Design of a lightweight toothbrush with low environmental impact

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MASTER THESIS

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Abstract

The work presented in this report investigates how a toothbrush can be designed to be lightweight and at the same time fast to manufacture. If a low weight and short manufacturing time can be obtained, several other advantages can be had, such as reduced carbon dioxide footprint, less need of material, and more cost-efficient manufacturing.

With the help of Ulrich and Eppinger's product development process a large number of different concepts have been developed and analyzed. The concepts have been created in different ways, mostly with the focus on reaching a concept with low weight. To test the concepts, mold flow simulations have been carried out. By using mold flow simulations, it was possible to identify future potential problems and find solutions for the problems. 3D-printed prototypes have also played an important part of the project. Test persons have evaluated the prototypes and indicated problems which not would have been noticed otherwise.

To validate that the new concept will fulfill the objectives, LCA-analyses have been performed. As a reference object, TePe Select toothbrush have been used.

The new concept fulfills the objectives and reduces the weight, compared to TePe Select, by 50% and the filling and cooling times by 66 percent.

Key words:

Product development, Injection molding, Dental products, Toothbrush handle, Mold flow analysis

Sammanfattning

I denna rapport analyseras koncept för tandborstar med låg vikt och kort tillverkningstid. Förhoppningen är att låg vikt och kort tillverkningstid kan leda till positiva effekter såsom lägre koldioxidfotavtryck, mindre materialanvändning och en mer kostnadseffektiv tillverkning än vad som gäller för dagens tandborstar.

Med hjälp av Ulrich & Eppingers produktutvecklingsprocess har flera olika koncept utvecklats och analyserats. Koncepten har tagits fram på olika sätt men främst med fokus på att uppnå en låg vikt för tandborsten. För att testa koncepten har formfyllnadsanalyser utförts. Dessa analyser har gjort det möjligt att identifiera framtida problem och hjälpt till att hitta lösningar för dessa problem. 3D-utskrivna prototyper har också spelat en viktig roll i projektet, eftersom testpersoner har kunnat testa och utvärdera prototyperna och därmed kunnat upptäcka problem som annars inte skulle ha upptäckts.

För att validera att det nya tandborstkonceptet ger upphov till de positiva resultat som önskas så har LCA-analyser utförts. TePe Select har utgjort referensobjekt i projektet.

Det nya konceptet uppfyller de krav som ställdes upp i början av projektet och reducerar vikten, i jämförelse med TePe Select, med 50 procent och fyll- och kyltid med 66 procent.

Nyckelord:

Produktutveckling, Formsprutning, Munhygienprodukter, Tandborstshandtag, Formfyllnad

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Lund, May 2023

Johan Hammarberg

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List of acronyms and abbreviations

ABS	acrylonitrile butadiene styrene
CAP	cellulose acetate propionate
CO_2	carbon dioxide
FDM	fused deposition modelling
LCA	life cycle analysis
MVP	minimum viable product
FEA	finite element analysis
PA1010	polyamide 1010
PA6.12	polyamide 6.12
PBT	polybutylene terephthalate
PE	polyethylene
PLA	polylactic
PP	polypropylene
VP-switch	velocity-pressure-switch

1 Introduction

In this chapter the overall goal of the project is presented. A brief description of the toothbrush history is also presented.

1.1 Objective

The objective of this master thesis is to present a procedure for the design of a toothbrush with low weight and short manufacturing time.

1.2 Initial discussions

The first draft of targets was established during discussions between the author and the supervisor from TePe Munhygienprodukter, (TePe). They had started to be interested in reducing their energy usage and at the same time reducing their manufacturing costs. The main components in Tepe's emissions are the raw material and the production energy consumption. To find a solution to reduce their emissions an idea came up to minimize the amount of plastic material used in a regular toothbrush. The raw material, in granulate form, consists of polymers manufactured from either fossil sources or organic sources, combined with a masterbatch (the color pigment).

1.3 Goal document

To make sure that all the partners in the project had the same expectations on the project, a document that presents the goal was created. In this document, it was stated that the goal of this thesis project is to find a design of a toothbrush that reduces the weight by a minimum of 25 percent. Furthermore, a 15 percent reduction of the manufacturing time should also be achieved. To make these goals measurable a reference toothbrush was needed. Therefore, TePe's Select toothbrush (Select toothbrush), was used as a reference. The handle for this toothbrush has been in production since 1973. The brush head has, however, been updated several times.

The Select toothbrush is the most selling toothbrush in Sweden and is therefore considered to be a good reference object in this project.

Select toothbrush is manufactured out of polypropylene (PP) and has a weight of 13 grams (excluding bristles and anchors). The weight was measured for a modelled version of it in CAD. The Select toothbrush is manufactured in an injection molding process, with 5 seconds filling time and 12 seconds cooling time.

The CAD-model of the Select toothbrush was analysed by mold flow analyses, to enable a comparison with mold flow results for the new concepts. The Select mold flow analyses resulted in a filling time of 7,0 seconds and a cooling time of 59,8 seconds. This means that the target of the outcome of this thesis project is to present a toothbrush with a weight of maximum 9,7 grams, a filling time of maximum 6,0 seconds and a cooling time of maximum 50,8 seconds.

The goal is also to obtain several other positive benefits, such as a smaller carbon footprint and a more cost-efficient manufacturing. The carbon footprint can be reduced by shortening the production time, reducing the amount of material to be transported, and the material needed for the toothbrush. The production costs can be reduced by using less energy, less material, and a suitable material choice.

1.4 Toothbrush history

Bristle brushes made of ivory and horsehair were used in China already approximately 1000 years ago. Toothbrushes, like the ones we have today, were first used in China in the late 1400s. These toothbrushes had ox bone handles with hog bristles (Fischman, 1997).

This kind of toothbrush was later used in the late 1700s and early 1800s, but they were not widely used until the late 1800s due to the high price of hog bristles. (Fischman, 1997).

In the late 1930s, nylon filaments started to replace the natural bristles and plastic was used in the handles. This made toothbrushes inexpensive, leading to that everyone could own one. (Fischman, 1997).

TePe started to manufacture wooden toothpicks in 1965 and launched their first toothbrush in 1973.

2 Project planning

In this chapter the beginning of the project is presented. What restrictions the project has and how the time is planned.

2.1 Pre-project planning

2.1.1 **Demarcations**

As brush design is an area where much time could be spent, it was decided to limit the project to only investigate the handle design and use the same brush head design as the Select toothbrush. To deliver a full product at the end of this project, it was decided to investigate what kind of filaments that could be used, as well as propose a packaging solution.

2.1.2 **Time planning**

To be certain that all goals would be met, a timetable was set up. It was created as a GANTT-chart. In the chart a timeline, activities and activity dependency were presented. The chart is attached in appendix A. The chart needed to be updated during the project, due to unforeseen events.

3 Background information

To be able to develop a functioning concept, background knowledge is needed. In this chapter information about plastics, injection molding, mold flow analysis, plastics and the environment, design rules within plastic product development, and information about Ulrich & Eppinger's product development process, are presented.

3.1 Approach

To be able to fulfill the goal of this thesis project, a broader understanding of areas that are involved in the manufacturing of toothbrushes was necessary. Therefore, background information was looked for and collected. The areas that were of interest were polymer materials, product development processes, plastic product development, sustainable product development, injection molding, ergonomics, and life cycle analysis.

3.2 Polymer materials

Polymers can be described as monomers bonded together in chains. If there are only one type of monomers in the chains it is a homopolymer, and if there are several different types of monomers it is called a co-polymer. (Bruder U, 2016).

Polymers can be divided into plastics and rubbers. Plastics can be divided into thermosets and thermoplastics. The main difference between thermosets and thermoplastics is that thermoplastics melts at elevated temperatures. This means that thermoplastics more easily can be recycled and reused.

Thermoplastics are also divided into amorphous and semi-crystalline materials, where amorphous thermoplastics softens when they reach their "glass transition temperature" while semi-crystalline thermoplastics have a melting point where they go from solid to liquid. (Bruder U, 2016).

3.3 Plastics and the Environment

Plastics plays an important part in reducing the emission of greenhouse gases. The use of plastics, instead of alternative materials that were used before, saves a lot of weight. For example, the car industry is using more and more plastic materials to reduce the weight of new cars and thereby also the release of emissions. (Bruder U, 2016).

Emissions from retails would also be approximately 50 percent higher if glass in liquid packaging had not been replaced by plastic materials. (Bruder U, 2016).

Plastic materials are affected by the environment to some extent. For example, UV-light, oxygen, water or vapour, temperature changes, etc. affects the properties. Furthermore, microorganisms and chemical can also affect the properties. (Bruder U, 2016).

3.4 Injection molding

Injection molding is one of the most common manufacturing methods for mass produced plastic parts. (Ebnesajjad S, 2016).

The general process is similar to other molding methods. A cavity is filled with a heated liquid, that while it is cooled takes the shape of the cavity. Injection molding requires multiple components to function. The most important components are presented in Figure 3.1.

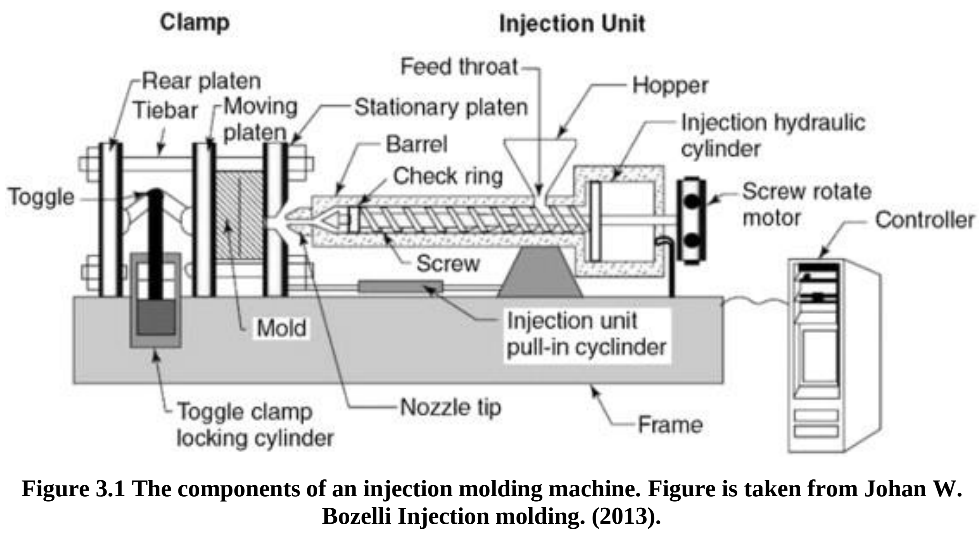

Figure 3.1 The components of an injection molding machine. Figure is taken from Johan W. Bozelli Injection molding. (2013).

Granulated plastics are filled into the hopper. From there, the granulate is fed through the feed throat into the barrel, that is housing the screw. When the screw is rotating, the granulate is moved forward towards the mold. The barrel is heated, so that the end towards the mold is the warmest. As the granulated plastic is transferred through the barrel, it is molten by the heat from the barrel and from the heat created by the friction between the plastic and the screw.

When the plastic has reached the nozzle, it is fully melted, and can be ejected into the mold. The plastic enters the cavity, through a gate. The location of the gate is important when designing and simulating a part. The mold stays closed and heated until it's filled, then it's cooled down. When the plastic inside of the cavity of the mold is cool enough, the mold opens, and the plastic part is ejected. Then, the mold can be closed again, and the same steps as presented above are repeated.

The main steps of the molding process are: Closing of the mold, filling, packing, cooling, opening, and ejection of parts.

3.4.1 Gas-assisted injection molding and microcellular injection molding

Since the project's goal is to reduce the weight and manufacturing time for a toothbrush, while maintain the properties, gas-assisted injection molding can be of interest.

Lars Jerpdal (2023) was therefore contacted to get a description of the fundamentals of microcellular injection molding, which is his research area. Jerpdal (2023) works for Scania AB as a Technical manager within plastic design. He explained the basics about gas-assisted injection molding as well. He said that gas-assisted injection molding is when a gas, often nitrogen, is inserted into the mold cavity after it has been filled with plastic. The redundant plastic is let out, and the gas is captured inside the molded part. By using this technique, the part will be lighter and can be cooled down faster since it contains less material.

Lars Jerpdal also explained how microcellular injection molding works. In this technique, gas is mixed with the granulate and the mixture is injected into the mold cavity. When heated the mixture gets properties like a foam. The foam is injected into the mold cavity, where the surface closest to the mold cavity, the area that will be the surface area of the manufactured part, only contains plastic. The gas content will increase from the surface towards the middle of the part.

The plastic granulates need to be mixed with fibres of some sort for the microcellular molding technique to work, as it is around these filaments the foam bubbles appear. These filaments could for example be wooden fibres, that are already in use in injection molded products to reduce the amount of plastic material.

Using microcellular injection molding, the resulting part can be up to 30 percent lighter, and also quicker to manufacture, since the foam mixture has a lower viscosity than the pure plastic. A similar technique is used today, but it needs large investments since both the screw and barrel needs to be optimized for the process. Lars Jerpdal therefore argues that the technique he is investigating is less money-intense, since not as many parts in the injection molding machine needs to be replaced.

3.5 Mold flow analysis

To be able to test different concepts without the need of manufacturing physical parts, mold flow analyses were used. The software mainly used in this project is an add-in tool for Solidworks 2022, called Solidworks Plastics. To gain more knowledge on how to use this tool, Peter Bjellheim was contacted (2023). He explained that it is important to always compare the developed concept with a reference. He said that: “One simulation is only a simulation, but two simulations are a small study”. Because of this statement, the reference toothbrush was also simulated by mold flow. Then the results of each concept could be compared to the reference, and via the reference be compared to the real-life process of injection molding. Therefore, all concepts are simulated with the same material, Borealis HD120MO. This is a PP homopolymer that is comparable to the PP used by TePe for the Select toothbrush. (Dingizian, 2023).

3.5.1 **Gate placement**

The gate is what the molten plastic flows through when entering the cavity. The positioning of the gate very much influences the outcome of several other data aspects mentioned below. Today, the Select toothbrush has its gate in the bottom of the handle, on the back side, see figure 3.2.

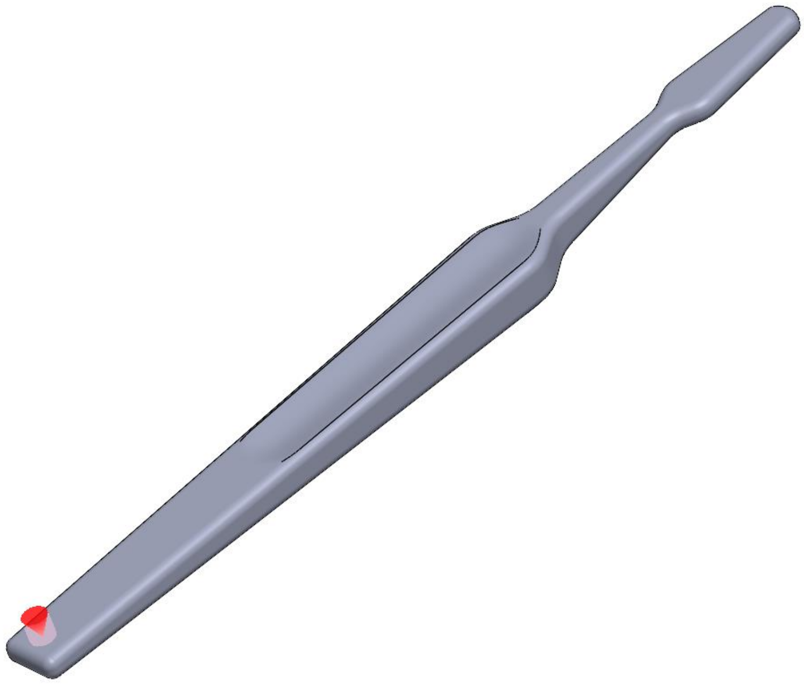

Figure 3.2 The red cone represents the gate placement on the Select toothbrush.

3.5.2 **Data of interest**

Mold flow analyses can display the results of several data, those that were of special interest are: Fill time, end-of-fill pressure, flow front temperature, cooling time, sink marks, and temperature at end-of-fill. These data are described below.

3.5.2.1 Fill time

The fill time is determined by multiple factors, such as injection pressure, the viscosity of the plastic material, the gate location, and the cavity's geometry. For an example of how the results are presented in Solidworks plastic, see Figure 3.3.

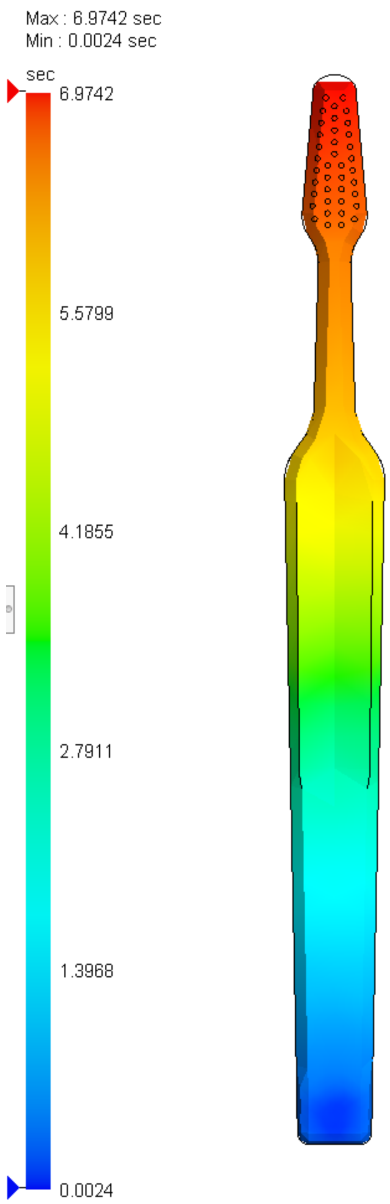

Figure 3.3 The result of running a mold flow analysis of the reference toothbrush.

3.5.2.2 Flow front temperature

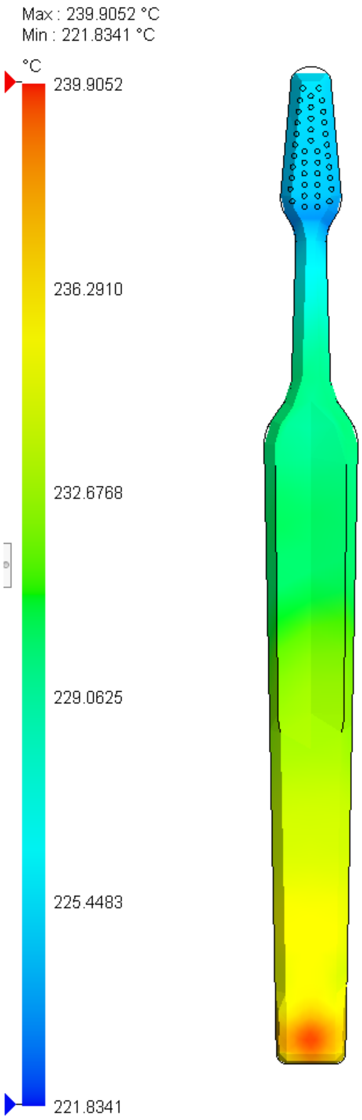

Figure 3.4 The temperature of the flowing plastic is displayed for any given time.

The flow front temperature is the temperature of the first molten plastic that flows through the cavity, at any given time, see Figure 3.4. Optimally, the temperature drop is less than 7°C. (Bjellheim, 2023).

3.5.2.3 End-of-fill pressure

Figure 3.5 Color-coding of toothbrush based on the pressure at end-of-fill.

Pressure can be measured when the cavity is filled to 100 percent, or at the velocity-pressure-switch (VP-switch) at about 90 percent filling. The VP-switch is when the process is switched from being velocity driven, to being pressure driven. After the VP-switch, the pressure increases until it reaches the holding pressure, and the pack-step is in progress, see figure 3.5.

3.5.2.4 Cooling time

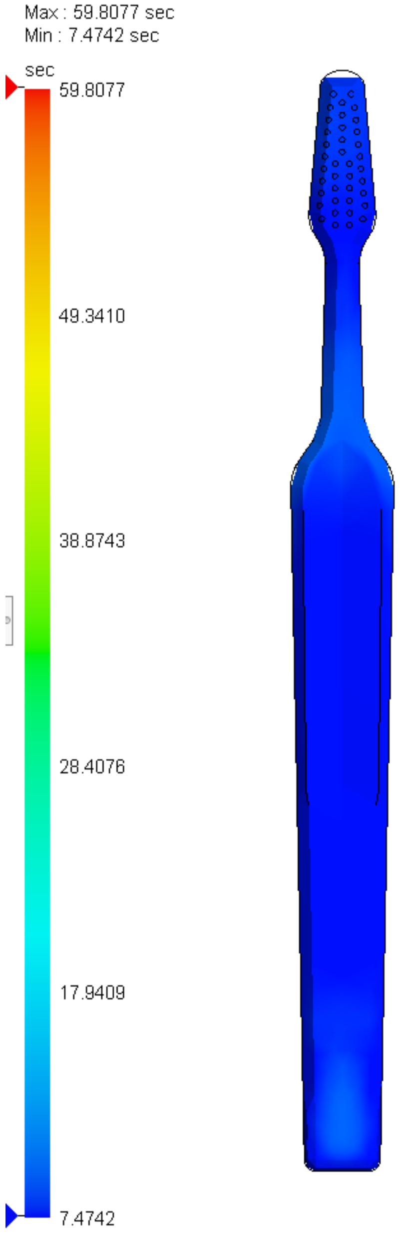

Figure 3.6 As seen most of the toothbrush seems to reach its ejection temperature in about 10 seconds.

