\ toughness$

a_c: $Length\ of\ largest\ crack\ contained\ in\ the\ material$

E: $Young's\ modulus$

So:

$$M_3 = K_{1C}/E \qquad (4.2)$$

The design guideline for choosing a *"spring of minimum volume" [6]* is defined as the materials lying below the *index line* of σ_f^2/E at the strength-modulus diagram (Figure 22). The *index line* has been achieved by using *"energy stored for the unit volume"* formula which is exhibited below in equation (4.3). In this context CFRP, GFRP and PA could make a good candidate for the purpose.

Energy stored for the unit volume: (block)

$$\mathrm{W_v} = \frac{1}{2}\frac{\sigma^2}{\mathrm{E}} \qquad (4.3)$$

$\mathrm{W_v}$:*Energy density*

So:

$$\mathrm{M_1} = \frac{\sigma_f^2}{\mathrm{E}} \qquad (4.4)$$

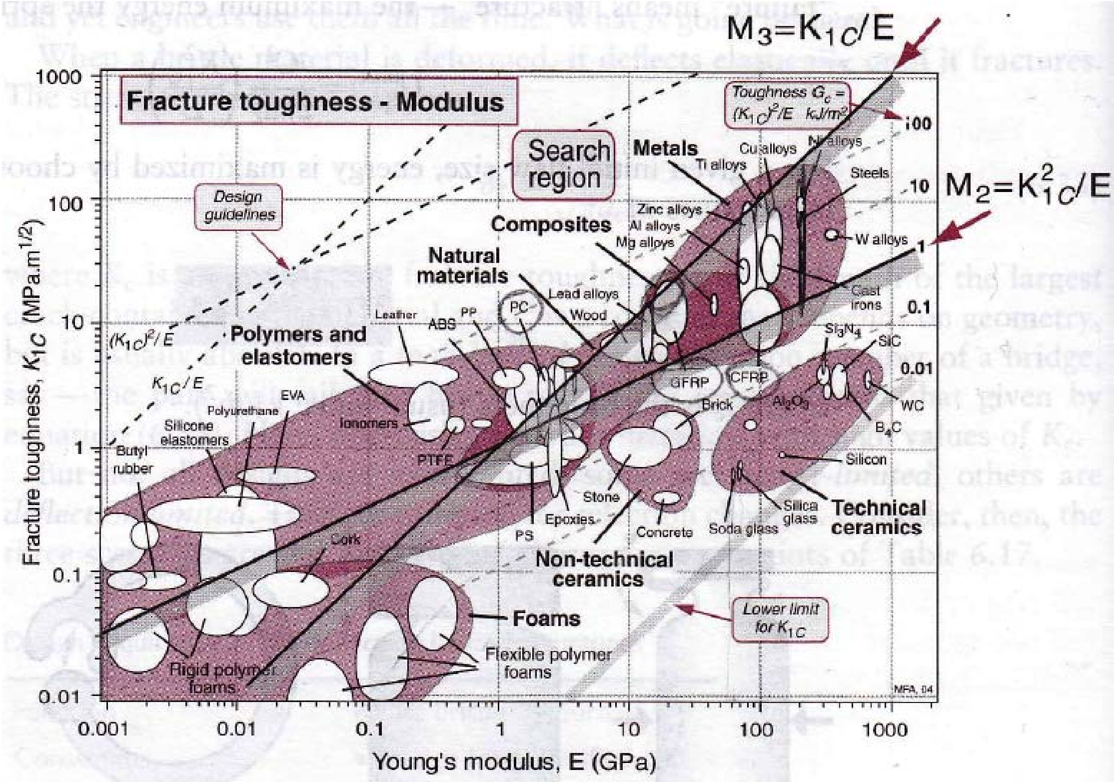

Figure 21: Ashby diagram for Toughness-Modulus [6]

