CHALMERS

Optimization of a Lightweight HUB Bearing Unit for Racing Cars

Application of Topology Optimization and Additive Manufacturing on a Lightweight HUB Bearing Unit

Bachelor Thesis in Mechanical Engineering

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Cover image: Outer ring of a HUB Bearing Unit

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Sammanfattning

Denna rapport beskriver produktutvecklingen av ett lager anpassat för racingbilar med syftet att minska vikten utan att förlora prestanda. Projektet är ett sammarbete mellan AB SKF och Chalmers Tekniska Högskola. Idag tillverkar AB SKF lagren med konventionella tillverkningsmetoder. Målet med detta examensarbete är att utveckla en design som är anpassad för additiv tillverking, specifikt laser-pulverbädds tekniken Powder Bed Fusion Laser Beam (PBF-LB).

Projektet följde en iterativ designprocess som började med brainstorming av designelement och klargörande av kriterier. Designen utgick från en topologisk optimerad HBU för att identifiera områden där material kunde tas bort. Varje koncept visualiserades med topologioptimeringsmjukvara och utvärderades med Finit Element Analys under verkliga förhållanden. Processen bestod av fyra iterationer av topologioptimering, där varje steg förbättrade resultaten. Den fjärde iterationen ledde till den slutliga designen

Koncept som klarade sträckgränsen och deformationsgränsen jämfördes baserat på viktbesparningsprocent och maximal deformation, där viktminskning var det viktigaste kriteriet. Det slutliga konceptet har en viktminskning på 17,5% jämfört med den ursprungliga designen. Konceptet är anpassat för PBF-LB genom att undvika överhängsvinklar större än 45 grader, inte ha några slutna hål och minskad behov av stödstrukturer.

Sammanfattningsvis är användningen av PBF-LB fördelaktigt eftersom det ger en hög designfrihet och möjliggör hög kundanpassning. Det tillåter optimering av komponenter för specifika applikationer.

Nyckelord: *Lager, Powder Bed Fusion Laser Beam, Metall Additiv Tillverkning, AB SKF, Produktutveckling, Topologioptimering*

Abstract

This report describes the product development process for redesigning a bearing application for racing cars with the intent of reducing weight without affecting performance. The project was carried out in collaboration between AB SKF and Chalmers University of Technology. Today, AB SKF manufactures the HBU bearing with traditional manufacturing methods. The aim of this bachelor's thesis is to develop a design concept suitable for the additive manufacturing technology Powder Bed Fusion Laser Beam.

This project followed an iterative design process, starting with brainstorming potential design aspects such as lattice structures and different ear placements, as well as clarifying the criteria. The design process started with a topologically optimized body of an HBU to identify areas where material could be removed. Each concept was visualized using topology optimization software and evaluated using Finite Element Design under conditions similar to real life. The process involved four topology optimization iterations, with each step tackling different problems and achieving improved results. The fourth iteration leads to the final design.

Concepts that cleared the yield stress and deformation limit were weighed against each other on the criterion in weight saving percentage and maximum deformation value where the criterion was assigned a weighting factor depending on its importance. The most important criterion was weight reduction.

The final concept has a weight reduction of 17,5% compared to the original HBU. The concept is designed to be optimal for PBF-LB by avoiding overhang angles bigger than 45 degrees, not consisting of any closed off holes as well as reducing the amount of support structures needed.

In conclusion, using PBF-LB is beneficial because it provides a high level of design freedom resulting in a high level of customization. It allows a component to be optimized for a specific application.

Keywords: *Bearing, Powder Bed Fusion Laser Beam, Metal Additive Manufacturing, AB SKF, Product development, Topology optimization*

Acknowledgment

We would like to express our sincere gratitude to everyone who contributed their time and effort to this project. A heartfelt thank you to the employees at the department of Manufacturing Development at AB SKF for your support throughout the entire project. Your contributions have not only driven the project's success but have also created a wonderful work environment.

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We also want to thank the Racing Department at AB SKF for providing us with the opportunity to work on a real-world engineering problem. They have also contributed with valuable feedback and development aspects that have contributed to the results of the project.

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Alva Sjöberg & Malin Stomberg, Gothenburg, June 2025

CONTENT PAGES

1

Introduction

Today, the manufacturing of bearings is being done using traditional methods. These methods involve subtractive processes (cutting/removing material). Additive Manufacturing (AM) on the other hand adds material to create the design. This enables a new way to design products that can reduce weight without compromising performance. Therefore, the theme of this bachelor thesis is to design a HUB Bearing Unit (HBU) using AM and topology optimization to reduce weight without compromising performance. This thesis is being done at AB SKF which is a leading Swedish bearing manufacturer. In this chapter, the background for the project is introduced as well as the purpose, limitations, and a specification of the research questions, which will be answered in Chapter 9.

1.1 Background

AB SKF is the leading company when it comes to designing and producing bearings, seals, and lubrication systems that are innovative and customized, meeting the customer demands. One of the departments, SKF Racing, focuses on bearing applications for racing cars, which require new designs involving lighter parts with unique features.

SKF Racing recently received a request from a customer to develop an HBU with the aim of reducing weight without losing performance. Today's HBU is manufactured using traditional machining processes, which are suitable for mass production, however, this limits design choices as the processes limit the production of complex geometries.

To create the most optimal design possible, design freedom is crucial. This is easily achieved using AM as a manufacturing method, as it allows for more complex geometries. The use of topology optimization software can assist in the design process to optimize the weight of a design without losing the needed performance.

Currently AM is an expensive method to use, as it is not yet used on a large scale within industry, which generates higher costs due to the expensive material cost and the high capital investment for the machinery.

1.2 Purpose

Currently, traditional manufacturing methods are regularly used to produce bearings, but these methods have design limitations as they cannot create complex geometries. Additive Manufacturing (AM) allows components with more complex geometries as the material is placed layer-on-layer where it is needed, offering greater design freedom. However, critical surfaces still need to be processed using traditional methods, which leads to some design constraints. The aim of this work is to take advantage of the design freedom as provided by AM and to use topology optimization to generate a new design that eliminates unnecessary material, resulting in a lighter bearing unit without impacting the performance of the HBU.

1.3 Limitations

The project is limited to optimizing the outer ring of an HBU for a racing car. The optimization is therefore, only done on a bearing model designed for a racing car. The rolling element, inner ring, and cage will not be optimized in this report.

The choice of material has already been made by AB SKF. Material properties are classified and will therefore, not be disclosed in this report. How the material properties are affected by Powder Bed Fusion Laser Beam (PBF-LB) will not be evaluated in the report.

This bachelor’s thesis will focus exclusively on PBF-LB as a production method, since the chosen material is developed for the PBF-LB process. Hence, no other additive manufacturing method will be considered, evaluated, or described.

The bearing that will be optimized is used in racing cars, and therefore, performance and weight are of higher value than durability. Consequently, a lifecycle analysis will not be part of the analysis.

The project will not include a cost analysis since it is considered to have limited relevance because the customer considered the performance to be of higher relevance than the cost of the product. No cost comparison will be conducted between the different AM methods, since PBF-LB is already the chosen production method.

The purpose of this work is to develop a concept of a design, not a final product. As a result, a physical model in metal will not be printed, but a model will be printed in plastic to get a physical representation of the concept.

Most values in this report are classified under AB SKF policy. Thus, are values replaced with "*Classified*".

1.4 Research questions

To get a clear picture of the purpose of this thesis, a set of questions is constructed based on the main goals of the thesis. These questions are presented in the following and will be discussed in Chapter 9.

1. Is it Possible to achieve a 30% weight reduction on the HBU without compromising performance?
2. How can the HBU design be optimized to be suitable for printing?

2

Theory

In this chapter, the theory behind the work will be presented. This includes the basics of what a ball bearing is, as well as a Hub Bearing Unit, which will be the focus of this bachelor thesis. Also, additive manufacturing is described, with a stronger focus on the theory behind Powder Bed Fusion Laser Beam and its design limitations. A brief introduction to Computer Aided Design (CAD) is provided to ensure the readers' understanding. To conclude the chapter, the theory behind Topology Optimization and the Finite Element Method is presented and discussed.

2.1 Bearing

A ball bearing mainly consists of five components: An outer ring, inner ring, rolling elements, lubrication, and a cage. The two types of rolling elements are balls and rollers. Balls achieve point contact with the raceways, leading to a small contact area. This contributes to low rolling friction, allowing high speeds, though it limits their load capacity. Rollers achieve line contact with the raceways, resulting in a larger contact area. This allows for a greater load capacity; however, it contributes to higher rolling friction (SKF Group, Bearing Basics, n.d.).

Rolling Bearings are designed to take up either radial or axial load although some bearings can handle both. The different types of bearings can be sorted into different categories. Some of the existing categories are, deep grove ball bearings, cylindrical roller bearings, angular contact ball bearings and spherical ball and roller bearings (Mägi, Melkersson, & Evertsson, 2017).

A deep ball bearing, as seen in Figure 1, exists with both one row and two rows of balls. They are mainly used to taking up radial force, however, they can take up axial force as well. The double row deep ball bearing especially can be loaded with a bending load as well (Mägi, Melkersson, & Evertsson, 2017).

Figure 1: Deep grove ball bearing

Cylindrical roller bearings, as seen in Figure 2, come in a wide range where the main difference is the number of roller rows, the inner/outer ring flanges as for the cage design and materials. They are made for heavy radial loads and high speeds, and some versions can accommodate for axial displacement. (SKF Group, Cylindrical roller bearings, n.d.).

Figure 2: Cylindrical roller bearing

An angular contact ball bearing, as seen in Figure 3, has the raceways displaced relative to each other on the inner and outer ring in the direction of the axis. This makes it possible for the bearings to accommodate combined loads where both radial and axial loads are acting at the same time (SKF Group, Angular contact ball bearings, n.d.).

Figure 3: Angular contact ball bearing

Spherical ball and roller bearings, as seen in Figure 4, accommodate mainly for radial loads and secondly for axial loads, however, it does not accommodate for bending loads. Instead, the bearing offers the opportunity to move perpendicular to the centerline so that the axis can self-adjust in the bearing (Mägi, Melkersson, & Evertsson, 2017).

Figure 4: Spherical ball and roller bearings

2.1.1 Hub Bearing Unit

Hub Bearing Units, in this report referred to as HBU, are a type of angular contact ball bearing which functions as a part of a vehicle wheel assembly. It provides a mounting point for the wheel to the vehicle while allowing the wheel to turn freely (SKF Group, What is a wheel hub bearing and why is it critical to your safety?, 2012). A wheel bearing assembly consists of a wheel bearing (HBU), a dust shield, and a knuckle, all connected using bolts. See Figure 5 for an illustration of the a) HBU, and b) Wheel bearing assembly. The HBU connects the shaft to the wheel and allows power to transmit to the wheel (Kim, et al., 2022).

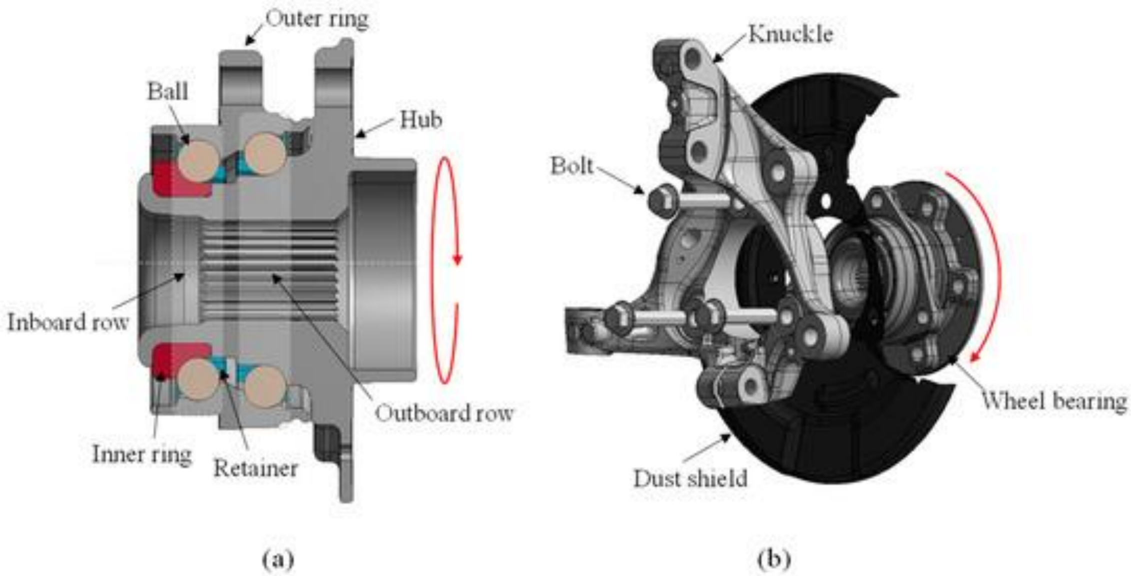


Figure 5: Car wheel bearing: (a) the HBU (b) assembly with main components (Kim, et al., 2022) Open access

When they are utilized for racing, there are, however, different performance criteria they must fulfil. While they operate in the same way as they would do in standard vehicles, they experience harsher conditions while racing. This includes the need to withstand a higher bearing load capacity for a given dimension. (SKF Group, Hub Bearing Units and Special HBUs, n.d.).

An HBU specifically designed for the car industry is based on double-row angular contact ball bearings (SKF Group, Vinkelkontaktkullager). An example of how a HBU designed for a car look is presented below in Figure 6.

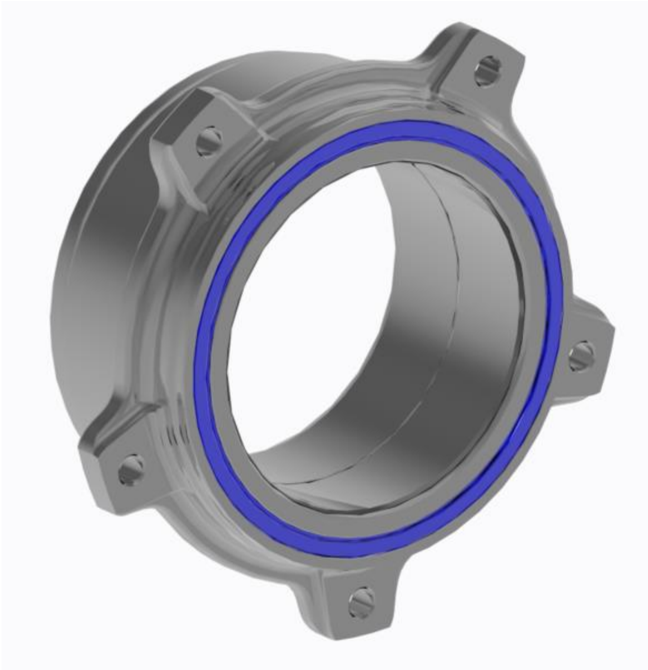


Figure 6: Hub Bearing Unit

To understand what components an HBU consists of an exploded view is shown below in Figure 7. As shown below, the outer ring is the only single component, while the other components consist of two separate mirrored parts. What purpose each component serves are explained below Figure 7.

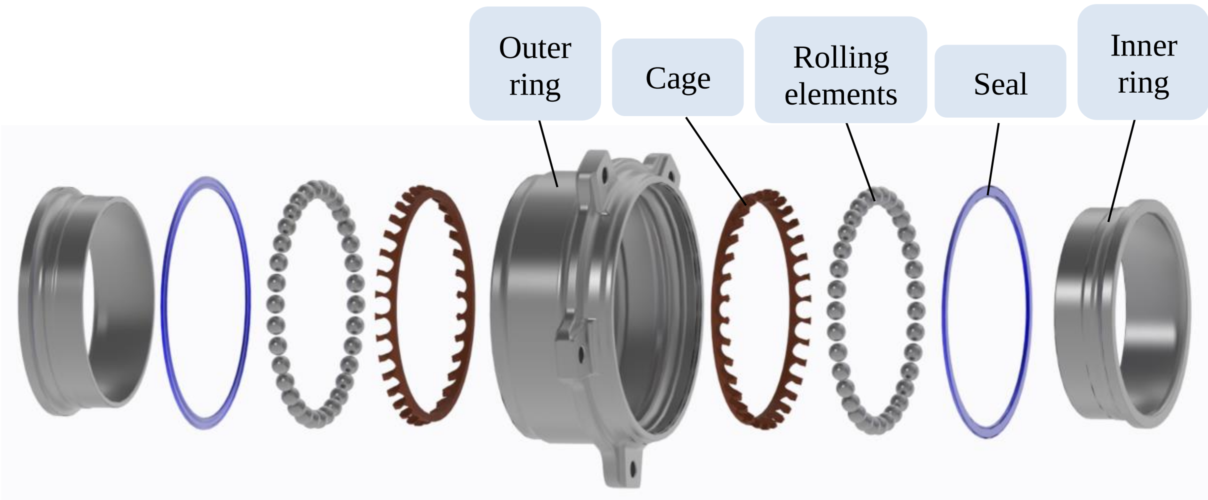


Figure 7: Exploded view of a Hub Bearing Unit

The set of cages serves the purpose of always keeping the rolling elements at a certain distance from each other. This is important to ensure four beneficial capabilities: i) reduce the frictional heat that is generated in the bearing, ii) optimize load distribution, iii)guide the balls in the unloaded zone of the bearing and iv) retain the rolling elements of separable bearings when one ring is removed during mounting (SKF Group, Components and materials, n.d.).

