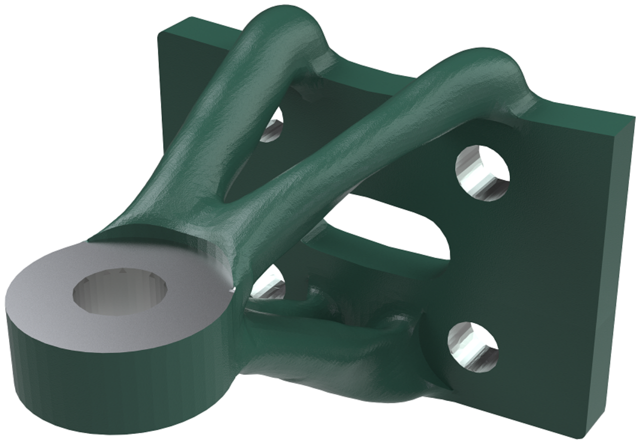

Applying Generative Design for Development of Optimal Parts

A case study on design and cost improvement through optimisation

Master’s thesis in Production Engineering

Lukas Andersson

DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2022
www.chalmers.se

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Supervisor: Martin Olofsson, Volvo Penta
Supervisor: Tommy Olsen, Volvo Penta
Supervisor: Kanishk Bhadani, Department of Industrial and Materials Science
Examiner: Gauti Asbjörnsson, Department of Industrial and Materials Science

Master's Thesis 2022
Department of Industrial and Materials Science
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

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Chalmers University of Technology

Abstract

In recent years generative design and topology optimisation have been added to CAD. Tools like generative design will generate an optimal design given a model that captures the part intent. Depending on the model criteria, optimal designs may be lighter, stronger and cheaper than parts developed through conventional means. Such benefits are of great interest and companies may want to introduce such tools into their development process.

In this project, a diverse selection of Volvo Penta parts is investigated using the generative design tool newly introduced to their CAD system. By reverse engineering the parts and understanding the system and requirements, a model describing the structure and volume of the part was created. Using this model several alternate parts were generated and evaluated using a cost model describing the cost of manufacturing and cost during operation. The parts generated through generative design were shown to be superior compared to the original with the performance indicator used. Drawbacks were also shown mostly relating to implementation and difficulties in defining the models.

Keywords: topology optimisation, generative design, product development, design, manufacturing, volvo

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To all those who have not been mentioned who in different ways have supported the thesis, thank you!

Lukas Andersson, Göteborg, 2022

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

AM	Additive Manufacturing
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CNN	Convolutional Neural Network
CoG	Center of Gravity
ISE	Isotropic Solid or Empty
KOLA	KOnstruktionsdata LAstvagnar
KPI	Key Performance Indicator
LB-PBF	Laser Beam Powder Bed Fusion
LSF	Level-Set Function
LSM	Level-Set Method
OMP	Optimal Microstructures with Penalisation
PDM	Product Documentation Management
SIMP	Solid Isotropic Material with Penalisation

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1
Introduction

This project is a master's thesis carried out in collaboration with Volvo Penta in Lundby, Göteborg. At Volvo Penta, there is an interest in applying a new tool called generative design included in their Computer-Aided Design (CAD) software. To this end, a project is carried out to evaluate why and how the tool could be applied in a company such as Volvo Penta. The background, purpose, limitations and research questions are described in this chapter.

1.1 Background

Volvo Penta is a company that sells engines for various applications such as marine propulsion, land drive and generator for electric power. The different applications make the development of structural parts a challenge. There is variation in the volumes of the parts developed, making the selection of manufacturing method a challenge but essential to reduce the overall cost per component. All this knowledge and more has to be considered when a CAD designer proposes a design which then needs to be verified by Computer-Aided Engineering (CAE) engineers and prepared for manufacturing.

The knowledge CAD designers generally are guided by is the experience gained through years of experience and general guidelines. The experience gained is by passing or failing verification. Even if a few recommendations can be provided during verification, it does not help the designer tell if it is a good design and if it can be improved. Newly introduced into the CAD software PTC Creo Parametric (creo) is a tool called generative design. Exploring generative design and its potential for the development of parts may provide some benefits where experience and knowledge are lacking.

Junk et al. [1] describe how different optimisation techniques are used in various industries, with product development being one such industry. The paper describes how generative design in product development provides a faster process and saves physical resources. Vlah et al. [2] are stating how CAD-based topology optimisation has been developed since the early 2000s. Still, the relevance of this topic could be seen in recent projects done at local companies to utilise similar tools [3] [4]. The update in Volvo Pentas CAD software is scheduled for February 2022 and gives the opportunity for this project to do a study at Volvo Penta as well.

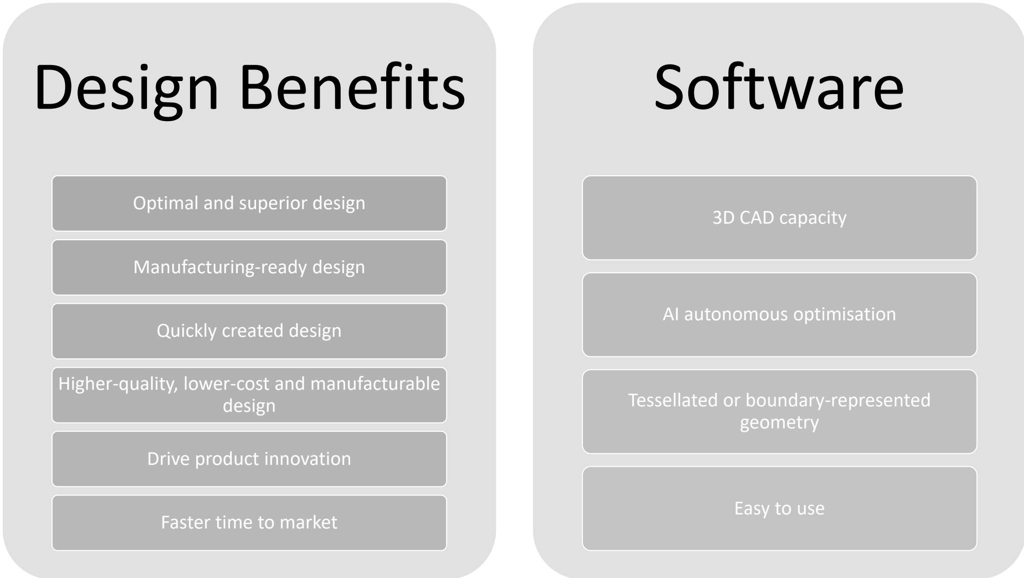


Figure 1.1: Properties of the generative design tool described by PTC [5]

Some benefits are described and marketed by the developers of the tool, PTC, which can be categorised as illustrated in Figure 1.1. Some advantages stated are higher quality, lower cost and driving product innovation. If these benefits not just marketing and can be shown, then would these tools could be of interest to companies such as Volvo Penta to implement.

1.2 Purpose

The project is studying how parts could be designed using generative design. The purpose is to determine what benefits could be achieved in terms of a reduced time to create the design, better design, reduced mass and lower cost of manufacture. The purpose is also to find how this tool can be used in the development of new products at Volvo Penta. In essence, the project aims to determine whether and how generative design could be implemented in the development of products at Volvo Penta.

1.2.1 Research Questions

With the project aim defined the following research questions can be formulated:

- What benefits and challenges can be found when implementing generative design in the development of parts?
- How would generative design be implemented for the development of new parts?

1.3 Scope and Limitations

To explore generative design and its possibilities, several parts will be investigated in the project. These parts should be different and selected from among parts developed at Volvo Penta in recent years. Since generative design optimises using mechanical properties, the parts should mainly have a mechanical function. The project will deliver an evaluation and comparison of parts developed using generative design. General aspects of how a process would be implemented will also be delivered. This scope is limited by:

- Generative design has a few targeted manufacturing methods to guide the generation of the part. These will be used in the evaluation of the parts.
- The design is to be generated to the system as is. No changes can be made to other parts.
- Other properties such as thermal and fluid calculations can not be done in generative design. No evaluation of thermal loads or efficiency of fluid ducts and channels will be done.
- Only the primary shaping method will be investigated, later steps of machining and post-processing may be discussed but not primarily in the project scope.
- Aspects of how a generative design process will be implemented will mainly be derived from findings when developing the parts through generative design. No company-wide surveys will be done.
- The project will be limited to 30 HP/ECT divided throughout the spring study periods. This is the time constraint set on the project.

2
Literature Study

The literature study investigates the subject of generative design and provides a background with knowledge of the concepts and vocabulary used throughout the project.

2.1 Defining Generative Design

In Vlah et al. [2] article comparing and evaluating topology optimisation and generative design, the differences and similarities are discussed. The main difference mentioned is that topology optimisation is mainly applied by structural designers and engineers, and is not widely used throughout product design. The term generative design is being introduced with the purpose being to inspire designs. Vlah et al. use a method called generative design study, which evaluates a range of options for manufacturing and materials. When this study is complete, multiple parts have been generated describing the range of materials and manufacturing options selected. In the generative approach, the tool would propose the design idea, compared to the traditional where the engineer would propose the design idea. This is a trend recently being addressed showing different CAD software introducing generative design tools aimed at proposing and inspiring design ideas. The main difference is by who (CAD engineers or CAE engineers) the software is targeted towards. Most of the principles and technology behind topology optimisation and generative design are the same and can be used interchangeably.

2.2 Theory on Design Optimisation

Optimisation as a wider subject exists in a range of applications such as designs optimisation as seen in [3] [4] and optimisation targeted towards production as seen in [6]. For linear programming, a common canonical form described by Papalambros [7] and Murota [8], seen in Equations 2.1, can be used to formulate an optimisation problem. In the canonical form described by the papers, $F(\boldsymbol{x})$ is the objective function used to define the objective of the optimisation. The objective can either be maximised or minimised with objective functions describing properties such as stress and compliance when doing design optimisation or time and cost when doing production-oriented problems. The model is usually subject to a number of constraints describing where $\boldsymbol{x}$ provides viable solutions to the objective function.

For linear programming, linear equality and inequality constraints are used and are shown in Equations 2.1 as $H(\boldsymbol{x}) = 0$ and $G(\boldsymbol{x}) \leq 0$.

$$\begin{aligned} \text{Minimise:} \quad & F(\boldsymbol{x}) \\ \text{Subject to:} \quad & H(\boldsymbol{x}) = 0 \\ & G(\boldsymbol{x}) \leq 0 \end{aligned} \tag{2.1}$$

Rozvany [9] describes how papers on the topic of topology optimisation have been published for more than a century. Rozvany further elaborates that research has been done and developments made on the subject throughout the years. With developments made since two main branches of approaching design optimisation are described in the chapter. One branch is the Finite element-based topology optimisation and the other is based on level-set mathematics.

2.2.1 Finite Element Based Topology Optimisation

Developed since the 1980s is a topology method called Solid Isotropic Material with Penalisation (SIMP) which Rozvany [10] describes as the most popular numerical finite element optimisation method. The paper describes how the SIMP method is an Isotropic Solid or Empty (ISE) type topology optimisation. This means according to Rozvany [10], that given a finite set of elements in a fixed shape, the elements may either be empty (zero density) or filled with an isotropic material (full density). However practically in the optimisation, the element densities are constrained to a continuous range and not set to a binary value. Although a continuous range is allowed, the paper describes how the intermediate densities can be penalised using different functions to suppress densities achieving the binary output. This method of penalisation is according to Rozvany [9] a standard technique of computational discrete value optimisation.