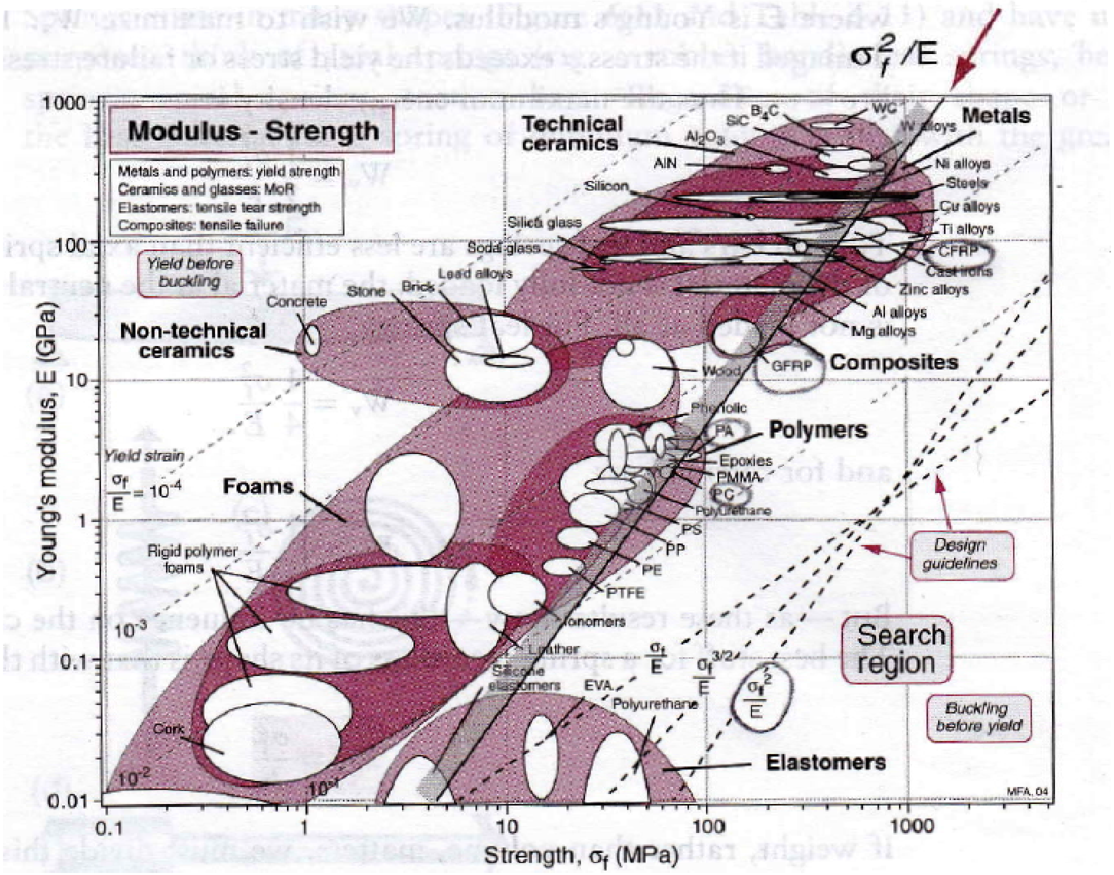

Figure 22: Ashby diagram for Strength-Modulus [6]

Combining the two results, some PA (polyamide) and some GFRP are the suitable material sub family. The further screening of materials was made on *Campus 5.2* and the most suitable resin for the job was chosen as a PA6 resin with mineral reinforcement. The commercial name of the resin given by LANXESS chemical company is "*Durethan® BM 240 H2.0*" and the datasheet for the material is provided in Appendix 6.

4.4.3 Calculations

Permissible deflection calculation for the snap fit cantilever (for repeated assemblies);

The deflection required for the cantilever to release [13]:

y = 3mm

So:

$$y = K * \frac{\varepsilon * l^2}{r_2} \qquad (4.5)$$

K: $Geometric\ factor$

ε: $Maximum\ permissible\ strain$

l: $cantilever\ length$

r_2: $Outer\ radius\ of\ the\ circular\ cantilever$

$$3mm = 2{,}5 * \frac{\varepsilon * 30mm^2}{16mm}$$

$\varepsilon = 0.021$

The Bayer's snap fit design guide states that the permissible strain for reinforced thermoplastics is half of the elongation at break. However this is recommended for single joining operation. For repeated assemblies, the recommended safe strain limit is 30% of this value [8]. So, elongation at break for the desired material should be equal or greater than;

$$\varepsilon_{break} = \frac{\varepsilon}{0.3} \cong 0.07$$

Elongation of break for the chosen material is 7% which is satisfactory.

Stress calculation for the snap fit cantilever:

$$P = Z * \frac{E_s * \varepsilon}{l} \quad (4.6)$$

P: $(permissible)\ deflection\ force$

Z: $section\ modulus$

E_s: $secant\ modulus$

ε: $(permissible)\ strain$

$l: length\ of\ arm$

$P = 20N$

$Z \cong 20mm^3$ (from Bayer design guide)

$\varepsilon_{permissible} = 0.021$

$l = 30mm$

So:

$$20N = 20mm^3 * \frac{E_s * 0.021}{30mm}$$

$$E_s = 1429\frac{N}{mm^2}$$

$$E_s = \frac{\sigma}{\varepsilon}$$

$$\sigma = 1429 * 0.021 = \mathbf{30MPa}$$

The yield strength of the selected material is stated as 85.6 MPa in the specs data sheet, so the design is expected to be safe for the stated load.

4.4.4 Finite element method analysis (FEM)

Since it was not possible to build a prototype because of some financial constrains in *Escape Outdoors*, FEM was the only available tool to test the final design. Some FEM analyses were made in the software called "Abaqus". The results of the analysis were helpful to approve the calculations made for the snap fit cantilever design. Results from the analysis showed that the empirical formulas provided by the literature were successful while designing the joint. The results from the FEM analyses made on the male fitment are as follows.

Pinch force analysis:

The first analysis made was to test if the cantilever will withstand the force applied to deflect the cantilever in order to split the paddle. The type of the grip will be "pinch grip" [14] and the optimum force that needs to be applied on the cantilever is estimated at 25N. This estimation was made depending on a previous study on the ergonomics of the grip forces [15].

As seen in Figure 23, a maximum Von Mises stress of 29.6 MPa in the inside corners of the cantilever was predicted from the analysis. The maximum expected stress was 30MPa according to empiric calculations so the safety of the cantilever has been verified. It should be noted that the displacement exhibited is visually exaggerated by the software which is a common feature of FEM software.