The set of seals serves the function of keeping the lubricant in place inside the bearing and to prevent contamination from getting inside of the bearing. A bearings life is very sensitive to contamination hence the grease must be kept as free from particles as possible to avoid damaging the bearing (SKF Group, Components and materials, n.d.).

The rolling elements, in this case balls, transfer the applied load between the inner and outer rings (SKF Group, Components and materials, n.d.) The bearing rings serve as a housing for the raceways, which handle both radial and axial loads (Mägi, Melkersson, & Evertsson, 2017).

2.1.1.1 Hub Bearing Unit Terminology

This report will focus on the outer ring of the HBU. To ensure clarity in the sections that follow, a reference figure is provided below, *see Figure 8*. In this figure, the key components of the outer ring are highlighted in red and labeled with the terminology used throughout this report.

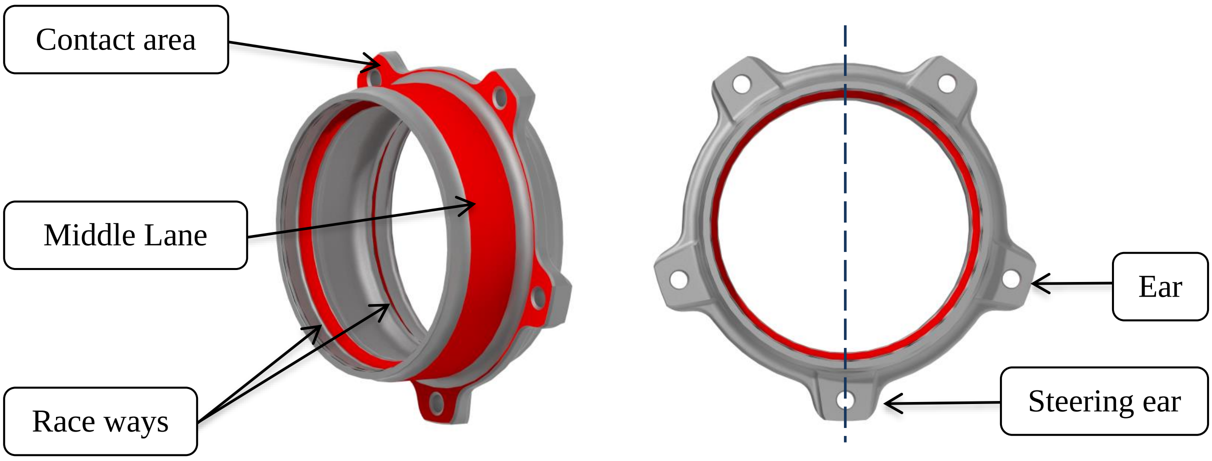


Figure 8: HBU terminology

2.2 Additive Manufacturing

Traditional machining shapes the final component by removing excess material from the piece being worked on (DATRON, 2025). In contrast, Additive Manufacturing (AM) operates by building one layer at a time, therefore, making it possible to create more complex geometries (Linköping University, 2025).

Multiple AM techniques exist, each capable of utilizing different materials, including plastics, metals and ceramics. This makes AM suitable for a broad spectrum of applications across industries. By taking advantage of the capabilities of AM, manufacturers can produce intricate designs that would be challenging or impossible to create with traditional machining methods (Redwood, Schöffer, & Garret, 2018).

There are seven standard AM processes, many of which have been adapted for metal. However, the industry has embraced a selected few for metal AM. The most popular are Powder Bed Fusion, Binder Jetting and Directed Energy Deposition. Material Extrusion, Material Jetting and Sheet Lamination are also commonly used by the industry for metal AM (Toyserkani, et al., 2022).

2.2.1 Powder Bed Fusion Laser Beam

Powder Bed Fusion Laser Beam (PBF-LB) is an additive manufacturing method that uses a laser as a thermal source to melt metal powder, building the component one layer at a time, ultimately creating a solid piece. The process involves spreading a thin layer of powder, followed by a laser scanning over the powder where the build is desired to be created. Then the process repeats, a new layer of powder is spread out and then the laser is melting again the consecutive layer. This is done layer by layer until the component is finished. The accuracy of the method mainly relies on the laser spot size, layer height and powder properties. For PBF-LB the tolerance is usually ± 0,1 mm (Redwood, Schöffer, & Garret, 2018). Figure 9 Shows the schematic of PBF-LB.

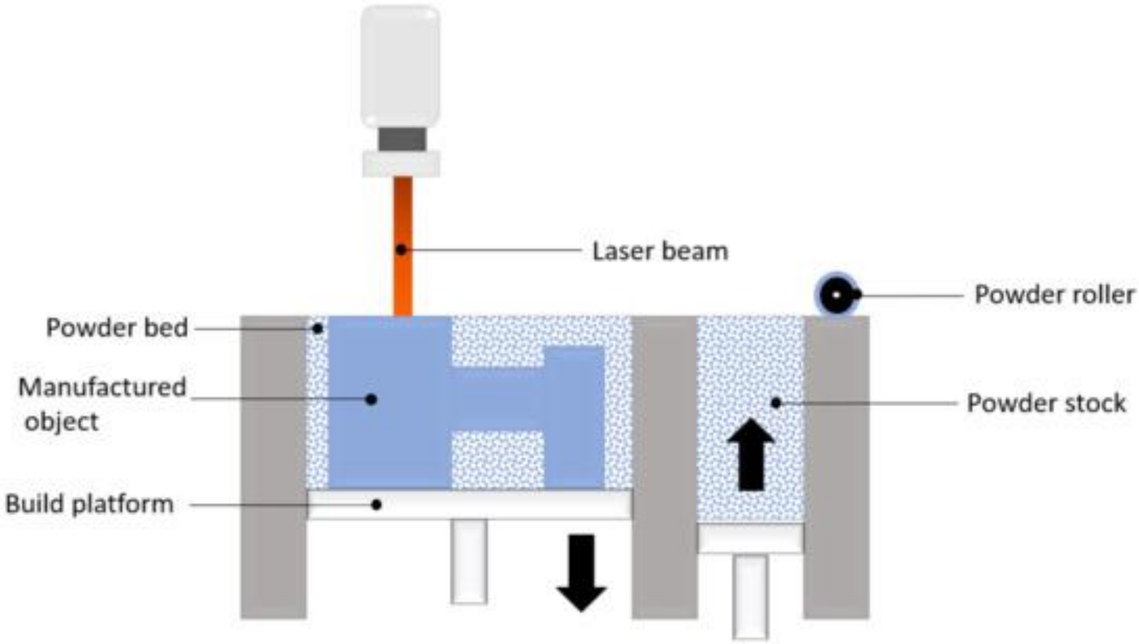


Figure 9: Schematics of a PBF-LB process (Pal & Basak, 2022) CC BY 4.0

2.2.2 Strengths and limitations with Powder Bead Fusion Laser Beam

The development of PBF-LB has experienced significant development during the last two decades. With the change from the use of low-power lasers to high-power lasers and even the use of multiple lasers, the processing speed has improved, which enables faster build times and larger scales in manufacturing. The recycling and reuse of powder has also been improved, resulting in less contamination of recycled powder, and therefore, a saving in cost for expensive materials. Another key improvement is the build volumes in the machines. Early machines were only enabling manufacturing of smaller parts, whereas today's machines offer build-platforms that exceed one cubic meter and can produce larger components (Rahmani, et al., 2025).

One of the strengths with AM is the possibility to produce lightweight parts. The freedom of design in AM enables the use of, for example, topology optimization with weight reduction as the goal. AM also enables the manufacturing of hollow structures for weight optimization purposes (Toyserkani, et al., 2022). However, it is crucial to remember the limitations of the processes, as for example, the use of support structures inside a hollow structure is limited since they cannot be removed. Additionally, when manufacturing hollow structures, escape holes must be added to ensure proper removal of loose powder within the structure (Redwood, Schöffer, & Garret, 2018).

Although it is possible, to some extent, to modify and design the microstructure of an AM-printed part using the PBF-LB process, post processing is needed in most cases. Post processing involves heat treatment (annealing, austenitization, etc.) and HIPing (Hot-Isostatic-Press), which are needed to ensure properties such as ductility and toughness and a part free from pores (Toyserkani, et al., 2022). The physical, and sometimes chemical, properties of a material can be altered using heat treatment. To achieve this, the material is heated and cooled, to different temperatures. There are several heat treatment methods that can be used depending on the requirement and possibilities (Bonami, 2009).

A common problem with AM, especially with PBF-LB is part distortion, is that the part is distorted during printing/cooling. This problem is mainly associated with inferior heat dissipation which can be found in areas with thick and thin sections, with different cooling rates. To reduce this phenomenon the use of constant thickness in a design can be helpful but also by studying the laser strategy, for example using chess pattern. (Redwood, Schöffer, & Garret, 2018)

Another issue in LPF-LB is the warping phenomena, also causing the part to distort. This can be reduced by better anchoring of part areas (specific regions) at risk to the build plate using stronger support structures that act as heat sinks. The support structures create a building platform for overhangs less than 45°. (Redwood, Schöffer, & Garret, 2018). To demonstrate the need for support structures when printing with an overhang greater than 45°, Figure 10 shows the warping of a part with too great of an angle, here the AM method is different, yet the principle is the same.

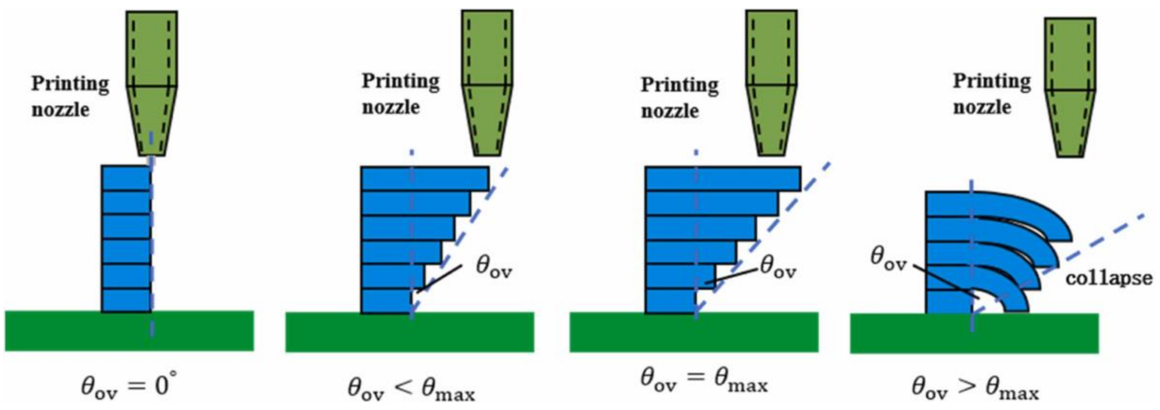


Figure 10: Demonstration of effects when using different overhang angles where θ_{max} is the maximum overhang angle (Guo, et al., 2024) CC BY-NC-ND 4.0

Support structures are used in PBF-LB for two main reasons, it anchors the component in its position and dissipates the heat. These need to be removed by subtractive methods such as milling and sawing or other processes alike. This must be taken into consideration since the surface where the support is attached will be impacted. This also affects the orientation in which the part should be printed (Redwood, Schöffer, & Garret, 2018). As seen in Figure 11 support structure anchors the parts that are floating in the air to the build plate.

Figure 11: A part (in white) with support structure (in blue)

Other limitations of PBF-LB are the cost, build size, and build time. In the current market, most of the industrial systems for metal printing are very expensive, as are the metallic powders. This indicates that it is usually not the most cost-effective manufacturing technique. Additionally, the build area is very limited even in the largest 3D printers on the market. (Redwood, Schöffer, & Garret, 2018).

2.3 Computer-Aided Design

Computer aided design (CAD) is a type of computer software that allows engineers to create and visualize various design solutions. These designs can be modeled into 2D drawings or 3D models, which can be modified, analyzed, and optimized before the physical object is manufactured (Heidari & Iosifidis, 2024).

2.4 Structural Optimization

Structural optimization (SO) is the term of optimizing a structure to sustain loads in the most optimal way possible. What is meant by “optimal” is in the SO defined by the constraints set on the optimization. Any one of the constraints defined can be set as an objective function which can be minimized or maximized (Christensen & Klarbring, 2009).

The mathematical form of a SO problem has three variables that are always present. These variables are objective functions (f), design variable (x) and state variable (y). As mentioned above, the objective function is used to indicate if the design is optimal. The design variable is a function or a vector that describes the design and what is included in the optimization. This variable can be changed during the optimization operation. The state variable is the response in the structure for a given design. This generates the general SO problem form where f (x, y) is minimized with respect to x and y and is subject to behavioral constraints on y, design constraints on x, and equilibrium constraint (Christensen & Klarbring, 2009).

2.4.1 Topology Optimization

Topology Optimization (TO) is the most general form of the three existing subclasses of SO. The other two SO subclasses are sizing optimization and shape optimization (Christensen & Klarbring, 2009). What makes TO stand out in relation to the other subclasses is that the optimization can start form a solid structure where number, size, shape and location of holes and structures are determined using the optimization. The only known quantities of the structure are the applied loads, support conditions, desired volume, and possible design restrictions, such as where and where not, changes are allowed to be made. Sizing and shape optimization, on the other hand, uses a starting design and optimizes either the size of, for example, the members in a truss structure or the shapes of the given domain. Figure 12 illustrates the difference between the three methods (Bendsøe & Sigmund, 2004).

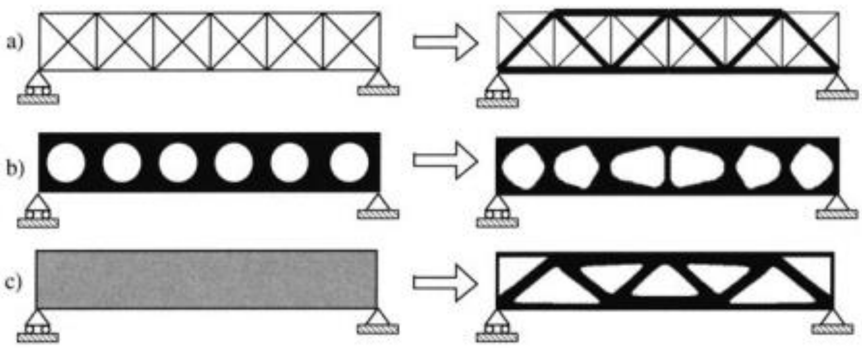


Figure 12: a) Size optimization b) Shape optimization c) Topology optimization (Bendsøe & Sigmund, 2004) Used with permission

2.5 Finite Element Method

Finite Element Method (FEM) is a mathematical method used to numerically analyze a boundary value problem. The method can in simplification be described as polynomial functions that represent field variables, such as displacement, that are dependent on set boundary conditions. To make the polynomials less complex the model is divided into smaller elements which create a mesh. The original boundary conditions are now represented as discrete loads and supports applied on the nodes of the elements (Kurowski, 2004).

The fundamental FEM equation can be seen in equation 2.1. The F stands for load vector and contains the force boundary conditions. K stands for stiffness matrix and is a function of the model geometry, material properties, and remaining boundary conditions. The d stands for vector of nodal displacements which are the primary unknowns. Secondary unknowns such as stress can be derived from the functions of the primary unknowns. Each element can further be described using polynomial function which is also called a shape function (Kurowski, 2004).

$$[F] = [K] * [d] \tag{2.1}$$

Finite element analysis (FEA) is the application of FEM. This is used by Engineers in the design process to make design decisions by generating data that may be analyzed. There are plenty of different FEA software, such as ANSYS, that can be used to numerically calculate the primary and secondary unknowns (Kurowski, 2004). Figure 13 shows an example of what an FEA can look like.

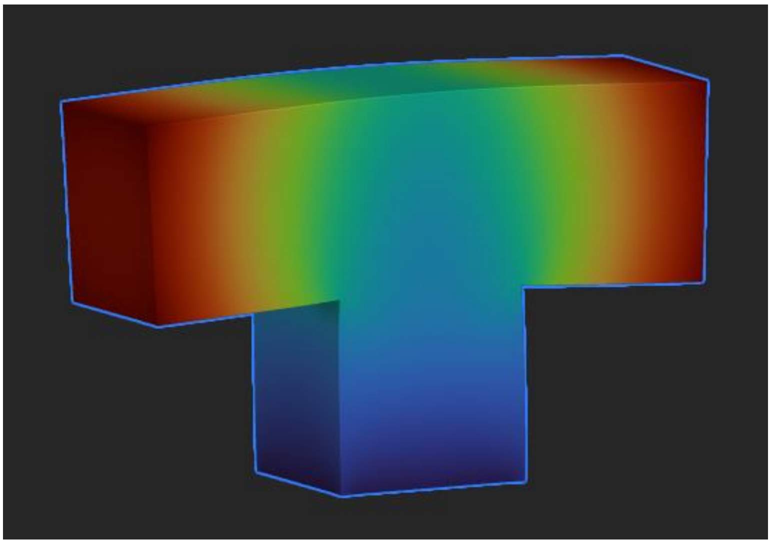


Figure 13: Example of a Finite Element Analysis on a part with displacement as output

3

Methodology

This chapter presents the methods used during the project. This involves the project development plan, the customer needs and requirements, the design process, concept selection, and concept evaluation.

3.1 Project development plan

The implementation of a project development plan was carried out to ensure a common goal and outline for the project. The plan was structured into tasks and milestones which in its turn generated a Gantt chart. A Gantt chart is according to Pinto (2012) a time-phased network which connects project activities to a schedule. Furthermore, Pinto (2012) clarifies that it can be used as an assessment tool for the difference between planned and actual performance. Pinto (2012) also explains that activities are ordered in a column, from first to last, and the duration of each task is drawn horizontally to the right of the activity column. The Gantt chart was used as an indication on which task was completed, and which were coming up.