Rozvany [10] describes the main benefits of the SIMP methodology as follows:

- Efficient processing due to single variable iterations for each element
- Robust and applicable to most design conditions
- Penalisation can be adjusted freely
- Simple mathematics
- No homogenisation required. (Material converges into a distinct solid shape without voids or porosity)

Zuo [11] describes another finite element-based optimisation technique called Optimal Microstructures with Penalisation (OMP). Zou further elaborates how this technique is aimed at also penalising the intermediate densities similar to the SIMP-method. Rozvany [10] describes how there are between 3 to 6 parameters per finite element is used and both authors [10] [11] describe how the method fails to achieve homogeneous microstructure. This is not necessarily a bad thing as Rozvany [10] describes it as being the sole advantage. The OMP methodology can in addition to solid and empty, generate a porous microstructure. A porous microstructure is

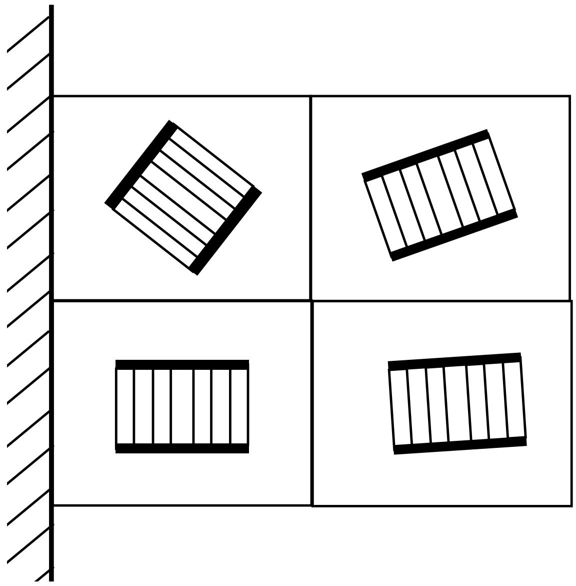


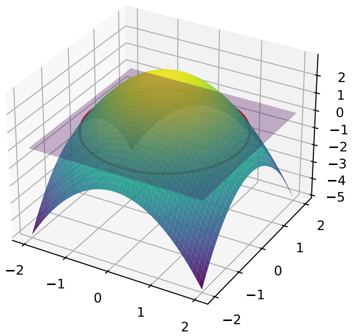
Figure 2.1: Pourus structure described by Rozvany [10]

illustrated for four 2D elements in Figure 2.1. Each element in the figure would require three free variables. Two variables describe the densities and one describes the angle. The disadvantages of the OMP methodology are many and have been described by Rozvany [10] where the main one is more computation required for each element and if porous microstructure is undesired, there will be a need for homogenisation.

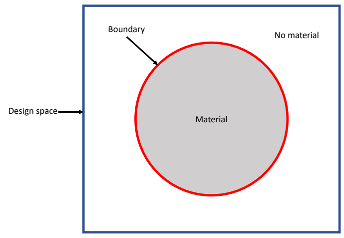
2.2.2 Level-Set Method

Van Dijk et al. [12] describe a different approach called Level-Set Method (LSM) that has been developed since the early 2000s. In the LSM approach, the material boundaries are defined using a Level-Set Function (LSF). For the LSF defined in the design domain, the paper describes how the material boundaries are defined at a constant value. This is usually represented for a 2D-design domain as in Figure 2.2a, where two directions in the horizontal plane represent the design area and the third direction is the value of the function. As shown in Figure 2.2b, where the function is below the constant there is no material and where the function is greater than the constant there is material. Shown as well is where the function intersects the constant value a boundary is defined. In the approaches described in the paper, this boundary is used to optimise. In one of the approaches, the boundary is discretised and parametrised with a free offset variable for each boundary element. This offset variable is used in the optimisation algorithm to optimise an offset to the constant value at that boundary point.

An advantage van Dijk et al. [12] mentions is the clearly defined boundary between the material phase and non-material phase. This means that there will be no need for homogenisation. Duan [13] mentions another advantage of the Level-Set Method



(a) A Level-Set Function represented by the colored surface. Intersecting a constant value represented by the plane creates a red boundary circle.



(b) Level-Set Method material representation

Figure 2.2: Level-Set Method

which is smooth evolution and the ability to handle drastic topology change. There are also different advantages and disadvantages when defining the Level-Set Function which van Dijk et al. [12] describes. The paper mentions three different approaches to apprehending the Level-Set Function. One of the approaches is a finite-element-based approach which is the most common. It is described how it may be computationally advantageous with a finite element-based scheme.

2.3 Design Evaluation

Implemented by Castagne et al. [14] is a design optimisation strategy for the aerospace industry. The general optimisation model would determine the trade-off between minimising the mass and reducing manufacturing costs. Mass is explained by the paper to be a factor in the airplane's direct operating cost due to increasing fuel costs. In the case study presented in the paper, a value can be found describing the money that could be saved per kilogram of mass removed. The model only factors the direct operating costs, but other factors such as environmental sustainability factors described by Barbier et al. [15] may also be of interest to include. In that model, a sum is added to the cost describing the amount of money required to compensate for the effects of the harm created by the product. However, such a model requires more detailed knowledge, more assumptions and may fall outside of the project scope.

A model similar to the one developed by Castagne et al. [14] would be possible to create for Volvo Penta's purposes such as marine transport with some adjustments. A proposed model for marine transport is found in Equation 2.2 where the terms are quantified in this chapter. Shown in Appendix A.1 is a relationship describing how the drag of a marine vessel is proportional to the mass of that vessel. The use of Volvo Penta products is not always marine applications, but the dependency of fuel consumption on mass can be seen for land vehicles in tests done by Pagerit et al. [16]. A similar model should be applicable for those purposes as long as the $Cost_{marine,mass}$ factor is adjusted to reflect land applications instead.

$$Cost_{Total} = Cost_{marine,mass} * mass + Cost_{Manufacturing} \tag{2.2}$$

2.3.1 Quantifying the Cost of Mass

Knowing that the drag is proportional to an added mass seen in Appendix A.1, it will be reasonable to assume that it would scale with fuel costs. According to Corbett [17], fuel can be the first or second largest cost in operating a cargo ship. Comparing shipping per kilogram found in [18] [19], a shipment from China to USA by ocean is 2-4$ per kg and by air 4-8$ per kg. This is the customer price and does not describe essential data such as what other costs drive the price. For the intent of this work, this is simplified and assumed that the relation 1:2 (ocean:air) is proportional to the direct operating costs. For the case study by Castagne et al. [14], a per kg increase in direct operating cost was calculated to 396$ for an airplane. This value could be scaled using the relation found and current fuel prices which have developed from 2$ per gallon used in the study to 4.2$ per gallon [20] in the United States as of May 2022 as per Equation 2.3. This results in a per kilogram cost of 417$ for marine vessels.

$$Cost_{marine,mass} = \frac{Cost_{air,mass} * Fuel_{now}}{Fuel_0 * Relation_{1:2}} \tag{2.3}$$

2.3.2 Applying Manufacturing Techniques and Quantifying the Cost

There are multiple estimation models described by Hueber et al. [21], one such being parametric techniques. Parametric techniques are described to be building so-called cost estimation relationships, providing mathematical relationships between parameters known as cost drivers. One such model is developed for Granta [22] and is modeling unit costs for the manufacturing process. The model used in Granta defines the model by the process inputs and outputs as shown in Figure 2.3 and provides data to some of the parameters. In the model developed for Granta, the cost is estimated using Equation 2.4. The data provided in Granta is presented in ranges and available for most parameters for cost relating to materials and manufacturing. This results in the cost estimate presented in a range. These ranges can be quite inaccurate making the estimation a bit inaccurate. However using the same assumptions unless an increase or decrease is known, this method would to an extent provide fair comparisons between parts and manufacturing options. Hueber et al. [21] describe other methods that are feature-based. Such methods are described to be more accurate but require better understanding and data. Due to the complexity

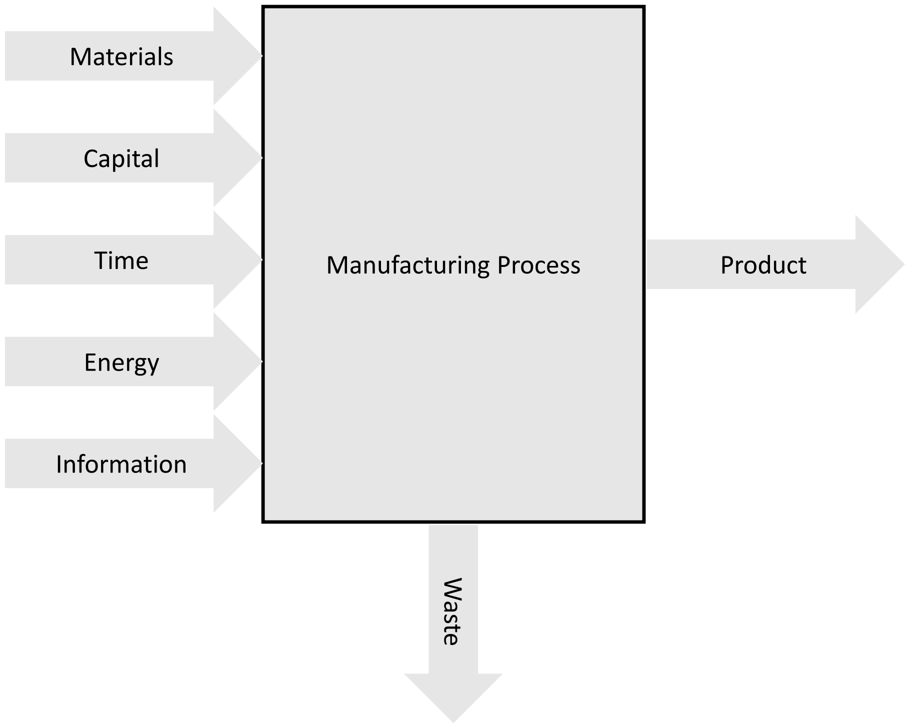


Figure 2.3: The manufacturing process as viewed by Granta in [22]

in topology often produced with topology optimisation as mentioned by Lin et al. [23], it would usually require countless simple machining features.

$$
\begin{aligned}
Cost_{manufacturing} =& \frac{Cost_{material} * mass}{utilisation_{Material}} + \frac{Cost_{tool}}{Size_{batch}}(1 + \frac{Size_{batch}}{Tool\ Life}) + \frac{1}{Production\ Rate} \\
& * (Cost_{Overhead} + \frac{Cost_{capital}(1 + Discount\ Rate^{Time_{write-off}})}{Time_{write-off} * load\ factor})
\end{aligned}
\tag{2.4}
$$

Limited for the project are the manufacturing methods the generative design tool has targeted unless proven beneficial. These are casting, additive manufacturing and linear extrusion.

Swift et al. [24] describe several casting methods such as sand casting and investment casting. In the guidelines for design, it is mentioned how these methods require draft angles illustrated in Figure 2.4. Different guidelines exist for different methods where no method guidelines have a negative draft angle. The draft angles are used to extract the part from the mold without binding. For these casting methods, different techniques can be used to allow draft angles in different directions such as parting the mold. Adding complex parting lines to the mold makes it more expensive. In creo, casting is defined using the direction of removal, draft angle and

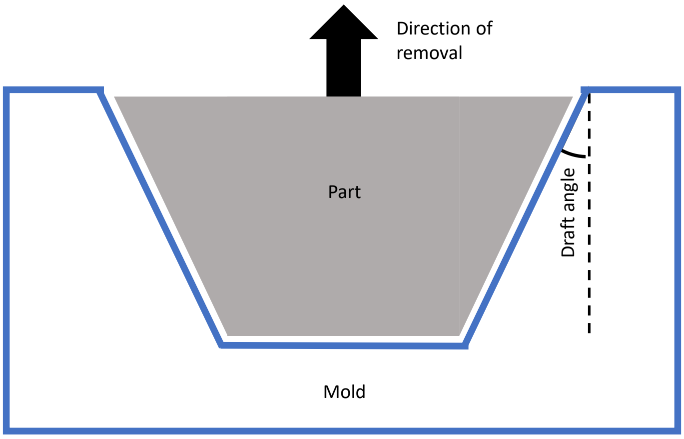


Figure 2.4: Draft angle is used to allow extraction from the mold when casting

information about the parting line.

In Additive Manufacturing (AM) described by Toyserkani et al. [25], the term build direction is used. Build direction is the axis in which additional material is added to complete the shape of the part. This additional material must be supported by the part or by support material for many AM methods. For many of these, some degree of overhang is allowed. In creo the AM process is defined by selecting a build direction and what overhang is allowed.

Linear extrusion is by PTC [26] described as a 2-axis or 3-axis milling process. The axes are in a milling process often set up as translation axes. This allows geometry to be cut on the surface accessible to the cutting tool. Geometries may not be created below this surface along the axis of the milling head. The linear extrusion allows the workpiece to be flipped 180 degrees in a bi-directional option allowing milling on one more surface. In creo, the linear extrusion constraint is defined by selecting a plane.

3
Methodology

Described in the methodology chapter are reverse engineering used throughout the project and the application of generative design.