After the packing is done, the cooling begins. This step continues until the highest temperature is not exceeding the ejection temperature, which is 135°C for the material Borealis HD120MO. As can be seen in figure 3.6, the cooling time for most of the toothbrush is about 10 seconds. But the scale is related to the slowest cooling part, and that's why it shows such a long time. Since the cooling time is about 12 seconds (Dingizian, 2023) when injection molding the Select toothbrush in real life, the simulated number can't be fully trusted.

3.5.2.5 Sink marks

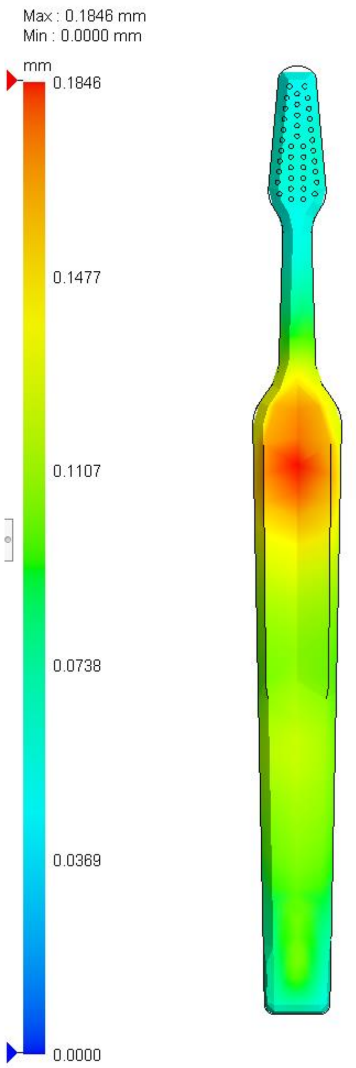

Figure 3.7 The red area is cooling down slower than other areas in the toothbrush.

Sink marks appear when the material is cooling down at different speeds. For example, as seen in Figure 3.7, the thumb grip is marked in red. This area is in the thickest part of the toothbrush and cools down significantly slower than other areas.

3.5.2.6 Temperature at End-of-Fill

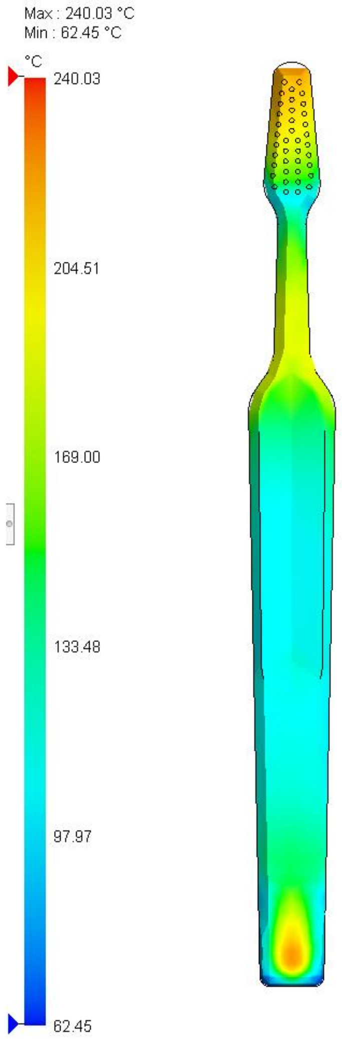

Figure 3.8 The dark blue areas are the ones with a low temperature at end-of-fill, the red areas have the highest temperature.

The temperature at end-of-fill determines for how long the molded part must be cooled before being ejected from the mold. The ejection temperature depends on what material is used. The temperature at end-of-fill for the select toothbrush can be seen in figure 3.8.

3.6 Design rules for thermoplastics

In the book “Design of Injection Molded Plastic Parts” Christoph Jaroschek (2022) claims that the use of plastic materials needs a rethink. He mentions how clothespins are designed in wood and plastic. He states that the plastic pins are more expensive and also wears out faster, compared to the wooden counterpart. Jaroschek argues that this is due to that the plastic part is designed very similarly to the clothespin made of wood. While the wood pin can be manufactured fast and cheap, the plastic version demands a more expensive manufacturing method.

Jaroschek suggests that a solution to this can be to design the plastic pin in one part, and by that using functional integration. He says that functional integration is when multiple functions are incorporated in one part. Parts manufactured with injection molding can be very complex, Jaroschek generalizes this: “Conventional components often consist of various individual parts that form an assembly. By contrast, good plastic components often consist of a single part.”

In “Robust Plastic Product design” Vikram Bhargava is reasoning similarly when he discusses reasons of why plastic products fail due to human causes, and how much of the guilt is upon the designer. He argues that a holistic view of the development of a plastic product is favourably, where material, design, tooling and processing are the four main parts.

Jaroschek mentions some quality issues with injection molded parts, such as that the part must be able to be ejected from the mold, meaning that the two parts that create the tool must be able to separate. And that the gate, where melted plastic comes into the cavity, usually leaves a visible mark.

Jaroschek continues with mentioning solutions for these problems. As an example, moving the gate to a non-critical area, where it isn’t seen, and designing for the parting line to follow edges of the detail as much as possible, is favourable.

To get an acceptable result, Ulf Bruder (2016) states that the designer should strive to keep the wall thickness the same around the part and locate the gate at the thickest part.

3.7 Data gathering – Questionnaires.

The book “Interaction design – beyond human computer interaction”, has an extensive chapter about data gathering, where one part covers questionnaires. The authors recommend questionnaires for projects that seeks many responders. They claim that it’s important to formulate the questions specific and use closed-end question as much as possible.

3.8 Product development method

There are several methods to follow when working with product development. For example, lean start-up methodology, where the designer is creating a minimum viable product (MVP) to test on users, and design thinking, where the developer creatively explores a range of different ideas (Pressman, 2018), are two common methods.

Another method is Ulrich & Eppinger's Product development process.

3.8.1 **Ulrich & Eppinger**

Karl T. Ulrich is a professor in at University of Pennsylvania and Steven D. Eppinger is a professor at Massachusetts Institute of Technology. They have published the book "Product Design and Development." The method that is used in this report is to a large extent based on their work. The decision to go by their method was based on that it is systematic and can be easily followed, ensuring that no important steps in the product design process is forgotten.

3.9 Life cycle analysis

To be able to justify the results in this project, a life cycle assessment (LCA) was carried out. LCA normally shows that a reduced mass really has an impact on the amount of produced Carbon dioxide. A source for life cycle calculations regarding plastic products is "Livscykelanalys – miljövärdering av plastprodukter" [Life cycle analysis – environmental evaluation of plastic products.] by Hans-Erik Strömvall. In the book he suggests that designers need to design plastic products in such a way that they are easily recycled.

In this project the author has decided (together with TePe) to calculate the carbon dioxide emissions at its worst-case scenario, meaning that all plastic materials go to incineration instead of recycling at end of life. This decision was made because the amount of plastic that is really recycled is difficult to calculate precisely.

3.9.1 **Materials**

Different materials have different impact on the environment. For example, plastics from a fossil feedstock contains carbon that haven't been in the carbon dioxide-cycle for millions of years, and therefore contribute with the same amount when incinerated. Plastics that are bio-based have carbon dioxide that have been captured by the photosynthesis, within the plastic material, when grown. When incinerating this kind of plastic, the emitted carbon dioxide is more or less the same amount that were previously captured, meaning that no new carbon dioxide has been emitted except for when the material is being manufactured.

3.9.2 Material selection

Plastic materials differ widely in properties, e.g., melting point, density, viscosity, stiffness, and appearance. Different plastics are suitable for different manufacturing methods. (Bruder, 2016).

To gain information about different plastics and their suitability for toothbrushes, Alexander Dingizian, plastic specialist at TePe, was consulted. Together it was decided to compare two materials for the handle in a life cycle analysis, polypropylene which is used in the now selling TePe Select toothbrush and Arboform which is a newly developed renewable material based on lignin.

For the bristles three materials was chosen to be compared, polyamide 6.12. (PA 6.12.), polybutylene terephthalate (PBT), and polyamide 1010 (PA1010). The first two mentioned materials are fossil based and widely used for toothbrush bristles, the last material PA101 is used by TePe for the Supreme toothbrush’s bristles and is based on renewable resources.

3.9.3 Definitions

To understand what is referred to later in this report, a defining figure of a toothbrush is presented in Figure 3.9.

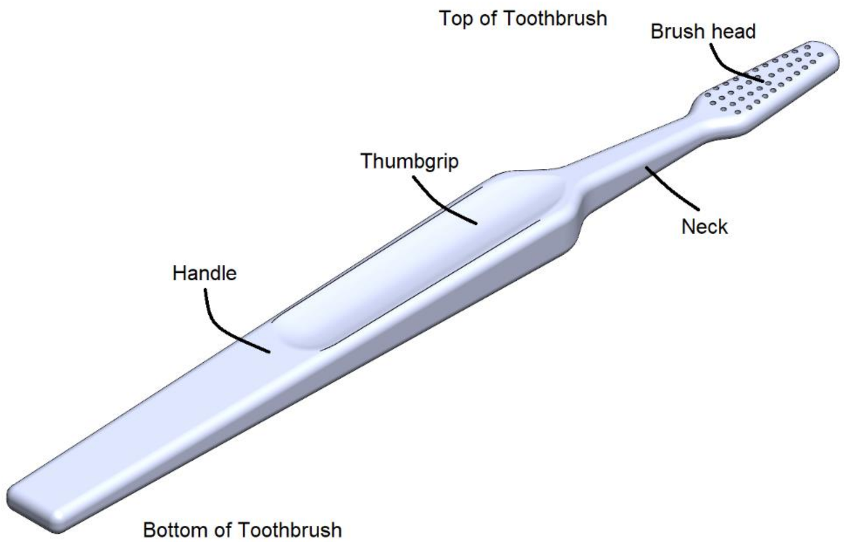

Figure 3.9 The Select toothbrush with names of the parts described.

4 The Product Development Process

In this chapter the process of development is presented. Firstly, the pre-process planning, then the customer needs identification and target specifications. After that the concept generation is presented.

4.1 Product Planning

4.1.1 **Mission statement**

Ulrich K. & Eppinger S. suggests starting with a mission statement where targets are defined and also under what assumptions that the project shall operate are defined.

4.1.1.1 Brief

This product is developed to become a toothbrush that is lighter and can be produced in shorter time, than a regular toothbrush, and that easily cleans all teeth and performs at the same level as a regular toothbrush.

4.1.1.2 Benefit proposition

A lightweight toothbrush, with pleasing design, and well-functioning grip and brush head.

Smaller environmental footprint, faster manufacturing times.

4.1.1.3 Key Business goals

It serves as comparison project for TePe. The project should be presented after twenty weeks.

4.1.1.4 Targets markets

The Primary Market is environmentally oriented adults.

The Secondary Market is dental clinics.

4.1.1.5 Assumptions and constraints

- Must be possible to injection mold.
- Must be able to fit in the downstream manufacturing belt.
- Mold filling needs to be fast.
- Must be able to withstand normal wear.
- Must fit an adult hand.
- Must reach all teeth.
- Needs to be hygienic, prevent old food from getting stuck in both the mouth and on the toothbrush itself.

4.1.1.6 Stakeholders

The stakeholders for this project is the author, the supervisor at LTH, and the supervisor at TePe.

4.2 Summary of goals

Beneath a summary of the stated goals and targets are presented.

- A weight of maximum 9,7 grams
- A filling time of maximum 6,0 seconds
- A cooling time of maximum 50,8 seconds.
- Must be possible to injection mold.
- Must be able to fit in the downstream manufacturing belt.
- Mold filling needs to be fast.
- Must be able to withstand normal wear.
- Must fit an adult hand.
- Must reach all teeth.
- Needs to be hygienic, prevent old food from getting stuck in both the mouth and on the toothbrush itself.

4.3 Identifying customer needs

To make sure that the new toothbrush will present solutions to needs from customers, and to find latent needs, it was important to identify customer needs.

First, raw data needed to be gathered, and from this raw data customer needs could be extracted. This can be done in several ways, for example by performing interviews, organizing focus groups, observing the product in use or create a questionnaire.

In this project, quantitative information was aimed for. Important information was e.g., form factors, importance of cost and environmental impact. To get as many answers as possible was also an important aspect, and to succeed with that a questionnaire was developed. (Sharp et al, 2019).

4.3.1 **Gather raw data.**

4.3.1.1 Questionnaire

The questionnaire was structured after studying the book "Interaction design beyond HCI" by Sharp, et al. (2019). The authors of this book underline the importance of carefully writing each question that end up in the questionnaire. The advice is to use close-end questions and have a "no opinion" or "other" field to fill in answers. This can help the person filling out the questionnaire to show that they don't agree to any alternative or explain their specific opinion.

The meaning of the questionnaire is to find and verify user needs. This information is important in the development of the target specifications for the product. (Sharp et al, 2019). The full questionnaire can be seen in appendix B.

4.3.2 **Interpretation of customer needs**

To be able to efficiently process the customer needs provided by the questionnaire, the needs are interpreted. (Ulrich & Eppinger, 2007). For example, if a customer statement is: "It's important that the toothbrush reaches all around the mouth", this was then interpreted as: "Toothbrush reaches all teeth". The list of expressed needs is attached in Appendix B.

4.3.3 **Needs Hierarchy**

To make the list of needs easier to handle, they are sorted into a hierarchy. Some needs are considered as primary needs and others are considered as secondary needs. The primary needs work as headline for needs in a similar category. The primary needs are the needs that are seen as the more important needs. For example, the primary need "Reaches all surfaces" is a headline to the secondary need: "Is easy to keep clean". (Ulrich & Eppinger, 2007). They are clustered together since both needs are about hygiene, see Table 4.1.

Table 4.1 Need hierarchy.

Ergonomic needs		ECO needs		Hygienic needs		Design/simplistic needs	
The grip is comfortable		**TB contains little mass**		**Reaches all surfaces**		**TB looks sleek**	
The grip fits different hand sizes	**	TB is robust	*!	Is easy to keep clean	**	Design is timeless	**
The TB is usable for persons with variated hand function	**!	Easy to recycle	**			The design is easy to understand	**!
TB grip provides friction	**					TB is sturdy	**
TB is easy to use	***!					TB emits confidence	***!
Brush head fits small mouths	***!						

Most critical need	***
Second most critical need	**
Least critical need	*
Latent need	!

4.4 Product Specifications

4.4.1 **Metrics List**

To be able to track and measure the needs they must be translated into metrics. This is done by sorting the needs into a list and finding ways on how to measure a specific need. The metrics are supposed to make sure that all needs are being fulfilled. (Ulrich & Eppinger, 2007). For example, the need “The grip fits different hand sizes” can be translated into two different metrics: Amount of test persons and anthropometric data.

4.4.2 **Needs-Metrics Matrix**

To get an overview of the needs and the metrics that fulfills the needs a need-metric matrix was created. (Ulrich & Eppinger, 2007), see Table 4.2. The matrix shows how each need can be measured and made sure that the concepts fulfill the needs.

Table 4.2. The Need-Metric matrix

		Can fit a special grip on the toothbrush	Amount of testpersons	Brushhead length	Neck length	Total length	Reduce mass to comparable TB	TB can withstand a force of 1 N	Amount of materials used	Amount of locations dirt can get stuck	Compare to other toothbrushes	Compare design to other toiletries	Brush head is offset from handle
		Binary	Qty	mm	mm	mm	kg	N	Qty	mm	Qty	Qty	Binary
1	The grip is comfortable		x										
2	The grip fits different hand sizes		x	x	x	x							
3	The TB is usable for persons with variated hand function	x											
4	TB grip provides friction		x										
5	TB is easy to use		x										
6	Brush head fits small mouths		x	x	x	x							
7	TB contains little mass						x						
8	TB withstands normal wear							x					
9	Easy to recycle								x				
10	Reaches all surfaces			x	x	x							x
11	Is easy to keep clean									x			
12	TB is proportionally designed										x		
13	TB looks sleek										x		
14	Design fits in a bathroom											x	
15	The design is easy to understand										x		
16	TB is sturdy										x		
17	TB emits confidence										x		

4.4.3 **Target Values**

To set up values for the metrics, for the developed product to be met, a competition analysis was performed.

4.4.3.1 Competition Analysis

The competitors were chosen due to their occurrence in stores and how well-known the brand is. The chosen toothbrushes were then listed in a competitive benchmarking chart, where they were graded according to the set metrics. This leaves the project with information about what metric values the developed concepts should reach. The competitive benchmarking chart is presented in Table 4.3.

Table 4.3 Competitive toothbrushes compared by the set metrics.

Metric no.	Need nos.	Metric	Importance	Unit	TePe Select	Dr. Collins Perio	Mentadent Adaptor	Tau-Marin Profession	Jordan Green	Jordan Ultralite	Dontodent Nature	Jordan pink	Jordan white	Colgate purple	Pepsodent green
1	3	Can fit a special grip on the toothbrush	2	Binary	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes
2	1,2,4,5,6	Amount of testpersons	5	Qty	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data
3	2,6,10	Total length	3	mm	185	195	196	179	192	No data	No data	196	191	193	190
4	2,6,10	Neck length	3	mm	35	39	37	41 (incl. BH)	40	No data	No data	40	40	40	48
5	2,6,10	Brushhead length	3	mm	25	31	29	41 (incl. BH)	29	No data	No data	30	30	30	28
6	7	Reduce mass to comparable TB	5	kg	0%	13%	-18%	40%	-8%	-34%	10%	14%	-14%	57%	-14%
7	8	TB can withstand a force of 1 N	5	Binary	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
8	9	Amount of materials used	3	Qty	3	4	4	3	3	2	4	4	4	5	4
9	11	Amount of locations dirt can get stuck	4	mm	1	1	2	1	1	2	2	2	1	5	2
10	12,13,15,16,17	Compare to other toothbrushes	4	Qty	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data
11	14	How well does the design fit with other toiletries	3	Subj.	Good	Good	Good	Good	Good	Good	Bad	Good	Good	Good	Good
12	10	Brush head is offset from handle	3	Binary	No	Yes	Yes	No	Yes	Yes	No	Yes	Yes	Yes	Yes

4.5 Concept Generation

When the various targets were set, the concept generation began. The aim of this part of the project was to create a variety of ideas to choose from. (Ulrich & Eppinger, 2007).

One way of finding different solutions is to design the toothbrush so it meets only one target. Such as: “How would a sleek toothbrush look like?”, see

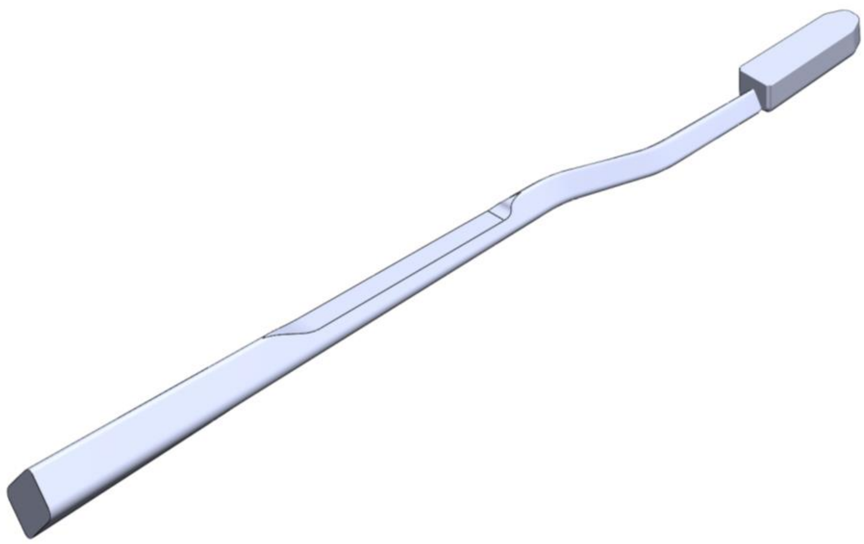

Figure 4.1, or “how would an ergonomic toothbrush look like?”, see Figure 4.2. These could later be combined to create a toothbrush that, in best case, meets both targets, see Figure 4.3.

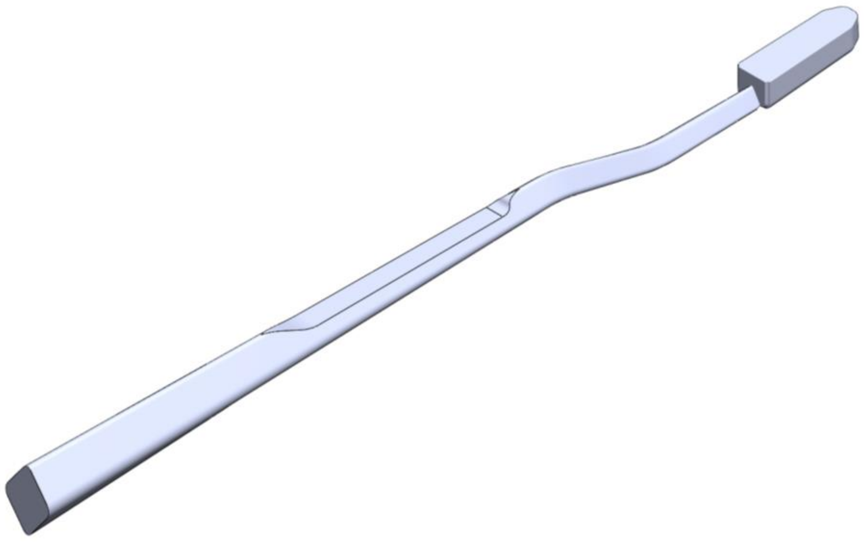

Figure 4.1 A sleek toothbrush.