As a complement to the Gantt chart, the Outlook calendar and an internal checklist were utilized. The Outlook calendar served as a bridge between AB SKF and the project group. The calendar allowed planning of meetings and events that were not planned at the beginning of the project. The internal checklist was used to divide each task into smaller, more detailed tasks as they came up in the schedule. This made sure that misunderstandings and double work could be avoided.

3.2 Customer needs and requirements

This section presents the methods used to set a clear direction for the project and a common ground for the project group. It involves gathering information about the customer needs, metricizing them, and sorting them into a requirement specification.

3.2.1 Identifying customer needs

To identify customer needs, data was gathered from two different types of sources. The first kind of source is the companies/departments collaborating on the project. Information about both the customer needs and other project-related needs was gathered. The second kind of source was experts within AB SKF. The experts who were advised were divided into different groups according to their field of expertise. The analysis of the customer needs was crucial to gather the data and information needed to ensure that the vision for the project was understood by both parts of the project group, as well as setting the basis for the requirement specification.

The data from both kinds of sources were gathered in two different ways. First, data was gathered through meetings where data was offered from the meeting attendees and asked for by the project group. Second, data was gathered through information sheets sent to the project group from different sources.

3.2.2 Requirement specification

To make a requirement specification, the customer needs had to be broken down into an attribute that could be quantified. These attributes were then used to establish clear and measurable metrics to ensure that the project group were on the same terms about the customer's needs. These metricized attributes were then grouped based on the requirements themes and placed into a requirement specification linking each requirement with a customer need and a quantification as well as how the requirement can be verified.

3.3 Design process

This section presents the methods used during the design process. Both an internal and external search is presented as well as the method of the iterative design process that was used when designing.

3.3.1 Internal and external search

To examine the possible design solutions for the HBU that could be used during the concept generation, an internal and external search was performed. The internal search was performed by having a brainstorming session. The group shared novel ideas that were sketched and documented. The brainstorming method was used to combine the information gathered about the project from the group members with their individual design experience. This method also opens possibilities for combining ideas and generating new ideas later in the process. In an external search, the possibilities of the software used to design the product were explored. Understanding of what kind of geometric structures the software could generate gave inspiration to design possibilities.

3.3.2 Iterative design process

The iterative design process is a method used after the customer's needs have been defined, and some initial ideas on how to meet the needs have been planned. The process is then used by developing a prototype using the initial ideas followed by testing to ensure that it meets the needs in the best possible way. When the results of the test have been evaluated, the insights gained can be used to amend the design. A new prototype can be created, and the process starts over from the beginning and continues in a loop until the best possible product has been reached. This method is effective when there are many different ideas within a team, as it can help to show which idea to pursue (Interaction Design Foundation - IxDF, 2025). This process is illustrated in Figure 14.

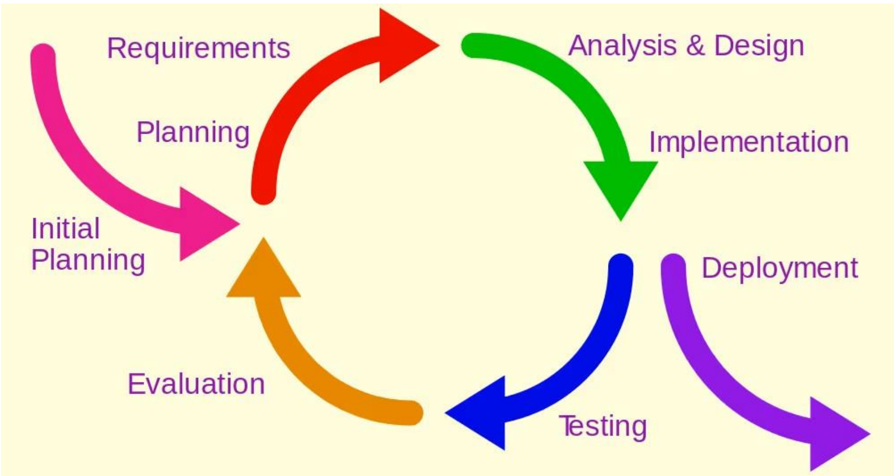


Figure 14: Iterative design process (Interaction Design Foundation - IxDF, 2025). Public Domain

In this project, the iterative design process was used in two different ways. First, it was used within each design, tested during the entire development process. Each design was tested using FEA and a weight-saving calculation to see if it met the needs of the customer in the best possible way. Secondly, the iterative design process was used within the topology optimization. Four major topology optimization runs were tested in which multiple design ideas were tested. Each new topology optimization was based on what was learned from creating different designs using the previous topology optimization as a basis. Each design was made using the software nTop as well as Creo Parametric for smaller components.

3.4 Concept selection

The concept selection process started by eliminating concepts that did not meet the requirements. Therefore, the concepts who had a higher deformation or stress than the criteria specification allowed, were not evaluated further and were removed from the participants.

To choose the final concept from the multiple options, each concept was evaluated based on its performance in deformation and weight-saving percentage. This evaluation involved two calculations that assigned each concept a score between 0 and 1.

The first calculation was done to normalize the values to scale them to a value ranging from 0 to 1, with 0 being the worst and 1 the best. Weight saving was a value that we wanted to maximize, hence equation 3.1 was used to normalize that value. Deformation was a value we wanted to minimize, hence equation 3.2 was used to normalize that value.

$$Normalized\ Value: X_{weight} = \frac{X_i - X_{min}}{X_{max} - X_{min}} \tag{3.1}$$

$$Normalized\ Value: X_{deformation} = \frac{X_{max} - X_i}{X_{max} - X_{min}} \tag{3.2}$$

Once both criteria were normalized to a scale of 0 – 1 were they combined with weights. Weight is an important value for each criterion, reflecting how much each factor should influence the final selection. Since all the remaining concepts passed the deformation and stress criteria, weight saving was of higher importance and given the value of $w_{weight} = 0{,}7$ while deformation got the remaining score of $w_{deformation} = 0{,}3$. The final score was calculated using equation 3.3.

$$Score = w_{weight} * X_{weight} + w_{deformation} * X_{deformation} \tag{3.3}$$

3.5 Concept evaluation

To evaluate each iteration made throughout the process, an FEA was made for each concept. The topology optimization software nTop has a tool to do FEA in the same software, which made it possible to set up a base file for each big iteration. The base file included both the topology optimization and the FEA, which ensured an equal FEA on all concepts within the same topology iteration. Since each design did not have to be exported and set up separately in another program, a lot of time was saved. This made it possible to run an FEA on each small iteration, making nTop the best choice for FEA. The boundary conditions, load cases and constraints set up in the FEA are further explained in Chapter 5.

4

Customer needs and requirements

This chapter presents the process of gathering information about the customer's needs and quantifying the needs. This is presented in section 4.1. The customer needs are then structured into a requirement specification in section 4.2.

4.1 Identification of customer needs

As previously mentioned, the collaborating companies on the project and a set of experts from AB SKF were advised to gather information about the project. These were divided into five groups based on their area of expertise; Customer, HBU Experts, Material, AM Experts and Product Development Experts, see Table 1 for a description of each group.

Table 1: Description of the areas of expertise

GROUP	DESCRIPTION
CUSTOMER	The AB SKF department SKF Racing works as the customer for the design and has knowledge of the end customer's requirements and desires on the project.
HBU EXPERTS	Possesses the knowledge of which areas of the HBU that can be redesigned, and which need to be left as is.
MATERIAL	The collaborating company that develops the material used, possesses knowledge on material properties
AM EXPERTS	Possesses knowledge of PBF-LB and suitable designs for AM. In addition, they have knowledge of design requirements for AM.

GROUP	DESCRIPTION
PRODUCT DEVELOPMENT EXPERTS	The product development experts know the opportunities and limits of the software used. They also know what to take into consideration during the design process.

4.1.1 Customer

SKF Racing, working as the customer representative, explains that the client wants a weight reduction on the HBU. Also mentioned by SKF Racing, a master thesis in collaboration with AB SKF on the same subject from 2020 showed a possible weight reduction of 29,9% (Danielsson & Salfjord, 2020). Therefore, SKF Racing desires a weight reduction of 30%, however, they also point out that a weight reduction of 10% is good enough.

The HBU will be exposed to extreme forces on the racetrack. To ensure there will not be any failure during the race, the HBU must be designed to withstand these forces. The customer has done a simulation on what forces the HBU is exposed to during a race. The simulation was given in five different load cases: Breaking, Cornering outer, Cornering inner, Bump and Contact. Each load case had a force in the x-, y- and z-directions and a moment. The values of these forces are classified. In the values given the customer has added a safety factor which means that there is no need to add a safety factor on the material properties. Therefore, the goal is to find a design that gets as close to the yield stress, without going over, when the loads are applied.

4.1.2 HBU expert

HBU experts explained that there was considerable freedom in altering the original design of the HBU. However, certain areas were considered critical for the overall functionality and post-processing ability of the bearing and, therefore, should not be altered or had limitation on what could be altered. To get a good understanding of what areas needed to be protected, the HBU got areas classified as ‘do not touch’ marked in red, as seen in Figure 15 below. This ensures that the post-processing ability and functionality of the bearing will be kept while the design freedom maintains relatively large. Areas classified as do not touch can be divided into three groups to more easily describe why they cannot be altered, as seen in Figure 15 below.

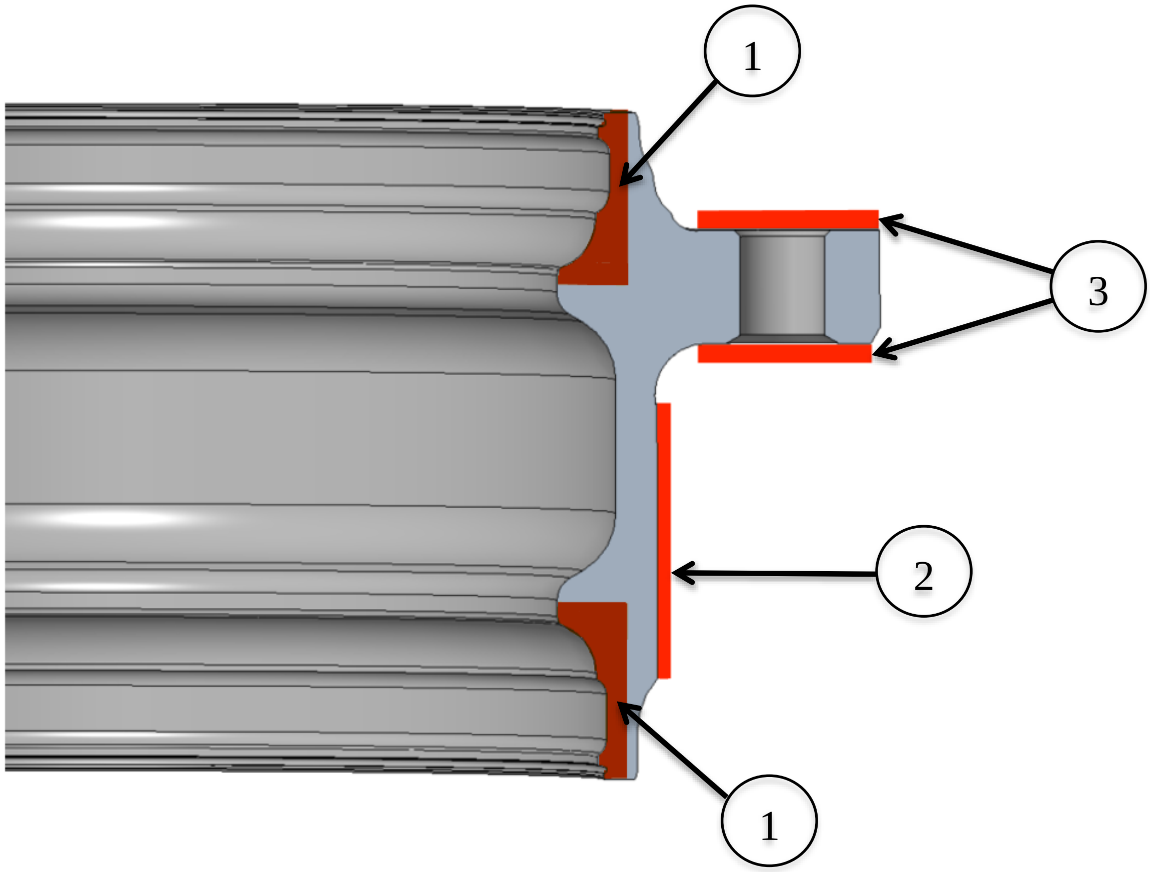


Figure 15: Do not touch areas on cross-section

Group 1 has an inner geometry that is in contact with the roller elements and seals. This area must be machined after printing, and therefore, is considered a critical area and cannot be altered.

Group 2, also called the middle lane, is a surface that adds to the stability between the HBU and knuckle. The HBU is inserted into the knuckle hence this surface is in contact with the knuckle. From the center point of the HBU to this surface, the distance is critical. This surface could be altered inward, but enough area must be kept at the specific radius to maintain the stability function that comes from the contact between the HBU and the knuckle.

Group 3 is for the ears on the HBU, and these have a relatively large design freedom. The current design has five ears in total, but the HBU experts expressed that the number of ears and the shape could be altered, if the hole diameter remains. However, the faces need to be kept as a flat surface to ensure good connection to the surrounding components.

4.1.3 Material expert

When discussing the material properties with the material experts they explained that because the chosen material is under development, not all parameters are yet available. They explained that temperatures that affect the material properties will not be reached in the bearing, hence how the material properties are affected under temperature change is not something we need to consider. They explained that the yield strength of the material is *Classified* before any heat treatment. This value must be considered in the areas of the bearing that will not be heat treated.

4.1.4 AM expert

When consulting experts within the field of AM some key points were made. The first key point was that although it is important to make sure the HBU is printable in the end, that variable should not limit the design process. Since the market of AM is still relatively young and has many opportunities for development, and what is not possible today may be possible in the future. Therefore, it is still worth designing without some of the limitations in mind and then add the variable again when picking the final concept. This allows for more creative and innovative ideas.

Another point that was made was that the printability of the competing concepts in the end should be evaluated together with the AM experts. This is done to make sure that the printability of each concept is evaluated correctly. The printability evaluation is roughly based on where support structures are needed and how much that is needed, if it is possible to remove all loose powder.

4.1.5 Product development expert

The product development expert explained that there were several design requirements that needed to be considered. They explained that the design must be mirrored to make it possible for the HBU to be used on both sides of the car, to avoid the need for two different designs for the two sides. This means that a design with an uneven number of ears must have a steering ear going through the symmetrical line upwards or downwards, whereas an even number of ears can have either no steering ears or steering ears both up and down. They also explained that because some material properties are not yet known, linear elastic properties are to be assumed for the material when topology optimization and FEA are performed.

4.2 Requirement specification

The initial requirements provided by the various groups resulted in a list of 12 criteria, see Table 2 below. Each criterion was assigned a specific target value that was expected to be met. These criteria were categorized into four distinct groups: dimensions, loads, mechanical properties, and manufacturing.

The criteria are assigned to the classification of required, R, or a desire, D. The criteria with the classification R need to be fulfilled. The criteria with classification D do not need to be fulfilled, however, by fulfilling these criteria, it could increase the functionality and customer satisfaction. An example of this can be seen in criteria 1.1 and 1.2, both of which relate to weight reduction. One criterion specifies a desired value, while the other specifies a required value. The required value is set at > 10% based on customer requirements. In contrast, the desired value is set at > 30%, derived from the previous design project. If this criterion were met it would increase customer satisfaction.

Criteria 1.3, 1.4 and 1.5 are based on the original design of the HBU. 1.3 is the diameter of the middle lane and this value cannot be changed. 1.4 is the diameter of where the center of the attachment holes is located, and these cannot be changed.

1.5 is the surface area of the middle lane, which is defined by the diameter specified in criterion 1.4. The amount of surface area at the set location can be adjusted, but the desired criterion involves reducing it by a maximum of 50%.

Table 2: Criteria Specification

Nr	Criterion	Measurement	Target/ Value	Justification	Evaluation/ Verification	R/D
1	**Dimensions**					
1.1	Weight reduction	Percentage	> 10%	Customer	CAD	R
1.2	Weight reduction	Percentage	> 30%	Customer	CAD	D
1.3	Diameter to attachment hole	mm	*Classified*	Customer	CAD	R
1.4	Outer diameter of the middle lane	mm	*Classified*	Customer	CAD	R
1.5	Middle lane area	Percentage	50%	Customer	CAD	D
2	**Loads**					
2.1	Axial load, y	N	*Classified*	Customer	FEA	R
2.2	Radial load, x	N	*Classified*	Customer	FEA	R
2.3	Radial load, z	N	*Classified*	Customer	FEA	R
3	**Mechanical properties**					
3.1	Maximum Yield Stress	MPa	*Classified*	Customer	FEA	R
4	**Manufacturing**					
4.1	Printable	Yes/No	Yes	AB SKF	AM Expert	R

5

Iterative design process

This chapter presents the iterative design process. First an internal and external search was made to gather information and ideas for the project. Secondly, four different topology optimization iterations were made, where each new iteration was based on what was learned in the previous iteration.