3.1 Reverse Engineering

The process of reverse engineering is described by Junior et al. [27] as a process of getting information and analysis of an existing system, in order to optimise the system being developed. This is done with the intention to inspire and not copy the existing technical solution. The reverse engineering process for a technical system proposed by the same authors has three categories; 1. Planning and purchasing, 2. Technical system analysis and 3. Redesign orientation. Reverse engineering was the process used for information gathering and verifying redesigned system solutions.

Junior et al. [27] describe the first step (1.) to plan activities and ensure the systems to be studied are available to be studied. This includes defining the reverse engineering objectives and scope. It will also require some way to acquire the system studied. The project scope is to study the mechanical properties of different systems and improve them through generative design. The study of the system can be done by analysing the paper trail of the product development process to recreate the loading conditions and requirements. The paper trail is left in internal Product Documentation Management (PDM) systems such as KOnstruktionsdata LAstvagnar (KOLA) and Phoenix. There also exists a digital model of the system which can be used to verify model conformity to the correct loading conditions and requirements.

Junior et al. [27] describe the second step (2.) as the analysis of the system. In this step, the information used to redesign the system is gathered. Parts included in this step include testing and analysis of the technical system and analysis of publications. Available for the project is internal publications of engineering reports where the system is approved. In these reports, some loading conditions are provided to different extents. The loading conditions often needed to be transferred to the specific system whilst maintaining the results. Other technical specifications such as material and mass were defined through data published in KOLA and drawings.

Junior et al. [27] describe the third step (3.) to be for the redesign of the system. For this step defining goals and requirements for the redesign will be done and comparing the analyzed system to the redesigned solution. The goal defined within the project was to create a better design whilst the same system requirements are fulfilled. A better design would be one with a better structure making it lighter requiring less material or a design cheaper to manufacture. This was mainly determined by collecting different parameters from the systems called Key Performance Indicators (KPI) and evaluated through Equation 2.2.

3.2 Applying PTCs Generative Design

In Chapter 2.2 a few strategies to perform the optimisation of structures are described. The generative design tool included in creo developed by PTC has not explained what optimisation strategy is used. However, this can be deduced as a likely candidate by investigating what properties are visible. When decreasing the resolution a finite element mesh is clearly visible. The materials available are also isotropic standard materials such as metals and plastics which provide a homogeneous structure. This is in line with the SIMP methodology described in Chapter 2.2.1.

While the SIMP methodology only describes the strategy, it does not explain how the generative design tool would include AI as described by PTC and seen in Figure 1.1. This is likely in line with an article written by Jiang et al. [28] where it is described how a Convolutional Neural Network (CNN) can be used to accelerate the optimisation using SIMP methodology. Other machine learning approaches can be applied. But in essence, the paper is describing different approaches to optimisation where the algorithm would bias the solution to shapes that have been trained to be beneficial. The objective function of the optimiser creo is using minimises the strain energy in the system. As mentioned in Chapter 2.2 the optimisers can be configured to optimise other properties with the objective function however such functionality is not available in creo.

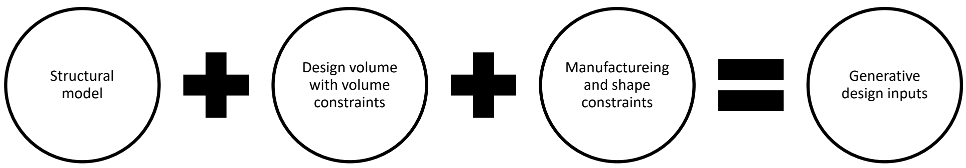


Figure 3.1: Generative design inputs

When applying the tool developed by PTC called generative design there are several inputs that need to be defined according to the documentation [26]. A workflow is described in the documentation and with familiarisation in the initial stages of the project inputs and parameters for different aspects were identified. These inputs can be categorised into three general input categories shown in Figure 3.1. With these inputs defined a generative study can be conducted specifying a mass as a target constraint.

3.2.1 Structural Model

In the input category of the structural model, one or more load cases have to be defined. Each requires boundaries and loads to be defined. The structural options available are shown in Figure 3.2. There usually exist multiple load cases giving the option to include acceleration in different directions to the generative study. Specific accelerations the engine is tested for are usually determined by engine applications such as marine, land drive or industrial and the part should sustain acceleration in all cartesian directions resulting in a total of eight standard load cases for each extreme. Other load cases may also be applied to cover part applications and model biases.

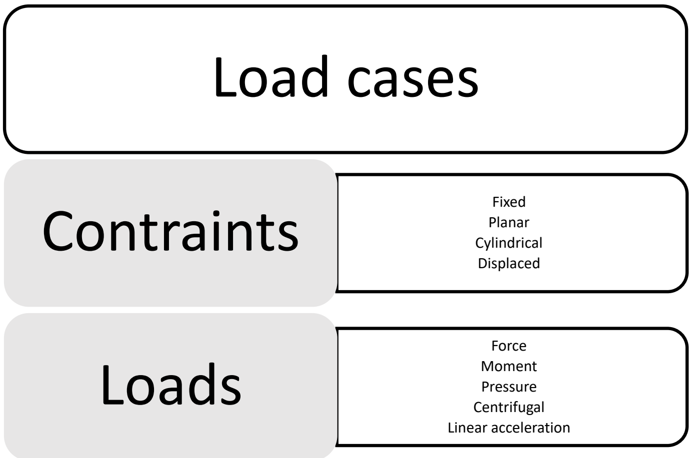


Figure 3.2: Options when defining a structure. Options are shown in white

Applying constraints and loads is done through analysis, calculation and other information gatherings as described in Chapter 3.1. The constraints Fixed, Planar and cylindrical are used to lock degrees of freedom. The planar and cylindrical constraints have their direction defined using the surface it constrains. The displacement constraint is a fixed constraint locking all degrees of freedom however it also includes an offset distance for all directions which would displace the surface regardless of the stiffness of the part. The force, moment and pressure loads are constant loads that do not change and have to be applied on a surface. In contrast, the centrifugal and linear acceleration load would scale dependent on how much mass is centrifuged or accelerated. These loads are not applied on a surface rather the force will be applied to the mass.

3.2.2 Volume Definition

Along with the upgrade of creo that included the generative design tool is a new approach to handling overlapping geometries. This is in creo called bodies and is what is used in generative design to define three types of volumes.

The first type of volume is the design space. The intent of the design space is to include the volume of interest to generate within. Selecting as large volume available would allow the optimiser to work without any prejudices about what a good solution would be.

The second type of volume is preserved geometry. This type of volume is used where the part geometry is known and must remain unchanged such as an interface with the assembly. These geometries are also used by the structural model to define what surfaces are loaded or boundaries. The preserved volume has to be located within the defined design space volume. The last volume type is the excluded geometry. This is used within the design space similar to the preserved geometry, but would instead exclude that design space.

3.2.3 Manufacturing and Shape Constraints

The optimiser can be further constrained using manufacturing and shape constraints. The constraints available are shown in Figure 3.3. The additive manufacturing constraint defines a build direction in which a maximum overhang angle can be defined. Similarly using the casting constraint a draft angle can be defined. Using the casting constraint a parting line will be generated or can be defined. The linear extrusion defines a direction in which a two or three-axis mill is oriented in. In the symmetry shape constraint, a plane can be selected in which the part generated will be symmetric. The material spreading restricts the spread of material biasing thicker sections and structures. The crease radius shape constraint is used for smother geometry reducing sharp changes in surfaces.

An initial part will be generated free from manufacturing and shape constraints unless it is a requirement. From this part, a survey on the potential of different manufacturing methods is done. From this survey, it will be determined what constraints and parameters could be applied to achieve a manufacturable solution. This is an iterative process and can create multiple possible solutions. These solutions are evaluated and compared to each other and the original part.

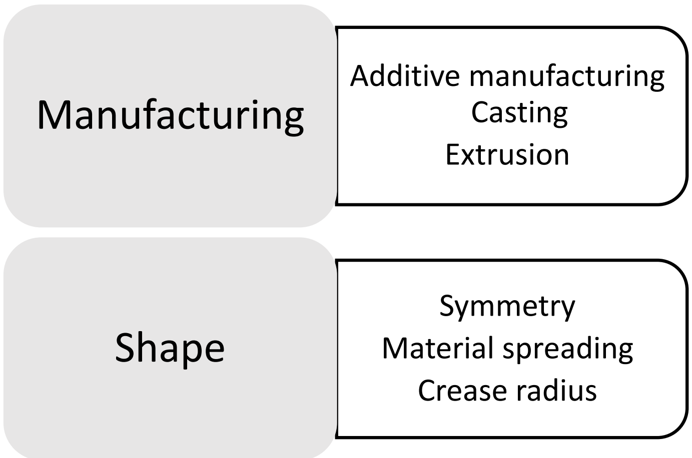


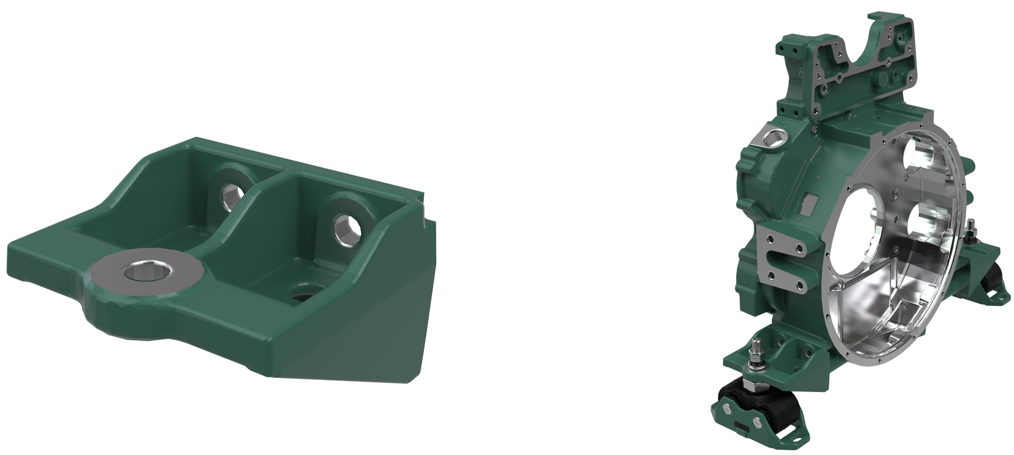
Figure 3.3: Manufacturing and shape constraints

4
Results

Four parts are investigated to see what possible solutions can be developed using generative design. These four parts are named engine bracket, alternator adapter ring, bracket for solenoid valve and filter bracket. The result for each part is presented in this chapter.

4.1 Engine Bracket

The engine bracket is one of four brackets that carry the engine of approximately 1800kg in marine conditions. Two brackets are located on the flywheel housing seen in Figure 4.1b transferring loads to a dampener. The part mass is 4.95kg and the production volume of this part is estimated to be 1000 units.

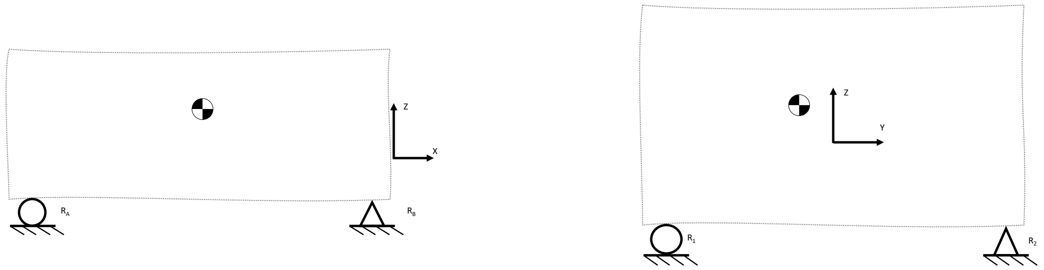


(a) The engine bracket **(b)** The engine bracket in a context

Figure 4.1: Overview of the engine bracket

4.1.1 Structural Model

The part is a structural component and is mainly loaded by the mass it carries in accelerations. The accelerations used in an internal report for marine conditions are -5g vertical acceleration, ±1g longitudinal and lateral acceleration. Additionally, there is also an engine moment of ±2800Nm applied from the crankshaft. The mass



(a) Position of Center of gravity in XZ-plane.

(b) Position of Center of gravity in YZ-plane.