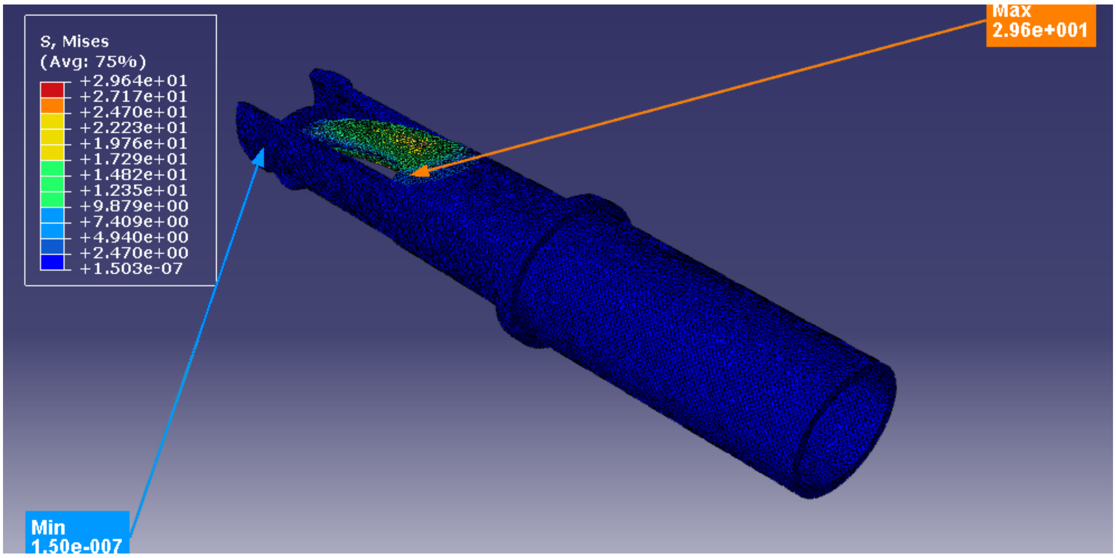

Figure 23: Von Mises stress

Pull force analysis:

The user study showed that there is not a lot of pulling of the paddle during the use but in emergency cases or such, the joint should be able to withstand a certain amount of load. The estimation of the force has been made for a 600N of static load on the direction of the length of the paddle. This load is assumed to be distributed evenly on four cantilevers and 150N of force was applied on one cantilever to test the durability of the male part. The result of the analysis is depicted in Figure 24.

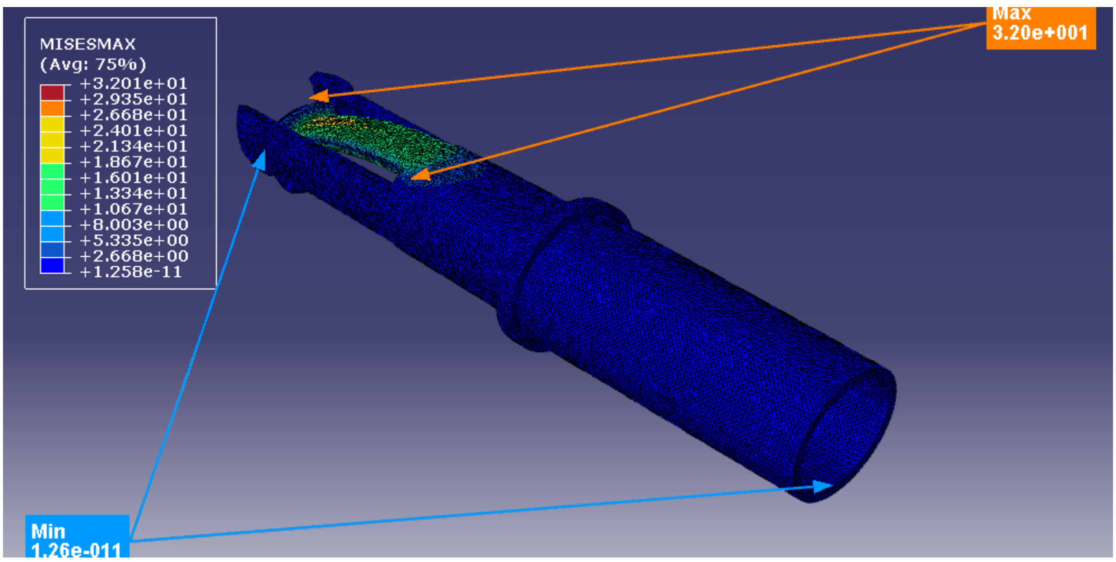

Figure 24: Von Mises distribution for pull force analysis

An attempt has also been made to test the stiffness of the assembly. Despite the considerable amount of time spend on the FEM model, the analysis made on the assembly resulted in errors many times. So, it was unfortunately not possible to provide a testing/validation for the stiffness of the assembly.

5 Results

5.1 Evaluation against specifications

Overall, the final design meets the following "Demands" that are perceived as the most important ones and took place in the weighting matrix for evaluation.

Dependability: The split mechanism is expected to be safe and dependable. The calculated forces required for disassembling the split makes is highly unlikely to have an accidental split of the parts.

Manufacturability: The material and the final design have proven themselves eligible for manufacturing. Fine refinements by the manufacturer on the design should be expected and are acceptable due to their broader view and expertise in the area.

Durability: Relying on the design guidelines provided by the material supplier, the concept has proven itself to be mechanically reliable. However, it was not possible to build an actual prototype and do real time testing.

Smooth loom: The plastic parts has the same profile as the loom and the holes provided to access the snap fit cantilever represents no obstacle for the user to slide hands on the loom.

Maintenance (replaceable): The adhesive attachment of the part makes it very easy to drill out the broken part and replace it with a new one.

Sand proof: The assembly is predicted to be reasonably forgiving among sand and dust due to the nature of plastic parts. However, validation of the criteria is subject to real life testing.

Saltwater proof: Plastic parts and the adhesive glue has no risk of corrosion or degradation when exposed to salt water.

Easy installation: The ease of installation is one of the strongest features of the "push and release" concept and the requirement is met more than desired.

Life time: The life time of the plastic part and the adhesive bonding is definitely more than the specified "10 years life time" question. However, the durability of the snap fit cantilever is a matter of user 's practices and real time testing.

Tool free installation: Installation only requires a pinch force by hand. The pinch and pull force calculations of the snap fit design has theoretically proven to meet the requirement.

Cost:

The cost estimation was made by using an online estimation tool for plastic injection parts [16].

Tooling cost estimate: $14830

Material cost per part estimate: $0.23

Process cost per part estimate: \$0.73

Assuming that there would be a production of maximum 400 pieces, the total cost per part will be;

(14830\$/400)+0.23\$+0.73\$ = 38.035\$

Considering that the requirement for the price is 1500SEK (240\$ approx.), the price estimated cost meets the specifications.