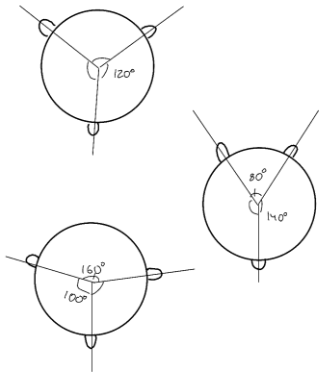
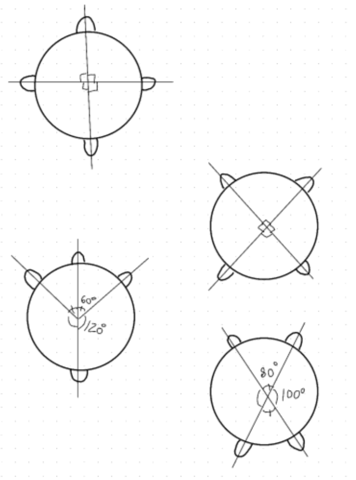
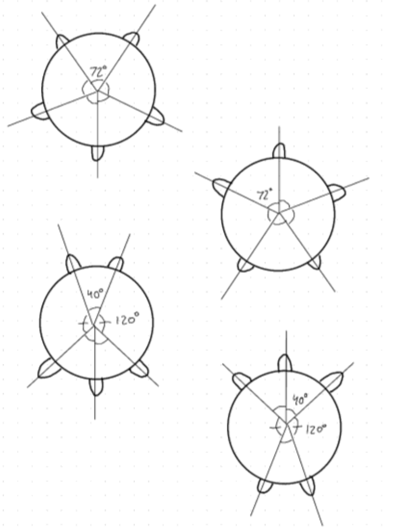
5.1 Internal and external search

An internal and external search was performed to investigate the different design ideas that were possible to use to decrease weight without the use of topology optimization. The results generated will be presented going forward.

5.1.1 Internal

In the internal search, the focus was on generating different ideas for the number and placement of the ears. The search generated eleven different ideas, which were organized into three categories. The three categories were based on the number of ears on the part. This means that the categories were three, four, or five ears. The ideas were then sorted into a table. All ideas were designed to be symmetric on the "y-axis" to make sure that the HBU would fit both front and rear axis of the car, as well as the left and right sides, without having to mirror the design, and therefore, having to produce two variants of the HBU for one car. The angles on the sketches are only there to help visualize the symmetry and spacing except for the designs that are completely symmetrical. The real angles that will be used will be explored at a later stage if needed. The sketched ideas are presented in Table 3.

Table 3: Ideas generated from internal search

Three ears	Four ears	Five ears
		

The category with three ears generated three ideas. The first idea was to spread out the three ears equally spaced out on the HBU with one ear pointing straight to the ground. The other two ideas were two different versions of the first, one with a smaller angle between the top two ears and one with a greater angle.

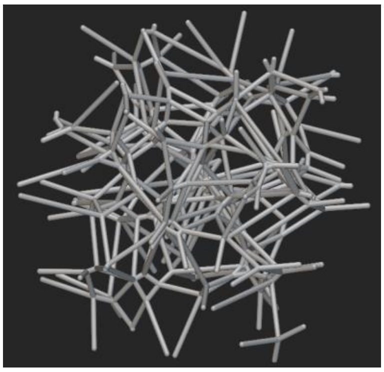
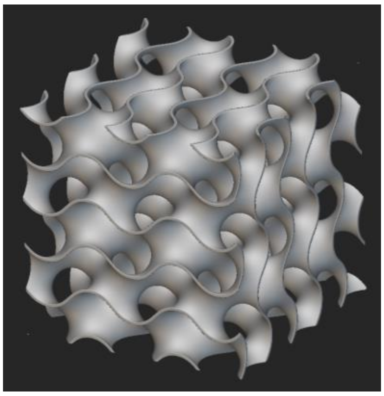
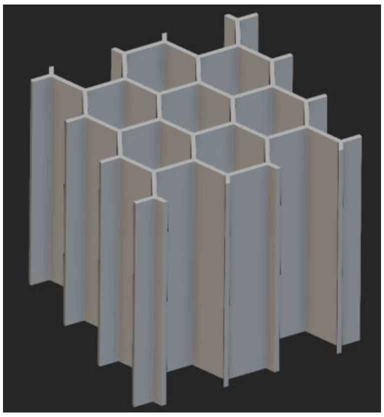
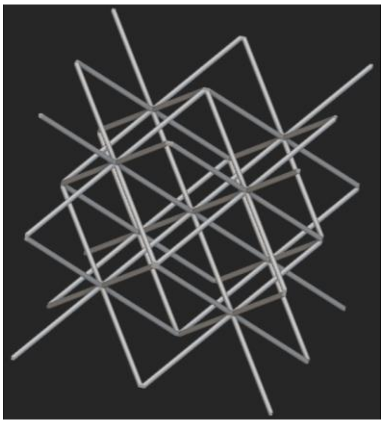
When generating ideas using four ears, four versions were explored. The two first ideas had ears that were equally spaced, one with the top and bottom ears on the "y-axis" and the other two to the sides, and one turned 45 degrees. The third idea was based on the fist but the two ears on the side were moved closer to the top ears. The last ear was based on the second ear but the angle between the top two ears and between the bottom two were decreased.

For the category with five ears two ideas were generated, and then two more by turning the two first 180 degrees. The first idea spaced out the ears equally with one ear pointing straight to the ground. The second idea increased the space between the ears on either side of the "y-axis".

5.1.2 External

The external search focused on exploring design possibilities for lightweight structures. Given the common use of lattice structures in additive manufacturing, the search primarily targeted this area. The search exclusively utilized information from nTop, the program used for this study. nTop categorized lattice structures into two main categories: volume lattices and surface lattices. The volume lattices consisted of four primary types of structures: Stochastic lattices, plates, and honeycombs, beam-based lattices, and TPMS (Triply Periodic Minimal Surfaces). The surface lattices consisted of three primary types of structures: Stochastic lattices, beam-based lattices and TPMS (nTop, 2022). To visualize the four categories, a cube was made in nTop and then transformed into the respective lattice structures. See Table 4.

Table 4: Table of lattice structures

Stochastic lattices:	
TPMS:	
Honeycomb:	
Beam based:	

5.2 Topological Optimization

This section will describe how the boundary conditions affected the topology optimization iterations and subsequently affected the path of how the final design came to be. Four different topology iterations will be explored individually.

5.2.1 First topology iteration

This section explores the first topology iteration. First, the boundary conditions will be explained followed by the load cases and constraints. Finally, the results of the first iteration will be presented and explained.

5.2.1.1 Boundary conditions

The goal of the first topology optimization iteration was to modify the ear shape to incorporate lattice structure in the middle lane. This was done by setting four areas as passive regions. These areas are where the seals, raceways, middle lane and the holes in the ears are seen in Figure 16. This allowed nTop to remove material around the ears and inside of the middle lane, which will be referred to as the middle region.

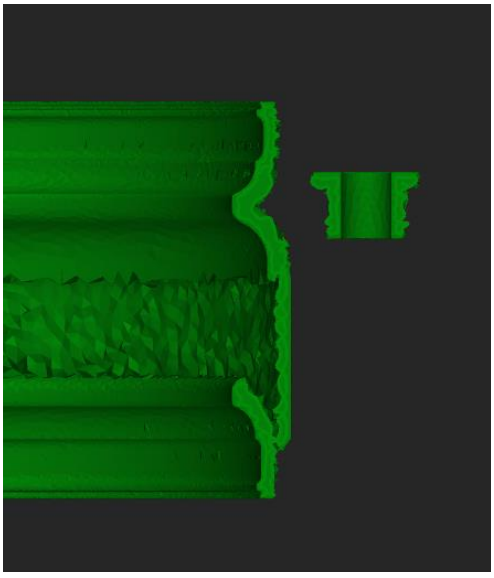


Figure 16: Passive regions in the HBU shown in cross section

5.2.1.2 Load case and constraints

The forces obtained from the data were divided into different load cases to be able to simulate the different load conditions. These forces were applied to the contact area from the balls to the raceway, resulting in the raceway encountering loads on all three axes seen in Figure 17. The middle lane and the backside of the ears were given a displacement restraint to simulate where the HBU is in contact with other components once assembled, as seen in Figure 18.

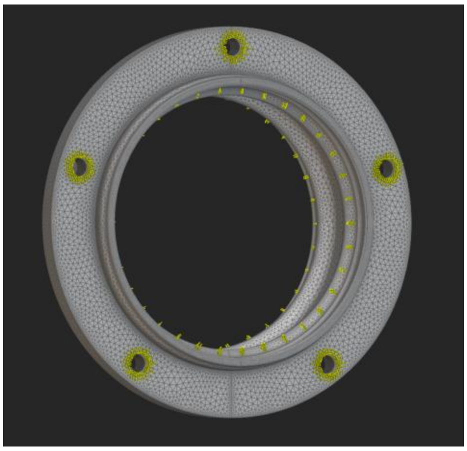


Figure 17: Loads applied on the HBU

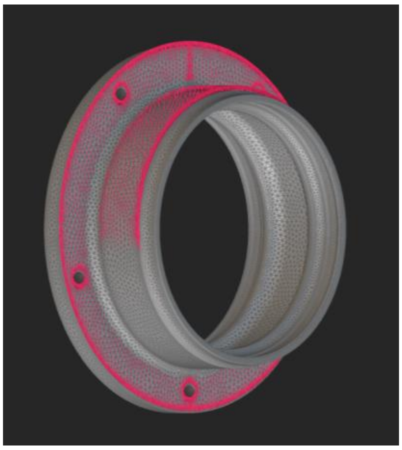


Figure 18: Displacement restraint on the HBU

Three additional design constraints were added to the topology optimization. The first was a volume fraction constraint set to 0,5 that allowed the topology optimization to remove 50% of the material. The second one was a stress constraint set to *Classified* that limits the topology optimization to only remove material, so the design won't reach stresses of *Classified* once the load cases are applied. The third constraint was an overhang constraint with the limit of 45˚ that limits the topology optimization to not create overhangs sharper than the limit value.

5.2.1.3 Running the first topology optimization

The constraints and load cases were imported into the topology optimization program and tested on 3,4,5 and 6 ears. The design generated with 5 ears can be seen in Figure 19.

Figure 19: Resulting design from topology optimization for 5 ears

As seen in the figure, the ears were barely connected to the HBU resulting in a non-functional design. To solve this problem, a basic geometry was added around the ears to connect them to the HBU, additionally, a smoothing body iteration was done on the whole body. This resulted in the design seen in Figure 20.

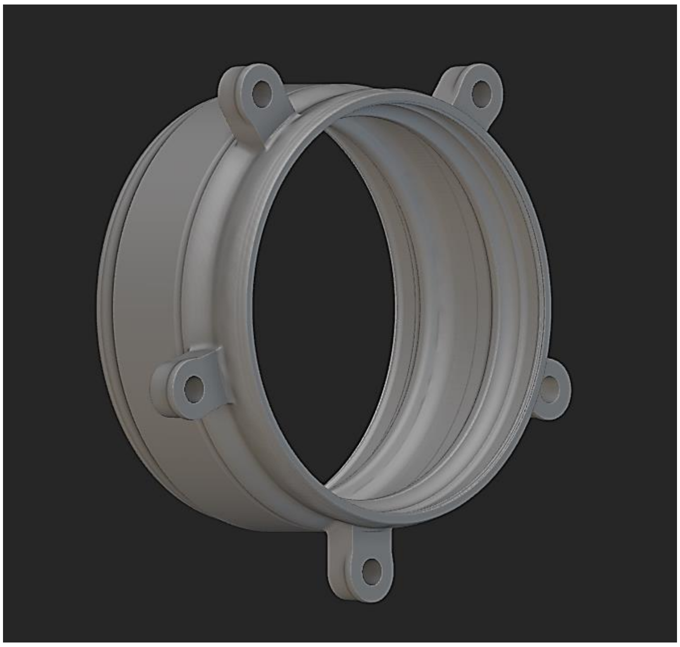


Figure 20: Design concept after first topology optimization

5.2.2 Second topology iteration

This section describes the ideas that came from the first iteration as well as how they were implemented. It also presents the general results of the second iteration. Finally, the generation of new ideas are presented and explored.

5.2.2.1 Ideas from the first topology optimization

After working with the first topology optimization for a while the cross-section was analyzed, see Figure 21. When analyzing the cross-section, it was discovered that the first topology optimization took away material above the front raceway (1) but not above the back (3) since the middle lane (2) was set as a passive region. This discovery generated the idea to split the middle lane and set only the part that didn't cover the back raceway, as a passive region and to add the radius circled in green to prohibit the possibility of large gaps in the design. After these changes were made the passive regions seen in Figure 22 were used.

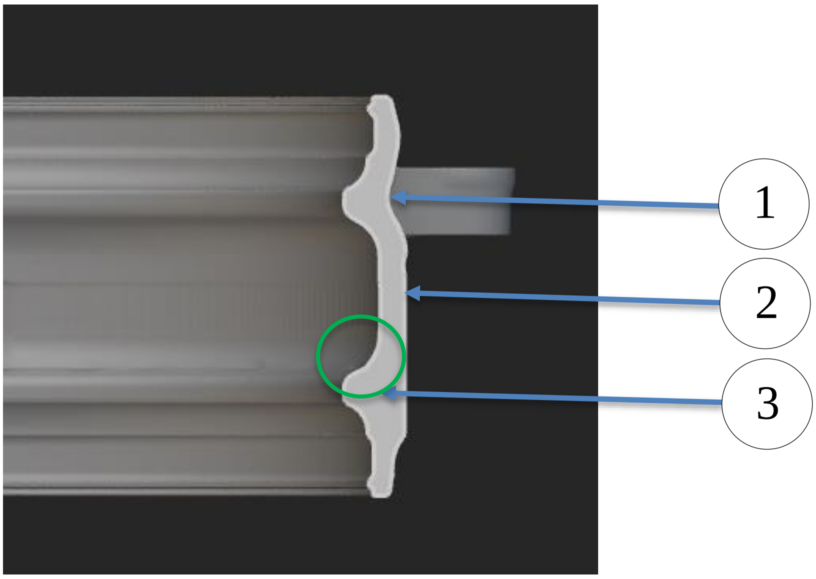


Figure 21: Cross-section of the first iteration

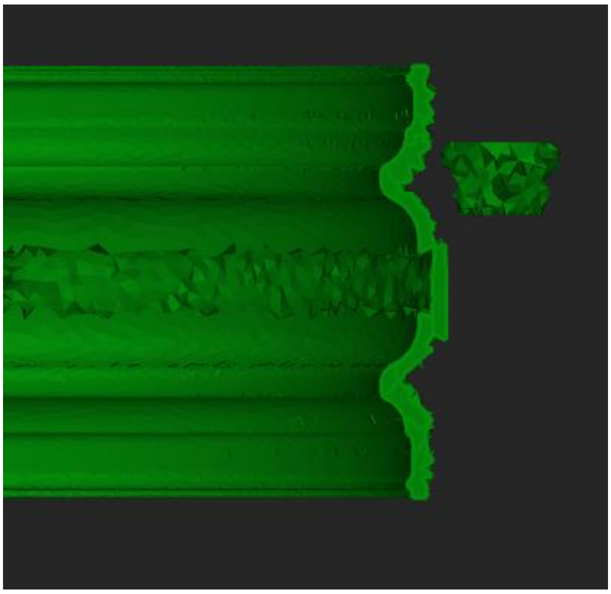


Figure 22: Passive regions used in the second topology optimization

5.2.2.2 Running the second topology optimization

To run the topology optimization, the optimization was set to use the same constraints as the first iteration, except for setting the volume constraint to take away 70% material instead of 50% and the change in passive regions as mentioned earlier. The load cases were not changed. Once all the changes were made the second topology optimization was run. This generated the cross-section seen in Figure 23, which confirmed the idea. Three, four and five ears were run with the second iteration set up.

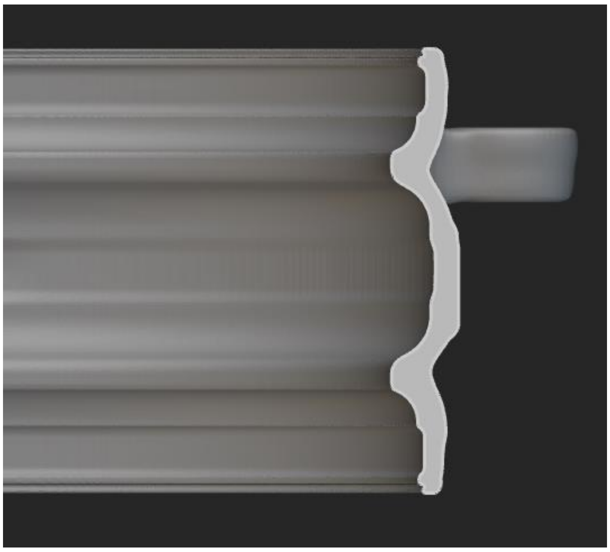


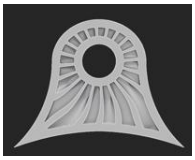
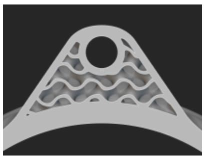
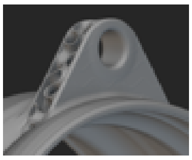
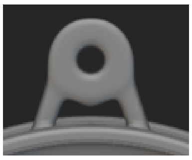
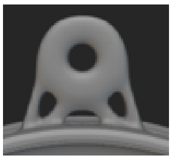
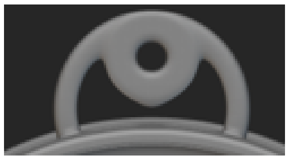
Figure 23: Cross-section after the second topology optimization

5.2.2.3 Idea generation

As defined earlier in the project, at least 50% of the middle lane must be kept to stabilize the HBU within the knuckle. This had to be taken into account when a big part of the middle lane had been removed. To get more area further out on the middle lane both rims, meaning a shape that extends the middle lane, and lattice were added to the grove to test different possibilities.