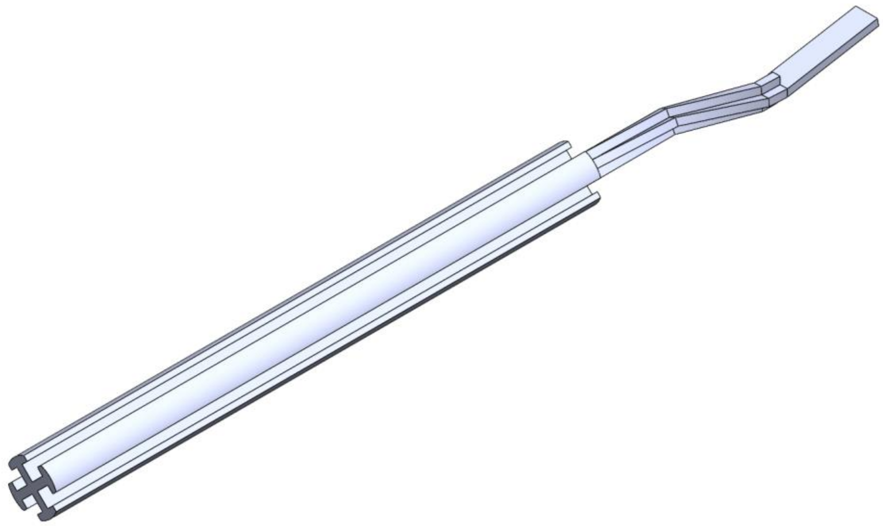

Figure 4.2 An ergonomic toothbrush

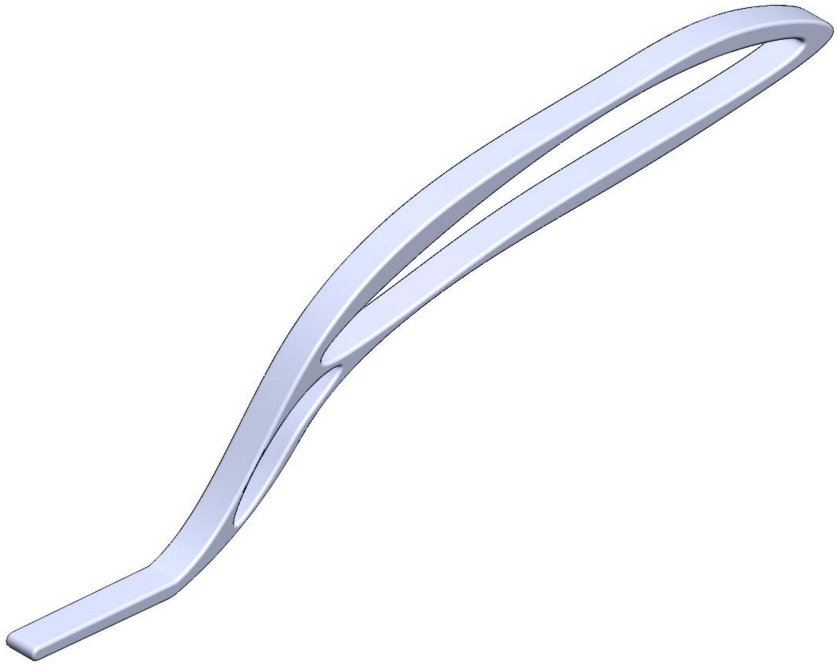

Figure 4.3 A sleek and ergonomic toothbrush.

This way of working gave some inspiration at a start. But other methods were needed to be able to design more concepts. Firstly, several rapid sketches were made, in this way different toothbrushes and shapes could be compared to each other. Clay models were then created based on the best sketches. The author found it very inspiring to work with the two different techniques, sketches, and clay models, at the same time. Concepts that looked interesting on paper, could later be found plain and boring when they were made in clay. During the manufacturing of the clay models, new inspiration was discovered, and small design decisions were made when working with the model.

The goal, when working with the sketches and the clay, was to create a lightweight toothbrush. Water and a cutting knife were used as tools, Figure 4.4. Firstly, prototypes were made to feel lightweight, but without a clear strategy, Figure 4.5.

Figure 4.4 Water and a cutting knife were used when working with the clay.

Figure 4.5 Toothbrushes made out of clay.

The ideas from this resulted in, for example, a slightly bent toothbrush with two thin connected handles, see Figure 4.6, and a similarly bent toothbrush with two thin separate handles, see Figure 4.7. The curvature was created to bring rigidity to the prototypes.

Figure 4.6 Toothbrush with two joined thin handles.

Figure 4.7 Toothbrush with two separate thin handles.

A toothbrush with a “wavy” handle were also created, to give an ergonomic feel but without the need of extra material, see Figure 4.8.

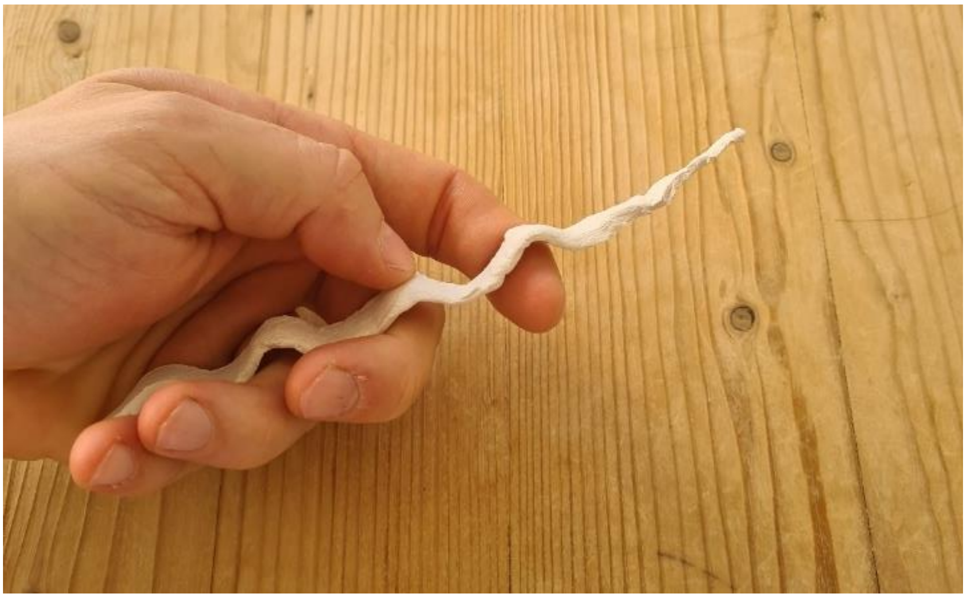

Figure 4.8 Toothbrush with “wavy” profile.

After these prototypes, it did not seem to be too much of a problem to design a toothbrush that weighed under 9,7 g. The concept generation therefore started to focus on the cycle time for the injection molding process. This meant that the parting line and wall thickness was of high priority.

This resulted in concepts with the focus lying on having a straight parting line and a uniform wall thickness, as can be seen in Figure 4.9 and Figure 4.10.

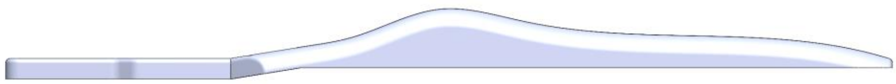

Figure 4.9 Concept 1 with a possible straight parting line and uniform wall thickness.

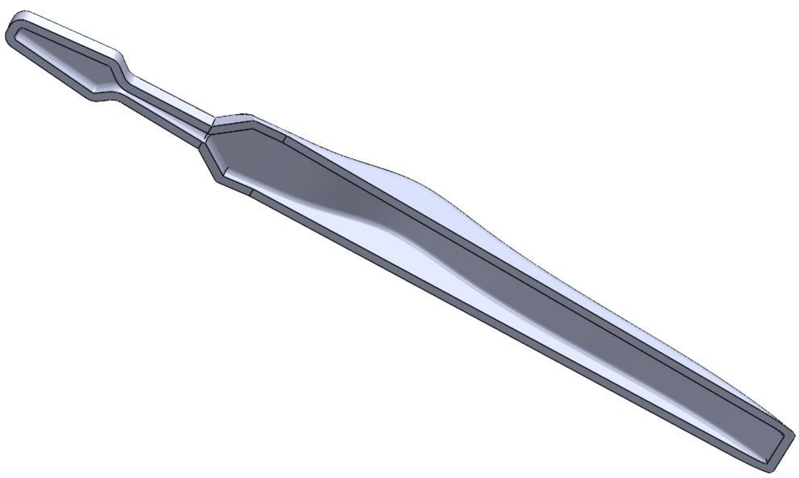

Figure 4.10 Concept 1 with a possible straight parting line and uniform wall thickness.

The concept in Figure 4.11 is made like single-use plastic cutlery. This design saves weight, time, and results in a rigid design.

Another concept with the same design thinking was created, that resembles the Spork design. The design has a convex surface both underneath and above the parting line. However, this design raised some doubts regarding where the surface crosses the parting line. The toothbrush would probably need some reinforcements and the brush head has an inverted surface compared to the handle, which could be problematic for the function, see Figure 4.11.

Figure 4.11 Concept 2 with a straight parting line and uniform wall thickness. The path from handle to brush head is very thin.

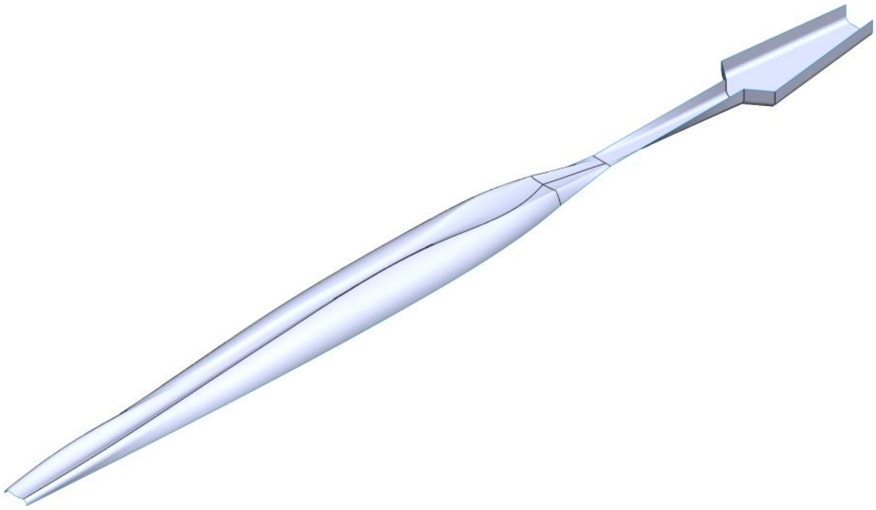

Figure 4.12 Concept 2 with a possible straight parting line and uniform thickness.

To be able to meet the target of having an inclined neck, together with a simple parting line, a new concept was created, see Figure 4.13. This design has a frame and a lattice structure within it. The parting line is designed to be simple, straight and with a slight curvature where the neck of the toothbrush is located, see Figure 4.14. The frame is to provide longitudinal bending stiffness while the lattice is there to provide stiffness in the transverse direction, for example when the toothbrush is gripped. The curved handle is there to provide a comfortable gripping experience. As can be seen in Figure 4.14, the lattice is thinner than the surrounding frame. This is thought to keep the wall thickness even.

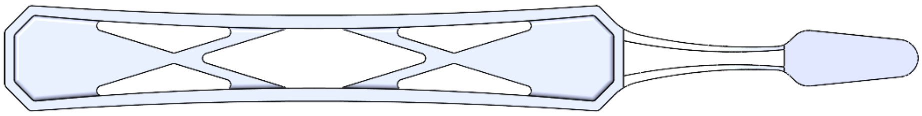

Figure 4.13 Concept 3 with lattice structure within a frame.

Figure 4.14 Concept 3 with a simple parting line.

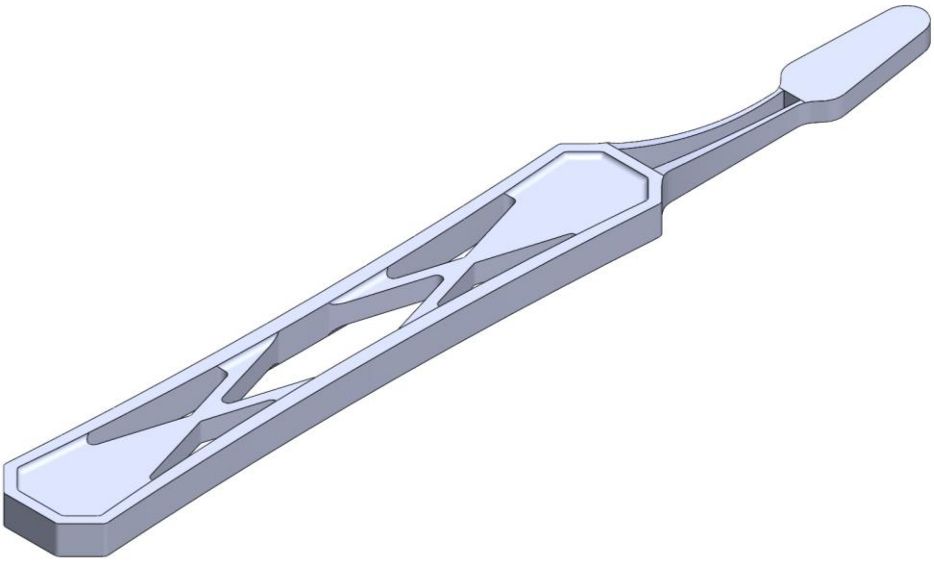

Figure 4.15 Concept 3 with a frame and a lattice. The wall thickness is similar around the toothbrush.

This concept was analyzed by mold flow analyses, see Figure 4.16.

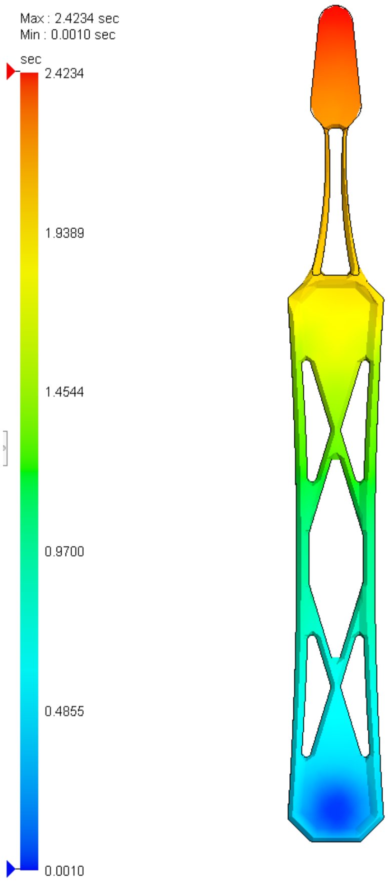

Figure 4.16 Mold flow result for concept 3. The figure represents the filling time in color, blue for about 0 seconds and red for the end of fill at 2,4 seconds.

After discussions with Peter Bjellheim, the pressure drop during the fill was also considered. Peter Bjellheim explained that a too big drop in pressure is problematic. The thin channels (neck) leading to a larger volume (brush head), indicates that the pressure will drop, see Figure 4.17. The pressure at end-of-fill, varies from 23 MPa to about 0,1 MPa. This resulted in an iterated concept, where the neck was filled with material. This should also increase rigidity in the neck area, see figure 4.18.

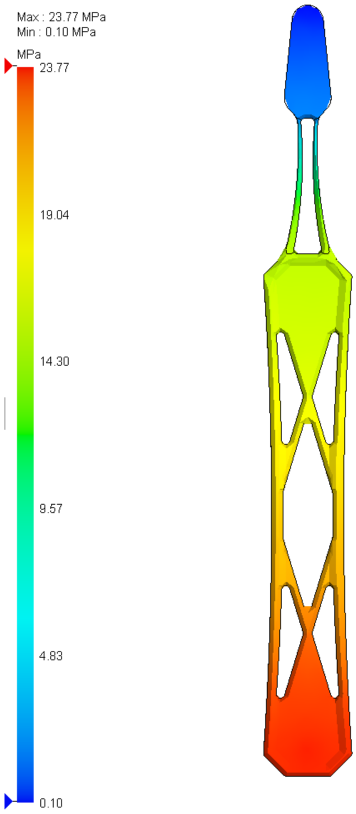

Figure 4.17 A significant pressure drop can be seen, where the neck leads into the brush head. This confirmed what consulted experts said.

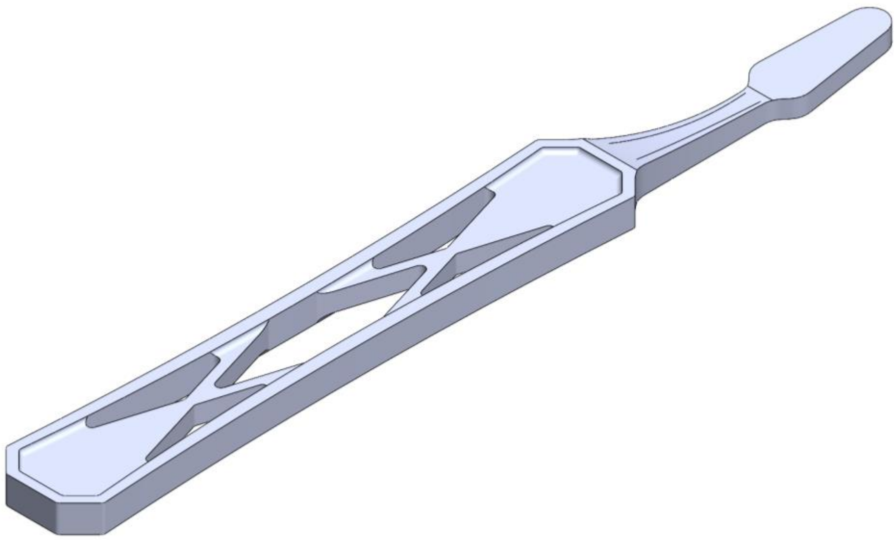

Figure 4.18 Concept 3b. Similar to concept 3 in Figure 4.13, but with a filled neck.

The flow simulation also showed problems with the filling of the manufactured part, see figure 4.19. This is probably due to the thin channels, located in the middle of the handle, together with a larger volume in the neck and brush head area. The frame was made thicker, to accommodate the needed flowrate, see Figure 4.19 4.20.

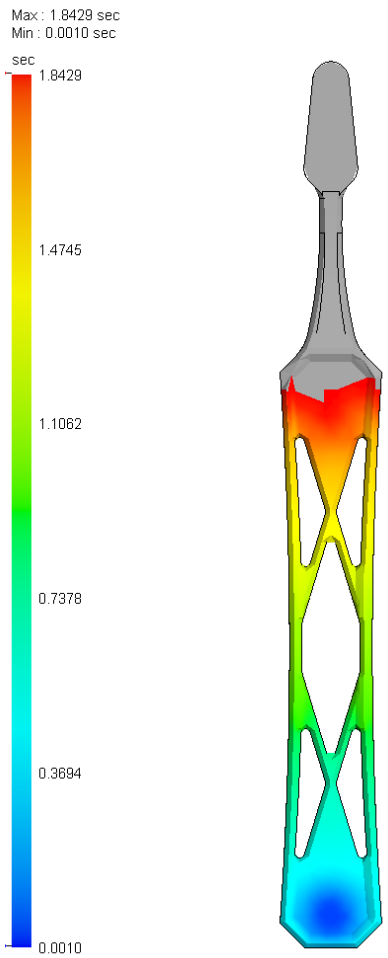

Figure 4.19 Mold flow analysis of concept 3b. The grey area has not been filled. The dark blue area indicates where the gate is located.

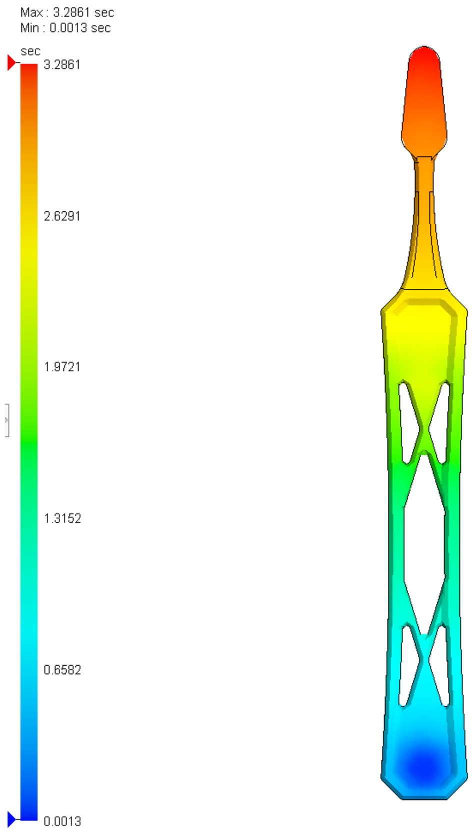

Figure 4.20 Fully filled model of concept 3b, with thick frame.

The redesign proved helpful, the pressure drop decreased from about 23 MPa, to about 8 MPa. See Figure 4.21.

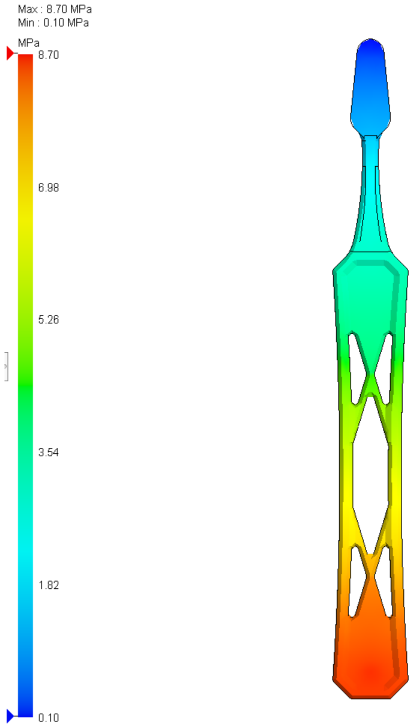

Figure 4.21 Concept 3b. Significantly reduced pressure drop with a solid neck.