Figure 4.2: Engine supported at four points

it carries is divided into three other brackets, where one of which is the same part symmetrically located on the other side. Shown in Figure 4.2 is the engine supported by engine brackets. In Figure 4.2a R_B represent both engine brackets under investigation. In Figure 4.2b the engine brackets are calculated separately.

Described in an internal Volvo report is the estimated location of the engine Center of Gravity (CoG). The four brackets' relation to the same reference is found by measuring in CAD. Position of CoG is estimated to $l_{x_{CoG}} = -630$mm, $l_{y_{CoG}} = -30$mm and $l_{z_{CoG}} = 272$mm, where the coordinate system location is shown in Figure 4.2. The distances using the same coordinate system as a reference are found to be located at $l_{x_B} = -47$mm $l_{x_A} = -1175$, $l_{y_1} = -275$mm, $l_{y_2} = 275$mm and $l_z = -140$mm

The engine support reaction forces F for all accelerations a and with the engine mass m is used to model the engine bracket. For the equations formulated using Figure 4.2a distances in y are neglected. Similarly, Equations formulated using Figure 4.2b is neglecting distances in x.

Equations formulated using Figure 4.2a:

$$
\begin{aligned}
\rightarrow X : ma_x &= F_{x_B} && (4.1)\\
\uparrow Z : ma_z &= F_{z_A} + F_{z_B} && (4.2)\\
\overset{\overset{\frown}{y}}{\oplus} : 0 &= (l_{x_{CoG}} - l_{x_A})F_{z_A} - (l_{x_B} - l_{x_{CoG}})F_{z_B} && (4.3)\\
&\quad - (l_{z_{CoG}} - l_z)F_{x_B}\\
&= (l_{x_{CoG}} - l_{x_A})(ma_z - F_{z_B}) - (l_{x_B} - l_{x_{CoG}})F_{z_B}\\
&\quad - (l_{z_{CoG}} - l_z)ma_x\\
F_{z_B} &= \frac{(l_{z_{CoG}} - l_z)ma_x - (l_{x_{CoG}} - l_{x_A})ma_z}{l_{x_B} + l_{x_A}} && (4.4)\\
\overset{\overset{\frown}{z}}{\mathrm{R_A}} : 0 &= ma_y(l_{x_A} - l_{x_{CoG}}) - F_{y_B}(l_{x_A} - l_{x_B}) && (4.5)\\
F_{y_B} &= \frac{ma_y(l_{x_A} - l_{x_{CoG}})}{l_{x_A} - l_{x_B}} && (4.6)
\end{aligned}
$$

Equations formulated using Figure 4.2b:

$$
\begin{aligned}
\rightarrow Y : F_{y_B} &= F_{y_2}\\
&= \frac{ma_y(l_{x_A} - l_{x_{CoG}})}{l_{x_A} - l_{x_B}} && (4.7)\\
\uparrow Z : F_{z_B} &= F_{z_1} + F_{z_2} && (4.8)\\
\overset{\overset{\frown}{x}}{\oplus} : \pm 2800 &= F_{z_1}(l_{y_{CoG}} - l_{y_1}) - F_{z_2}(l_{y_2} - l_{y_{CoG}}) - F_{y_2}(l_{z_{CoG}} - l_z)\\
&= F_{z_B}(l_{y_{CoG}} - l_{y_1}) + F_{z_2}(l_{y_1} - l_{y_2}) - \frac{ma_y l_{x_{CoG}}(l_{z_{CoG}} - l_z)}{l_{x_A} - l_{x_B}} && (4.9)\\
F_{z_2} &= \frac{\pm 2800 - F_{z_B}(l_{y_{CoG}} - l_{y_1}) + \frac{ma_y l_{x_{CoG}}(l_{z_{CoG}} - l_z)}{l_{x_A} - l_{x_B}}}{l_{y_1} - l_{y_2}} && (4.10)\\
\overset{\overset{\frown}{z}}{\mathrm{R_1}} : 0 &= F_{x_B}(l_{x_1} - l_{y_{CoG}}) - F_{x_2}(l_{x_2} - l_{x_1}) && (4.11)\\
F_{x_2} &= \frac{F_{x_B}(l_{x_1} - l_{y_{CoG}})}{l_{x_2} - l_{x_1}}. && (4.12)
\end{aligned}
$$

The reaction forces for $\mathrm{R_B}$ are calculated in Equations 4.1, 4.4 and 4.6. $\mathrm{R_B}$ is then used to find the reaction force on reaction point $\mathrm{R_2}$ in Equations 4.7, 4.10 and 4.12.

This creates an approximate model with similar tendencies to the one found in an internal report however the stresses are higher. Adjusting the reaction forces in the horizontal directions by a factor yields a good model shown in Figure 4.3. This model has the same magnitude of stresses and the location of stress concentrations are located in a similar way as in an internal CAE-report at Volvo.

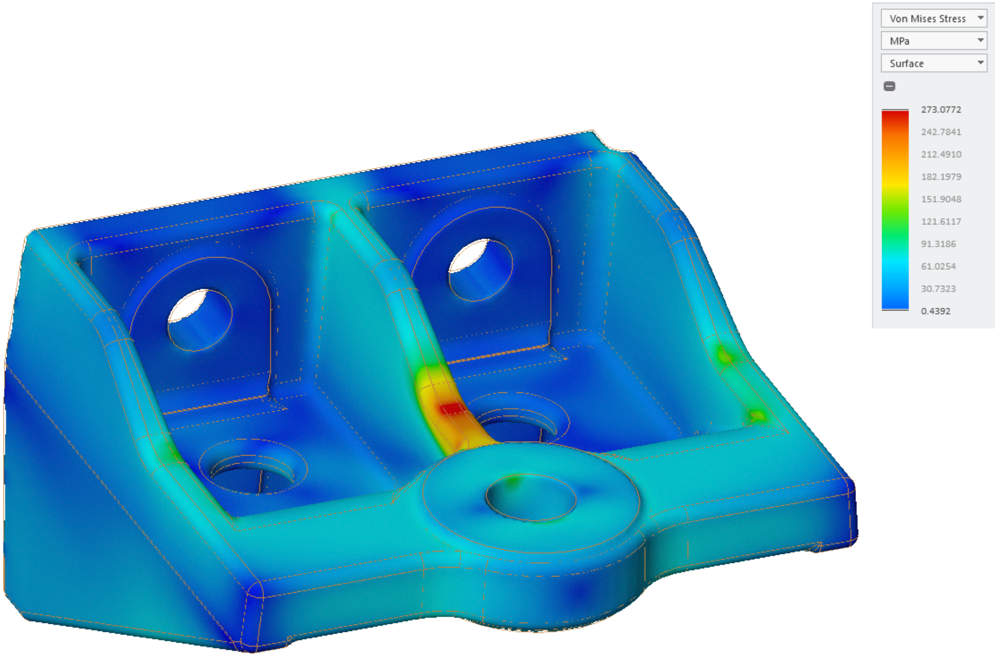
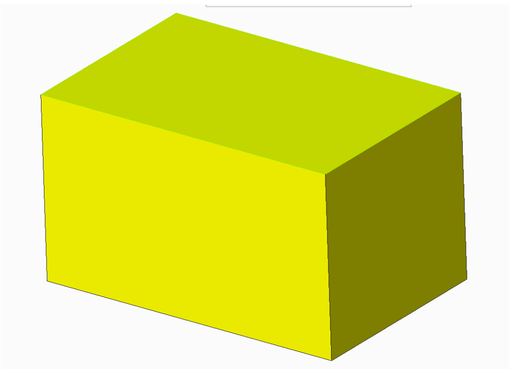


Figure 4.3: Structural model of the engine bracket

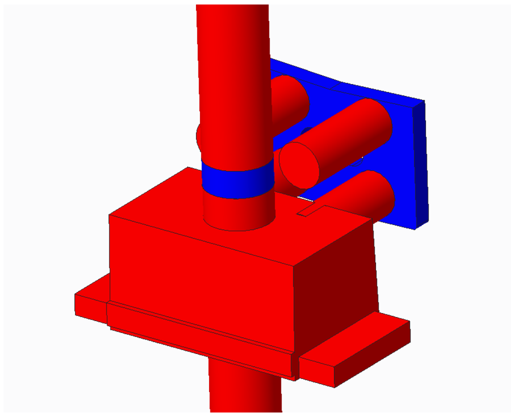
4.1.2 Volume Definition

The design space is limited by the flywheel housing to which the part is mounted to. Other than the flywheel housing, parts such as rubber cushions and bolts have to be considered but can be solved through exclusion volumes. The design space may be extended to a limit where it is determined that the part will not benefit from transferring the load through. The design space is shown in Figure 4.4a.

There are four bolts the engine bracket should both provide a through-hole with a clamping surface and the ability to mount and tension the bolt. An exclusion volume and a preserved volume are added to account for this. Similarly, there is a bolt that carries the load to the rubber cushion. A similar implementation of exclusion volume and preserved volume is used to handle this. The preserved and excluded volumes are shown in Figure 4.4b



(a) Design space of the adapter ring in transparent green



(b) Preserved geometries in blue and excluded geometries red

Figure 4.4: Design space, preserved volume and excluded volume for the engine bracket

4.1.3 Design Evaluation

The original part is manufactured in cast iron. Cast iron material is used for the casting proposals and for additive manufacturing pricing of steel powder found in [29] is used. Since the part has to be mounted on both sides of the flywheel housing, a symmetry constraint is used.

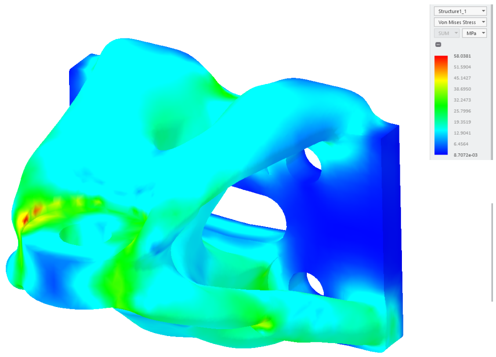
The parameters of proposals developed in this chapter are presented in Table 4.1.

Table 4.1: Parameters shown for Original Part (OP), Casting In Same Plane (CISP), Casting In Vertical Plane (CIVP) and Additive Manufacturing (AM). The resulting cost of manufacturing is calculated using Equation 2.4

Parameter	OP	CISP	CIVP	AM
$Cost_{material}$ [SEK/kg]	6.35	6.35	6.35	1200
$Cost_{tool}$ [SEK]	504000	554400	554400	0.4425
$Cost_{Overhead}$ [SEK/h]	1327.34	1327.34	1327.34	1327.34
$Cost_{capital}$ [SEK]	4575000	4575000	4575000	4555000
$Discount\ Rate$ [%]	5	5	5	5
$load\ factor$	0.5	0.5	0.5	0.5
$mass$ [kg]	4.95	2.97	2.72	2.52
$Production\ Rate$ [units/h]	101	101	101	0.54
$Size_{batch}$ [units]	1000	1000	1000	1000
$Tool\ Life$	510000	510000	510000	550000
$Time_{write-off}$ [years]	5	5	5	5
$utilisation_{Material}$	0.775	0.775	0.775	0.6
$Cost_{manufacturing}$ [SEK]	562.50	544.76	535.09	7491.60
$Cost_{Total}$ [SEK]	21203	12938	11890	18000
σ_{max} [MPa]	273	209	235	186

4.1.3.1 Freely Generated

(a) The proposed solution



(b) Stresses in the proposed solution

Figure 4.5: Proposed solution when freely generating the engine bracket

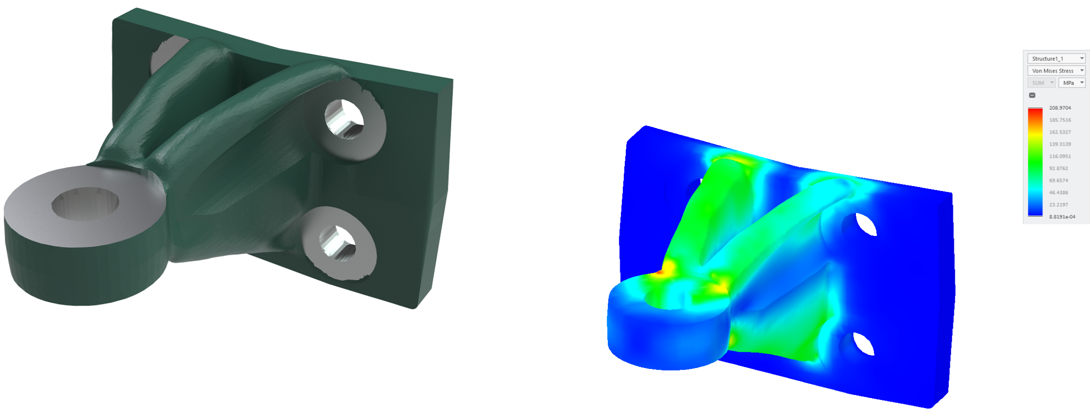
The solution found when freely generating the part is shown in Figure 4.5. This solution has significantly lower stresses for the same amount of material. The shape has changed significantly from the original part, which would indicate that the previous shape is far from an optimal solution using the model developed. Further attempts to decrease the amount of material can be done based on the freely generated model. Discussed in Table 4.4 is how the solution can be constrained to achieve a solution for manufacturing.