The topology optimization generated a design where the ears were floating in the air above the HBU. To fix the floating ears a bunch of different ear designs were tested. The test involved different solid ear designs, designs with legs, as well as ears using different lattice structures. The different ear designs tested can be seen in Table 5.

Table 5: Ear designs tried to connect the floating ears

Lattice				
Legs				
Solid				

5.2.3 Third topology iteration

This section presents the addition of moments into the boundary condition list, which generates the third iteration. The results of topology optimization are presented and explained. Finally, the resulting problems of the iteration are explained.

5.2.3.1 Boundary conditions

What initialized the third iteration was the realization that each load case included a moment, caused by the movement of the wheel axis, that was missing in the initial setup of the boundary conditions. Each moment was added to the original boundary conditions list as a point moment applied to the balls and was rotated around the center of the HBU in the direction of each moment as seen in Figure 24: Example of a moment added.

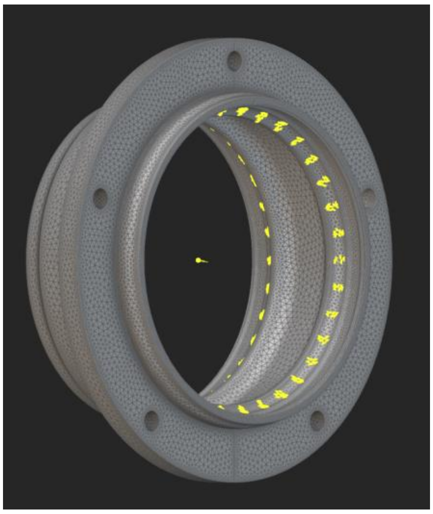


Figure 24: Example of a moment added

5.2.3.2 Results of topology optimization

The topology optimization that was run using the updated boundary condition list generated a model where four out of five ears were in some capacity connecting to the HBU as seen in Table 2. Two of the ears were generated with a broad back and a thinner front. Below those ears two supporting pieces were also kept. The other two ears that were connected only left two small pieces connecting the ear to the HBU.

Figure 25: Topology optimization of the third iteration

5.2.3.3 A deflecting HBU

A few concepts were tried using the new iteration using the simplest ears from the last iteration, as well as previous ideas for the middle lane. However, it was starting to become apparent that the HBU was displacing quite much. A discussion was held with design experts to investigate what this meant for the performance. The problem was in the deformation of the raceways. If the raceways deform too much, the performance of the bearing is at risk. This made it clear that the deformation should be taken into consideration.

5.2.4 Fourth topology iteration

The fourth topology optimization had the sole intent of solving the problem with the high displacement values reached in the previous topology optimization designs. The results of this topology optimization iteration led to the final designs that will be presented in the following chapter.

5.2.4.1 Boundary conditions

An additional constraint was added to the list of constraints. This was a displacement constraint with the value of *Classified* in all directions over the whole body. The intention of this was to force the program to keep the material to limit the deformation in all directions.

5.2.4.2 Resulting Topology Optimization

By adding this new displacement constraint to the list of constraints, a new design was generated that can be seen in Figure 26 below. This design saved much more material around and between the ears than previous iterations.

Figure 26: Generated Topology Optimization

5.2.4.3 Analysis of the generated design

As seen above, the topology optimization left material between the ears creating a raised flange that almost connects all the ears together. To be able to see if this flange was the solution to the displacement problem, FEA was done on the design seen in Figure 27 below with deformation scale 1000.

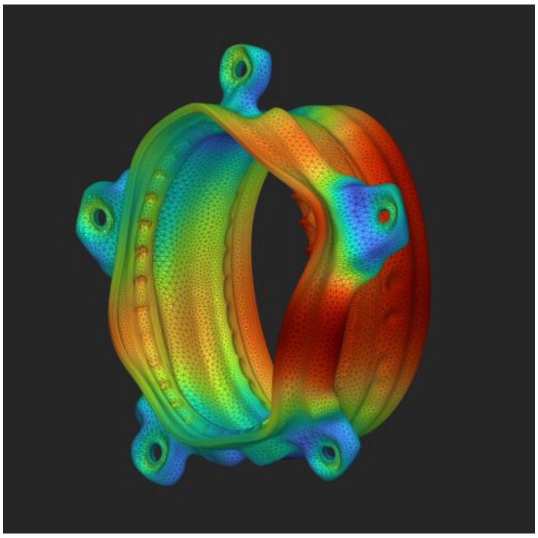


Figure 27: Deformation of the fourth topology optimization design. Scale:1000

As seen in Figure 27, it still displaced too much. A comparison was made with this design and the original design. A comparison can be seen below in Figure 28, both models with a deformation scale of 1000.

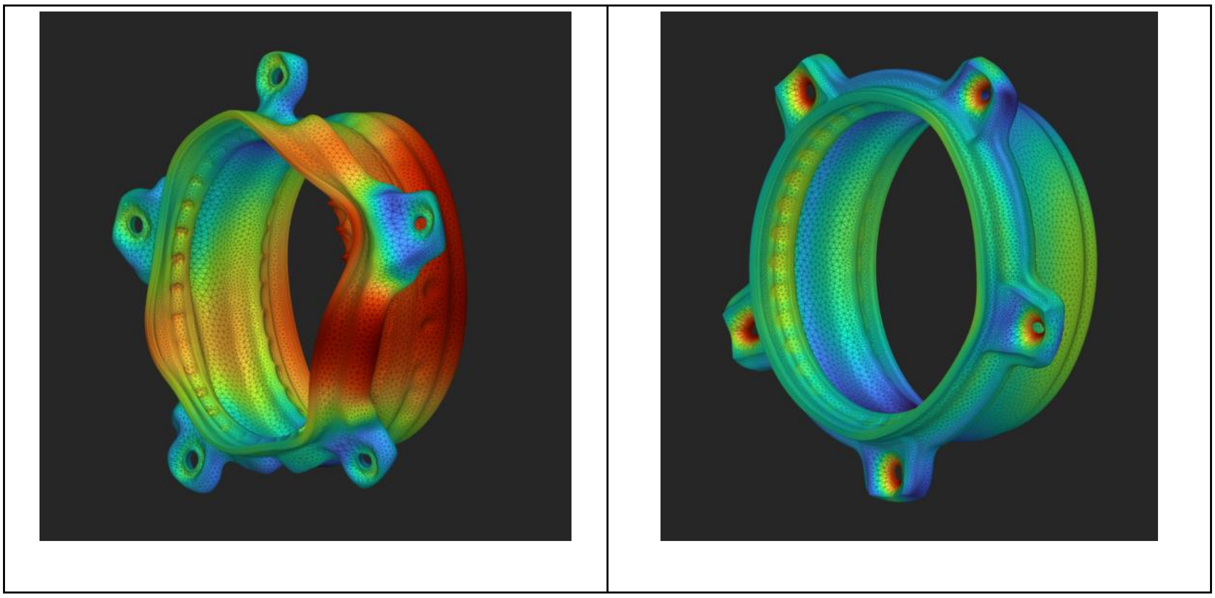


Figure 28: Deformation of fourth topology optimization (left) and original design (right). Scale: 1000.

The key difference between the designs was the flange between the ears. The original design has a solid flange between the ears that connects them. The fourth topology optimization design does not have a solid flange all the way around, subsequently not connecting the ears to each other. The concept of having a raised solid flange all the way around connecting all the ears became the base of the designs going forward.

This new knowledge was use on the following designs. Since displacement had become an issue the thought of changing the number of ears was revisited. Therefore, both designs using five and six ears were explored.

5.2.4.4 Finite Element Method

When doing the topology optimization, all load cases are added because the program considers one load at a time. This list of load cases was used in the previous FEA, and subsequently some forces canceled out each other without giving an accurate result. This was fixed by doing one FEA per load case.

5.2.4.5 Maximum displacement value

To be able to evaluate the designs going forward, an exact displacement value was needed. This was collected by adding all material data and loads from our case to the original design. Since the displacement in the raceways is the critical value, the maximum displacement value from the original design was gathered and used as a maximum value for the new designs. Since new requirements had appeared the requirement specification was updated with the new values. The maximum value from the original design was set as the desired maximum displacement value, and a 10 % increase of displacement was set as the maximum required value. An extract of the updated requirement specification can be seen in Table 6 and the entire can be seen in Appendix A.

Table 6: Extract of the updated requirement specification

3	**Mechanical properties**					
3.1	Maximum Yield Stress	MPa	*Classified*	Customer	FEA	R
3.2	Maximum displacement in raceways	µm	*Classified*	AB SKF	FEA	R
3.3	Maximum displacement in raceways	µm	*Classified*	AB SKF	FEA	D

6

Results

This chapter will present the first elimination process of the resulting concepts from topology optimization four. It will present the remaining concepts as well as the selection process of the final concept. Lastly, it will present what changes were made to the final concept based on desires from the customer.

6.1 Generated concepts

This chapter will present the first elimination process that took place. Chapter 6.1.2 will include the presentation of the remaining concepts. The results of the final selection of concepts will then be presented.

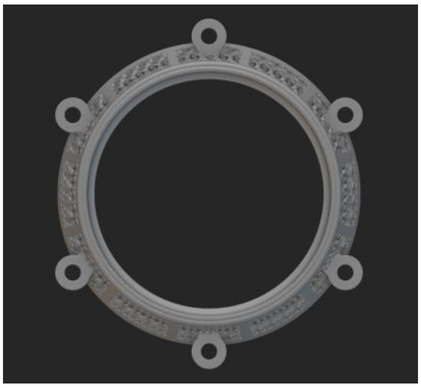
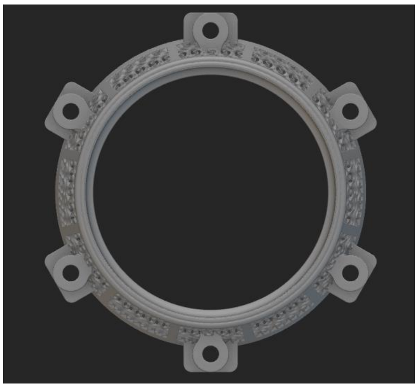
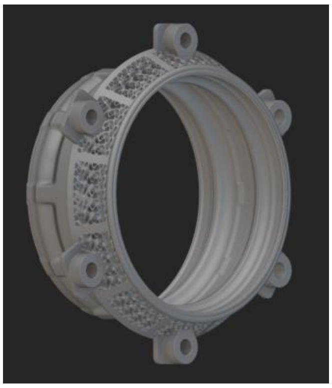
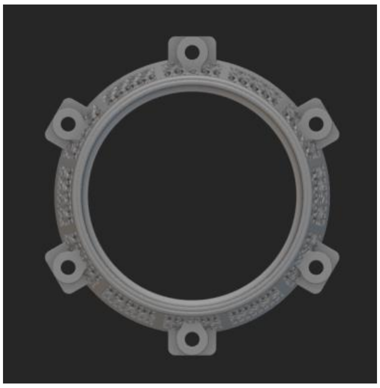
6.1.1 Elimination

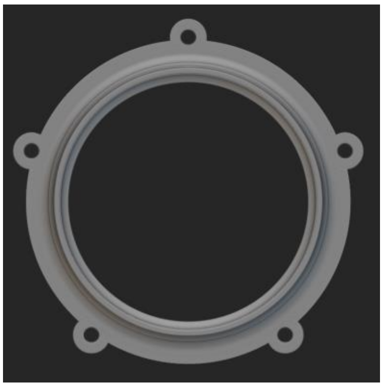
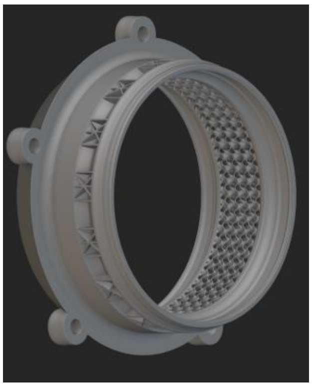
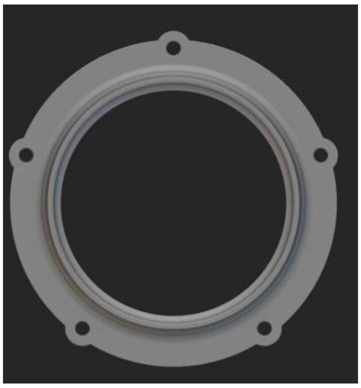
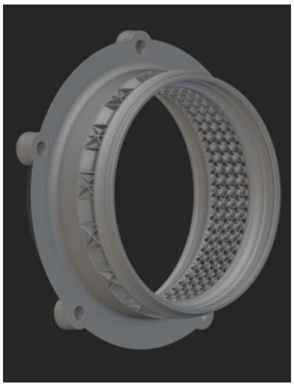
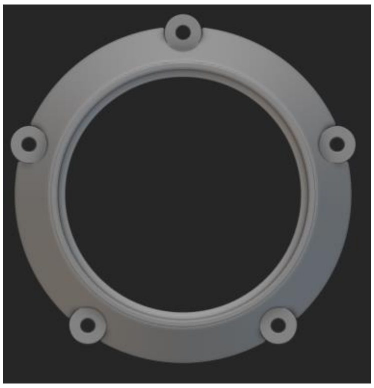
In topology optimization iteration four, 15 concepts were created. To reduce this number, any concept exceeding 7% above the desired displacement value was disqualified, as all concepts require further refinement, which could potentially increase deformation. This reduced the number of concepts from 15 to 8 concepts. The disqualified concepts are listed in Appendix B.

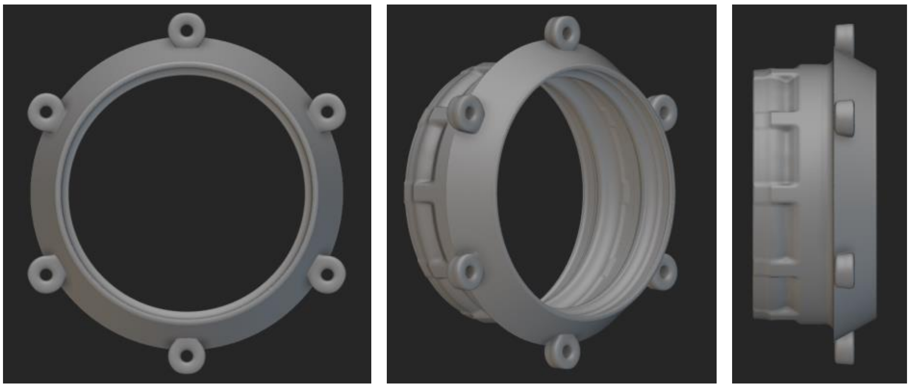
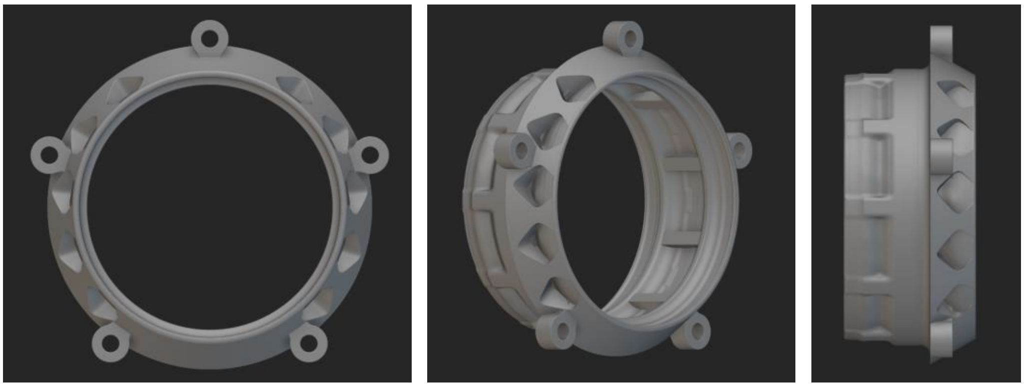
6.1.2 Concepts

The final eight concepts will be presented in Table 7 below. Each concept is numbered and has a short explanation of the main design elements. They are presented in three views: front, angle and side.

Table 7: The final 8 concepts

Concept 1: Simple ears, lattice flange and rims
  
Concept 2: Reinforced ears, lattice flange and rims
  
Concept 3: Reinforced ears, lattice flange and lattice
  

Concept 4: Simple ears, field optimized lattice middle region and lattice
  
Concept 5: Simple ears, field optimized lattice middle region, higher flange and lattice
  
Concept 6: Simple ears, normal lattice, higher flange and lattice
  

Concept 7: Simple ears, solid flange and rims

Concept 8: Simple ears, cut out flange, rims middle region and rims


6.2 Final concept selection

To select a final concept from the remaining eight, FEM simulations were conducted for each concept, analyzing both deformation and stress. The stress in all concepts was approximately one-third of the allowed stress according to the criteria specification. Therefore, stress values do not influence the selection of the final concept. The factors that impact the performance of each concept are deformation and weight saving percentage. The deformation and weight-saving values for each concept can be seen in Table 8, while the corresponding figures from each FEM simulation are available in Appendix C.

Table 8: Values of each concept

Concept	Deformation	Weight-saving
1	*Classified*	17 %
2	*Classified*	15,6 %
3	*Classified*	13,5 %
4	*Classified*	14,1 %
5	*Classified*	8,8 %
6	*Classified*	4,9 %
7	*Classified*	9,6 %
8	*Classified*	12 %

The weighing process described in Chapter 3.4 was carried out in two phases. Initially, concepts 1 – 3, which are very similar, were compared against each other, as well as concepts 4 – 6. The concepts that outperformed these separate evaluations advanced to the next stage, while the others were eliminated. The normalized values as well as the score for each concept can be seen in Table 9 for concepts 1 – 3, as well as Table 10 for concepts 4 – 5.