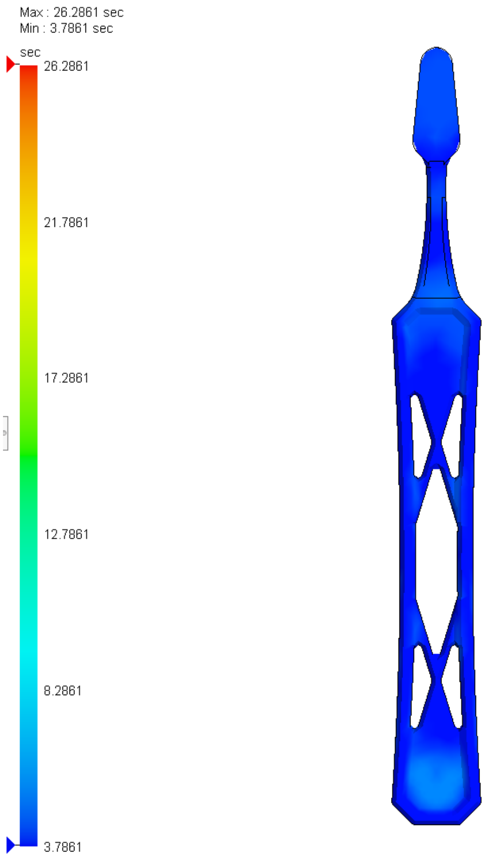

Figure 4.22 Cooling time results of concept 3b.

As can be seen in figure 4.22., the cooling time does not seem to be more than 8 seconds for any part of the toothbrush. The volume that needs more time was located in the brush head. Since this concept did not have the holes for filaments made, that would be the reason, see figure 4.23.

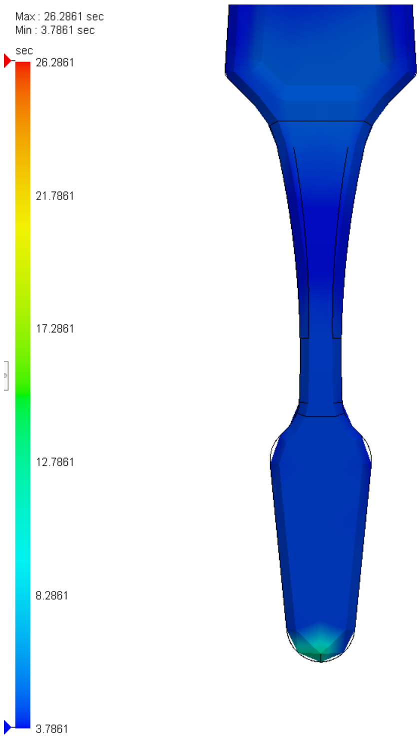

Figure 4.23. Brush head for concept 3b.

To be able to test the concept and let test persons try it, a prototype was created. 3D-pritning with a filament printer (FDM-printer) was used to make the prototype, see figure 4.24.

Figure 4.24 A prototype of concept 3, together with two of TePe’s regular toothbrushes.

The test persons made it clear that there was room for improvements of the concept. The lower part of the handle was not used when holding the toothbrush and was in the way sometimes. It was therefore made narrower, from the middle of the handle and downwards. They also noted that the thumb needed a deeper place to sit when using the toothbrush.

Concept 4, an iteration of concept 3b can be seen in Figures, 4.25, 4.26 and 4.27.

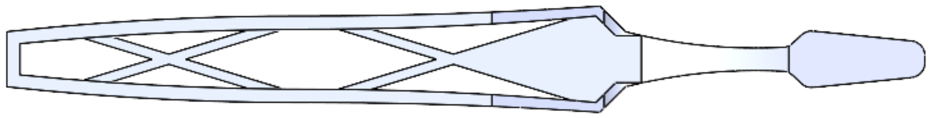

Figure 4.25 Top view of concept 4

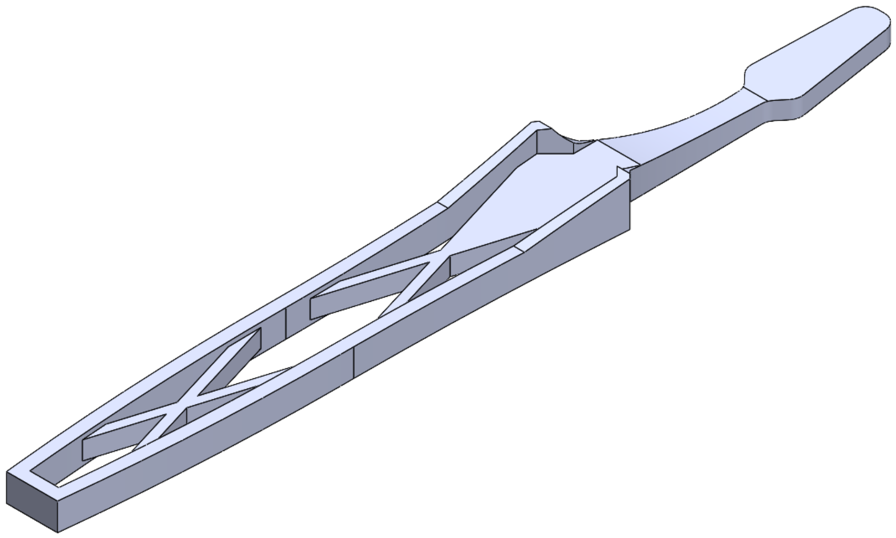

Figure 4.26 Perspective view of concept 4.

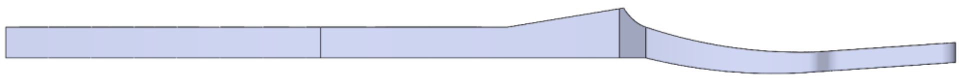

Figure 4.27 Side view of concept 4. Here the thumb grip can be seen.

The concept 4 with the narrower lower part was also made with an FDM-printer. See Figure 4.28.

Figure 4.28. Prototype made by FDM.

The same test persons who tested the previous concept was let to use this new concept. The narrower bottom part was appreciated as well as the thumb grip. Criticism of this concept circled around the lattice design. It seemed to be able to collect dirt. The test persons also wanted the edges around the toothbrush to be more rounded.

The lattice in this concept was further developed, to find other solutions that are not so sensitive to collection of dirt. The edges were also rounded, together with changing the lattice to create, design wise, a more interesting pattern. See figure 4.29 and figure 4.30.

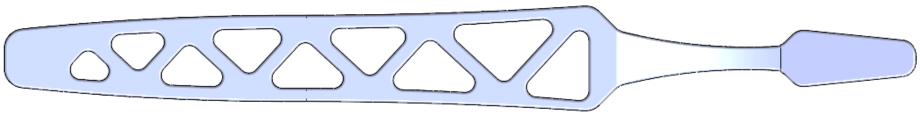

Figure 4.29 The same outer shape as concept 4, but with an asymmetrical lattice design.

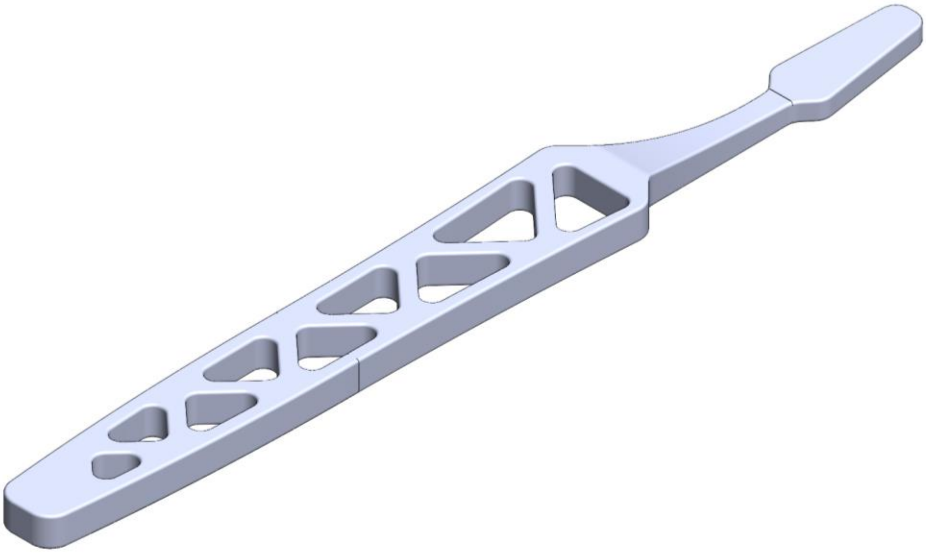

Figure 4.30 Perspective view of concept 5, with an asymmetrical lattice design.

However, after discussion the designs with the supervisor at TePe, there was a worry that the asymmetrical pattern would lead to warpage of the handle. Therefore, an alternative concept was created, with a symmetrical pattern made of circular holes. This pattern can enhance the manufacturing quality, together with less dirt collection, see Figure 4.31.

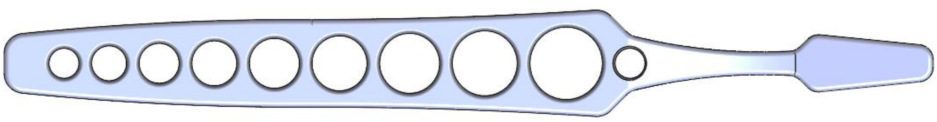

Figure 4.31 Concept 6. This concept has the same profile as concept, 4 and 5, but with different sized holes instead of a lattice design.

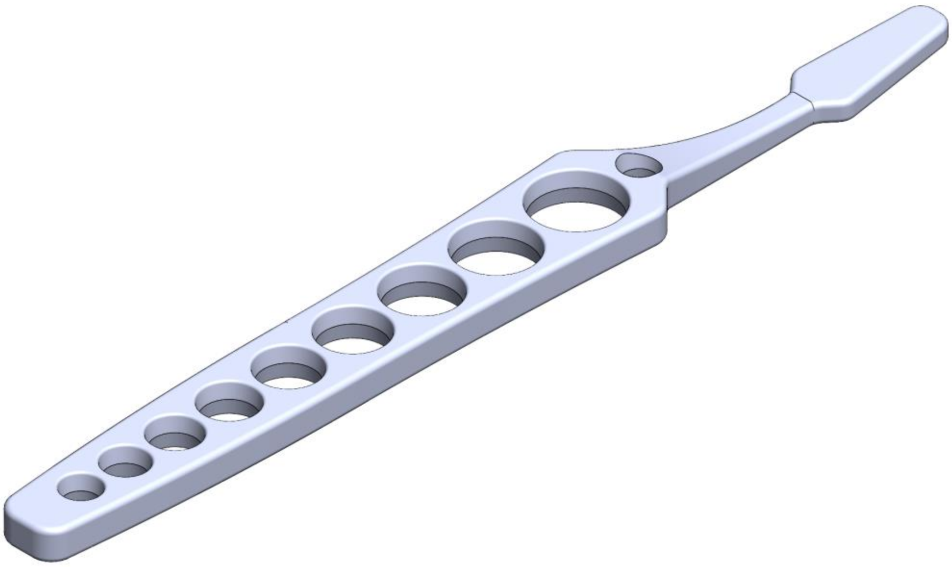

Figure 4.32 Concept 6 in perspective view.

As can be seen in figure 4.32., the circular holes are not straight cut, but have a tapered inside. This is to provide easier cleaning of the toothbrush handle. An issue was the appearance of weld lines. Weld lines will, as an example, appear when holes are incorporated in the toothbrush, see Figure 4.33.

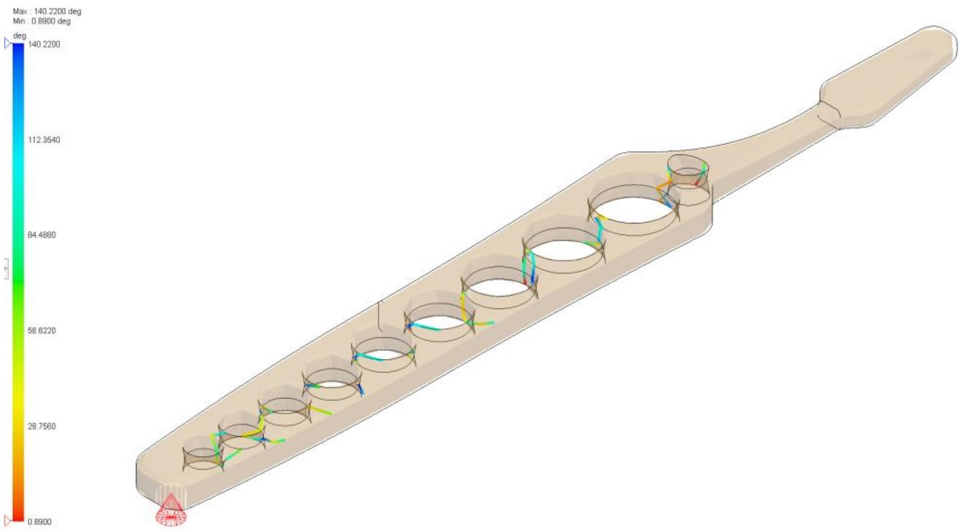

Figure 4.33. Locations for weld lines.

The colored lines in the model in Figure 4.33 are locations where there is a risk of weld lines. Because of the flowing plastic coming from two different directions when the flow passes a hole, they will meet and create a weld line. In the example in figure 4.33 this should not be a problem, since there are no weld lines in highly loaded areas, such as the neck.

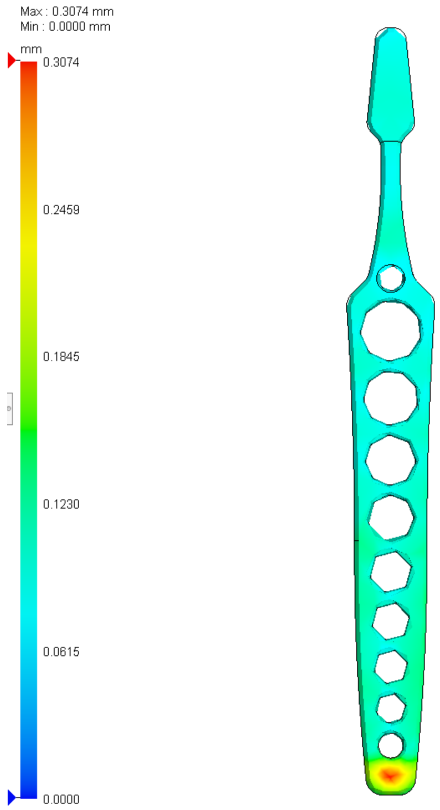

Figure 4.34 The red areas indicate a sink mark of 0,3 mm.

In figure 4.34, locations where sink marks can appear is presented. Above the gate is the highest risk of a sink mark, but also where the handle becomes the neck. After discussions with the supervisor at TePe, the design was changed to hide eventual sink marks. This can be done by understanding where sink marks can appear and then design for examples curvatures and dimples at these spots, and also by moving the gate.

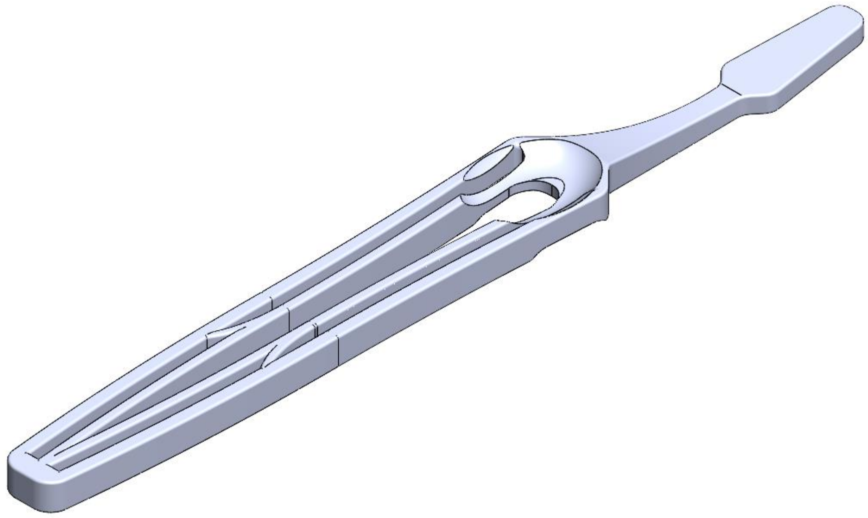

Figure 4.35 Concept 7

The next prototype further developed the inside structure, see figure 4.35. Here the thumb grip is incorporated in the handle in such way that the thickness stays the same as in the rest of the handle.

But, since the thumb grip is located right above the index finger grip, concerns of the bending stiffness was raised. Therefore, a prototype was made, see figure 4.36.

Figure 4.36. Prototype based on concept 7.

The prototype showed that the concerns were well-founded. The prototype flexed around the thumb grip and index finger grip, combined with also showing significant flex in transverse direction from holding the toothbrush.

The flexibility of concept 7 gave inspiration to create a concept with the focus of providing stiffness for bending in both longitudinal- and transvers direction, see figure 4.37, 4.38, and 4.39.

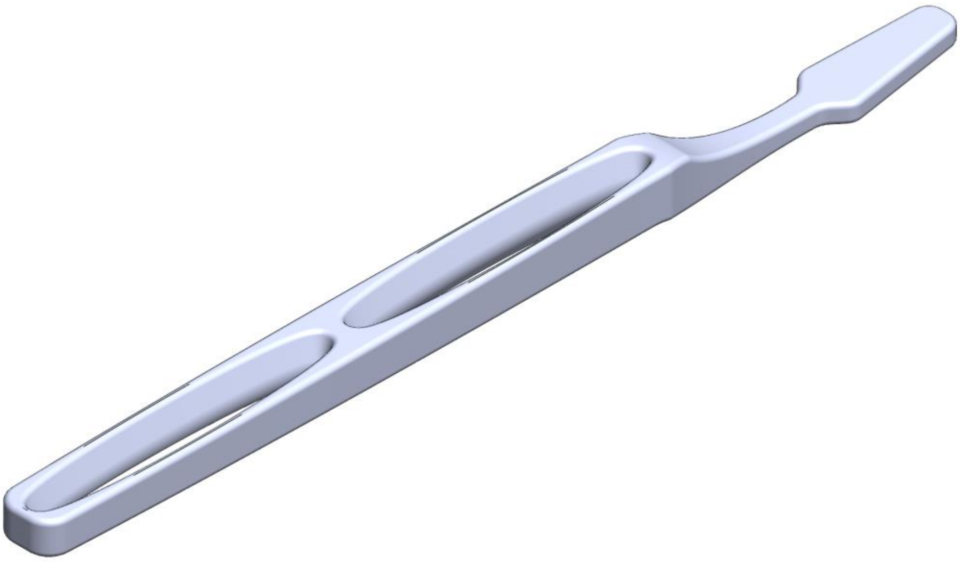

Figure 4.37 Concept 8, with high bending strength in multiple directions.

Figure 4.38 Top view of concept 8.

Figure 4.39 Side view of concept 8.

To incorporate a thumb grip in the high bend stiffness design, concept 9 was created, see figure 4.40. A hanger was incorporated in the design. The idea to have a hanger came when talking to test persons, many thought that the lattice design made room for hanging the toothbrush when not in use. This would also be a way to fulfill the targets of hygiene, since the water would drop off from the toothbrush.

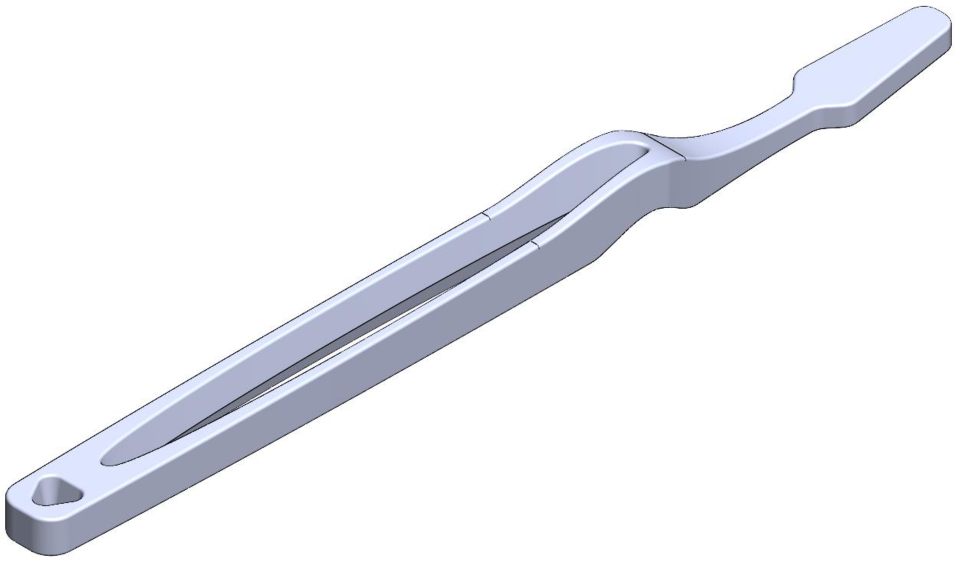

Figure 4.40 Concept 9 and the hanger in the bottom of the toothbrush.

The high bend stiffness concepts were also printed using an FDM-printer, see figure 4.41.

Figure 4.41 Concept 8 and 9.

Concept 8 met the expectations of being stiff, in multiple directions. However, this was not the case for concept 9. Since this concept has one large hole, instead of two smaller ones, this meant that it was more flexible when gripping the handle.

Test persons also expressed that these designs were too narrow to be able to grip comfortably. Therefore, a concept that was a combination of concept 8 (with high stiffness) and the formfactor of concept 4 (with wider handle), was developed, see figure 4.42.