<u>Weight:</u>

V1(Female part) + V2(Male part) 4.285 E-005m^3 = Vt

2.525E-005m^3 + 4.285 E-005m^3 = 6.81 E-005m^3

Density of the plastic: d=1460 kg/m^3

Mass = Vt *d = 6.81 E-005m^3 * 1460 kg/m^3 = 0.0994kg = **99.4g**

Since the total weight requirement is 650g for the entire paddle, 99.4g of weight for the joint leaves 550g weight limit for the paddle itself which is about 50g more than what the one piece paddle weights.

5.1.1 Delighters

In addition to meeting the requirements the design has some delighters such as; not having moving parts, not requiring any special tools for installation, haptic feeling of installation and no maintenance requirement. The paddle might be taken into an airplane as well but taking it in to the cabin depends on the specific airline and airport regulations.

6 Discussion

The aim of this project was to develop a detachable version of an existing one piece carbon fiber paddle. The scope of the study was on the development of the split mechanism only.

There were some limitations on the projects as a result of *Escape Outdoors* having no manufacturing capability and the split mechanism would only be manufactured by a third party manufacturer. Hence, the detailed design for manufacturing of the snap fit joint was not included in the study. A manufacturer with the expertise of injection molded plastic parts would naturally come up with a better final design for the same "push and release" concept.

The cost estimation was also made with the help of minimal expert opinion. An expert in the area would definitely make a more accurate estimation for the cost. However, the estimated cost is around 15% of the maximum limit set by the requirement and this still leaves a lot of space for the uncertainty of the estimation.

The validation of some critical requirements such as shock proof and the rigidity of the assembly were limited to theoretical studies. Despite the fact that the chosen plastic is a shock grade material, it's very important that the *shock proof* requirement is validated via mechanical testing of a prototype. Same thing goes with the *rigidity* requirement.

The only weak point of the concept is the risk of breaking the snap-fit cantilever by applying a load greater than 70N which has been stated as the maximum load limit. This issue could be avoided by simply putting a stopper between two adjacent cantilevers so that the deflection would be limited to a specified safe limit.

The *push and release* concept has been chosen as the final concept and went under further development. However, *tent pole* and *pin button* concepts have been ranked as the two highest after the first one and they would have been developed further and exposed to a second elimination if the time and resource provided. A single phase and slightly more narrow development funnel had to be chosen for the nature of the project.

7 Conclusion

The result of the project meets the goals stated in the project description and largely satisfies the requirements specified. These results have been verified via calculations, material property and FEM analysis. *Push and Release* concept is a very unique concept among other designs available which would give a serious advantage to *Escape Outdoors* in the market through *product distinctiveness*.

The absence of a functional prototype and real time testing was a real issue in the project. Building a prototype and testing would definitely be the next step in the project. Nevertheless, the absence of a prototype highlighted the importance of simulation tools, such as FEM, in the product development process.

The development process of the project has once again proved the importance of the *supplier involvement* in product development process. Defining possible suppliers for the manufacturing, keeping close contact with them and getting them involved in the development process would have taken the project to a further state.

Another outcome of the project is the importance of project schedule estimates in a project. Success of a project is highly dependent on shorter project lead times and, timely delivery of expected outcomes from different stages of a project is an important managerial issue. The final result of the project has been delivered on time but allocation of more or less time on different stages of the project would have given more space for better results. This puts a strong emphasis on *project management* as a field of study in the area of product development.

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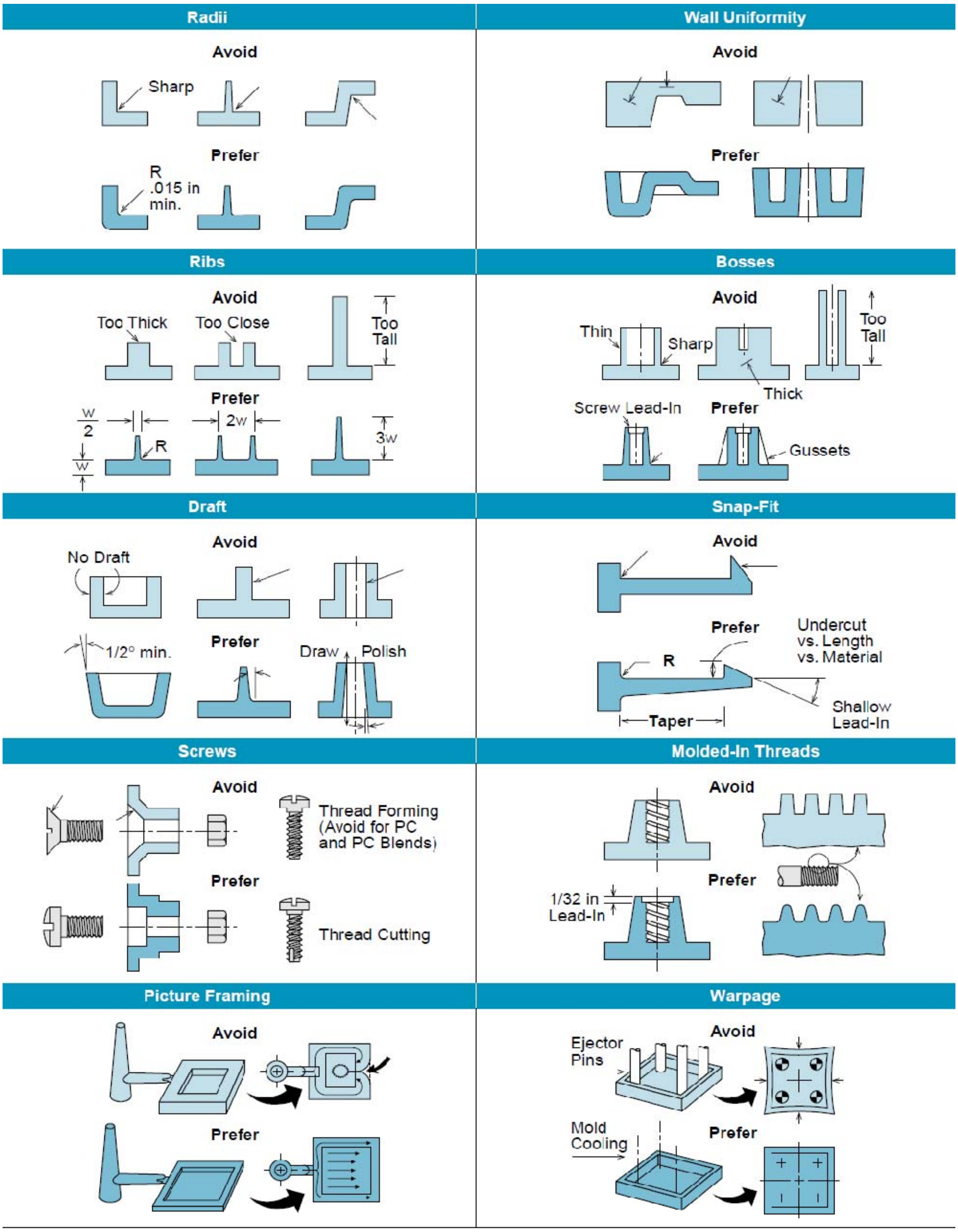
Appendix 1: Plastic part design guidelines