Table 4.2: Freely generated adapter ring potential for manufacturing using additive, casting and linear extrusion manufacturing constraints

Additive manufacturing	Casting	Linear extrusion
The engine bracket can currently as proposed be manufactured using additive manufacturing methods. However, the amount of material needed for this current solution would be prohibitively expensive for any high quality powder part. An attempt to lower the amount of material until similar stresses can be seen. The build direction normal to the flywheel mount surface may show potential.	The engine bracket as proposed in the solution is difficult to be manufactured using casting. However, testing different pull directions may yield one or two that shows promise.	No solution can be found where the extrusion constraint is used.

4.1.3.2 Casting in Same Plane

In this solution, the pull direction used is in the same direction as the original part. This solution has lower max stresses than the original part and weighs 2.97kg. The parting line is most likely more advanced than the original, making the tooling cost a bit higher. The tooling cost for this part is selected to increase by 10% from the original part. The solution is shown in Figure 4.6.

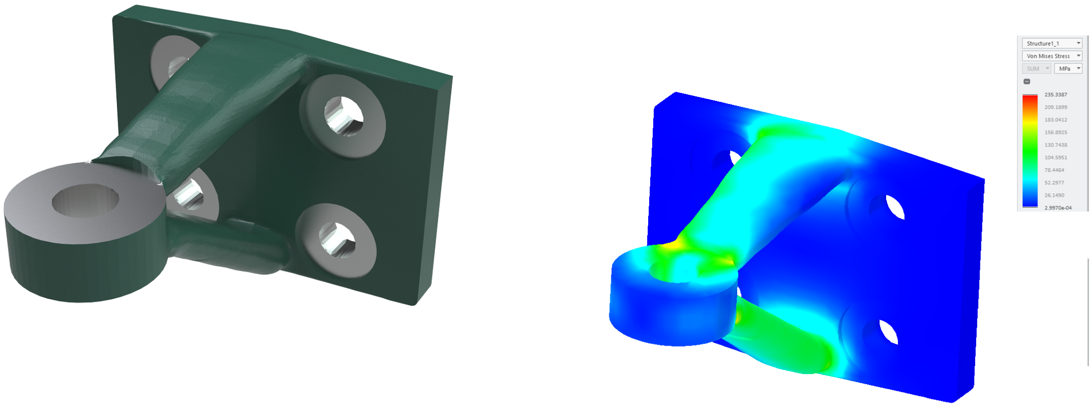


(a) The proposed solution **(b)** Stresses in the proposed solution

Figure 4.6: Proposed solution of the engine bracket using casting constraint in the same plane as original part

4.1.3.3 Casting in Vertical Plane

In this solution, the pull direction used is normal to the symmetry plane. This solution has lower max stresses than the original part and weighs 2.72kg. The parting line is most likely more advanced than the original, making the tooling cost a bit higher. The tooling cost for this part is selected to increase by 10% from the original part. The solution is shown in Figure 4.7

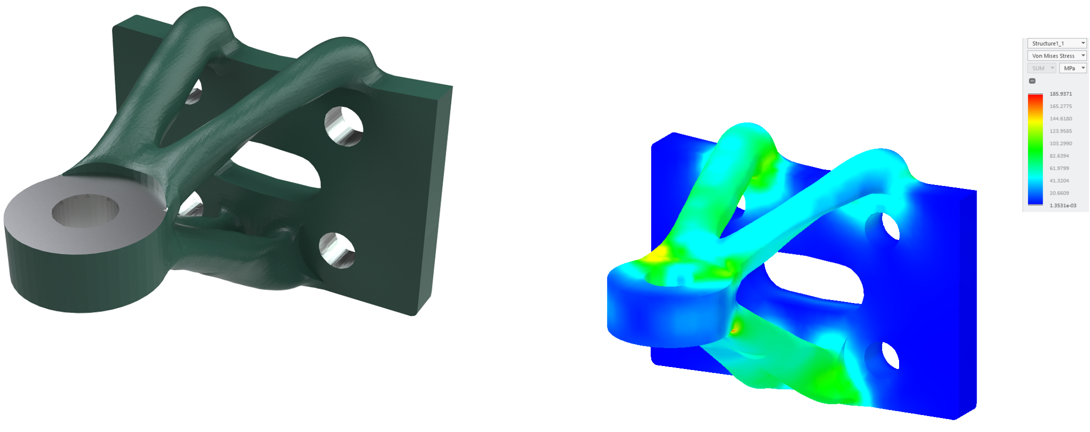


(a) The proposed solution **(b)** Stresses in the proposed solution

Figure 4.7: Proposed solution of the engine bracket using casting constraint in another plane

4.1.3.4 Additive Manufacturing

In the additive manufacturing solution, the build direction selected is normal to the contact surface of the flywheel housing. This solution has lower max stresses than the original part and weighs 2.52kg. The solution is shown in Figure 4.7.

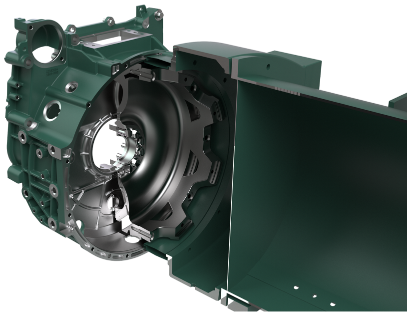


(a) The proposed solution **(b)** Stresses in the proposed solution

Figure 4.8: Proposed solution of the engine bracket using additive manufacturing constraint while reducing the amount of material

4.2 Alternator Adapter Ring

The alternator adapter ring is mounted to the flywheel on one end and the alternator rotor on the other. The part will be used at an angular velocity of 1500 RPM and 1800 RPM to transfer torque to the alternator. The alternator ring is used in generator applications which in most cases are stationary throughout its operating life. It is unlikely that a change in mass would impose any significant extra cost due to higher fuel consumption. The alternator adapter ring is shown in Figure 4.9.



(a) Location of the adapter ring

(b) The adapter ring

Figure 4.9: Adapter ring is the interface between the engine and the alternator

The production volume of the adapter ring is estimated to be a low volume of around 300 units. The part is likely cast using a method with lower relative equipment cost such as sand casting or evaporative pattern sand casting.

4.2.1 Structural Model

The alternator ring is transferring torque to the alternator whilst sustaining centrifugal forces induced both from itself and other components such as the flywheel. The flywheel is rotating with significant mass and it is likely that the flywheel will be the main driver for the radial deformation regardless of the stiffness of the adapter ring. This is possible to model using displacement constraints and get good results in capturing the findings in an internal Volvo report. The model does however not converge to a satisfying result when optimising. This is due to the model becoming overly constrained either not converging at all, or to an unrealistic solution. The model is simplified using a force load instead of a displacement constraint, making the force induced from the flywheel constant regardless of the adapter's radial stiffness. This leaves greater freedom for the optimisation algorithm and allows for satisfactory model convergence. The same simplification will be done when it comes to the other side where the alternator is located, although for this it is unknown how dependent the adapter ring would be on the rotors' radial deformation.

In an internal report at Volvo, the standard J1456 is applied to the part and is described as requiring the part during a test to be able to sustain significantly higher angular velocity than the rated called a burst. The multiple used in the report is

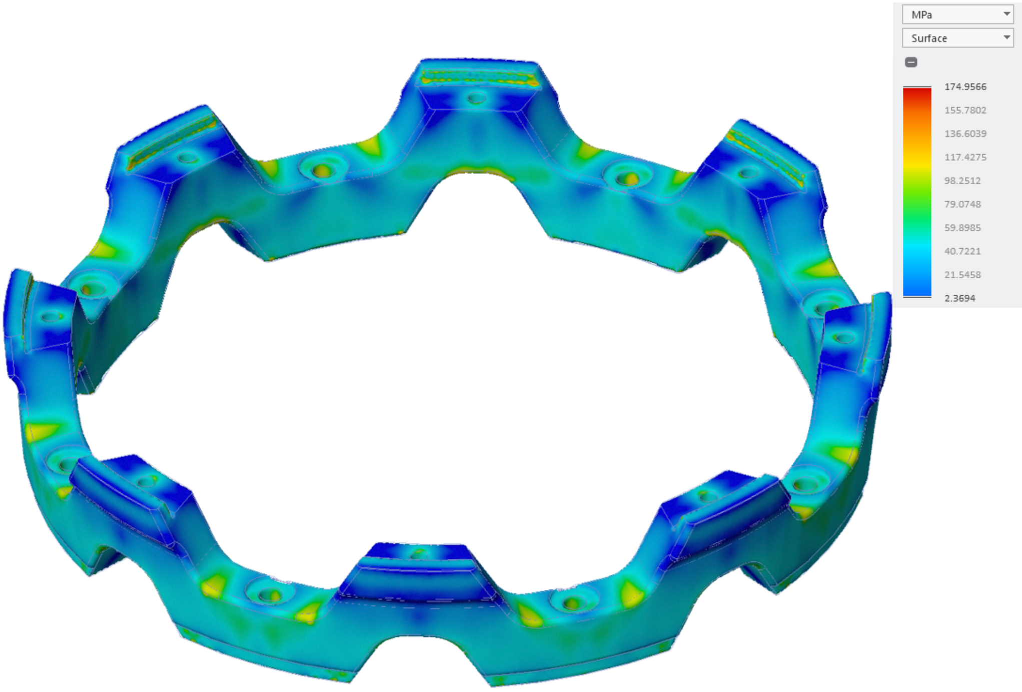
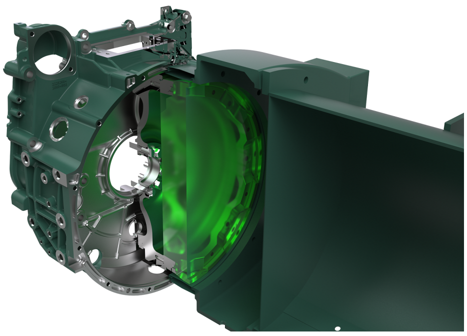


Figure 4.10: Structural model of the adapter ring displaying stresses in the part during the burst load case

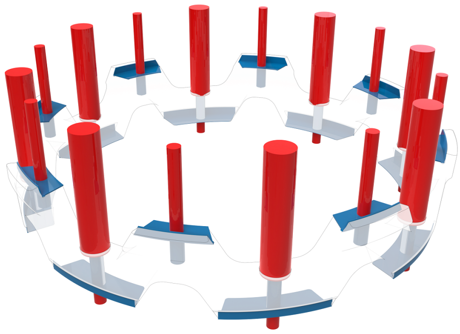
2.5 times the approved angular velocity. The model is created using a centrifugal force at 4500RPM. Unspecified in the internal report about the burst condition is if the engine is transferring torque to the alternator, and if so, how much torque is transferred. It is assumed that the transfer of torque is that of the rated for normal operation. To capture the forces induced by the flywheel and alternator, a force is placed on the contact surface and is scaled to capture the tendencies and magnitude of the stresses found in the report. The model that was created is shown in Figure 4.10. Presented in the figure are the stresses, where the max stress is 175MPa. According to the internal report, the aluminum used has a tensile limit of 230MPa, making the part pass verification. The model developed is different from the model proposed in the report. The locations of the stress concentrations are similar and it was determined that the model is capturing the tendencies and will suffice.

4.2.2 Volume Definition

The outer radial limits of the coupling are constrained by the flywheel housing. The coupling is limited by the flywheel and the fixture for the rotor in the alternator. How geometry for the rotor is defined is unknown. It will be assumed that the rotor does not extend past the contact surface to which the coupling attaches to. The coupling has contact surfaces that need to be preserved and screw mounting holes that need to be preserved and accessible. The geometry describing this is shown in Figure 4.11.