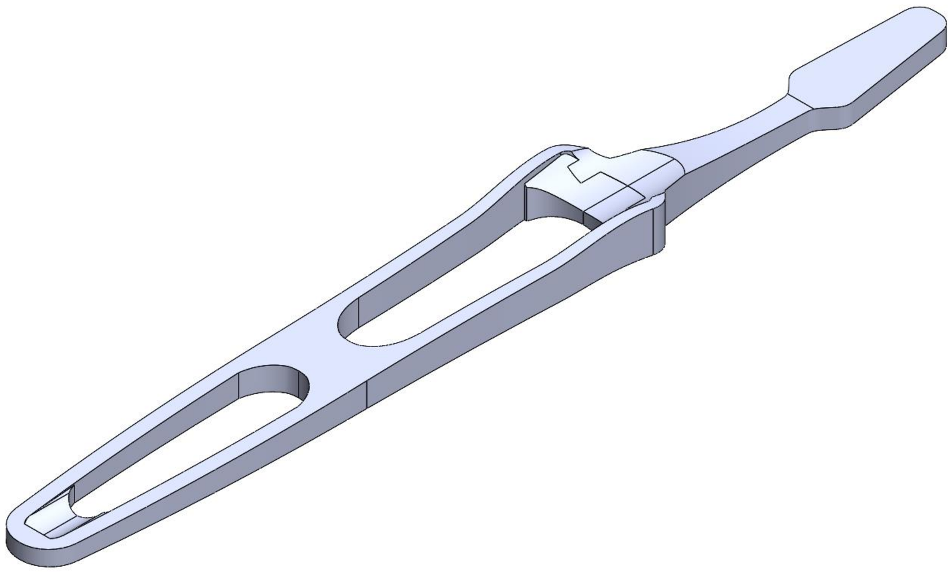

Figure 4.42 Concept 10.

Concept 10 was also printed with an FDM-printer, see figure 4.43. Test persons expressed that it has good qualities. It is stiff when holding it, stiff when bending it and also lightweight. It is also comfortable to hold with the wide grip, but the thumb grip is not very comfortable, and the design was claimed to be too rough. Since this concept seemed to have much potential, this led to an iteration. The iteration, concept 10b, had a refined design with an added feature on the backside, and a weight-saving slit, see figure 4.44. The slit is designed to not capture dirt, but still save weight, see figure 4.45.

Figure 4.43 Concept 10. Printed in PLA.

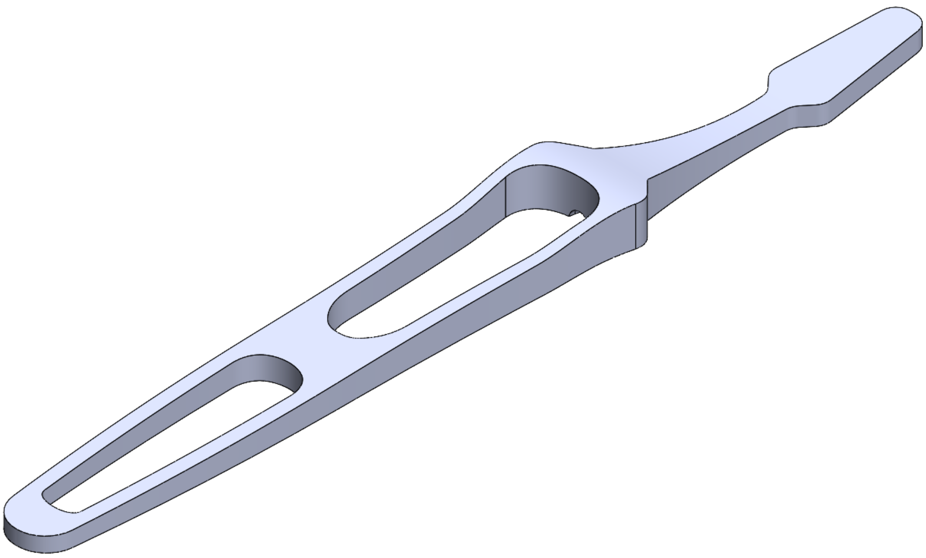

Figure 4.44 The second iteration of concept 10, called concept 10b.

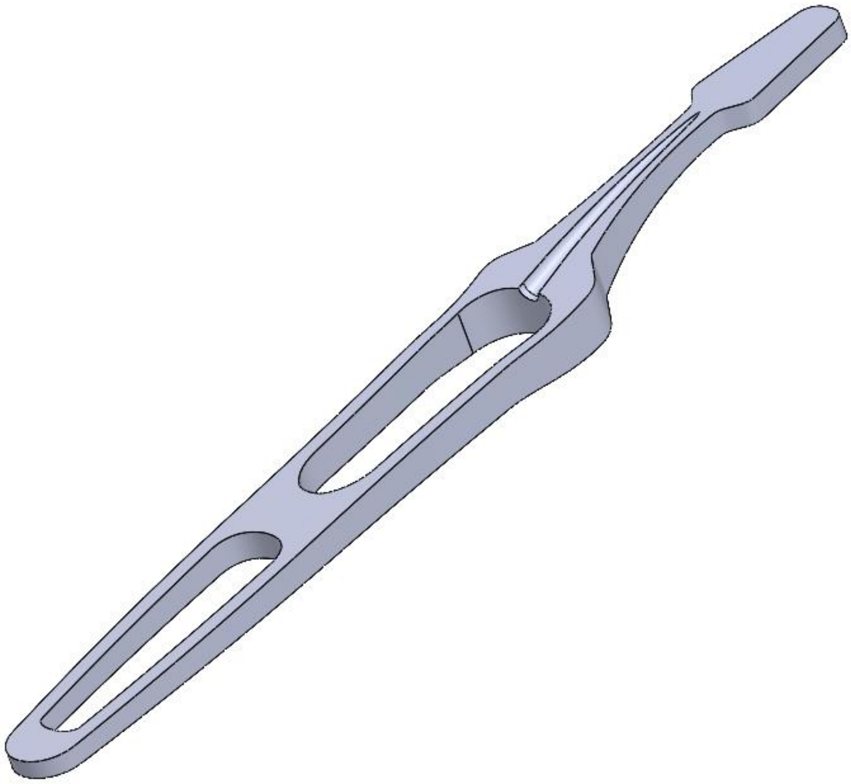

Figure 4.45 Concept 10b backside, with weight-saving slit.

4.6 Concept Selection

The process of selecting a suitable concept was based on the targets created from costumer statements, test persons and professionals' opinions and on subjective design preferences by the author.

To decide which concept that becomes the final one, a concept scoring matrix was used, see appendix C. The matrix consists of areas which are of interest for the product. The concepts get a score in each area based on their performance.

As sustainability was an important part of the project, several sustainability targets were included in the selection process as well.

Some properties are difficult to express in targets, but they appear when the toothbrush is in the hand of a test person. An example of this kind of target is the flexibility of a toothbrush. If it flexes too much in one direction, it can be considered to be of lower quality compared to one with a more rigid feel.

The concept scoring was based on the concept scoring matrix (Ulrich & Eppinger, 2012). Targets that was earlier established, was set as selection criteria and was given an individual weighting. For example, mass reduction was given the highest weighting of 30 percent and the target comfortable to grip was given the second highest weighting of 20 percent, and the target, easy to keep clean, had the third highest weighting at 15 percent. It resulted in the chart presented in figure 4.46. In the chart each concept is presented with its weighted score, showing that concept 10b was the highest scoring and could be further developed. Concept 10b had the lowest weight, were one of the most comfortable, and is easy to clean, even before developed further. The full concept scoring matrix is presented in Appendix C.

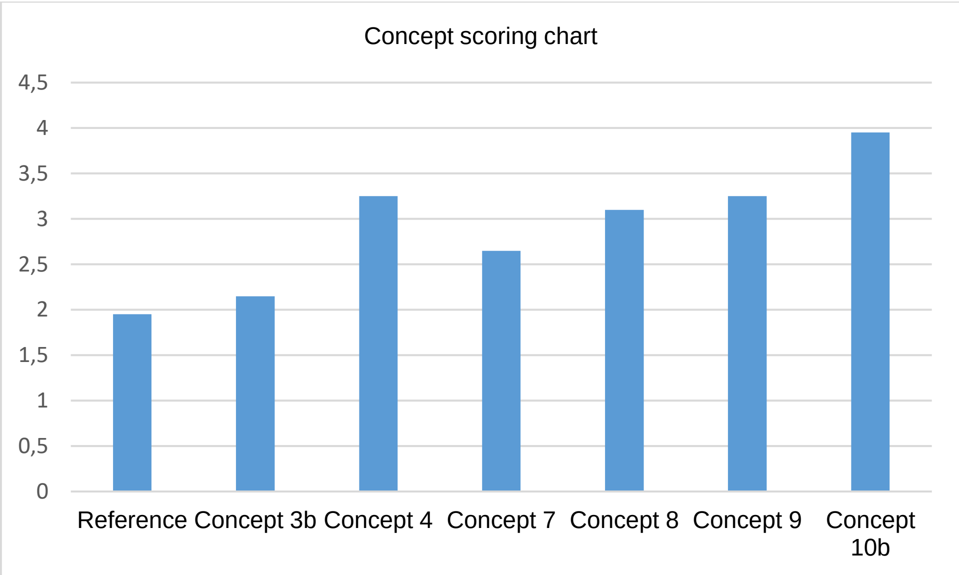

Figure 4.46 Results from the concept scoring, where concept 10b scored the highest.

4.7 Concept Testing

To test the developed concepts, both virtually and physically, prototypes were manufactured. The virtual prototypes were created with computer aided design, in Solidworks. In Solidworks the plug-in, Solidworks Plastics were used. The plug-in enables the user to perform mold flow analyses. Solidworks were also used to investigate the mechanical properties of each concept, by performing finite element analyses (FEA). The license for Solidworks and its plug-ins was provided by Lund University.

To validate the results produced in the mold flow analyses, Peter Bjellheim was consulted. Bjellheim works with another mold flow software, called Moldex 3D, which showed to present a more complex and deep analysis of both the reference toothbrush and an iteration of the last concept.

From the CAD-models created in Solidworks, STL-files could be created. An STL-file includes information about the surface geometry of the model and is a universal file format widely used for 3D-printing. The files were imported into Prusa Slicer, a free slicer software used for printing in FDM-printers, fused deposition modeling, made by Prusa research. The slicer software is needed to transform the STL-file into a format that the 3D-printer can read. In this case, a Prusa i3 MK3S+ were used and the final output file needed to be a gcode-file. The models were printed in ABS and PLA.

4.8 Final concept development

The concept who scored the highest, i.e., concept 10b, was iterated after the comparison. A thumb grip was added on both the front and the back side, see figure 4.47 and figure 4.48. The backside thumb grip replaced the weight-saving slit. To be able to evaluate the concept once more, it was printed in ABS, see figure 4.49.

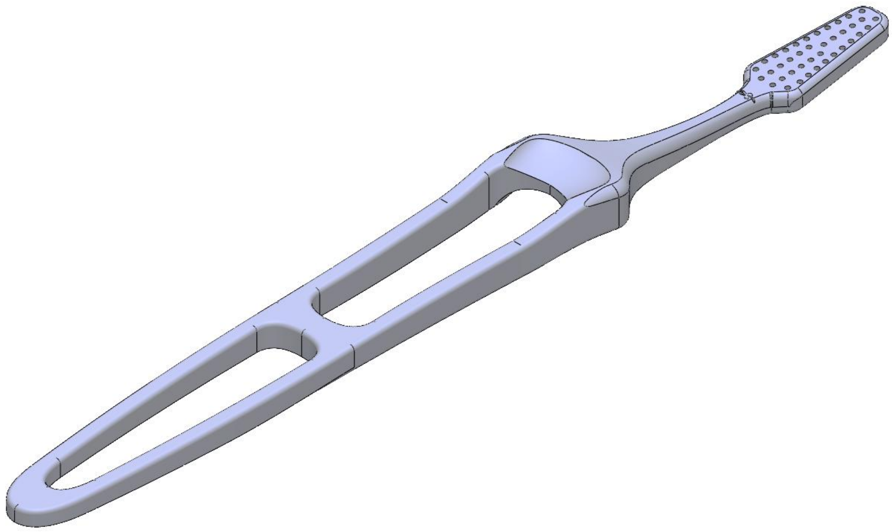

Figure 4.47 The final concept in CAD.

Figure 4.48 The backside of the final concept. Here the weight-saving thumb rest is visible.

Figure 4.49. 3D-printed prototype of the final concept.

The printed prototype was evaluated by test persons and got a good reception. Though, there was complaints over the bending stiffness. Therefore, another iteration was made. Here the thickness of the toothbrush was increased, from 3 mm in the lower end, to 4 mm. Meaning that the thickness of the hole handle increased, see figure 4.50 and figure 4.51. Since recyclability was one of the targets to reach, it was necessary to increase the chances of it getting recycled. To achieve this, a marking of where to cut the toothbrush was made, see figure 4.52. This way the handle, that only contains one material, can be recycled for material use and the brush head, that contains three different materials can be recycled for energy use.

Figure 4.50. Sideview of the final concept, with 3 mm of thickness at the bottom.

Figure 4.51 Sideview of the final concept, with 4 mm of thickness at the bottom.

Figure 4.52. Symbol to make recycling easier for the customer.

4.9 Material choice

Several plastic materials are used for toothbrushes, for example PE, PP, and CAP. Today PP is used in the Select toothbrush. PP's low cost and flow makes it a good choice. Though, since it's fossil based other materials that has a lower carbon dioxide footprint could also be used. For example, is bio-PP underway, and other biomaterials such as Arboform (Tecnaro) already exist on the market.

To be able to tell what difference each of the interesting materials, an LCA was performed. In this analysis all carbon dioxide (CO2) -emissions during the toothbrush's life is accounted for, from cradle-to-grave. The materials that were considered for the handle, and therefor used in the LCA, was PP and Arboform.

4.10 Concept validation

To validate that the chosen concept fulfills its goal, i.e., to reduce its carbon footprint, a life cycle assessment (LCA) was carried out.

Data for energy usage while manufacturing has been collected (PIMA, 2012), data for transportation has been collected from DHL (https://www.dhl-carboncalculator.com/#/scenarios, 2023), and data about CO_2-emissions from electricity has been collected from electricity maps (https://app.electricitymaps.com/zone/SESE1?solar=false&remote=true&wind=false, 2023). Material data has been collected from the supplier, and weight data has been generated from the CAD-model.

To make sure that the results in Solidworks Plastics are reasonable, an expert that uses another software were also asked to validate the results and compare the chosen concept 10b to Tepe's Select. Even if the results may differ from reality for the Select toothbrush, the same error margin can be assumed to apply for concept 10b as well. The new software that was used is called Moldex3D. The results from this software can be found in chapter 5.

5 Results

In this chapter the results are presented and discussed.

5.1 Chosen toothbrush concept.

The final iteration of concept 10b was chosen as the final concept. It reduces the mass by 50 percent (a total weight of 6.5 g), the fill time by 66 percent (a total fill time of 2,4 sec), and cooling time also by 66 percent (a total cooling time of 19,4 sec). The concept is presented in figures 5.1 and 5.2.

Figure 5.1 Top view of the final concept.

Figure 5.2 Perspective view of the final concept.

5.2 Properties of the final toothbrush

5.2.1 FEA

An FE-analysis was performed on the final concept and the reference toothbrush. The Polypropylene yield strength is 28,6 MPa at 42 degrees Celsius. The temperature was chosen to represent the temperature in a human mouth. Even though this temperature is highly exaggerated, polypropylene is losing yield strength with an increasing temperature (Hartmann, 1987). Therefore, the choice of 42°C is conservative. It showed that the final concept reaches a higher amount of stress compared to the Select toothbrush. Though, since the maximum amount reached is about a tenth of the allowed yield strength, this is result is considered to be acceptable, see figures 5.3, and 5.4.

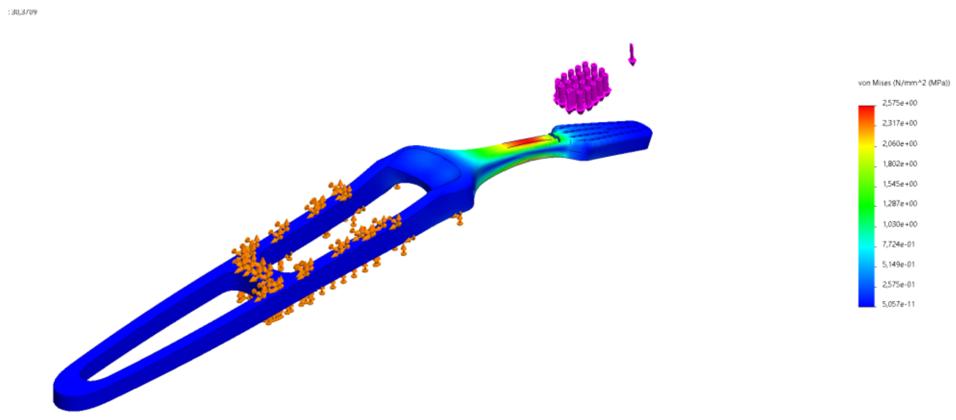

Figure 5.3 The new concept experiences a maximum stress of 2,6 MPa.

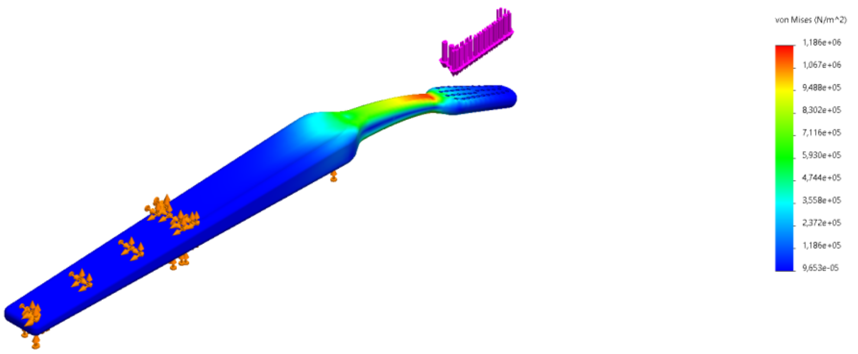

Figure 5.4 The Select Toothbrush experiences a maximum stress of 1,2 MPa.

5.2.2 **Mold flow analysis**

In figure 5.5 the gate location can be seen. It was placed according to the recommendations by Jaroschek (2022) and Bruder (2026). The location is in a thick area of the toothbrush, and it's located on the back side of the toothbrush, which means that it's not so easily seen by the user.

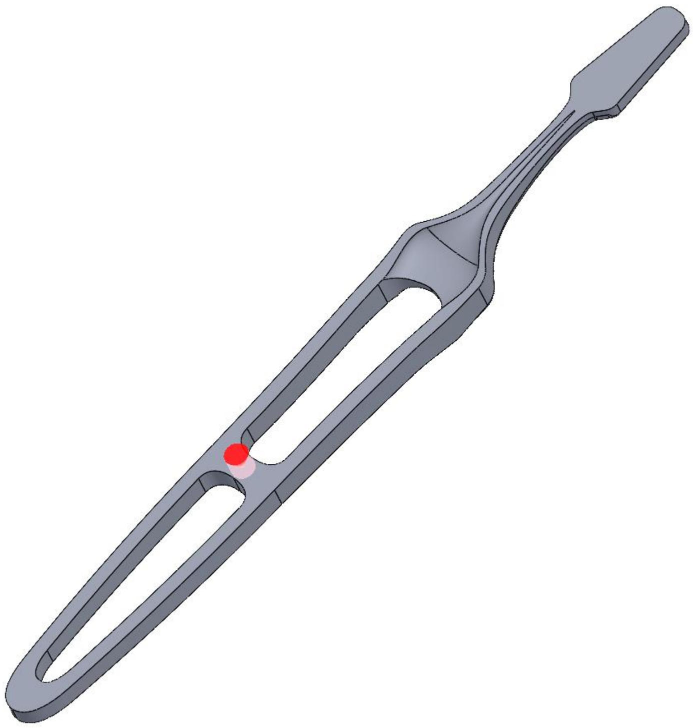

Figure 5.5

5.2.2.1 Results from Solidworks plastics

In figure 5.6 the fill time of the final concept is presented (2,4 seconds).

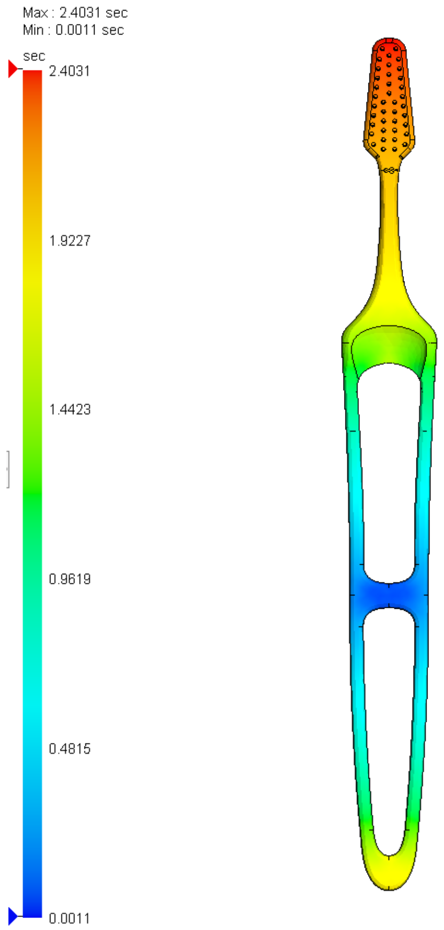

Figure 5.6 The dark blue area surrounds the gate, and the red area is furthest away from the gate location.