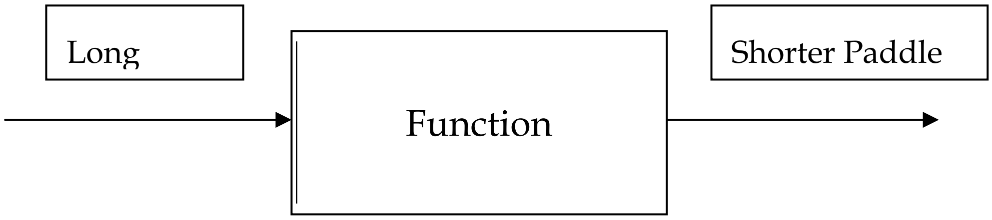
Appendix 2: Requirement specification

Requirement specification

Criteria Nr.	Criteria	D/W	Value	Unit	Verification Method	Stakeholders
	Design					
1	Maximum weight of the final product	D	650	g	Calculation	Developer/Manufacturer
2	Durability	D	Y/N	-	Material Check	Developer
3	Recyclable materials whenever possible	W	Y/N	-	Material Check	Developer
4	Dust and sand proof	D	Y/N	-	Check	Developer
5	Saltwater, sweetwater and ice proof	D	Y/N	-	Check	Developer
6	Adjustable length	W	-	-	-	Developer
7	Oval grip loom	D	-	-	-	Developer
8	No moving parts	W	Y/N	-	-	Developer
9	Split into 3 pieces	W	Y/N	-	-	Developer
	Manufacturing					
10	Suitable for manufacturing	D	Y/N	-	-	Developer/Manufacturer
11	Environmental friendly manufacturing	D	Y/N	-	Standards Check	Manufacturer
12	Maximum manufacturing capacity	D	400	Annual	Calculation	Manufacturer
13	Maximum extra cost of split	D	1500	SEK	Cost Check	Developer/Manufacturer
	Transportation					
14	Possible to take in the airplane	D	Y/N	-	Regulation Check	Developer
15	Small enough to fit in a car trunk	D	Y/N	-	Testing	Developer
16	Small Enough to take in the airplane cabin	W	30 x 117 x 38	cm	Regulation Check	Developer
	Installation					
17	Installation by one person	D	Y/N	-	Installation Testing	Developer
18	Haptic feeling of installation	W	Y/N	-	-	Developer
19	Require ergonomic force/torqu values for installation	D	Y/N	-	Literature Check	Developer
20	Installation does not require any special tools	D	Y/N	-	Installation Testing	Developer
	Use					
21	Smooth connection (for hans sliding on the loom and blade)	D	Y/N	-	Testing	Developer
22	Dependable (prevent accidential split)	D	Y/N	-	Testing	Developer
23	Shock proof	D	Y/N	-	Material Check	Developer
24	Keep the body rigid	D	-	-	Analysis	Developer
25	Float on the water	D	Y/N	-	-	Developer
26	Let no water inside the paddle	D	Y/N	-	Testing	Developer
	Maintenance					
27	10 Years life time minimum	D	Y/N	-	Material Check	Developer/Manufacturer
28	Replaceable	D	Y/N	-	-	Developer/Manufacturer
29	Require no maintenance	W	Y/N	-	-	Developer/Manufacturer

Appendix 3: Brainstorming reflections

Function Illustration:



Means of Function:

Fold, shrink, fold, split, join, assemble, deploy, mobilize...