Table 9: Concepts 1 - 3 weighing values

Concept	Normalized value weight saving	Normalized value deformation	Score
1	1	0,47	0,84
2	0,6	1	0,72
3	0	0	0

Table 10: Concepts 4 - 6 weighing values

Concept	Normalized value weight saving	Normalized value deformation	Score
4	1	0	0,7
5	0,42	0,96	0,58
6	0	1	0,3

As seen in the tables above, concepts one and four, marked in blue, got the highest score in their weighing stages, consequently advancing to the last phase. The remaining concepts were 1, 4, 7 and 8. These concepts were weighed against each other as in the previous methodology. The resulting normalized values and scores are presented in Table 11. The concept that got the highest score was concept 1, marked in blue in Table 11, and therefore, was chosen as the final concept.

Table 11: Weighing values of the final four concepts

Concept	Normalized value weight saving	Normalized value deformation	Score
7	0	1	0,3
1	1	0	0,7
8	0,27	0,32	0,31
4	0,61	0,2	0,49

6.3 Changes based on customer requests

After presenting the final concept as well as its contenders to the customer, some changes were requested. The customer requested to combine two different concepts. They wanted the final concept but with the lattice in the middle lane instead of the rims, and they wanted it with only 5 ears and an ear design with a wider base. The change from rims to lattice derived from that the lattice made the raceways deform evenly whereas the rims caused the raceway to deform more between the rims, see Figure 29. The number of ears was requested to be reduced since it could improve the weight savings as well as keep the original number of ears.

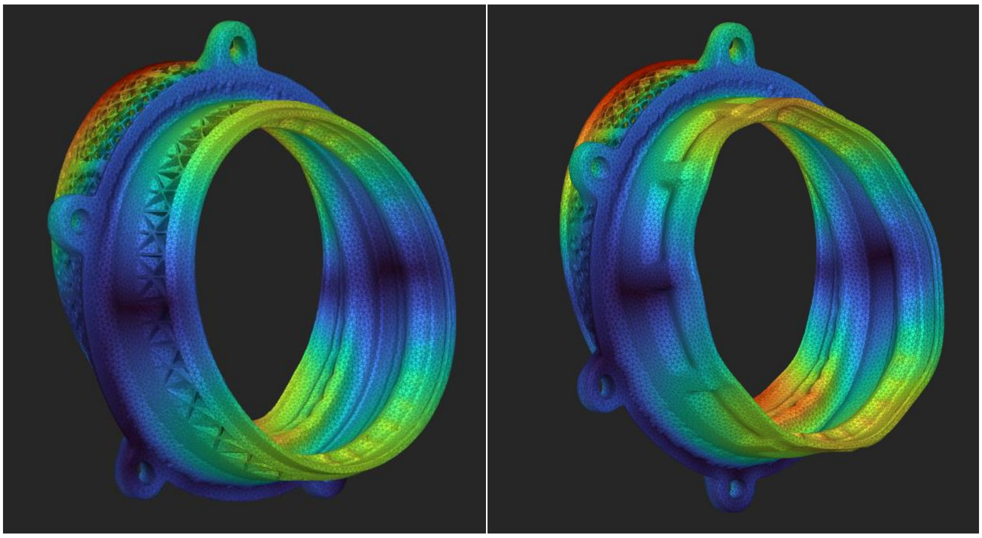


Figure 29: Deformation in the raceway using the lattice (left) and rims (right)

7

Design and assessment of final design concept

In this chapter the final design will be presented and explained. Chapter 7.2 will include several FEA simulations of the design. Finally, the concept will be evaluated against the specified criteria.

7.1 Design

The design made after the changes presented in Chapter 6.4 generated the final concept. The concept has an angled flange from the front edge of the HBU to the backside of the ears. The flange has a back wall, and the front part is a gyroid lattice with a thickness that varies depending on the density of the topology optimization where the lattice is placed, meaning that it is thicker where material was left in the topology and thinner where the topology optimization had removed the material completely. Evenly spread within the lattice are ten supporting rims. The area over the back raceway has been strengthened with a triangular honeycomb lattice to recreate the supportive area of the middle lane for the knuckle and help distribute the forces. There are five ears with a simple design with a rounded top and a slightly wider base than the diameter of the top. The steering ear for this design is placed upward. Finally, the topology optimization created a grove in the middle region to save material. The final concept, with its changes, can be seen in three different views in Figure 30.

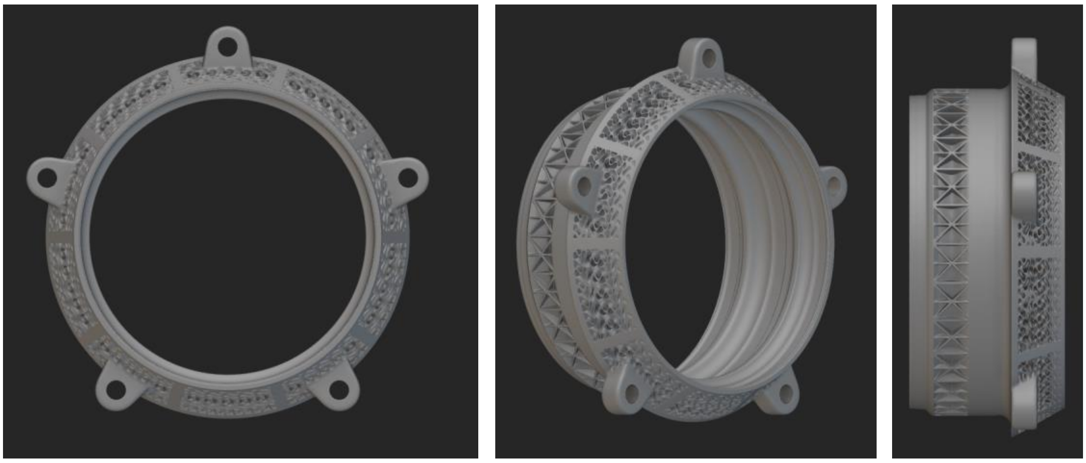
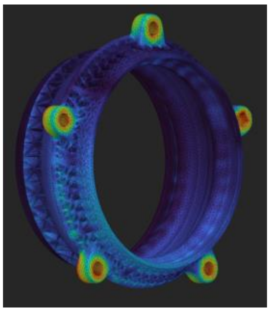
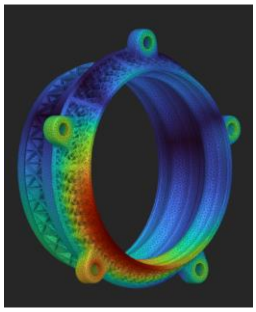
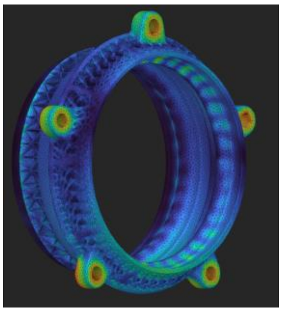
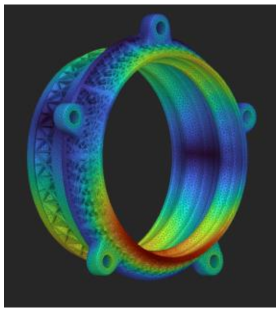


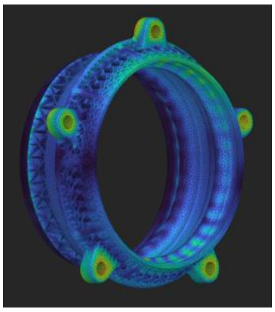
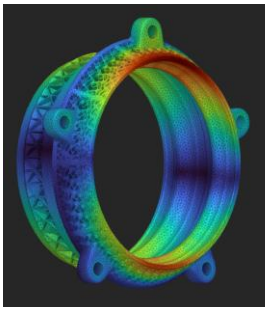
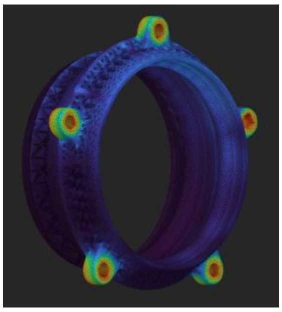
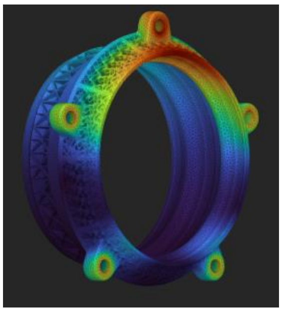
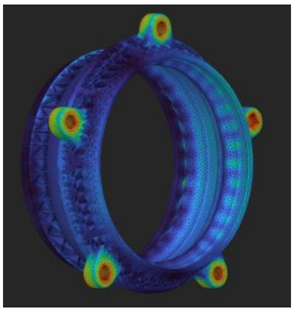
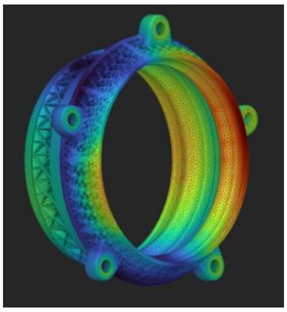
Figure 30: Three different views of the final concept

7.2 Finite Element Analysis

Table 12 shows the FEA on stress and deformation for each load case applied on the final design. The values from the FEA are not shown since that is classified information, however, these values are the basis for the evaluation in section 7.3

Table 12: FEA on stress and deformation for each load case

Load case	Stress	Deformation
Braking		
Cornering outer		

Cornering inner		
Bump		
Contact		

7.3 Fulfilment of requirement specification

The fulfillment is set to three levels as seen in Table 13. Green indicates that the target is completely met and verified, while yellow means that the target is met but not fully verified. Red, at last, represents that it has been verified that the target is not being met. The verification method that has been used for each criterion, are the one defined in the requirement specification.

Table 13: Description of fulfillment levels

Fulfillment level	Description
Green	Verified and fulfilled
Yellow	Not fully verified yet fulfilled
Red	Verified but not fulfilled

The final concept fulfills all required criteria that were defined in the requirement specification that was presented in section 4.3 with some additions in section 5.2.4.5. Two of the desired criteria were, however, not met. Criteria 1.2, weight reduction, stated a desired weight reduction of more than 30%, however, the final concept reached a weight reduction of 17,5%. Another desired criterion that was not met was criteria 3.3, maximum displacement in raceways, the final concept had a displacement higher than the desired value. However, it meets the required value in criteria 3.2. At last criterion 1.5, middle lane, was evaluated as being fulfilled but not verified. This criterion was evaluated to be fulfilled since a little more than 50% of the original middle lane was removed in the second topology optimization, yet more material was added with the lattice. The criterion has, however, not been verified since the area added with the lattice has a complex area that is hard to calculate. Since the criterion has a desired target, the exact number is not required to reach good enough. Table 14 shows the fulfillment of the requirement specification.

Table 14: The fulfillment of requirement specification

Nr	Criterion	Measurement	Target/ Value	Justification	Evaluation/ Verification	R/D	Fulfillment level
1	**Dimensions**						
1.1	Weight reduction	Percentage	> 10%	Customer	CAD	R	Green
1.2	Weight reduction	Percentage	> 30%	Customer	CAD	D	Red
1.3	Diameter to attachment hole	mm	*Classified*	Customer	CAD	R	Green
1.4	Outer diameter of the middle lane	mm	*Classified*	Customer	CAD	R	Green
1.5	Middle lane area	Percentage	50%	Customer	CAD	D	Yellow
2	**Loads**						
2.1	Axial load, y	N	*Classified*	Customer	FEA	R	Green
2.2	Radial load, x	N	*Classified*	Customer	FEA	R	Green
2.3	Radial load, z	N	*Classified*	Customer	FEA	R	Green
3	**Mechanical properties**						
3.1	Maximum Yield Stress	MPa	*Classified*	Customer	FEA	R	Green
3.2	Maximum displacement in raceways	µm	*Classified*	AB SKF	FEA	R	Green
3.3	Maximum displacement in raceways	µm	*Classified*	AB SKF	FEA	D	Red
4	**Manufacturing**						
4.1	Printable	Yes/No	Yes	AB SKF	AM Expert	R	Green

8

Discussion

In this chapter, the content of this report will be discussed. In section 8.1 the different methods will be evaluated and discussed. Section 8.2 focuses on discussing the results of the project. The environmental consideration of the project is discussed in section 8.3 and finally, the possibility to further development is presented in section 8.4.

8.1 Discussion of methods

This section will discuss the methods applied in the project which were presented in Chapter 3. Both methods used will be discussed concentrating on their effect on the results, as well as the possible use of other methods.

8.1.1 Project development plan

The Gantt schedule worked well to keep focus on what needed to be done and when. It helped keep track of milestones and gave a clear path forward in the project. Some changes had to be made during the project due to changes in the plan as well as unforeseen complications, however, it worked well to keep the project on track with not too much work.

8.1.2 Customer needs and requirements

The process of gathering information from different groups worked somewhat well. The problems that arose during the process were that some groups gave mixed information. This could have been fixed by doing more thorough research, where some clearer questions and goals with the interviews were planned beforehand. The process to sort and quantify all the information gathered from the given groups gave a good basis for the process to sort the information into a requirement specification.

8.1.3 Design process

The internal and external search created the initial plan for the iterative design process, although many ideas were eliminated fast due to the realizations that came during the design process. The idea generation, therefore, both worked and did not work. It provided the basis for what areas could be changed and what methods could be used when designing. However, the method only worked for the initial planning for the iterative process and then failed when more knowledge was gathered throughout designing process.

The iterative design method contributed to understanding how different components affected each other in the whole design, mainly how deformation and stress spread throughout the entire body based on how parts of the body were supported. This analytical possibility led to a rapid understanding of what combination of components worked, as a result of being able to disregard concepts knowing they will not work without the need to test them. It also allowed for the conclusion that a raised flange connecting all the ears was needed to prevent high deformation in the body.

The iterative design method worked mainly as a time saver in this project. As previously mentioned, the understanding of how components interacted with each other led to being able to generate a lot of working concepts because time was saved on not needing to test concepts that would have failed.

The drawback of the iterative design method is that a lot of concepts were not tested because it was assumed that they did not fulfill all the criteria. Soley relying on assumptions based on results from similar designs might not be sufficient to disregard a concept. It could lead to eliminating a concept that could have shown unexpected strength when tested.

8.1.4 Concept selection

The weighing method used to select the final concept worked well considering the two main factors. However, more requirements could have been taken into account to create a more dynamic selection. The decision to focus on only two requirements came from the fact that those criteria were the ones that led throughout the design process. The other criteria were not a problem during the design process, and therefore, they were only validified during the selection process.

Another thing that could have been improved is that not all concept ideas were compared to each other using the weighing method. As mentioned above, all concepts that had a deformation over *Classified* were eliminated even though they were within the maximum limits of the deformation. These concepts could have been tested in the same way as the others, since it is possible that the weighing method would have chosen one of those concepts. However, since small changes had to be made to the final concept the deformation would have risked going up, and therefore, it was most likely that the eliminated concepts would not have met the requirements after the final changes.

8.1.5 Concept evaluation

The validation methods defined in the requirements specification were straightforward for the concept evaluation. Since the FEA were evaluated for each concept throughout the entire design process, each value was easily compared to the requirement specification. As for the CAD validation, most measurements that had to be validified were not touched at all and, therefore, they were self-validated. The weight reduction was easily calculated for each concept using a tool in nTop and could, therefore, also be validified easily. As for the middle lane, the method was not clearly enough defined, and the criteria could have been formulated in the wrong way. This made it difficult to validate and get a clear result. Finally, the printability was confirmed in a meeting with the AM experts. By comparing each criterion from the requirement specification to the results of the final concept, a thorough evaluation could be made.

8.2 Discussion of results

This chapter will discuss the limitations of working with material that is under development and has not been used before. It will also discuss the limitations of not having direct information about how deformation should be managed.

8.2.1 Deformation

An underlying challenge in this project was the lack of a specified deformation limit for the component. Initially, information was given that the yield stress was the limiting factor of how far the design could be pushed according to the load cases.

The safety factor was 1:1, which led the project to focus on reducing weight as much as possible while ensuring that the stress remained below the yield limit. Since no upper deformation limit was provided, it was assumed that if the design remained below the yield strength, it would be considered acceptable.

However, when the first designs were presented, a design expert pointed out that the deformation was too large. Even then, a quantitative limit for the allowable deformation could not be set, which complicated further development. To guide the design process more effectively and avoid similar issues, a simulation was done on the original design with our material and load cases and its maximum deformation in the raceways was used as a reference limit for our own concepts. Although this approach involved certain assumptions, it allowed for a more focused and practical development path.

The fact that time was initially spent working on designs that were later deemed to deform too much resulting in some lost time. At the same time, many design ideas came from this phase as well as highlighting the importance of having clear and quantifiable requirements from the beginning of a project, especially when components must meet mechanical performance criteria.

Despite these obstacles, the workflow was able to adapt to the circumstances thanks to the iterative design process. The final design decisions are based on a data-driven deformation reference. This strengthens the credibility of the final design and allows for a concept with a high weight reduction while still maintaining performance.