In figure 5.7 the cooling time for different areas for the final concept can be seen. The simulation suggests that the model needs 19,4 seconds to cool down enough to be ejected from the mold.

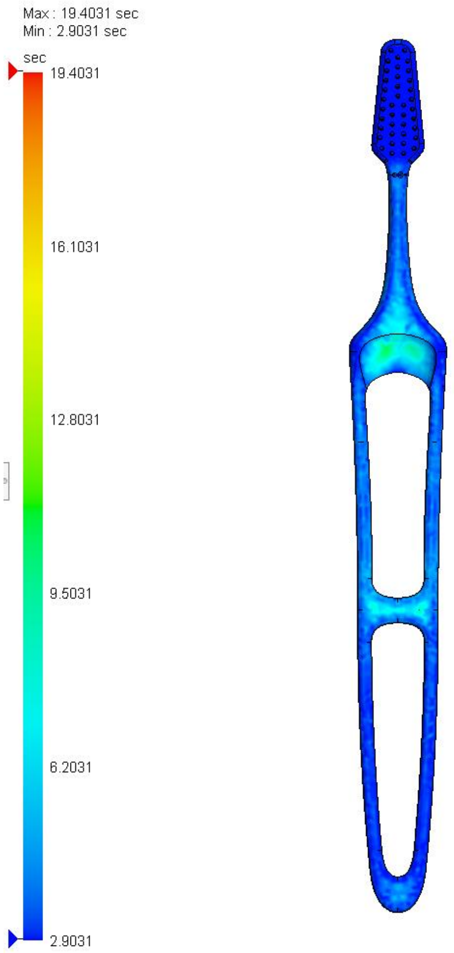

Figure 5.7 The areas in turquoise needs the longest time to cool down, these are the thickest area and the gate location.

In figure 5.8 the areas where sink marks can appear is presented. They are in the same spots as where the plastic takes the longest time to cool down.

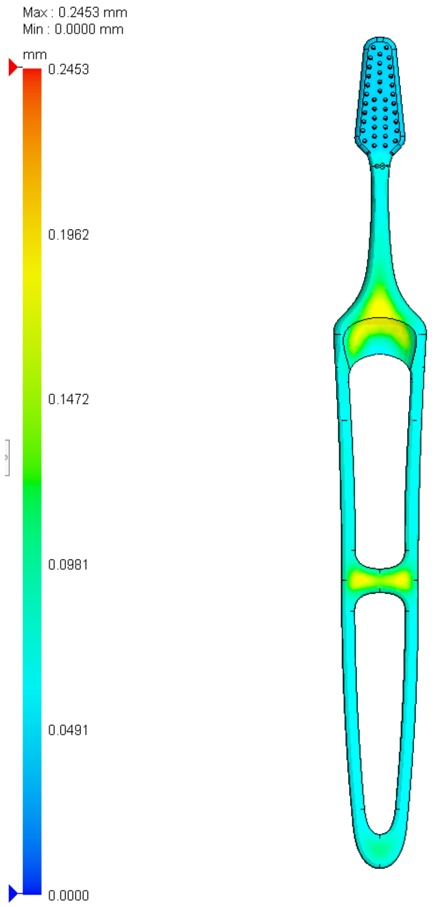

Figure 5.8 Sink marks are presented in yellow and green.

A tool that was used in Moldex3d is molten core, here the software displays where in the model the plastic is last solidified. As can be seen in figure 5.9, concept 10b is solidifying in significantly shorter time.

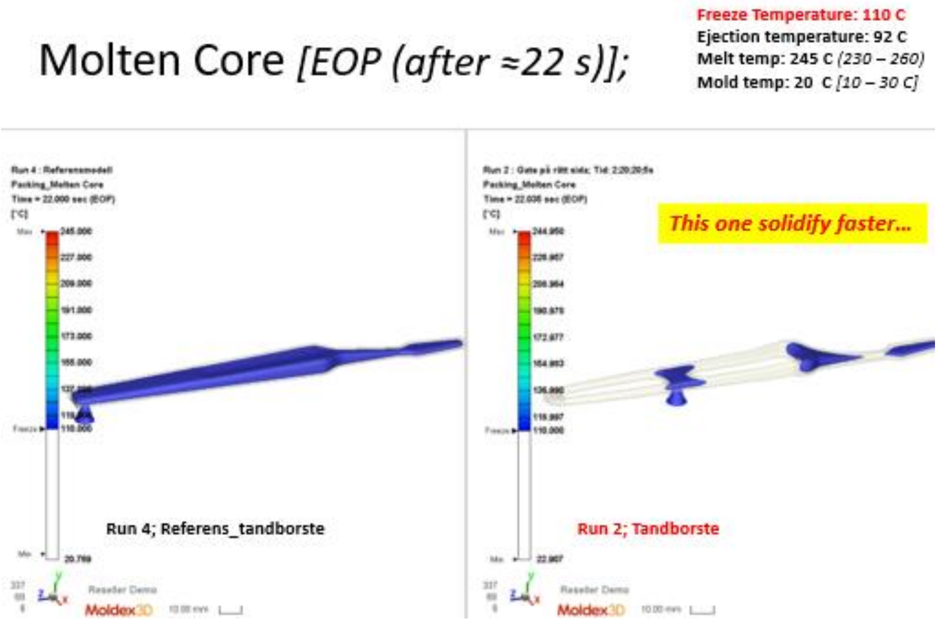

Figure 5.9 The molten core is the blue volumes.

In figure 5.10 the volumetric shrinkage can be seen. The average shrinkage of concept 10b is significantly lower than in the reference toothbrush.

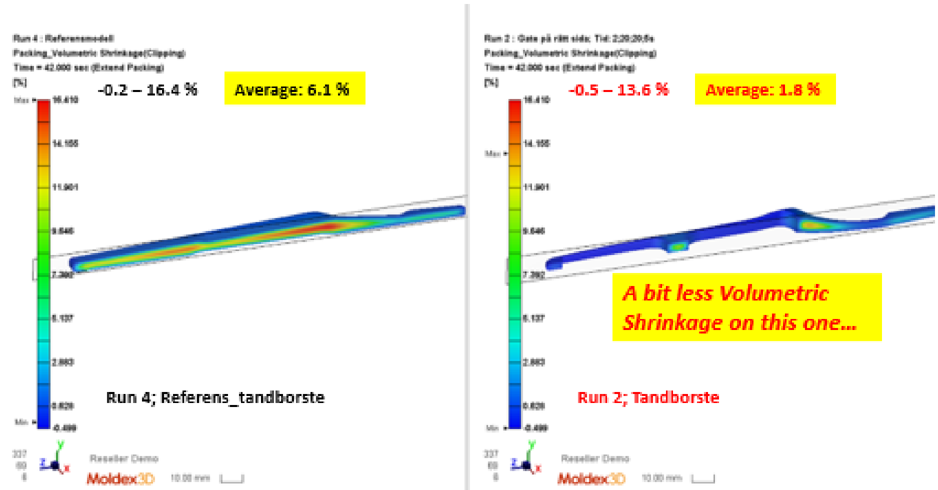

Figure 5.10 Volumetric shrinkage of the Select toothbrush and the final concept.

5.3 LCA

The LCA showed as expected that the final concept has a smaller CO_2-footprint than the Select toothbrush. If compared with the same material, PP, the CO_2-emissions are 0,022 kg CO_2/ kg of material instead of 0,040 kg CO_2/ kg material. Which is a reduction by 44 percent. When Arboform was used instead of PP, the emissions were 0,019 kg CO_2/ kg material. The results are fully presented in Appendix D.

5.4 Filament choice

The filaments are being placed in the same formation as in the Select toothbrush, but the material can be changed for a smaller carbon footprint. Similar to how the toothbrush concept has been evaluated with LCA, the footprint of different materials can be compared. The materials compared is Polyamide (PA6.12, PA1010) and Polybutylene Terephthalate (PBT).

PA6.12 is the material used in the filaments in the Select toothbrush and were therefore used as a reference. PA1010 is also a polyamide and is based on a renewably feedstock. PA 6.12. and PA1010 has similar properties, such as high stiffness and a high water-absorption rate. PBT is a thermoplastic crystalline polyester, with high stiffness and is suitable for manufacturing by extrusion. PBT is also highly recyclable. (Bruder, 2016). When performing the LCA, PBT was the material with the least amount of carbon dioxide emissions. The results are fully presented in Appendix D.

5.5 Packaging suggestion

To present a complete product a packaging is needed for the toothbrush. Instead of using a regular blister packaging, with plastic and cardboard combined, a full cardboard package was suggested. To keep the see-through capability of the packaging a see-through cellulose could be used. The research company VTT has developed a material that can be recycled as paper. This means that the recycling possibilities of the product would increase, since the whole packaging could be recycled as paper (vttresearch.com, 2022).

6 Discussion

In this chapter the results presented in chapter 5 is discussed.

Depending on what numbers used, the calculated figures are different. If the numbers calculated for the final concept is compared to the numbers given by TePe, for the Select toothbrush manufacturing, the fill time is reduced by 50 percent. However, the cooling time is 8 seconds longer (Select's cooling time is 12 seconds in reality). This is not reasonable, and it fits with the statement of Peter Bjellheim (2023) "That a simulation is a simulation". The simulated results are difficult to compare with the real-life numbers, since there are many unknown parameters. To get a comparison it would be possible to assume that the final concept would shorten its cooling time by the same percentage as the Select toothbrush does, compared to the mold flow results. The simulated Select toothbrush's cooling time is divided by the real Select toothbrush's time.

$$\frac{59\ seconds}{12\ seconds} \approx 4{,}92.$$

Since the simulated time is 4,92 times larger than the cooling time in real-life, the simulated cooling time for the final concept is divided by the same amount.

$$\frac{20}{4{,}92} \approx 4{,}07\ seconds.$$

This means that the final concept could reach a cooling time of about 4 seconds. This number is not certain, since many factors has been left out.

In Moldex3D, the simulation works different. Here the filling time is set from start, and the other data is calculated from this. For this simulation concept 10b was used. This is an earlier iteration of the final concept. Since these simulations was run by Peter Bjellheim, the model was sent to him before the final concept was finished. Therefore, the corresponding cooling time in Solidworks is 30 seconds, as calculated for concept 10b.

The filling time for concept 10b (an earlier iteration of the final concept) was set to 2 seconds and the cooling time achieved was 47 seconds. For the select toothbrush the corresponding times were, 2 seconds for filling and 87 seconds for cooling. These cooling times is significantly longer than the achieved times in Solidworks, but it can be seen that the proportions between the select toothbrush and concept 10b stays similar in the two software programs.

Moldex3D cooling times divided:

$$\frac{87}{47} \approx 1{,}85.$$

Solidworks cooling times divided:

$$\frac{59}{30} \approx 1{,}96.$$

This means that the developed toothbrush concept consistently having both shorter filling- and cooling times than the reference toothbrush.

Another discussion point of the mold flow analysis is the element size in the mesh. To be able to mesh the final concept, the mesh had to include about 954000 elements, compared to 4400 elements in the Select toothbrush mesh. This may have affected the results, in some way. Earlier iterations of the concept had much fewer elements and longer cooling times. The cooling time of the final concept with many elements was about 30 percent shorter than the earlier iteration. The difference may be due to other changes in the geometry as well.

As for the final concept, it is considered to fulfill its needs. In table 4.1, needs are presented in groups. The groups are named ergonomic needs, ECO, needs, hygienic needs, and design needs. The primary needs are; the grip is comfortable, toothbrush contains little mass, reaches all surfaces, and toothbrush looks sleek. The final concept has fulfilled the first two primary needs. It has been showed that, when testing the toothbrush on test persons the concept was regarded as comfortable. And the fact that the concept has reduced its mass by 50 percent from the reference toothbrush, must be regarded as “contains little mass”.

The last two needs are more difficult to objectively reach. The need of, reaches all teeth, the concept should meet since it has a regular sized brush head, but with tapered sides. This means that it fits in smaller mouths. It also has an inclined neck, for better reach inside the mouth.

The last primary need is subjective. But test persons have suggested that the final concept has an appealing design, and it therefore fulfills also this need.

The positive consequences of a smaller carbon dioxide footprint were also reached, see Table D.1. Arboform was the handle material with the lowest carbon dioxide emissions, but it’s also more expensive than PP.

The PBT filaments resulted in lower carbon dioxide emissions, compared to the PA 6.12. in the Select toothbrush and the renewable PA1010 filament alternative.

Why PBT, that is 100 percent fossil based, has a lower carbon footprint than the renewable PA1010 is due to the production process of the raw material. PBT emits about 50 percent less carbon dioxide while being produced, compared to PA1010, see Table D.5 and D.6.

During the project other methods of reducing mass and cycle times have been discussed. Topics such as gas injection and microcellular molding has been investigated. One of these methods could help to reduce both material and production time, but when talking to Lars Jerpdal, he thought that microcellular injection could be difficult to implement when manufacturing toothbrushes, mostly because a high gloss surface, at the time of conversation, cannot be guaranteed. The method could work with toothbrushes if the surface finish is not expected to be of a high gloss character.

After working with the project, it was discovered that although the main method followed during the project was the one established by Ulrich & Eppinger, some aspects of the workflow was similar to that of the lean start-up methodology. Lean start-up methodology is based on creating an MVP, test it on users, and from that iterate the MVP.

This project started with a development of several different concepts, but when focused on creating a toothbrush that is easy to manufacture a concept similar to an MVP was created. This concept fulfilled the targets of ecology and hygiene since it was lightweight and with a good ability to clean teeth. This concept was tested on users and then iterated into slightly different concepts, that performed better. This process continued until the final concept.

7 Conclusions

In this chapter, conclusions based on the results in chapter 5 and the discussion in chapter 6 are presented.

A new toothbrush concept has been developed that fulfills the goal of the project and reduces the weight, compared to TePe Select, by 50 percent and the filling and cooling times by 66 percent.

The new concept has been developed and validated by the use of CAD, FE-analyses, and mold flow analyses. Prototypes have also been manufactured by additive manufacturing (FDM).

Future development could include a deeper investigation of gas-injection or microcellular injection molding, to reduce the weight and manufacturing time even more.

Figure 7.1 The final concept.

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Appendix A Work distribution and time plan

In this appendix the work distribution is presented. The main platform for time planning is the GANTT-chart that is attached here.

A.1 Project plan and outcome

The project started with planning. In this step a GANTT-chart was made for planning each day of the project. However, this chart needed to be updated during the project, since some tasks took longer time than expected, and some tasks wasn’t considered at all in the beginning. For the performed schedule see Table A.1, and for the planned schedule see Table A.2.

Table A.1. Performed GANTT-chart.

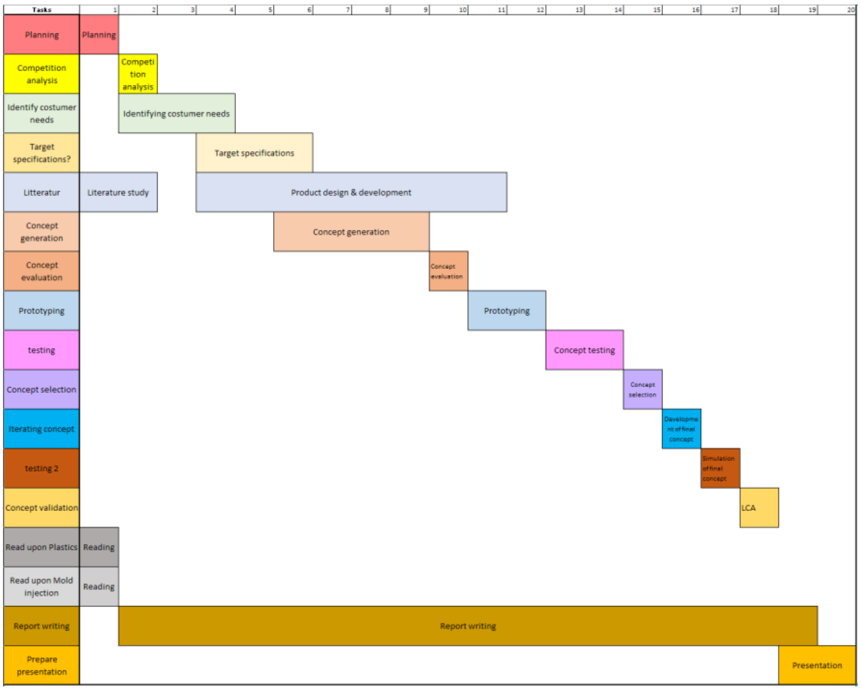
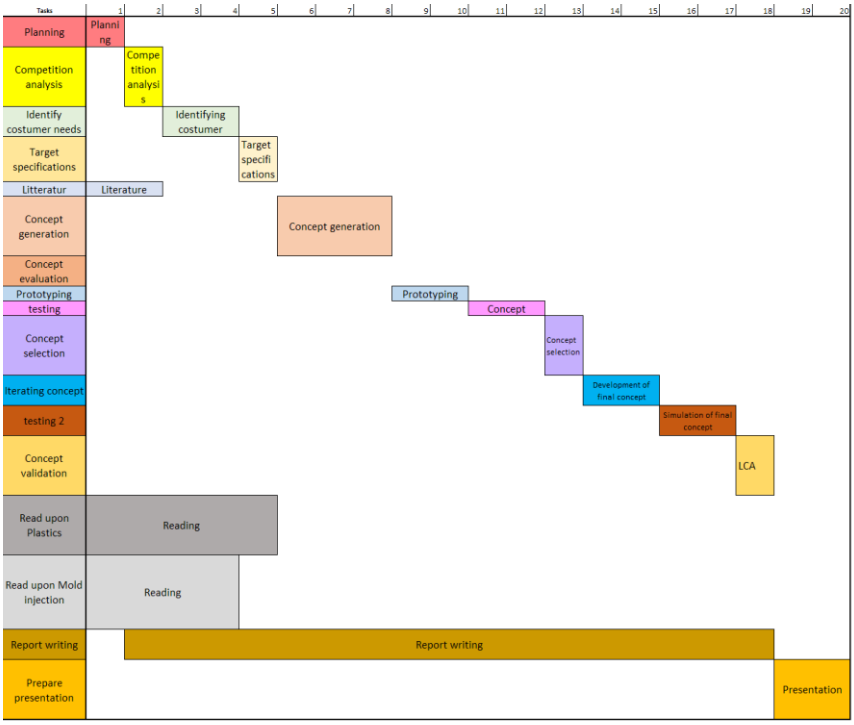


Table A.2. Predicted GANTT-chart.



Appendix B Questionnaire answers

In this appendix the answers to the sent-out questionnaire are attached. The answers are next to their interpreted costumer need.

B.1 Costumer needs table.

Table B.1. Answers to the sent-out survey. The answers are categorized.

Ergonomic choices	**ECO choices**	**Hygienic choices**	**Simplistic choices**
	I don't like the design, it just looked eco, i would not buy	simplicity	
I like A firm grip. But it doesn’t need to be heavy. It also looks like a normal toothbrush			
Looks normal and Nice to handle			
looks the best, the other two looks too cheap or made for kids			
Grip don't matter			
Looks nice			
Cause it looks like my toothbrush			
Looks like the most standard			

Most like the one I have today			
I like the the grib is good			
Looks like you could reach past the wisdom tooth which would be good since that's something I Struggle with			
I think it is important to be able to reach all teeth in an Easy way. Hopefully the brusch is also a little tender in the bend			
Looks most "normal"			
Looks better	Looks eco	Prettier	Prettier
Ergonomisk	Feels like an organic material	The dirt is visible	Nice design
Small Head and a god grip	I always buy Tepe products	Because I always buy Tepe Products	Tepe is the best ones
Its looks like the one i have	I like it	I like it	Like cLassic design
Bäst	Which of these toothbrushes would you consider more ECO friendly?	I like it	I like it
Inbillar mig att mindre borsthuvud kommer åt bättre	Recircle	Verkar komma åt bra	Bra grepp och litet huvud
Because of the look.	Because the toothbrush is made of wood.	I think that is the best one for my teets	Looks best
Had one of these before and it worked just fine, now I have das Electric toothbrush	Have heard many good thing about this brush over the last couple of years	Had one of these before and have had zero problem with it neither my teeth	It simple and easy to get from your normal day store

I have not tried the other two	No plastic!	Simple design.	The last looks plastic and the first seemed thick
Tycker den så mest "vanlig" ut	Halva tandborsten återanvänds	ogillar en smutsig tandborste	jag gillar när de ser ut som de ska.
Middle one feels like it would break, last one looks like a childrens toothbrush	Feels most eco-friendly	What I am used to	Looks nice in a bathroom
Bra grepp	Wood is good		Bra
Important to brush all over the teeth	I don't find the tree/bamboo brushes so hygenic	It should be easy to brush and it should be fresh	I like it because it is well know with great reputation
Want clean theeth	Looks like it's recyclable	Hygienic	Like it the best
Seems easy to use.	Biobased seems to be eko.	No spot for dirt to get stucked.	Looks clean 😀
I prefer that one	Its made out of bambo	Looks good	Looks good
Like better reach	Just need to change the head	I like the form	The design
Den ser bekväm ut att hålla i	Att Återanvända använt material borde vara Eco friendly	Som där står, svårt gör smuts att fastna	Tycker om den designen
FFör att kunna hålla bättre	För att jag tror sockerrör är ekovänligare än bambu	Enkel	Enkelhetensskull
Looks stable and good	It's not plastic the hole brush	It's the one I use today	I know what I get
Greppvänlig	Miljövänligt alternativ	Känns mest effektiv	Vana

Den tilltalar mig mest	Känns som om bambu är mer ekologiskt än plast	Den känns mest okomplicerad	Gillar den klassiska
I just think it looks most comfortable	It is à natural product.	It seems to be the most hygienic one.	I really don't think it is important.
Valde den som såg smidigast ut o hade minst plast	Tror de jag valde gör minst avtryck	Snyggt med vit	Snygg
Habit, I guess	Lack of knowledge in the field	Hygiene	Well known
The grip is important so the brush doesn't slip	Great product having a changeable head	Important dirt doesn't get stuck	I like the classic design the most among these options
I think this is small and look god.	It is clean	Simpel	Nice
Ser ut som den är smidigare att nå alla tänder med		Ser smalare och smidigare ut	
Passade bäst. Dock skulle jag gärna vilja jämföra olika grepp för sig och olika borst för sig. Frågan blir lite svår när den ena är grepp, den andra huvud och den tredje böjd borste.	Gissar att den påverkar miljön minst	Man vill inte se smuts på en tandborste, och den bör inte heller vara för komplex. Nr 2 passar mig bäst.	Ser mest bekväm ut att hålla i
It looks like the one I have Moe and it feels comfortable		It looks familiar to the toothbrushes I have had before and I liket it	I like Classic design
Easy to grip.	Köpa så få som möjligt bara byta huvudet	Vill inte tvätta tandborsten	Är van vid det
Looks easier to hold	I guess that bamboo and bioplastic don't use normal plastic	Wouldn't like a manual toothbrush with replaceable parts	Looks more clean

Ser ut att göra bäst nytta o verkar greppvänlig	Utbytbar detalj - då borde den passa min mun	Liten o smidig borst	De raka verkar för tjocka o osmidiga
So my thumb doesnt cramp	Less material you have to discard	Because its more clean looking	It doesnt stick out
I don't like sporty looking toothbrushes	Nature can break down wood	Want to know my brush is clean	Looks more modern and sleek
I like a bigger head	I don't know about the environmental impact of thootbrushes	I like the shape	Bigger head
Looks comfortable to use	Ecofriendly and hygienic	Seems to best answer to hygienic needs	Looks comfortable
Important with a good grip/feel when holding the brush	Feels like it wastes less material	It's a good tooth brush	Familiar with that model
Vissa med värk i händerna behöver tjockare handtag	Bättre material	Enklare o hålla ren. Vill inte lägga tid på o rensa	Modernt coolt nytt
För det är en sådan jag alltid har haft.	För den ser ut att vara det.	Enkel design och lätt att hålla ren.	Servit som det brukar.
I just like this type of toothbrush.	It feels eco friendly.	Easy to clean.	Easy to clean
I am use to a toothbrush looking like that	Because it doesn't contain plastic	Metal seems like a material that uses a lot of resources	Did not
Bekvämare att hålla.	Av de valen så var detta närmast. Ingen betydelse egentligen.	Lätt att göra ren.	Ingen preferens

B.1.1.1 Example of a filled-out form.