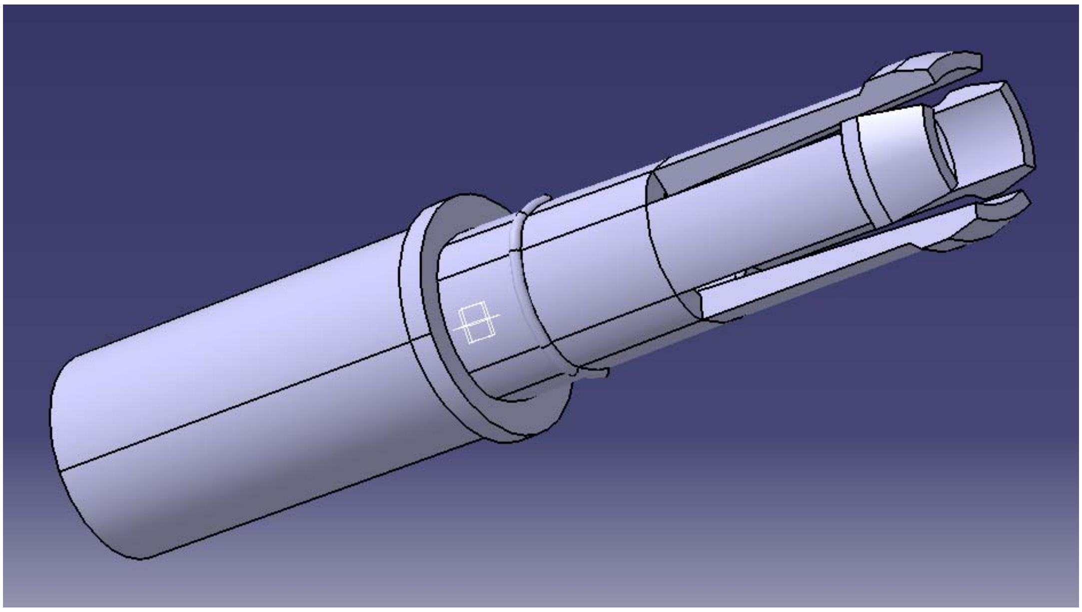
Brainstorming Ideas:

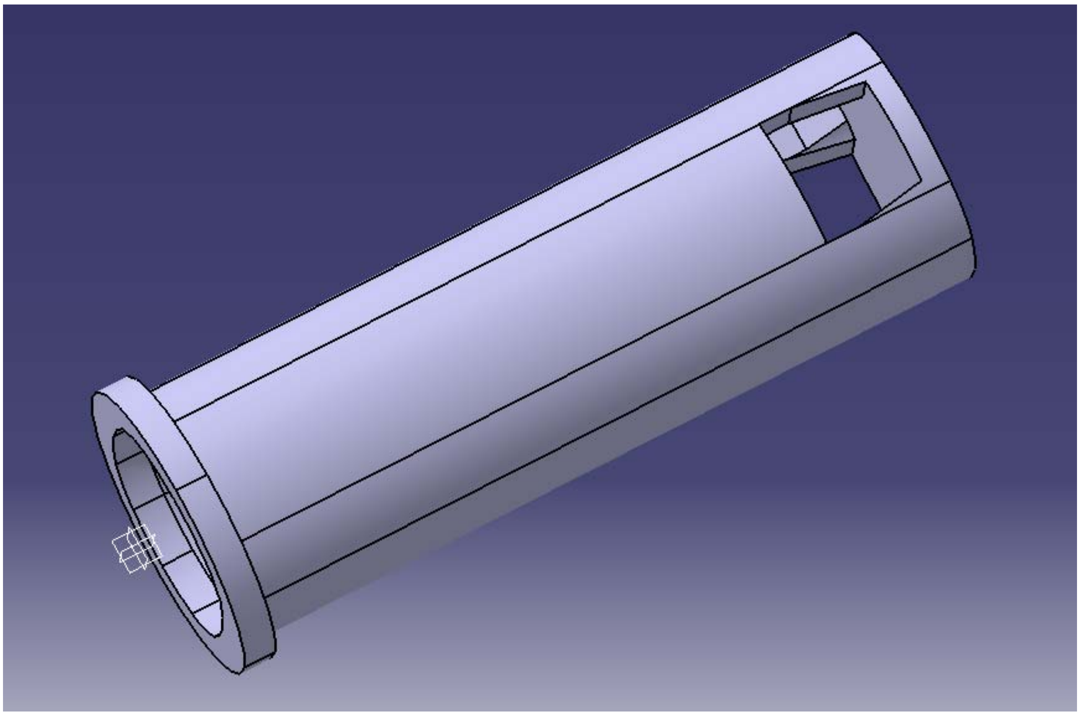
• Feather craft Inc. • Baby stroller • Bikes • Boat industry (joint applications for deployable boat equipment) • Transformers • Tent poles • Spiral coil • Cone Shape • Push button release • Screw / Slot trail • Bolt, nut • Hinge • Padlock • Bearing • Laminar clutch (Friction hold) • Telescopic • Lego • Glue • Magnetic • Bungee (Elastic) • Elastric Fabric • Kid proof medicine jar • Acordion	• Latex • Post-it • Vacuum • Jigsow puzzle • 3D Puzzle • Push/Pull Curtain roller • Twist and Release • Latch / Pin • Velcro • Bi-material (differential therman expansion) • Expanding bolts • Wedge expander • Train carts coupling • Vans coupling • Multiple action release • Jar • Electric Plug • Screw driver • Seatbelt clips • Guitar jack • Blind man stick • Assault rifle • Rails • Tread