8.2.2 Material properties

Another limitation in the project was the lack of complete material data. Although, we had the Young’s modulus and Poisson’s ratio, we only had access to the yield strength of the untreated material even though the final component will go through hardening treatment. As a result of this, we initially had to base our design decisions on a conservative assumption regarding the materials strength, which influenced our early designs. At that stage, our goals were to stay as close to the yield limit as possible without exceeding it, which could restrict further weight saving potential.

However, when the focus shifted from stress being the limiting factor to deformation being the limiting factor, the simulation shows that the concepts only reached about one third of the yield limit. This meant that the designs were significantly below the actual strength of what the material would have after the hardening process. Consequently, the lack of actual yield strength did not significantly impact the outcome. Nevertheless, this also highlights the importance of having access to complete material data early in the design process, especially when a material undergoes treatment that alters the mechanical properties.

8.3 Environmental considerations

AM is a technique that usually uses less waste material than traditional methods due to the method of adding material instead of removing material. There are still some waste materials due to the need for support structures. However, the amount of support structures could, be optimized through the design on parts such as the ears where a large amount of the support structures is needed. It is also possible to re-use the excess powder from the printing which saves material.

The weight reduction could also come with an environmental benefit. A weight reduction on the car could result in less fuel consumption both during the use of the new product and during transportation. The weight reduction on the HBU could, therefore, lower the environmental impact from the use and transportation.

Since the HBU is made specifically for racing cars they are designed more towards performance and lightweight than to have a long lifecycle. The weight reduction could, therefore, cause a greater need of changing HBU often which increases the need for producing more parts. However, no lifecycle analysis has been made in this project, hence this is something that must be explored further.

8.4 Further development

There are many possibilities going forward in this project. First, it would be appropriate to perform an FEA with specific FEA software for bearings. As previously mentioned, the software nTop is not designed to simulate bearings. Although it is possible to simulate a decent bearing FEA with some bearing specific tools, the FEA is not completely suitable for bearing simulations. Therefore, a real bearing FEA would be suitable to ensure that the important values are correct.

Going forward with the chosen design some real-life testing must be done. The part must be printed to ensure that the design can be printed without it collapsing. When the design has been printed the post-processing needed for the part must be tested. This includes machining important surfaces and heat treatment. Finally, some strength and performance tests need to be done.

As previously mentioned there has been some back and forth with the importance of deformation. This uncertainty could be fixed by doing a thorough investigation on how the performance of a bearing is affected by deformation in the raceways. An investigation like this can lead to the possibility of further design possibilities which can generate greater weight savings.

Another possibility is to investigate two variables that have been set as limitations for this project: choice of material and AM-method. The investigating of alternative materials or AM techniques could reveal new design opportunities or performance improvements that were previously restricted.

9

Conclusion

This project focused on the possibility of using PBF-LB as a manufacturing method. The use of PBF-LB could open the design possibilities and, therefore, also reduce weight. The focus was to reduce as much weight as possible without losing performance while at the same time designing specifically for AM. This conclusion aims to answer the questions that were stated in section 1.4.

Question 1: Is it Possible to achieve a 30% weight reduction on the HBU without compromising performance?

In this project, the resulting weight reduction was 17,5%. This weight reduction came from the final concept that met the performance requirements regarding stress and displacement that were mentioned in the specification of the requirements. However, the displacement is higher for the final concept than it is for the original design. This could be argued to be a loss of performance. The big question here is the discussion of how much the HBU can deform without losing performance. Although this project only reached 17,5% and not 30%, a higher value could be reached if it was found that a higher displacement is allowed without losing performance.

Another reason why the 30% weight reduction could not be achieved could be due to the different conditions of the project that reached 30%. The original project had a different HBU to start with, as well as a different material. The project also had different load cases and boundary conditions, which could make it possible to remove more weight.

Question 2: How can the HBU design be optimized to be suitable for printing?

To ensure that the final design is optimized for PBF-LB, several design rules have been considered. Firstly, minimizing the amount of support structure is crucial to reduce material usage and waste. This is achieved by optimizing angles to avoid overhangs greater than 45 degrees. Additionally, since PBF-LB builds components layer by layer using powder, designs must avoid closing the holes to allow excess powder to be removed. Using lattice structures like a gyroid addresses both these concerns by eliminating the need for support structure and ensuring no closed off holes, thanks to its interconnected holes and lack of overhangs larger than 45 degrees.

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A

Appendix 1 – Updated requirements

A.1 Updated requirement specification

Table A.1.1: Updated requirements specification

Nr	Criterion	Measurement	Target/ Value	Justification	Evaluation/ Verification	R/D
1	**Dimensions**					
1.1	Weight reduction	Percentage	> 10%	Customer	CAD	R
1.2	Weight reduction	Percentage	> 30%	Customer	CAD	D
1.3	Diameter to attachment hole	mm	*Classified*	Customer	CAD	R
1.4	Outer diameter of the middle lane	mm	*Classified*	Customer	CAD	R
1.5	Middle lane area	Percentage	50%	Customer	CAD	D
2	**Loads**					
2.1	Axial load, y	N	*Classified*	Customer	FEA	R
2.2	Radial load, x	N	*Classified*	Customer	FEA	R
2.3	Radial load, z	N	*Classified*	Customer	FEA	R
3	**Mechanical properties**					
3.1	Maximum Yield Stress	MPa	*Classified*	Customer	FEA	R
3.2	Maximum displacement in raceways	µm	*Classified*	AB SKF	FEA	R
3.3	Maximum displacement in raceways	µm	*Classified*	AB SKF	FEA	D
4	**Manufacturing**					
4.1	Printable	Yes/No	Yes	AB SKF	AM Expert	R

B

Appendix 2 – Eliminated concepts

B.1 Simple ears, cut out flange and rims, weight saving: 19,1%

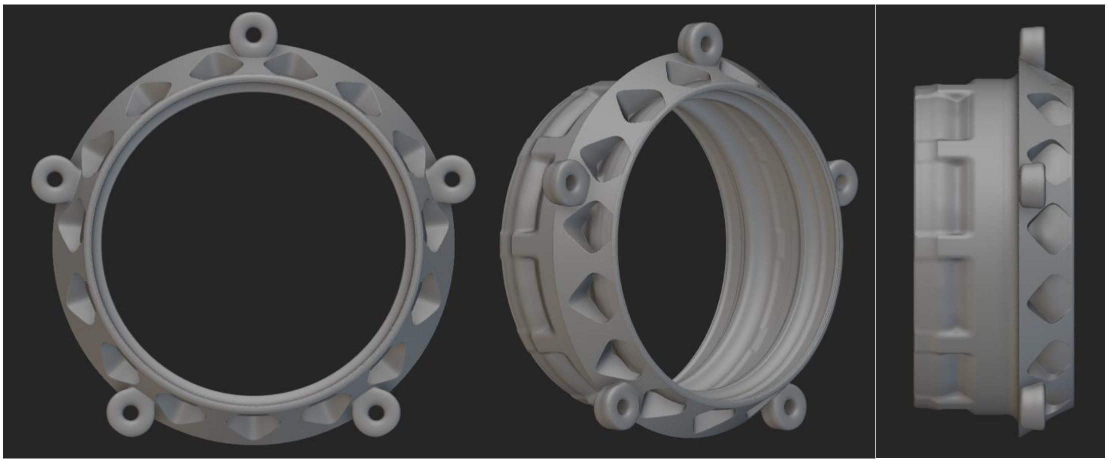

Figure B.1.1: Eliminated concept 1

B.2 Simple ears, cut out flange, rims in middle region and rims, weight saving: 14,8%

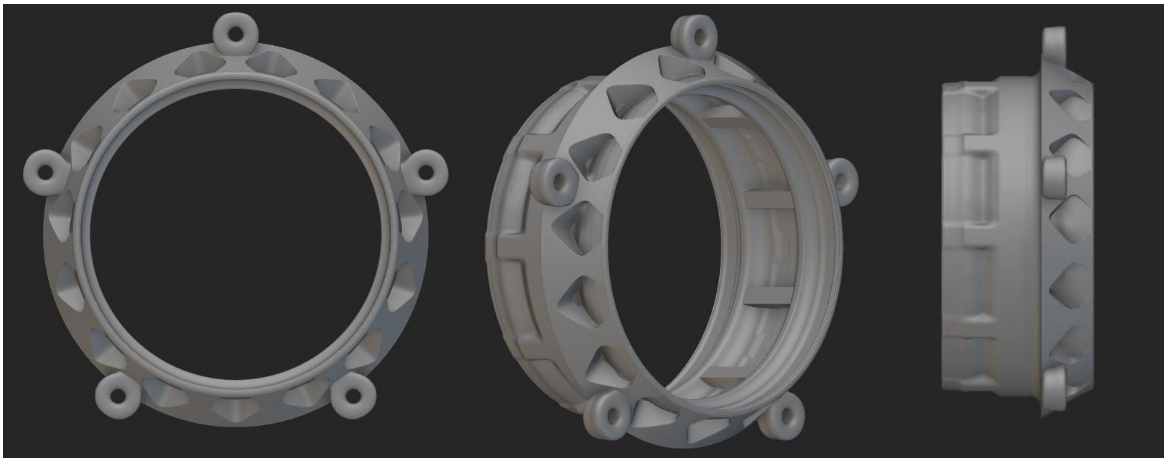

Figure B.2.1: Eliminated concept 2

B.3 Simple ears, cut out flange filled with lattice and rims, weight saving: 14,6%

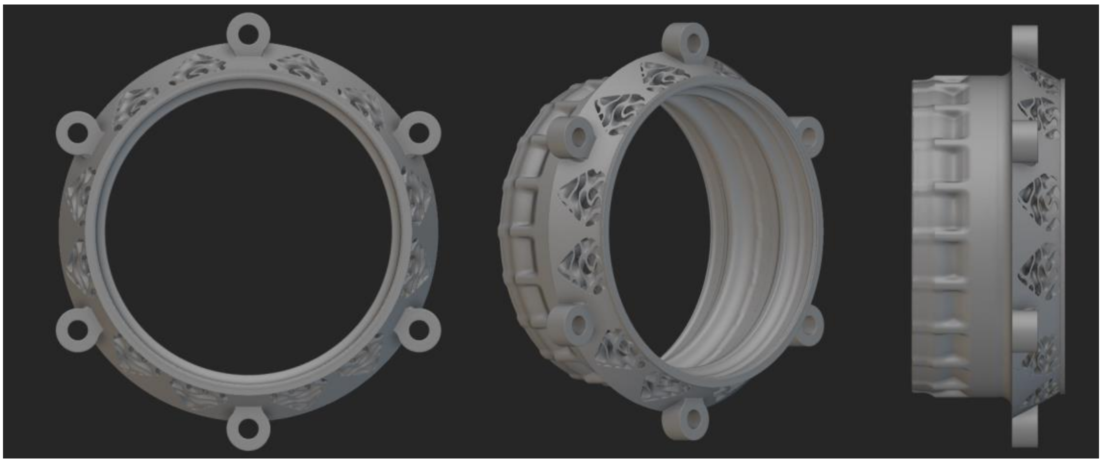

Figure B.3.1: Eliminated concept 3

B.4 Rounded ears, lattice in flange, weight saving: 15,7%

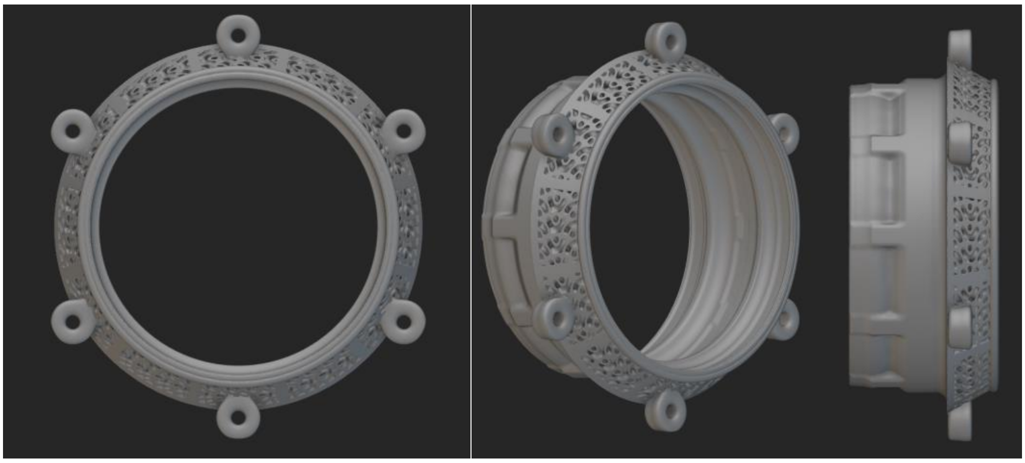

Figure B.4.1: Eliminated concept 4

B.5 Simple ears with extra support, lattice in flange, simple rims, weight saving: 16,7%

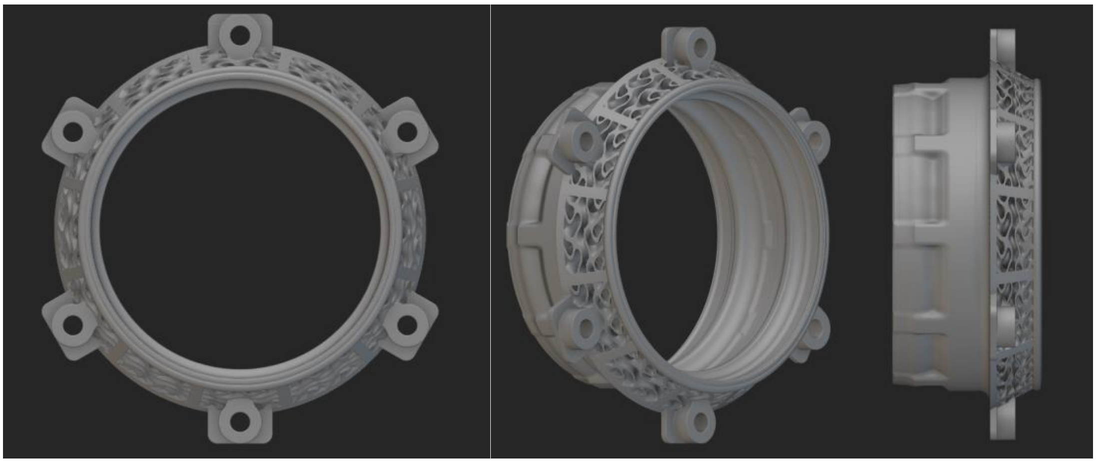

Figure B.5.1: Eliminated concept 5

B.6 Simple ears with extra support, lattice in flange, double amount of flanges, weight saving: 16,7%