(a) Design space of the adapter ring in transparent green



(b) Preserved geometries in blue and excluded geometries red

Figure 4.11: Volume definition

4.2.3 Design Evaluation

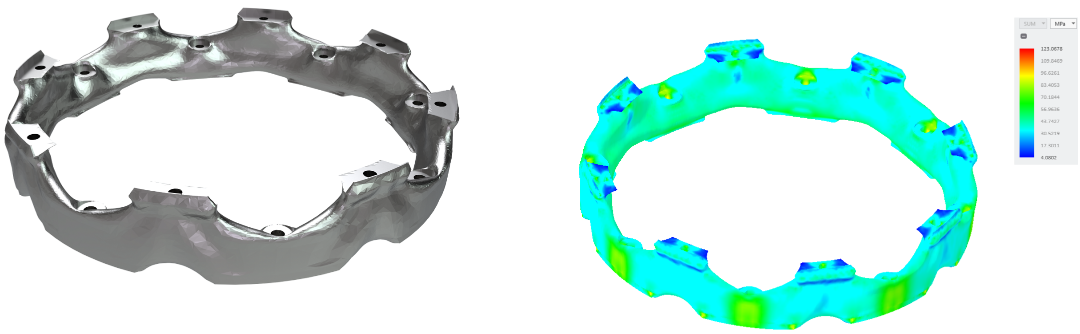
The adapter ring is spinning and having the mass balanced would be essential for stability and to reduce vibrations. Balancing the adapter ring can be done through symmetry shape constraints. However, only one symmetry constraint is permitted which would allow for the part to be unbalanced in the plane perpendicular to the symmetry plane along the rotation axis. This plane would preferably also be symmetric, but this is not possible in creo. If the center of gravity is offset to the center of the ring for the generated designs these will be discarded. The evaluation of the viable parts generated in this chapter is shown in Table 4.3

Table 4.3: Parameters shown for Original Part (OP) and Balanced Casting (BC). Investigating both Evaporative Pattern Sand Casting (EPSC) and Sand Casting (SC). The resulting cost of manufacturing is calculated using Equation 2.4

Parameter	OP EPSC	BC EPSC	OP SC	BC SC
$Cost_{material}$ [SEK/kg]	18.55	18.55	18.55	18.55
$Cost_{tool}$ [SEK]	1813	2357	7975	10368
$Cost_{Overhead}$ [SEK/h]	1327.34	1327.34	1327.34	1327.34
$Cost_{capital}$ [SEK]	16675	16675	43550	43550
$Discount\ Rate$ [%]	5	5	5	5
$load\ factor$	0.5	0.5	0.5	0.5
$mass$ [kg]	5.8	4.8	5.8	4.8
$Production\ Rate$ [units/h]	5	5	10	10
$Size_{batch}$ [units]	300	300	300	300
$Tool\ Life$	16	16	550	550
$Time_{write-off}$ [years]	5	5	5	5
$utilisation_{Material}$	0.5	0.5	0.7	0.7
$Cost_{manufacturing}$ [SEK]	600.20	598.90	327.77	313.60
σ_{max} [MPa]	175	134	175	134

4.2.3.1 Freely Generated

Freely optimising the adapter ring with only a symmetry constraint while maintaining the same material and amount of material gives a solution shown in Figure 4.12.



(a) The proposed solution

(b) Stresses in the proposed solution

Figure 4.12: Proposed solution when freely generating the adapter ring

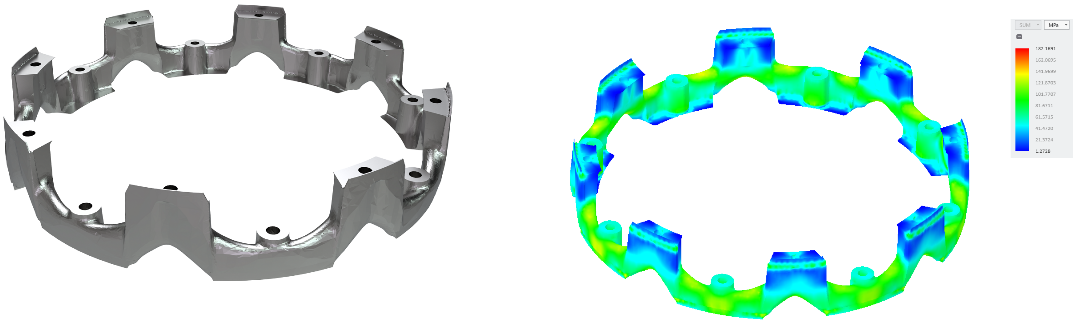
In this solution has the max stress been reduced to 125MPa. This solution is similar to the original solution but distributes the loads better. The part has the center of gravity very close to the center of the ring, making it balanced. Some surface contacts are not as supported as in the original part, which may or may not be a problem. The freely generated adapter ring is not easily manufactured as described in Table 4.4 and is discarded.

Table 4.4: Freely generated adapter ring potential for manufacturing using additive, casting and linear extrusion manufacturing constraints

Additive manufacturing	Casting	Linear extrusion
The suggested adapter ring is heavy, meaning additive manufacturing would be prohibitively expensive due to material costs. And due to the size of the part, it would not fit any chambered additive methods such as powder bed fusion and material/binder jetting, which provide good quality and material properties. The only possible method to manufacture the part would be directed energy deposition which allows for larger structures but provides worse quality and material properties. Further investigation of this additive manufacturing was determined to not yield any competitive solutions.	The suggested adapter ring has complex surfaces and no matter the orientation, no solution can be found due to a negative draft angle making it challenging to manufacture using this method. Investigating possible solutions constraining by selecting a pull direction.	No realistic and competitive part could be created using this constraint.

4.2.3.2 Casting with Less Material

Known from the previous part is that the max stress is significantly reduced meaning the original part structure is not optimal. It is argued as well that the freely generated part has potential as a cast component. For this proposal, a cast manufacturing constraint is used while reducing the amount of material until the original parts' max stress is achieved. The proposed alternator ring is shown in Figure 4.13.



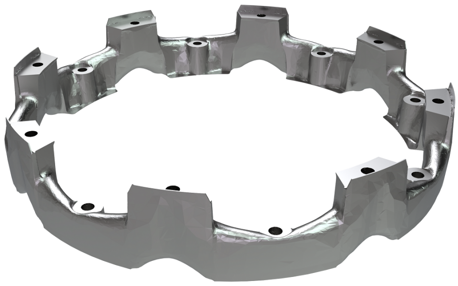
(a) Proposed solution. (b) Stresses in proposed solution.

Figure 4.13: Proposed solution when casting while reducing the amount of material for the adapter ring

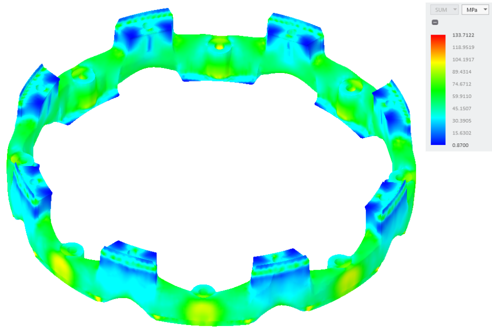
The part mass is 3.5kg compared to the original part with a mass of 5.8kg, while the stress is marginally increased from 175MPa to 181MPa. The surfaces are still quite advanced, but the part has a clear parting line with sufficient drafts to argue that it would be possible to manufacture. Although since the parting line is not located in the same plane, more advanced tooling would be required. It is unknown whether the contact surfaces are sufficiently supported or too thin for the casting process. Due to this, the *casting with less material* solution is discarded. To ensure that the surfaces are fully supported, the preserved volume can be redefined by adding more material to the surfaces, material manually added in a post-process step or allowing the optimiser to use more material.

4.2.3.3 Balanced Casting

When targeting a bit more mass, most thin wall surfaces get supported and max stresses are quickly reduced. A balanced version of the part was done when slowly increasing the mass target until a satisfactory solution was found as seen in Figure 4.14.



(a) Proposed solution.



(b) Stresses in proposed solution.

Figure 4.14: Casting with balanced amount of material

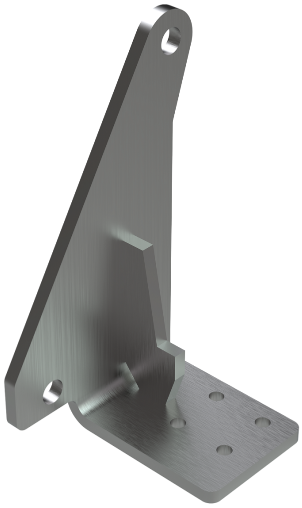
The alternator ring has, compared to the *casting with less material* solution, increased in mass to 4.8kg and the max stress has decreased to 134MPa. This solution has better-supported contact surfaces. If required the number of contact surfaces that may be determined as too thin a post-processing step could be added minding the parting line and draft angle required to allow casting.

The same production volume as the original part is assumed, making selecting the same sand casting or evaporative pattern sand casting methods the best candidates. The manufacturing parameters describing the manufacturing cost in Equation 2.4 are set to an average value or pre-assigned value found in Granta for the original part unless the parameter is known such as the mass. The parts are similar and most parameters are expected to remain constant. The parameter that is expected to change is the tooling cost, which is due to the more complex surfaces and parting line, making it more expensive. A factor arbitrarily selected suggesting that the tooling would become 30% more expensive to cover this. The parameters used and the cost calculated is shown in Table 4.3. Since the alternator is expected to be stationary the term $Cost_{marine,mass}$ in Equation 2.3 is set to zero. The best solution is the balanced casted using sand casting as a manufacturing method, being both the cheapest and having as low or lower maximum stress levels as the alternatives.

4.3 Bracket for solenoid Valve

The bracket is located on the side of the engine and is carrying a solenoid. The bracket is attached to the engine block with several cables and pipes in proximity as seen in Figure 4.15. Less than 100 of this part are forecasted to be manufactured.

(a) The solenoid bracket holds a solenoid and attaches to the engine block. The bracket is highlighted in red



(b) The solenoid bracket

Figure 4.15: The solenoid bracket in context and by itself

4.3.1 Structural model

The solenoid bracket is fixed to the engine using two bolts. There will be an acceleration in which the part is required to sustain itself and the solenoid valve. The center of gravity of the solenoid valve is unknown, however, it can be deduced that it is located within the part and will be assumed to be located at the position calculated when the solenoid is of solid material with constant density. Using Figure 4.16, the center of gravity in the horizontal directions is located at lengths l_h 0.6mm and 2.8mm from where the solenoid is fixed. The center of gravity is in the vertical direction and is located at lengths l_v distance of 37.8mm from where the solenoid is fixed. The force and moment induced by the acceleration will be located at the surface where the solenoid is fixed on the bracket. These are calculated for marine acceleration forces seen in Equations 4.13, 4.14, 4.15 and 4.16, where v is the vertical direction, h is a horizontal direction, $h^{(*)}$ is the perpendicular horizontal direction to h and R is the reaction point. In the equations, the mass m of the solenoid is 0.46kg and accelerations a is the same load case as given in Chapter 4.1. The model for one of the acceleration load cases is shown in Figure 4.17a

$$\rightarrow: ma_h = F_h \tag{4.13}$$
$$\uparrow: ma_v = F_v \tag{4.14}$$
$$\overset{\overset{\frown}{h^{(*)}}}{R}: M_{h^{(*)}} = ma_h * l_v + ma_v * l_h \tag{4.15}$$
$$\overset{\overset{\frown}{v}}{R}: M_v = ma_h * l_h + ma_{h^*} * l_{h^*} \tag{4.16}$$