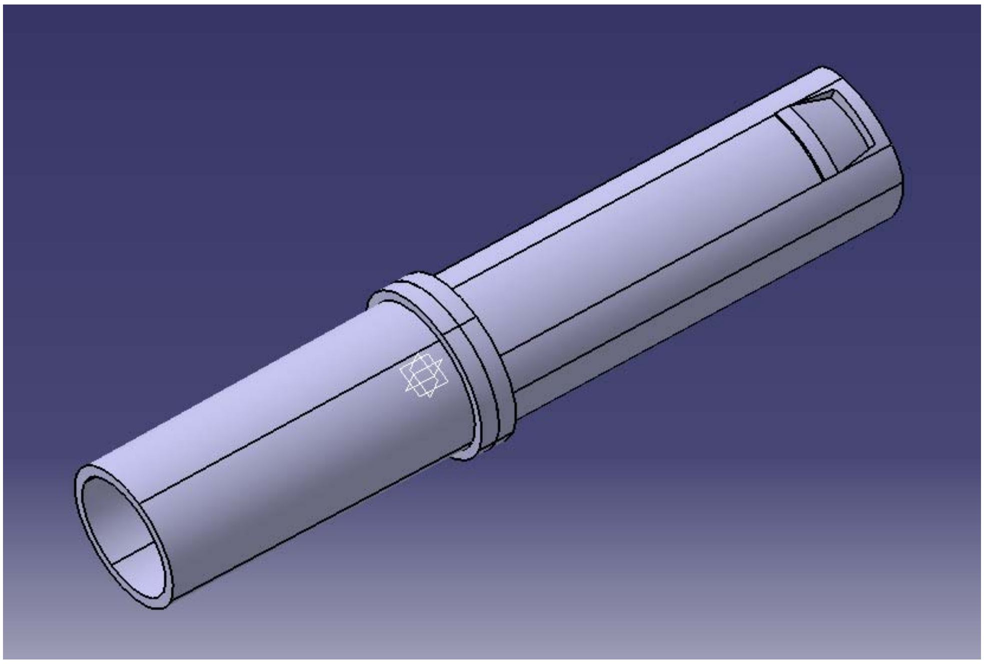
Appendix 4: Kesselring Matrix

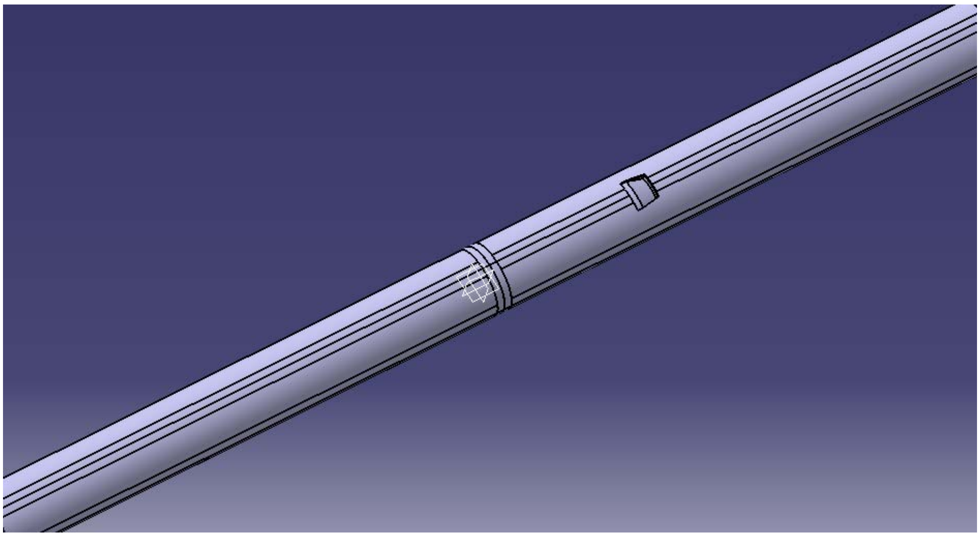
		Ideal concept		The Screw		Pin Button		Pad Lock		Push and Release		Medicine Jar		Friction		Tent Pole	
Criteria	Weight %	Rating (1-5)	Weighted Score	Rating (1-5)	Weighted Score	Rating (1-5)	Weighted Score	Rating (1-5)	Weighted Score	Rating (1-5)	Weighted Score	Rating (1-5)	Weighted Score	Rating (1-5)	Weighted Score	Rating (1-5)	Weighted Score
Weight	3.03	5	15.15	4	12.12	5	15.15	4	12.12	5	15.15	5	15.15	4	12.12	5	15.15
Durability	9.85	5	49.24	3	29.55	4	39.39	3	29.55	4	39.39	2	19.70	3	29.55	4	39.39
Sand proof	9.47	5	47.35	2	18.94	3	28.41	2	18.94	4	37.88	2	18.94	2	18.94	5	47.35
Saltwater proof	9.47	5	47.35	4	37.88	4	37.88	4	37.88	5	47.35	3	28.41	3	28.41	5	47.35
Manufacturability	10.61	5	53.03	2	21.21	5	53.03	2	21.21	5	53.03	1	10.61	4	42.42	4	42.42
Cost	4.17	5	20.83	3	12.50	3	12.50	3	12.50	4	16.67	2	8.33	4	16.67	5	20.83
Easy installation	9.47	5	47.35	3	28.41	5	47.35	5	47.35	5	47.35	2	18.94	3	28.41	3	28.41
Tool-free installatio	5.30	5	26.52	5	26.52	5	26.52	5	26.52	5	26.52	5	26.52	5	26.52	5	26.52
Smooth loom	9.85	5	49.24	5	49.24	5	49.24	5	49.24	5	49.24	4	39.39	3	29.55	5	49.24
Dependability	10.98	5	54.92	4	43.94	3	32.95	3	32.95	4	43.94	5	54.92	4	43.94	3	32.95
Life time	7.95	5	39.77	3	23.86	4	31.82	4	31.82	4	31.82	2	15.91	3	23.86	4	31.82
Maintenance	9.85	5	49.24	5	49.24	4	39.39	4	39.39	4	39.39	4	39.39	5	49.24	5	49.24
			500		353.41		413.64		359.47		447.73		296.21		349.62		430.68

Appendix 5: Final concept snapshots









Appendix 6: Material datasheet for *Durethan® BM 240 H2.0*

Durethan® BM 240 H2.0	PA6-MD40	LANXESS Deutschland GmbH - 2010-03-04

Product text

PA 6, injection molding grade, 40 % mineral, isotopic properties, good heat-ageing resistance