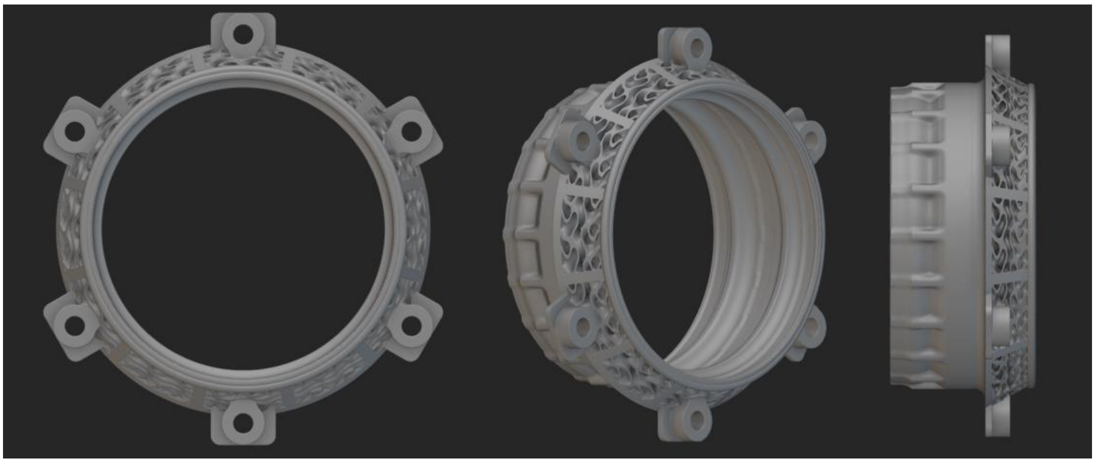

Figure B.6.1: Eliminated concept 6

C

Appendix 3 – FEA final concepts

C.1 Concept 1, FEA

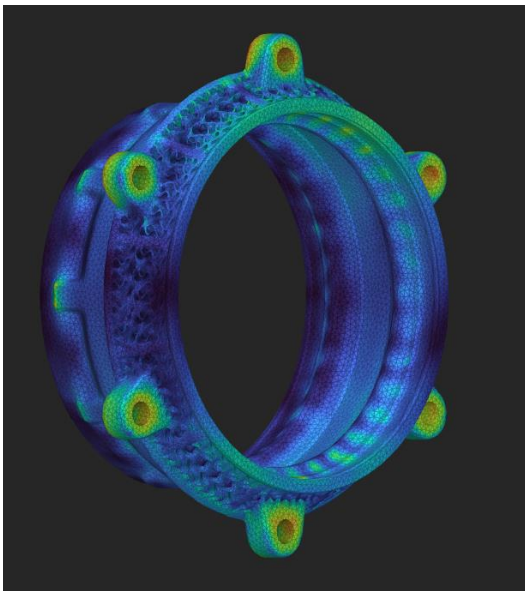

Figure C.1.1: Concept 1, FEA Von-Mieses Stress

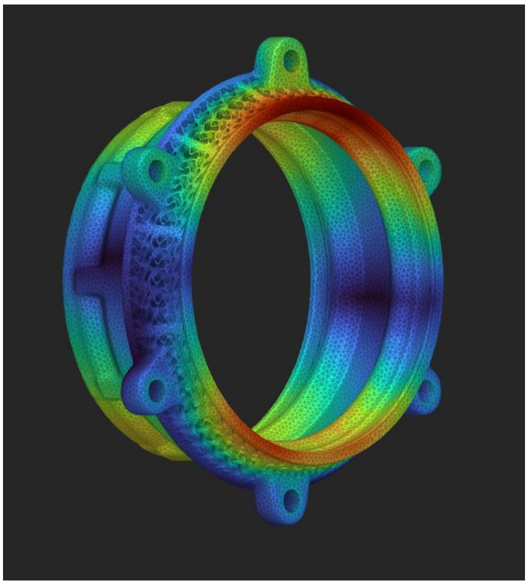

Figure C.1.2: Concept 1, FEA Deformation

C.2 Concept 2, FEA deformation in raceways

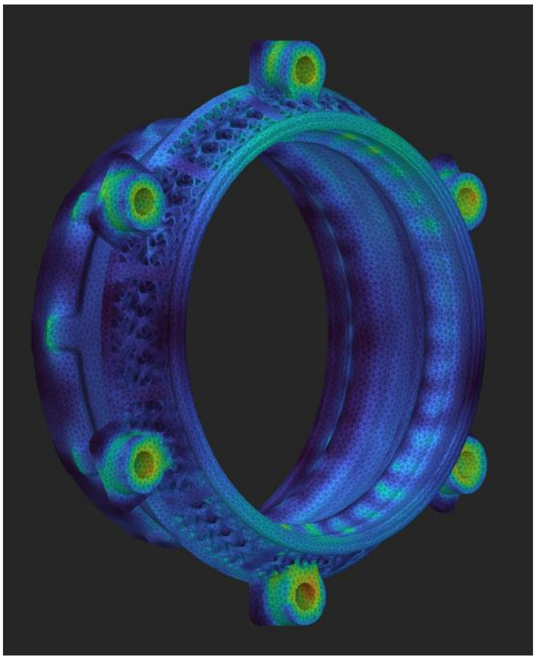

Figure C.2.1: Concept 2, FEA Von-Mieses Stress

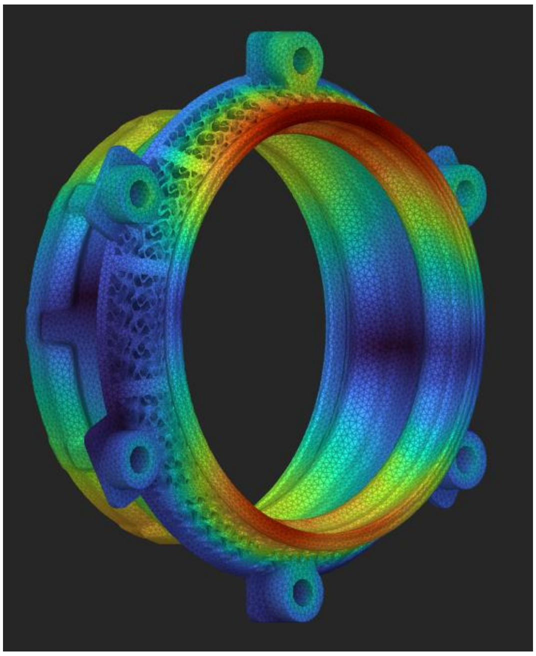

Figure C.2.2: Concept 2, FEA Deformation

C.3 Concept 3, FEA deformation in raceways

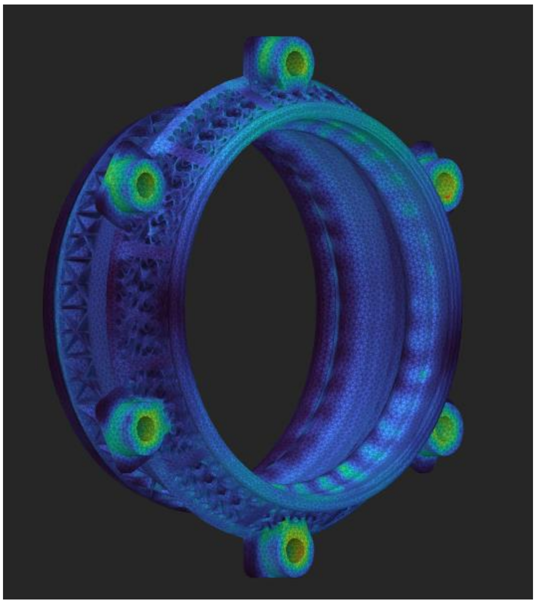

Figure C.3.1: Concept 3, FEA Von-Mieses Stress

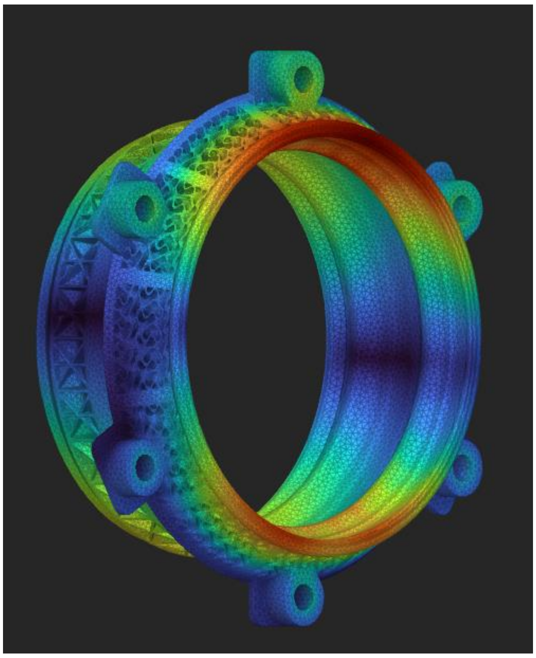

Figure C.3.2: Concept 3, FEA Deformation

C.4 Concept 4, FEA deformation in raceways

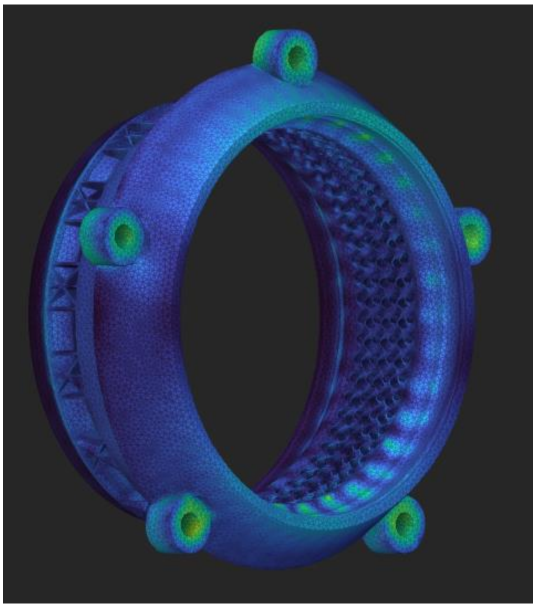

Figure C.4.1: Concept 4, FEA Von-Mises Stress

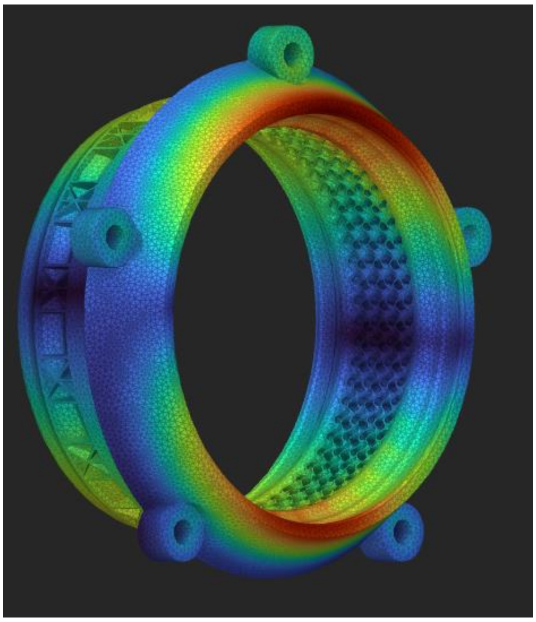

Figure C.4.2: Concept 4, FEA deformation

C.5 Concept 5, FEA deformation in raceways

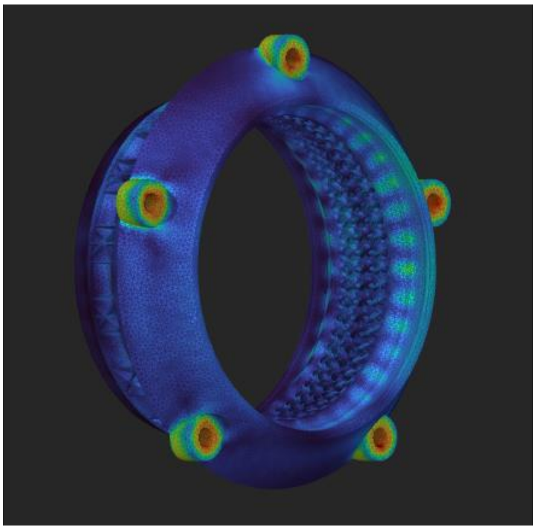

Figure C.5.1: Concept 5, FEA Von-Mises Stress

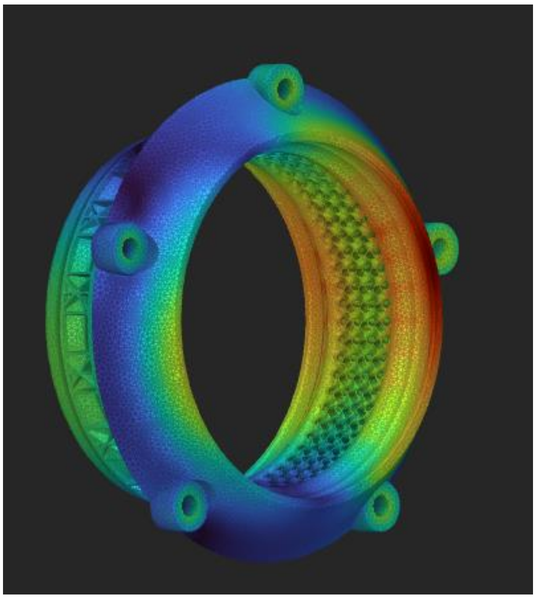

Figure C.5.2: Concept 5, FEA deformation

C.6 Concept 6, FEA deformation in raceways

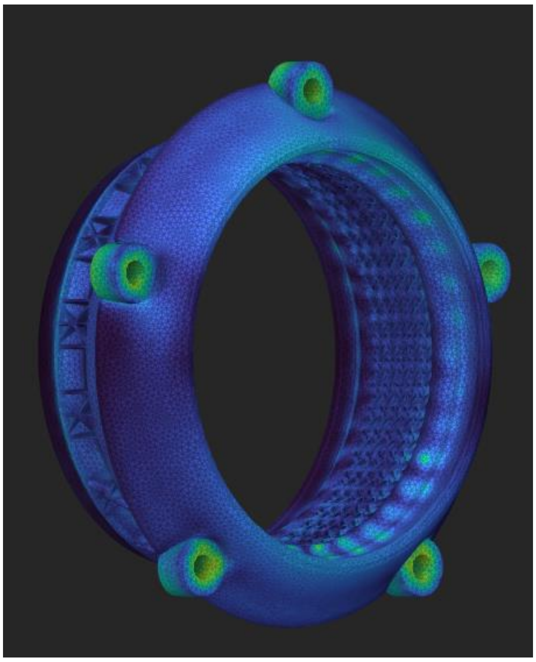

Figure C.6.1: Concept 6, FEA Von-Mieses Stress

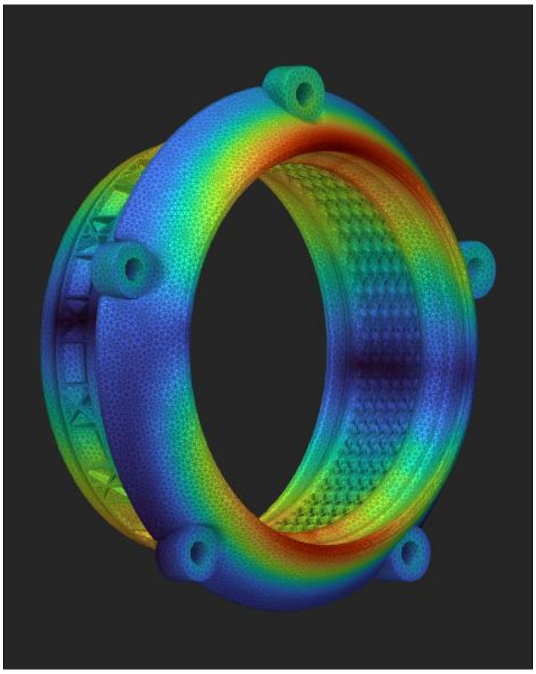

Figure C.6.2: Concept 6, FEA Deformation

C.7 Concept 7, FEA deformation in raceways

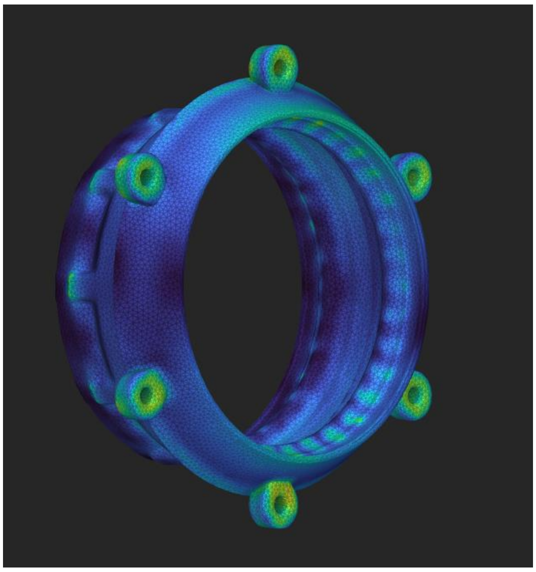

Figure C.7.1: Concept 7, FEA Von Mieses stress

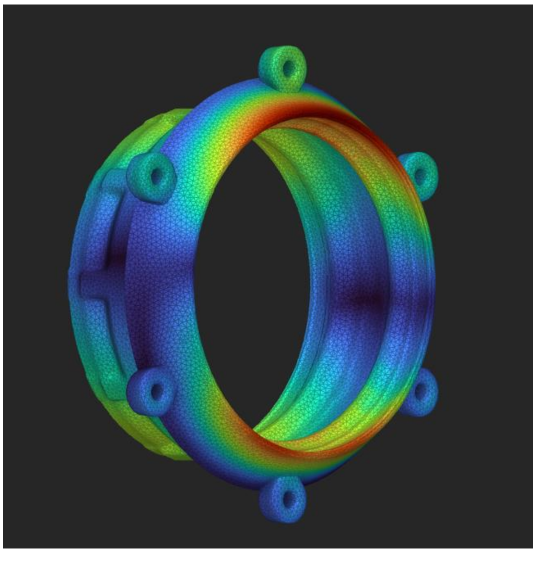

Figure C.7.2: Concept 7, FEA Displacement

C.8 Concept 8, FEA deformation in raceways

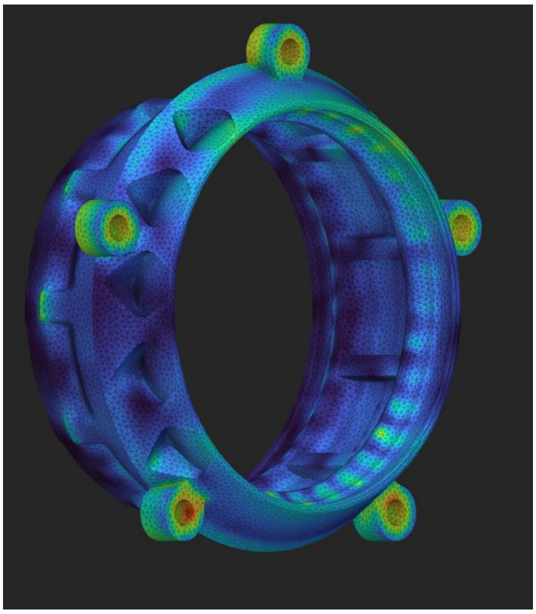

Figure C.8.1: Concept 8, FEA Von-Mises Stress

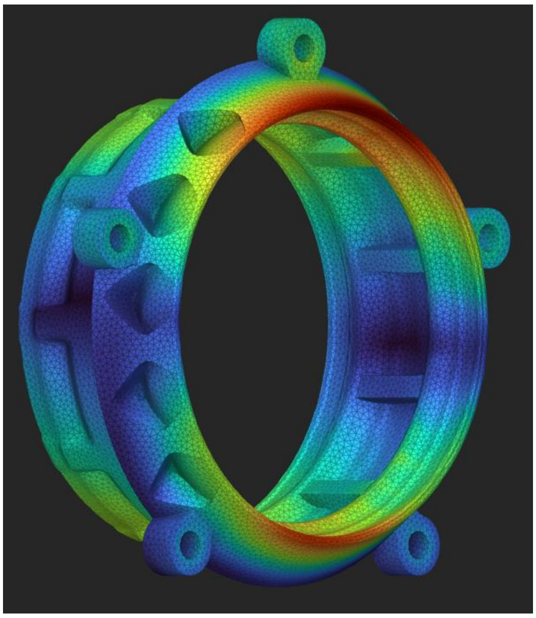

Figure C.8.2: Concept 8, FEA deformation

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