Manual toothbrushes

Frågor Svar 77 Inställningar

Manual toothbrushes

Hello.

This is an questionnaire about humans perceptions and preferabilities while choosing a manual toothbrush.
It only takes about 1 min to finish.

It is voluntarily to participate, but if you do it will be greatly appreciated. If you have any wonderings about a question or about the survey, send an E-Mail to: johan.h.hammarberg@gmail.com.

Thank you so much for your time and support.

* Anger obligatorisk fråga

How old are you? *

- ○ Under 18
- ○ 19-24
- ○ 25-34
- ○ 35-44
- ○ 45-54
- ◉ 55-64
- ○ 65-74
- ○ 75+

Statements

The cost is important to me when buying a new toothbrush. *

Strongly disagree

- 1 ○
- 2 ◉
- 3 ○
- 4 ○
- 5 ○

Strongly agree

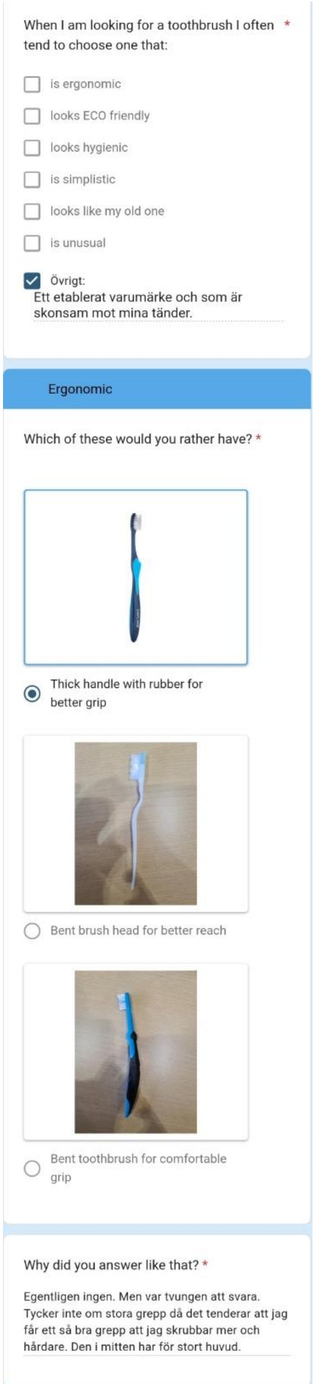
The environmental aspect is important to me when choosing a toothbrush. *

Strongly disagree

- 1 ○
- 2 ○
- 3 ○
- 4 ◉
- 5 ○

Strongly agree

Figure B.8.1 First page of the questionnaire. Here the user filled out personal information and if the price and environmental impact is important when buying a toothbrush.



When I am looking for a toothbrush I often tend to choose one that: *

- [ ] is ergonomic
- [ ] looks ECO friendly
- [ ] looks hygienic
- [ ] is simplistic
- [ ] looks like my old one
- [ ] is unusual
- [x] Övrigt:
Ett etablerat varumärke och som är skonsam mot mina tänder.

Ergonomic

Which of these would you rather have? *

(•) Thick handle with rubber for better grip

( ) Bent brush head for better reach

( ) Bent toothbrush for comfortable grip

Why did you answer like that? *

Egentligen ingen. Men var tvungen att svara. Tycker inte om stora grepp då det tenderar att jag får ett så bra grepp att jag skrubbar mer och hårdare. Den i mitten har för stort huvud.

Figure B.8.2. The second page of the questionnaire asked the user to choose between several alternatives.

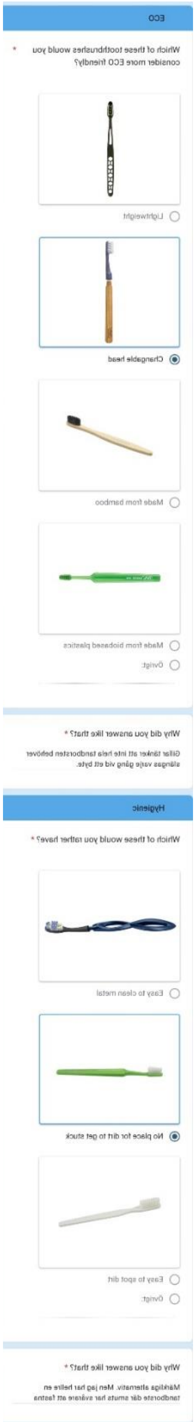


Figure B.8.3 On the third page of the questionnaire more alternative questions was presented.

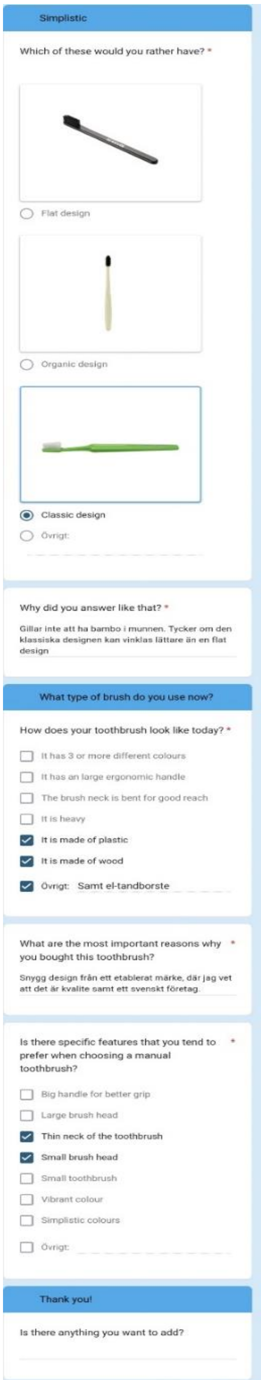


Figure B.8.4 On the last page of the questionnaire the last set of multi-choice questions was presented.

Appendix C Concept scoring

This appendix contains the concept scoring matrix and the pictures of each concept that is included.

C.1 Concept scoring matrix.

Table C.1. The concept scoring matrix.

		Reference		Concept 3b		Concept 4		Concept 7		Concept 8		Concept 9		Concept 10b	
Needs	Weight	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score
The grip is comfortable	20%	3	0,6	3	0,6	4	0,8	4	0,8	3	0,6	3	0,6	4	0,8
TB grip provides friction	10%	3	0,3	3	0,3	3	0,3	4	0,4	3	0,3	5	0,5	4	0,4
Brush head fits small mouths	5%	3	0,15	3	0,15	3	0,15	3	0,15	3	0,15	3	0,15	3	0,15
TB contains % less mass	30%	0	0	1	0,3	4,0	1,2	2	0,6	3	0,9	3	0,9	5	1,5
Easy to recycle	10%	3	0,3	3	0,3	3	0,3	3	0,3	3	0,3	3	0,3	3	0,3
Is easy to keep clean	15%	3	0,45	2	0,3	2	0,3	2	0,3	4	0,6	4	0,6	4	0,6
TB is sturdy	5%	3	0,15	4	0,2	4	0,2	2	0,1	5	0,25	4	0,2	4	0,2
			Reference		Concept 3b		Concept 4		Concept 7		Concept 8		Concept 9		Concept 10b
Total score			1,95		2,15		3,25		2,65		3,1		3,25		3,95

C.1.1 Concepts

C.1.1.1 Reference

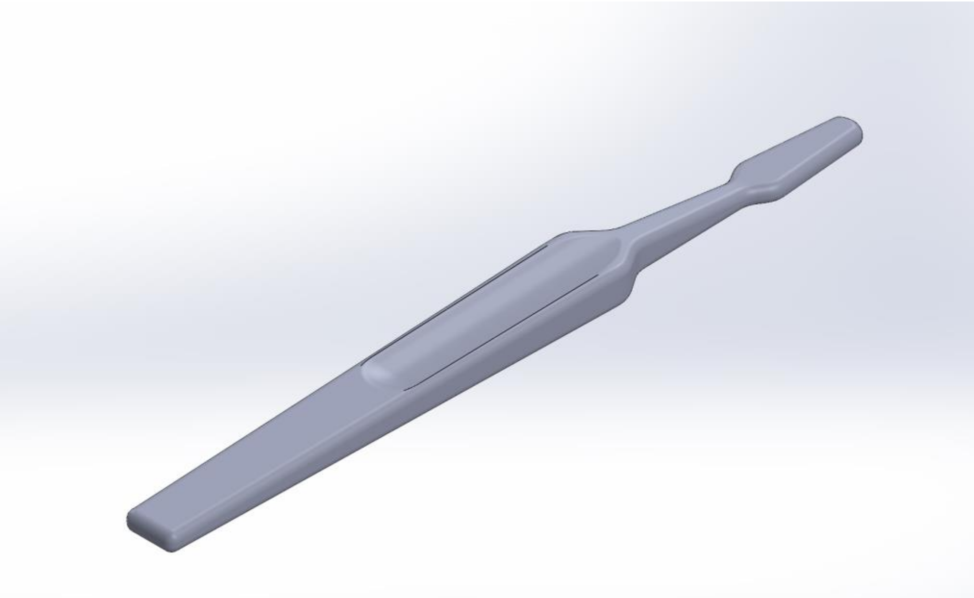


Figure C.1. Mass: 13 g

C.1.1.2 Concept 3b

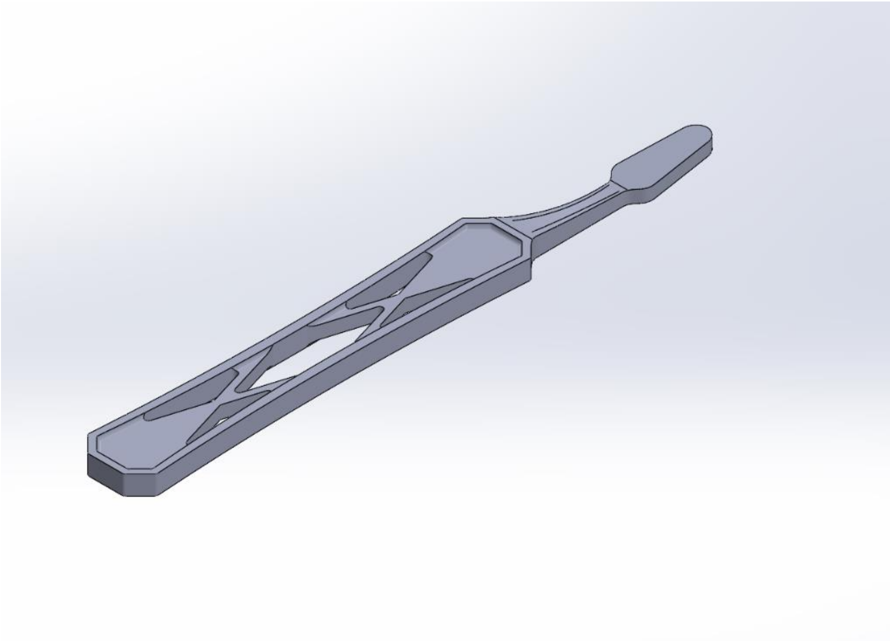


Figure C.2. Mass: 8,9 g

C.1.1.3 Concept 4

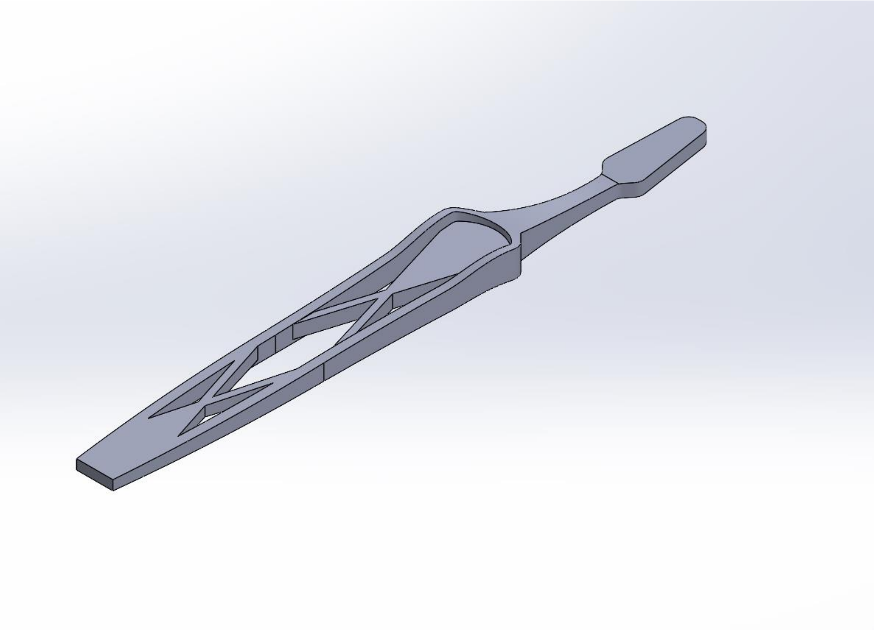


Figure C.3. Mass: 7,3 g

C.1.1.4 Concept 7

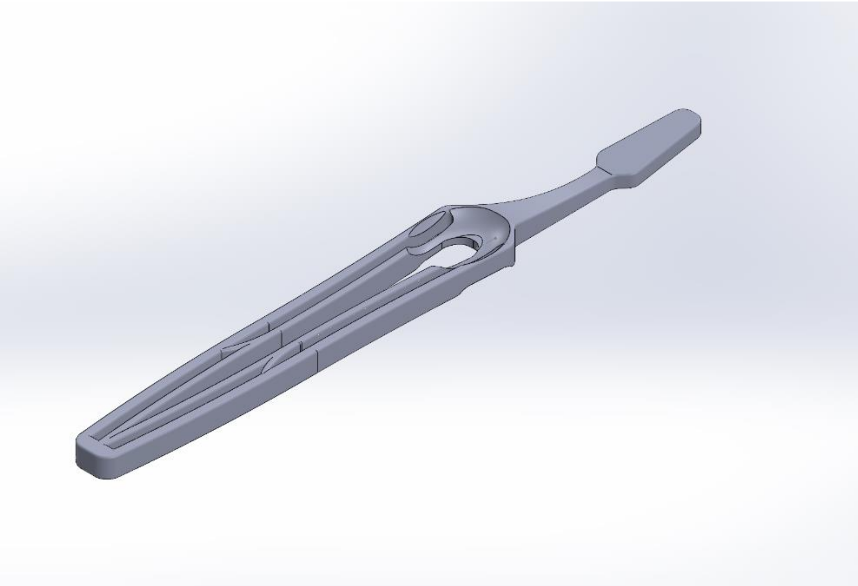


Figure C.4. Mass: 7,9 g

C.1.1.5 Concept 8

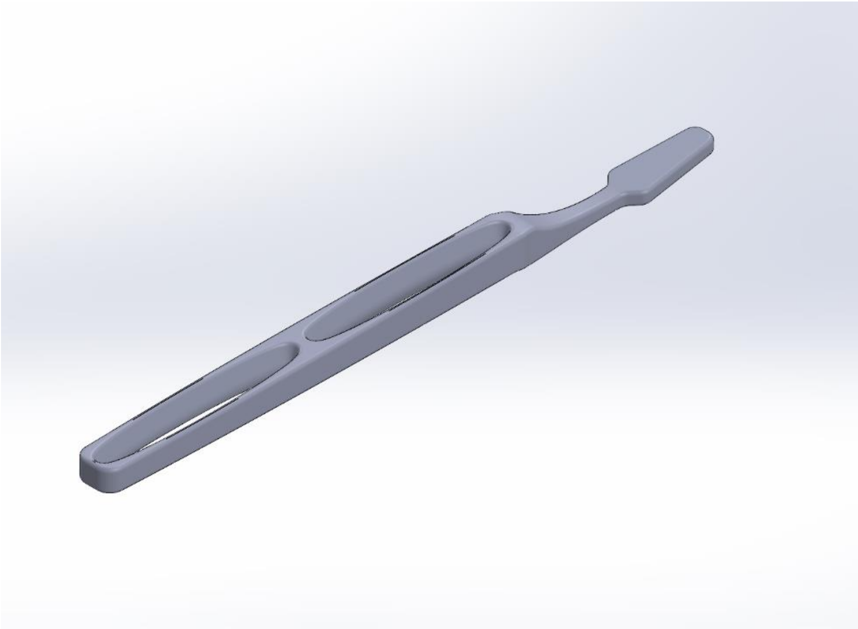


Figure C.5. Mass: 7,7 g

C.1.1.6 Concept 9

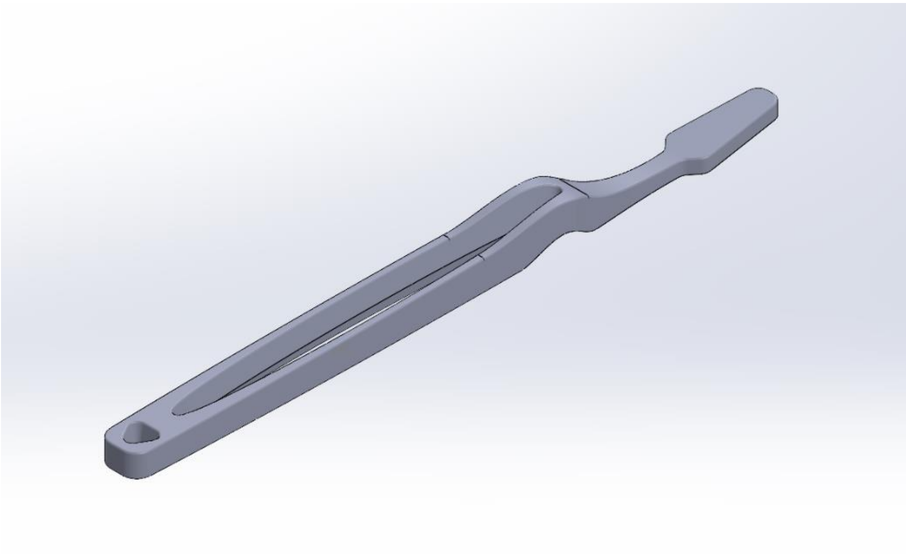


Figure C.6. Mass: 7,5 g.

C.1.1.7 Concept 10b

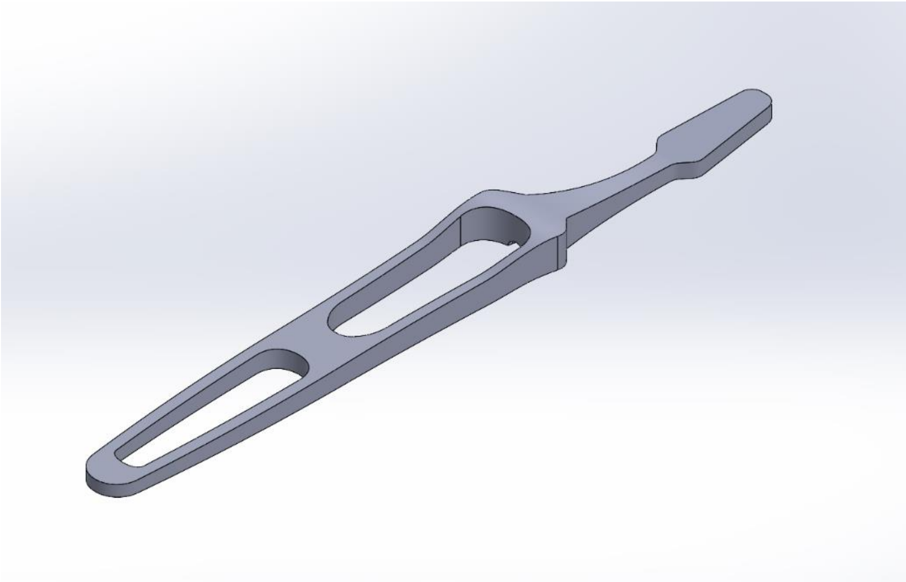


Figure C.7. Mass: 6,5 g

Appendix D Life Cycle Analysis

Here are the calculations for the CO_2 -emissions presented in the report.