Single-point data

Rheological properties	dry	cond.		
Melt volume-flow rate	18	*	cm³/10min	ISO 1133
Temperature	260	*	°C	ISO 1133
Load	5	*	kg	ISO 1133
Molding shrinkage (parallel)	-	*	%	ISO 294-4, 2577
Molding shrinkage (normal)	-	*	%	ISO 294-4, 2577

Mechanical properties	dry	cond.		
Tensile modulus	6000	2200	MPa	ISO 527-1/-2
Yield stress	*	*	MPa	ISO 527-1/-2
Yield strain	*	*	%	ISO 527-1/-2
Nominal strain at break	*	*	%	ISO 527-1/-2
Stress at 50% strain	*	*	MPa	ISO 527-1/-2
Stress at break	85	50	MPa	ISO 527-1/-2
Strain at break	7	40	%	ISO 527-1/-2
Tensile creep modulus (1h)	*	-	MPa	ISO 899-1
Tensile creep modulus (1000h)	*	-	MPa	ISO 899-1
Charpy impact strength (+23°C)	120	N	kJ/m²	ISO 179/1eU
Charpy impact strength (-30°C)	90	90	kJ/m²	ISO 179/1eU
Charpy notched impact strength (+23°C)	10	12	kJ/m²	ISO 179/1eA
Charpy notched impact strength (-30°C)	10	10	kJ/m²	ISO 179/1eA
Tensile notched impact strength (+23°C)	-	-	kJ/m²	ISO 8256/1
Puncture - maximum force (+23°C)	3050	-	N	ISO 6603-2
Puncture - maximum force (-30°C)	825	-	N	ISO 6603-2
Puncture energy (+23°C)	9.2	-	J	ISO 6603-2
Puncture energy (-30°C)	1.6	1.6	J	ISO 6603-2

Thermal properties	dry	cond.		
Melting temperature (10°C/min)	222	*	°C	ISO 11357-1/-3
Glass transition temperature (10°C/min)	-	*	°C	ISO 11357-1/-2
Temp. of deflection under load (1.80 MPa)	90	*	°C	ISO 75-1/-2
Temp. of deflection under load (0.45 MPa)	190	*	°C	ISO 75-1/-2
Temp. of deflection under load (8.00 MPa)	*	*	°C	ISO 75-1/-2
Vicat softening temperature (50°C/h 50N)	200	*	°C	ISO 306
Coeff.of linear therm. expansion (parallel)	60	*	E-6/K	ISO 11359-1/-2
Coeff.of linear therm. expansion (normal)	70	*	E-6/K	ISO 11359-1/-2
Burning Behav. at 1.5mm nom. thickn.	-	*	class	IEC 60695-11-10
Thickness tested	-	*	mm	IEC 60695-11-10
UL recognition	-	*	-	-
Burning Behav. at thickness h	-	*	class	IEC 60695-11-10
Thickness tested	-	*	mm	IEC 60695-11-10
UL recognition	-	*	-	-
Burning Behav. 5V at thickn. h	-	*	class	IEC 60695-11-20

Thickness tested	-	*	mm	IEC 60695-11-20
UL recognition	-	*	-	-
Oxygen index	26	*	%	ISO 4589-1/-2

Electrical properties	dry	cond.		
Relative permittivity (100 Hz)	4.4	15	-	IEC 60250
Relative permittivity (1 MHz)	4	4.7	-	IEC 60250
Dissipation factor (100 Hz)	110	2500	E-4	IEC 60250
Dissipation factor (1 MHz)	150	1000	E-4	IEC 60250
Volume resistivity	1E13	1E9	Ohm*m	IEC 60093
Surface resistivity	*	1E13	Ohm	IEC 60093
Electric strength	35	38	kV/mm	IEC 60243-1
Comparative tracking index	525	-	-	IEC 60112

Other properties	dry	cond.		
Water absorption	6	*	%	Similar to ISO 62
Humidity absorption	1.9	*	%	Similar to ISO 62
Density	1460	-	kg/m³	ISO 1183

Material specific properties	dry	cond.		
Viscosity number	142	*	cm³/g	ISO 307, 1157, 1628
Indicative density (PE only)	-		kg/m³	ISO 1872-1
Luminous transmittance	-		%	ISO 13468-1, -2

Rheological calculation properties			
Density of melt	1240	kg/m³	
Thermal conductivity of melt	0.247	W/(m K)	
Spec. heat capacity of melt	1990	J/(kg K)	
Eff. thermal diffusivity	1E-7	m²/s	
Ejection temperature	140	°C	

Test specimen production			
Processing conditions acc. ISO	-	-	ISO....-2
Injection Molding, melt temperature	290	°C	ISO 294
Injection Molding, mold temperature	80	°C	ISO 10724
injection velocity	-	mm/s	ISO 294
pressure at hold	-	MPa	ISO 294
Compression Molding, molding temperature	-	°C	ISO 293
cooling rate	-	K/min	ISO 293
molding time	-	min	ISO 293
demolding temperature	-	°C	ISO 293

Mechanical properties (Film)	dry	cond.		
Stress at yield (parallel)	*	*	MPa	ISO 527-3
Stress at yield (normal)	*	*	MPa	ISO 527-3
Strain at yield (parallel)	*	*	%	ISO 527-3
Strain at yield (normal)	*	*	%	ISO 527-3
Maximum stress (parallel)	*	*	MPa	ISO 527-3
Maximum stress (normal)	*	*	MPa	ISO 527-3
Maximum strain (parallel)	*	*	%	ISO 527-3
Maximum strain (normal)	*	*	%	ISO 527-3
Elmendorf Tear resistance (parallel)	*	*	N	ISO 6383-2
Elmendorf Tear resistance (normal)	*	*	N	ISO 6383-2
Trouser Tear resistance (parallel)	*	*	N/mm	ISO 6383-1