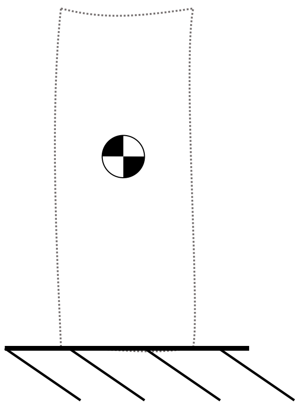
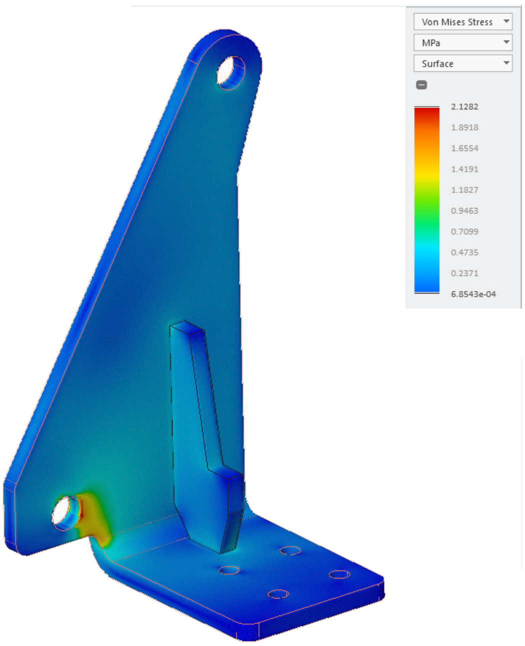
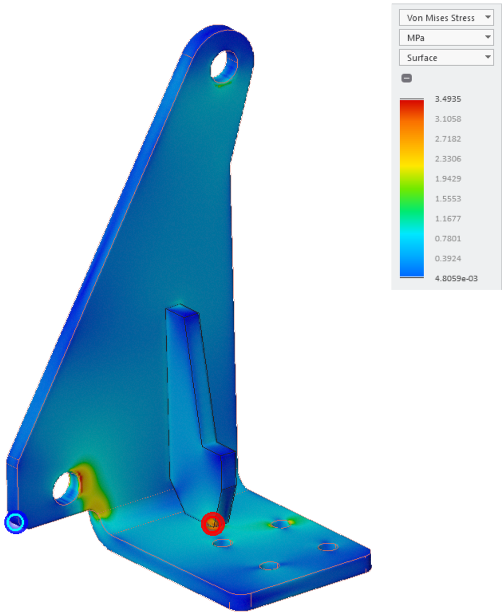


Figure 4.16: Center of gravity of solenoid valve fixed to the engine bracket

As seen in Figure 4.17a the max stress is well below most material limits. The designer of the original part explained that this was due to a concern about how the solenoid is affected by the vibration caused by the engine phases. In an internal Volvo report, the deflection in the current part is investigated at different frequencies. As long as the general shape of the generated bracket is similar, it is assumed that the part would oscillate in a similar manner. Using a force in the direction that the current part is deflecting in the internal report, a bias can be placed on reinforcing this direction when optimising. The load case biasing the model for vibration is shown in Figure 4.17b.



(a) Structural model in one acceleration direction

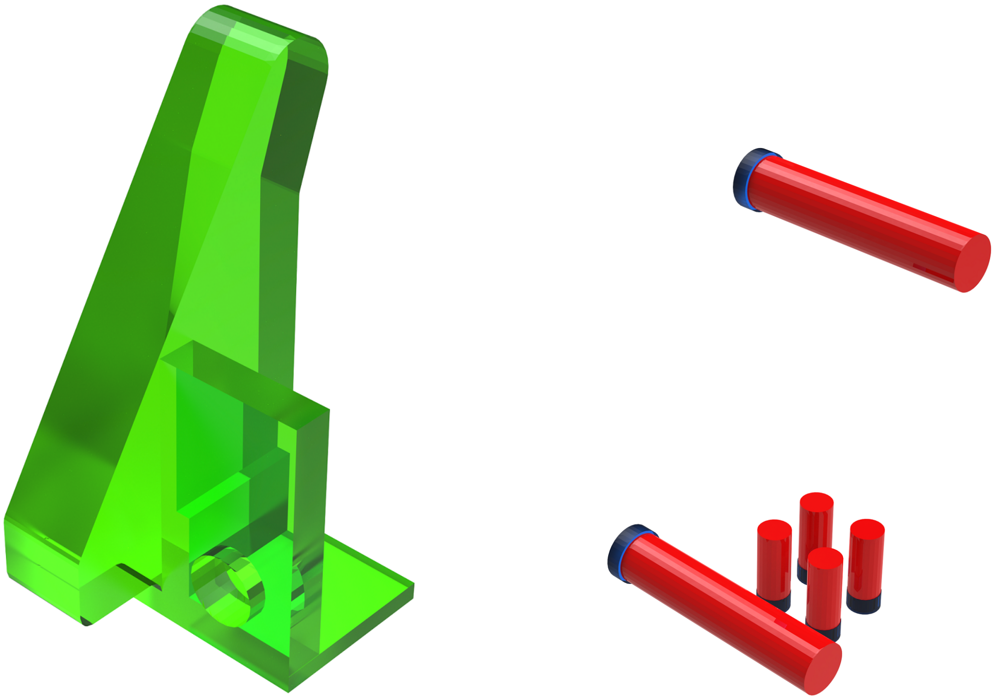


(b) Vibration biasing model

Figure 4.17: Structural model in one of the acceleration directions and vibration

4.3.2 Volume Definition

The bracket is constrained by the solenoid geometry and engine geometry. There are also other geometries such as cables and pipes that would have to be considered. The design space used is the silhouette of the part when looking at it on the engine. It extends to the solenoid and includes the volume where the solenoid is fixed and some extra volume available. Where the bracket is bolted to the engine and the solenoid is bolted to the bracket, there need to be preserved surfaces. Some volume must also be excluded to allow the distances to be placed. This volume configuration is shown in Figure 4.18.



(a) Design space of the solenoid bracket in transparent green

(b) Preserved geometries in blue and excluded geometries red

Figure 4.18: Volume definition

4.3.3 Design Evaluation

The original part is manufactured using sheet metal. It is likely that due to the limited production volume the solenoid bracket would be manufactured not using specialised tooling such as stamping. General tools such as a laser cutter, a bender and a welder would be able to manufacture this part. Such tools may already be available and instead be sharing the capital investment cost with other parts manufactured in the workshop.

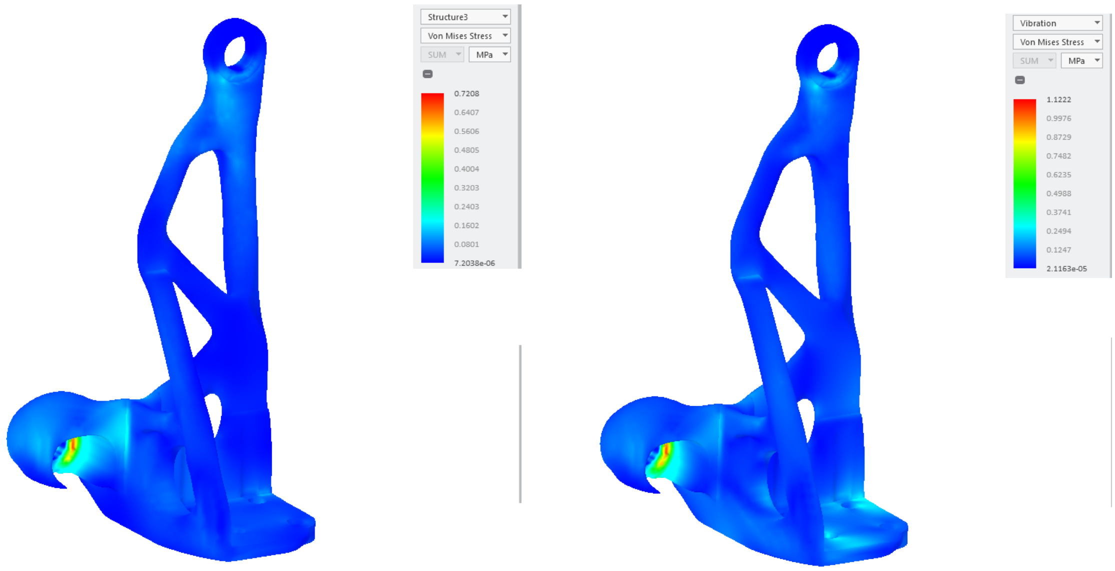
For such a workshop instead increasing the overhead rate parameter in the cost model and setting the capital and tooling cost to zero would be a possible way to implement the cost model. The parameter $Cost_{Overhead}$ is estimated to increase by 20% from the standard value used in Granta. The parameters showing this for the original solution and proposed solutions used are shown in Table 4.5.

Table 4.5: Parameters shown for Original Part (OP), Additive Manufacturing with Less Material (AMLM) and Casting with Less Material (CLM).

Parameter	OP	AMLM	CLM
$Cost_{material}$ [SEK/kg]	6.35	1200	6.35
$Cost_{tool}$ [SEK]	0	0	7975
$Cost_{Overhead}$ [SEK/h]	1592.81	1327.34	1327.34
$Cost_{capital}$ [SEK]	0	4555000	43550
$Discount\ Rate$ [%]	(5)	5	5
$load\ factor$	(0.5)	0.5	0.5
$mass$ [kg]	0.762	0.356	0.441
$Production\ Rate$ [units/h]	5	0.54	10
$Size_{batch}$ [units]	100	100	100
$Tool\ Life$	(1000)	(550000)	550
$Time_{write-off}$ [years]	(5)	5	5
$utilisation_{Material}$	0.7	0.6	0.7
$Cost_{manufacturing}$ [SEK]	325.47	3662	231.24
$Cost_{Total}$ [SEK]	3503	5147	2070
σ_{max} [MPa]	2.13	1.03	0.83

4.3.3.1 Freely Generated

The design is freely generated to eventuate possible manufacturing and shape constraints. The part freely generated is shown in Figure 4.19. The max stress is reduced for both the vibration and acceleration load cases. It suggests that some amount of material may be removed. Some sharp transitions are visible where the design space and excluded geometries abruptly end using crease radius constraints may produce a smoother part. Targeting a lower mass while using the manufacturing constraints available is discussed in Table 4.6.



(a) Structural model in one acceleration direction

(b) Vibration structural model

Figure 4.19: Structural model in one of the acceleration directions and vibration

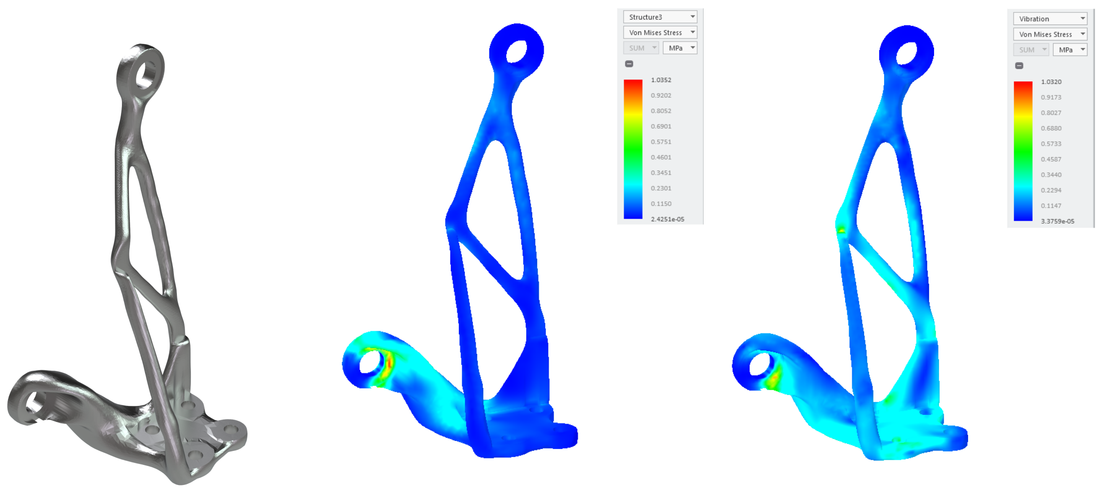
Table 4.6: Freely generated adapter ring potential for manufacturing using additive, casting and linear extrusion manufacturing constraints

Additive manufacturing	Casting	Linear extrusion
The solenoid bracket already has a shape that may be manufactured using additive manufacturing. The freely generated bracket is quite heavy but would fit chambered metal manufacturing additive methods. General guidelines for additive manufacturing would orient the holes along the build direction. However, both sets of holes are being used to clamp and not pin, making the roundness of the holes not as important. The build direction selected is the vertical direction as seen in Figure 4.19.	Testing pull direction along all three cartesian directions defined by the planes created by the hole clamping surfaces yields promising results in one of the directions. This pull direction is normal to the plane where the solenoid bracket is mounted to the engine.	No realistic and competitive part could be created using this constraint.