Table D.1. LCA calculations for the final concept made in polypropylene.

Handle			
Weight (kg)	0,0061	GWP Resource (kg eq. CO2/kg resource)	GWP Product (kg eq. CO2/product)
	Raw material - Fossil	1,3900	0,00831
	Raw material - Biogenic	-3,14	-0,01915
	Masterbatch (share 2%)	*1,15*	0,00014
	Transportation	1,134	0,0069165
	Manufacturing	0,000361	0,00000
	Incineration	3,1400	0,01915
	SUM		0,0154

Ankartråd			
Weight (kg)	0,0003	GWP Resource (kg eq. CO2/kg resource)	GWP Product (kg eq. CO2/product)
	Raw material - fossil	3,3000	0,0010
	Raw material - Biogenic		0,0000
	Transportation	0,006	0,0000
	Manufacturing	0,100	0,0000
	Incineration		0,0000
	SUM		0,0010

Filament	PBT		
Weight (kg)	0,00078	GWP Resource (kg eq. CO2/kg resource)	GWP Product (kg eq. CO2/product)
	Raw material - fossil	5,05	0,0039
	Raw material - Biogenic		0,0000
	Transportation	0,10	0,0001
	Manufacturing	0,00	0,0000
	Incineration	2,40	0,0019
	SUM		0,0059

Tot. produkt:	0,0223	kg CO2 /product

Table D.2. LCA calculations for the final concept made in Arboform.

Handle			
Weight (kg)	0,0080	GWP Resource (kg eq. C02/kg resource)	GWP Product (kg eq. CO2/product)
	Raw material - Fossil		0,00000
	Raw material - Biogenic	-2,32	-0,01817
	Masterbatch (share 2%)	*1,37*	0,00022
	Transportation	1,134	0,00906
	Manufacturing	0,000473	0,00000
	Incineration	2,3200	0,01854
	SUM		0,0097

Ankartråd			
Weight (kg)	0,0003	GWP Resource (kg eq. C02/kg resource)	GWP Product (kg eq. CO2/product)
	Raw material - fossil	3,3000	0,0010
	Raw material - Biogenic		0,0000
	Transportation	0,006	0,0000
	Manufacturing	0,100	0,0000
	Incineration		0,0000
	SUM		0,0010

Filament	PBT		
Weight (kg)	0,00078	GWP Resource (kg eq. C02/kg resource)	GWP Product (kg eq. CO2/product)
	Raw material - fossil	5,05	0,0039
	Raw material - Biogenic		0,0000
	Transportation	0,10	0,0001
	Manufacturing	0,00	0,0000
	Incineration	2,40	0,0019
	SUM		0,0059

Tot. produkt:	0,0166	kg CO2 /product

Table D.3. LCA for Select toothbrush made in polypropylene.

Handle		GWP Resource (kg eq. CO2/kg resource)	GWP Product (kg eq. CO2/product)
Weight (kg)	0,013		
	Raw material - Fossil	1,3900	0,0177
	Raw material - Bioge	-3,14	-0,0408
	Masterbatch (share 2	*1,37*	0,0004
	Transportation	1,134	0,0147
	Manufacturing	0,000	0,0000
	Incineration	3,1400	0,0408
	SUM		0,0328

Filament		GWP Resource (kg eq. CO2/kg resource)	GWP Product (kg eq. CO2/product)
Weight (kg)	0,00078		
	Raw material - fossil	5,0500	0,0039
	Raw material - Biogenic		0,0000
	Transportation	0,100	0,0001
	Manufacturing	0,013	0,0000
	Incineration	2,40	0,0019
	SUM		0,0059

Ankartråd		GWP Resource (kg eq. CO2/kg resource)	GWP Product (kg eq. CO2/product)
Weight (kg)	0,0003		
	Raw material - fossil	3,3000	0,0010
	Raw material - Biogenic		0,0000
	Transportation	0,006	0,0000
	Manufacturing	0,100	0,0000
	Incineration		0,0000
	SUM		0,0010

Tot. produkt:	0,0397	kg CO2 /product

Table D.4. Filament carbon dioxide emissions for PA 6.12.

Filament	PA 6.12			
Weight (kg)	0,00078	**GWP Resource** (kg eq. C02/kg resource)	**GWP Product** (kg eq. CO2/product)	
	Raw material - fossil	8,50	0,0066	
	Raw material - Biogenic		0,0000	
	Transportation	0,05	0,0000	
	Manufacturing	0,00	0,0000	Extrudering. Se manufacturing för handle
	Incineration	2,43	0,0019	
	SUM		0,0086	

Tot. produkt:	0,0250	kg CO2 /product

Table D.5. Filament carbon dioxide emissions for PBT.

Filament	PBT			
Weight (kg)	0,00078	**GWP Resource** (kg eq. C02/kg resource)	**GWP Product** (kg eq. CO2/product)	
	Raw material - fossil	5,05	0,0039	
	Raw material - Biogenic		0,0000	
	Transportation	0,10	0,0001	
	Manufacturing	0,00	0,0000	Extrudering. Se manufacturing för handle
	Incineration	2,40	0,0019	
	SUM		0,0059	

Tot. produkt:	0,0223	kg CO2 /product

Table D.6. Filament carbon dioxide emissions for PA 1010.

Filament	PA1010			
Weight (kg)	0,00078	**GWP Resource** (kg eq. C02/kg resource)	**GWP Product** (kg eq. CO2/product)	
	Raw material - fossil	9,70	0,0076	
	Raw material - Biogenic	-2,40	-0,0019	
	Transportation	0,05	0,0000	
	Manufacturing	0,00	0,0000	Se manufacturing för handle
	Incineration	2,62	0,0020	
	SUM		0,0078	

Tot. produkt:	0,0242	kg CO2 /product

Appendix E Moldex3D results

In this appendix the full result report from Moldex3D is attached.

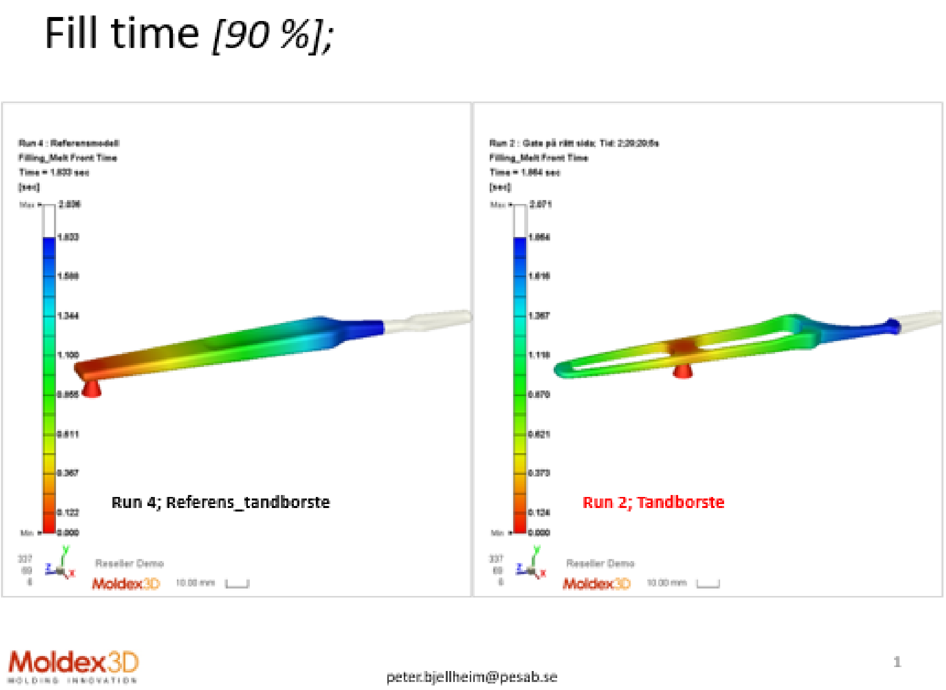


Figure E.1 The fill time for the reference toothbrush and concept 10b.

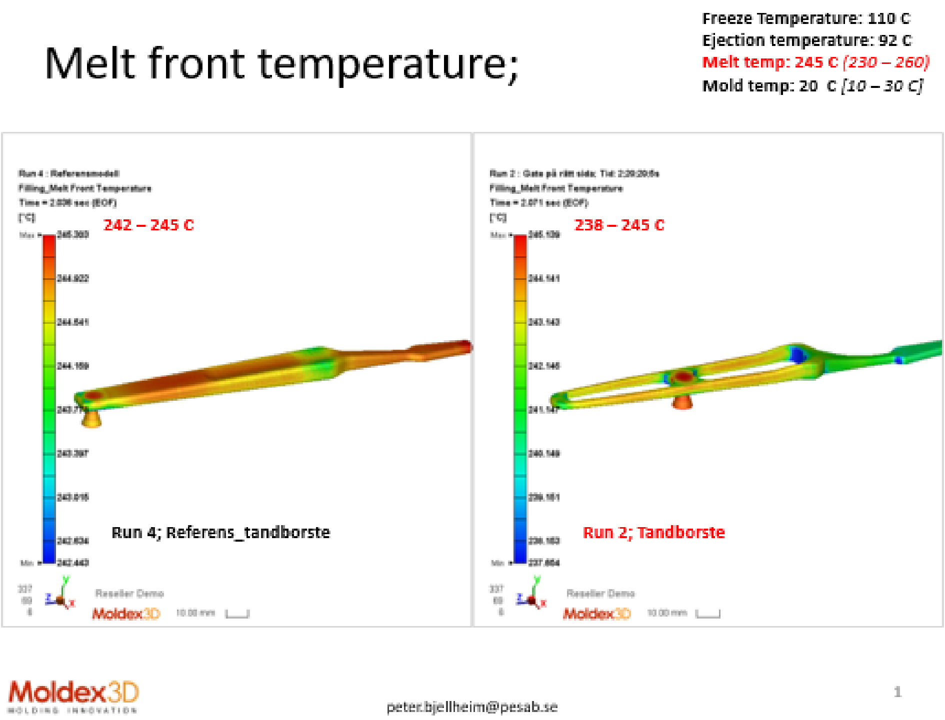


Figure E.2 The melt front temperature at any given time, for the reference toothbrush and concept 10b.

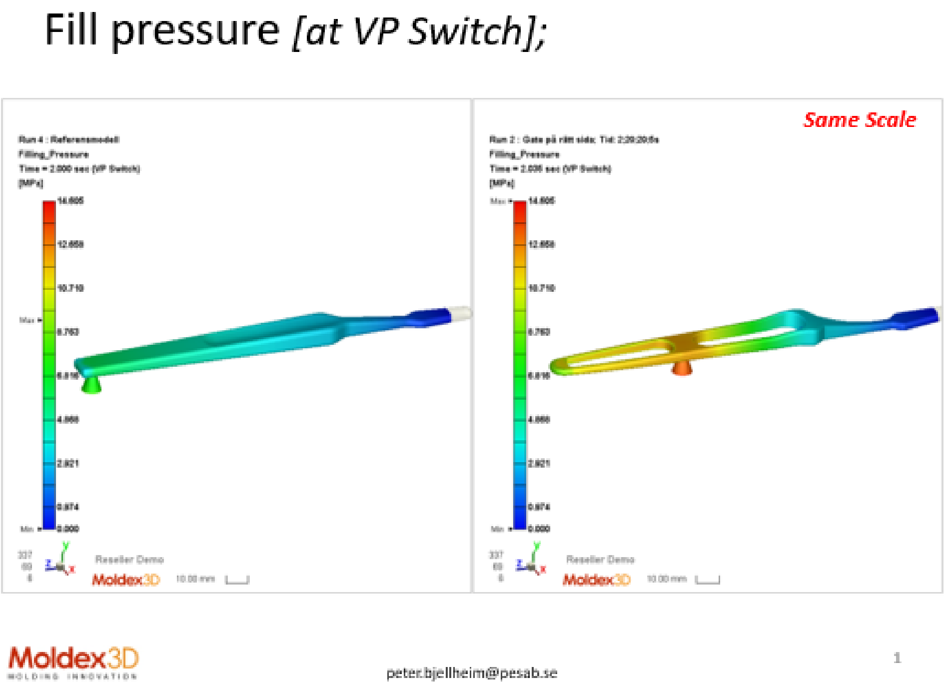


Figure E.3 The fill pressure, presented in the same scale for both toothbrushes.

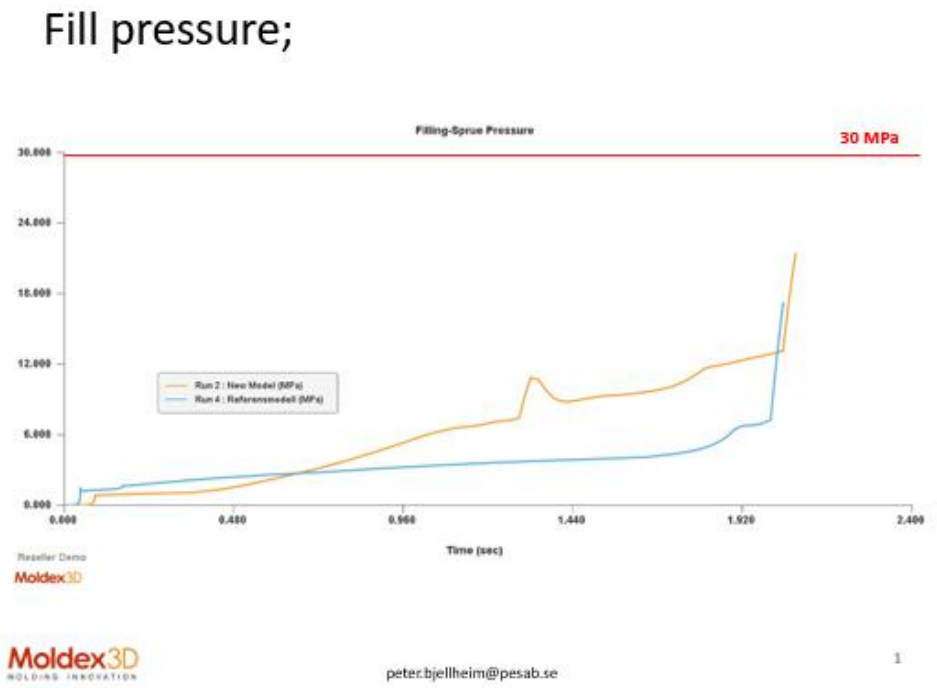


Figure E.4 Graph showing the pressures for the reference toothbrush and concept 10b.

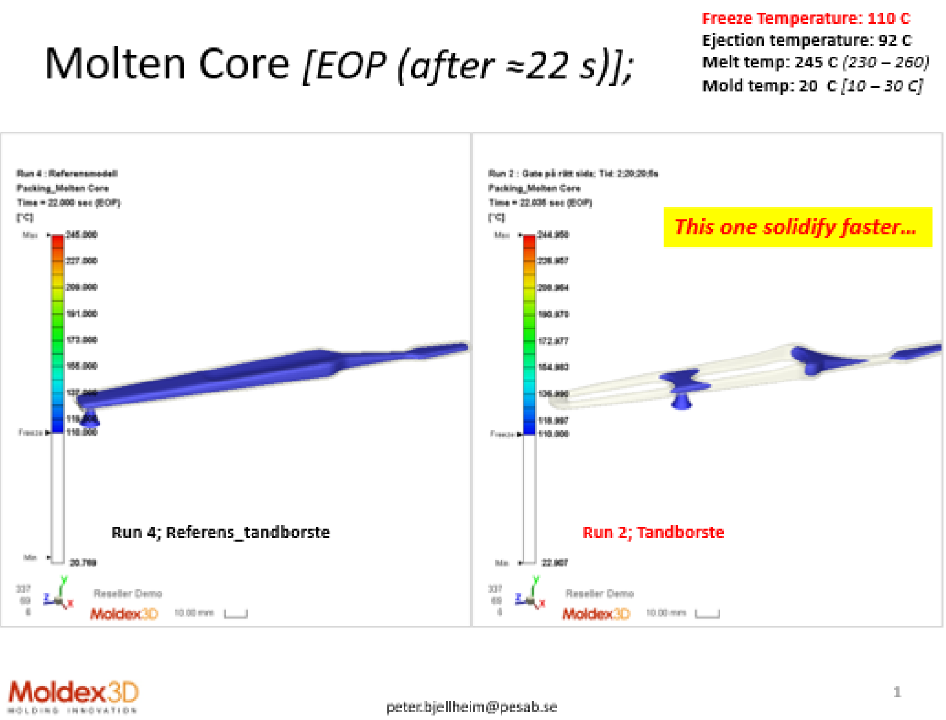


Figure E.5 The molten plastic volume within the molded parts (the reference toothbrush and concept 10b), after the packing stage.

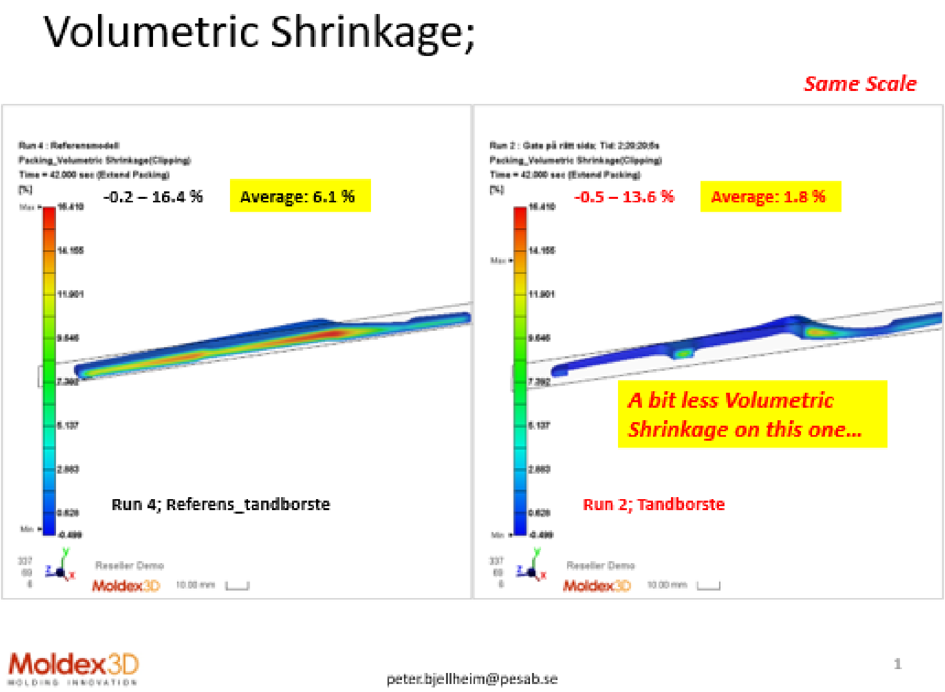


Figure E.6 Overall volumetric shrinkage, for the reference toothbrush and concept 10b.

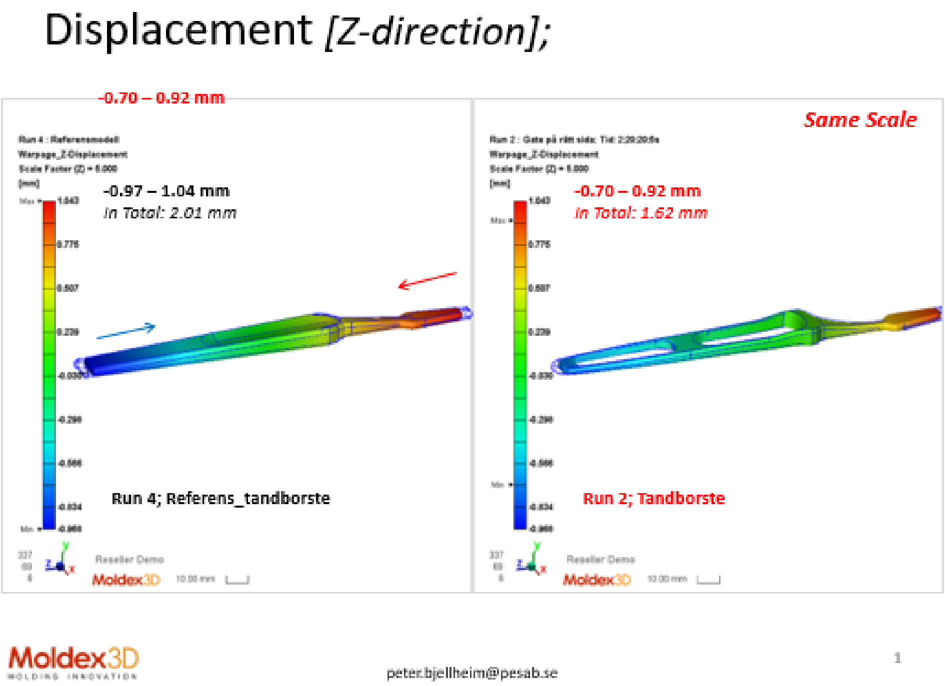


Figure E.7 The shrinkage of the reference toothbrush and concept 10b, in longitudinal direction.