4.3.3.2 Additive Manufacturing with Less Material

The process result of generating the solenoid bracket using an additive manufacturing constraint while reducing the amount of material is shown in Figure 4.20.

With the material reduced to 0.356kg the part weighs significantly less as well as maintains lower stresses than the original part. Decreasing material further would make the solution converge to only using one hole which would be undesirable. It is converging to one hole due to fixed constraints locking all degrees of freedom. Using fixed constraint is not wrong since in reality the surface is clamped with sufficient force for the degrees of freedom to be locked to an extent. Locking all degrees of freedom results in undesirable convergence to only use one of the fixed points. It is unknown whether the fixed point by itself is clamped tightly enough to assume a fix in all degrees of freedom if that is the case. Another problem is the assumption of the part deflection. The vibration model assumed that the part generated would deflect in a similar way, however, it is likely that the harmonics of the part have changed significantly. Due to this, the direction of deflection of the model could become exceedingly inaccurate due to the model of part deflection.



(a) The solution

(b) Structural model in one acceleration direction

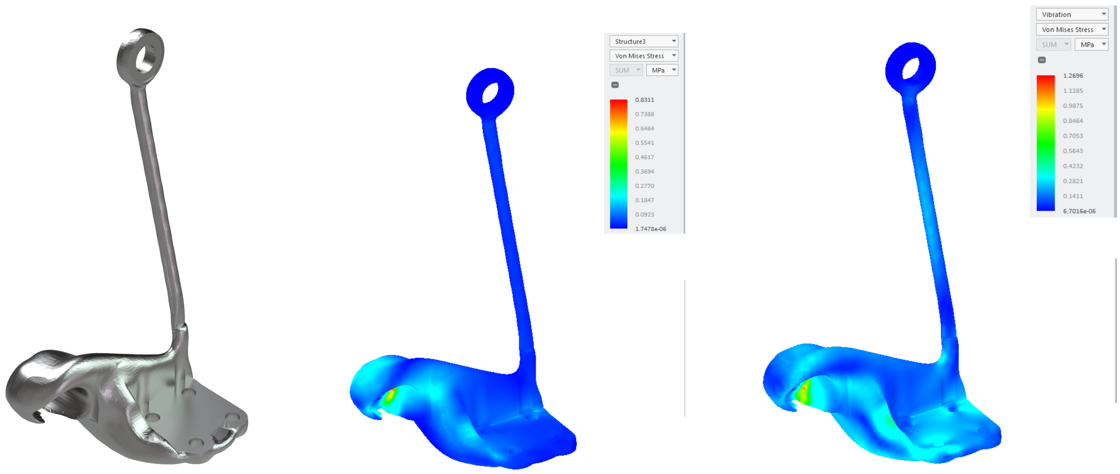
(c) Vibration structural model

Figure 4.20: Structural model in one of the acceleration directions and vibration for additive manufacturing

For ferrous metals, Laser Beam Powder Bed Fusion (LB-PBF) is an established method providing good quality and good material properties. The using parameters for steel sold by EOS [29] and average parameters of the manufacturing cost are calculated in Table 4.5.

4.3.3.3 Casting with Less Material

The process result of generating the solenoid bracket using a casting constraint while reducing the amount of material is shown in Figure 4.21. The mass of the part has decreased to 0.441kg with potential for further material reduction however due to the reason stated in Chapter 4.3.3.2, having the part converge to only use one fix point is undesirable.



(a) The solution

(b) Structural model in one acceleration direction

(c) Vibration structural model

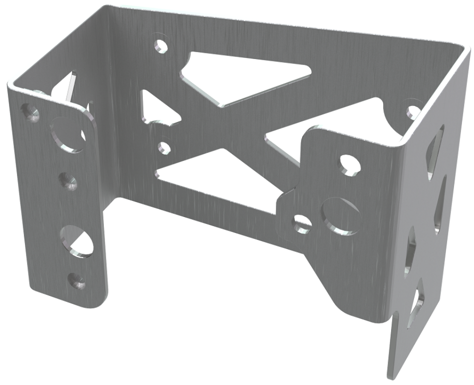
Figure 4.21: Structural model in one of the acceleration direction and vibration for casting

Sand casting is described Swift et al. [24] as favorable with production volumes of around 100 which is the case. The parameters selected are the average values found in Granta [22] for Sand casting and shown in Table 4.5.

4.4 Filter Bracket

The filter bracket is shown in Figure 4.22. It is suspected that the cutout geometry has not been calculated to be optimal, rather it is probable that the cutouts are defined through the experience of the designer or just arbitrarily. The production volume of the filter bracket remains undetermined and has a mass of 0.974kg.

(a) The filter bracket is part attaching to other brackets



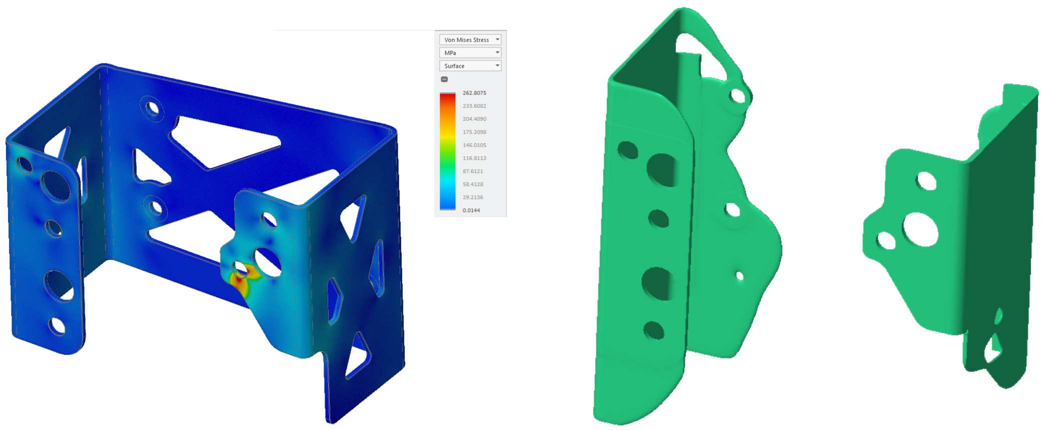
(b) The filter bracket have cutouts making it lighter

Figure 4.22: The filter bracket shown in a context and by itself

4.4.1 Structural model

The filter bracket already has a structural model defined from when it was passed through CAE verification. In this model, the forces and moments are located at the center of the holes attaching the bracket, whilst some holes are being fixed. The model is shown in Figure 4.23a and observable is that stress concentration around the holes being loaded is present when this is not the case in the FEM model shown in an internal report. It is unknown whether the filter bracket gets some stiffness by surrounding assembly parts or if there is some other problem. However, this mostly affects the area in proximity to the holes and would not significantly change how the part deflects over the side cutouts. Aside from the area around the holes, the model is determined to be accurate. The maximum stress found is 262MPa, well below the material limit of 350MPa yield strength stated in an internal report but when probing the cut-out volumes the stress never exceeds 80MPa.

The implementation of this model does not work when optimising. The problem is that the holes that are being fixed overly constrain the bracket, making the solution converge to a solution that is determined to be undesired shown in Figure 4.23b. It is probable that the holes being fixed are loaded independently in an unspecified load case. It is determined that the longer side would require some interconnecting material to be a realistic competitor.



(a) Structural model

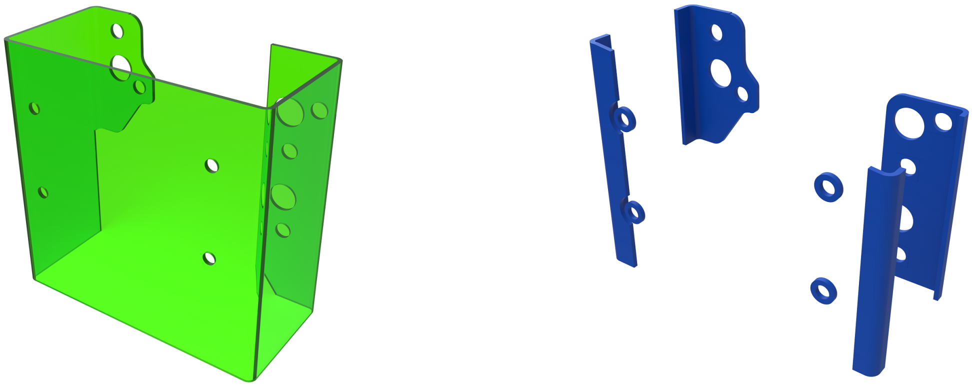
(b) Undesirable convergence, where no material is used at the back portion

Figure 4.23: Structural model displaying stresses and the undesired convergence case of the filter bracket

To generate a realistic competitor to the original part the overly constrained problem must be solved. This is done through multiple case loads allowing some degree of freedom in the previously fixed holes. This forces the component to distribute the loads in that degree of freedom to the other fix points forcing the optimiser to insert material where it determined none was required. These models are not determined to be accurate and it is likely that the longer side is not optimal for the original load cases. The solution using these load cases would still be preferable and a comparison can still be performed with the more accurate original model.

4.4.2 Volume Definition

There is limited knowledge of what volume is available for the filter bracket to generate within. Partly due to this the scope was set to optimise the cutouts. Having the bracket remain the same sheet metal part with the same radius bends is the preserved volume, leaving the cutout areas as free design space to generate within. When manufacturing sheet metal it is not preferable to have drilled or cut holes located close to a bend. The preserved volume is extended to include the bends with some margins. Normally the manufacturing method would be determined by manufacturing constraints, analysis and post-processing. For this case, the design volume is used to target a specific manufacturing method. No exclusion volume is used. The design space and preserved volume are shown in Figure 4.24



(a) Design space

(b) Preserved geometries in blue

Figure 4.24: Volume definition

4.4.3 Design Evaluation

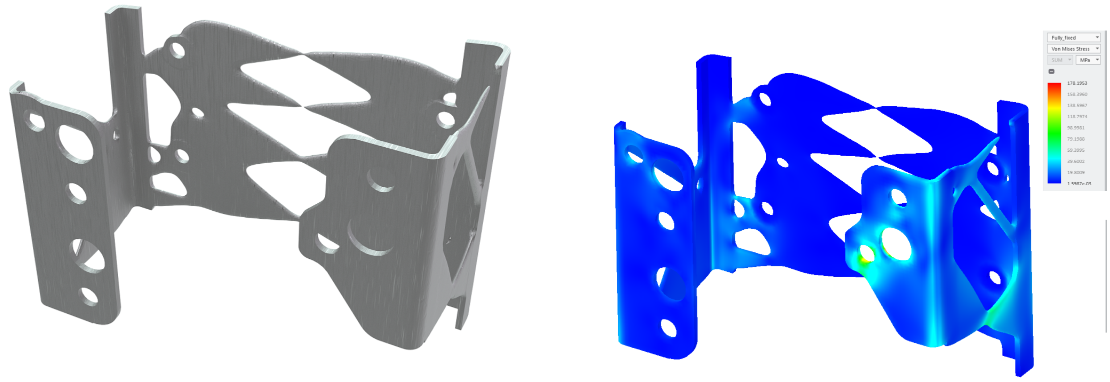
The production volume is unknown, however, due to the solution targeted having the same manufacturing method it is assumed changing where the cutouts are made will have a negligible impact on the manufacturing cost. When evaluating the part manufacturing cost, the model developed is not used due to the negligible impact of moving the cutouts. The only cost driver when evaluating the parts would be the amount of material used. When optimising the target mass will be reduced until stresses in the cutouts being generated stresses approach 80MPa as the original part. The parameters showing the original solution and the proposed solutions are shown in Table 4.7.

Table 4.7: Evaluation shown for Original Part (OP), sheet metal with higher resolution and Spread (S), and sheet metal with higher resolution and Less Spread (LS)

Parameter	OP	S	LS
$Cost_{Total}$ [%]	100	75	65
σ_{max} [MPa]	263	265	258

4.4.3.1 Sheet Metal with Less Material

Seen in Figure 4.25 is the proposed solution with a mass of 0.676kg. As could be in the figure is how the material fails to connect. It is clear that the tool believes that loads may be transferred through this non-material section. This part would therefore be discarded. It is probable that a bug exists in the way the tool handles singularity nodes. Manually increasing the resolution would increase the number of elements that could solve this. Inserting a spread constraint could also yield some interesting results.

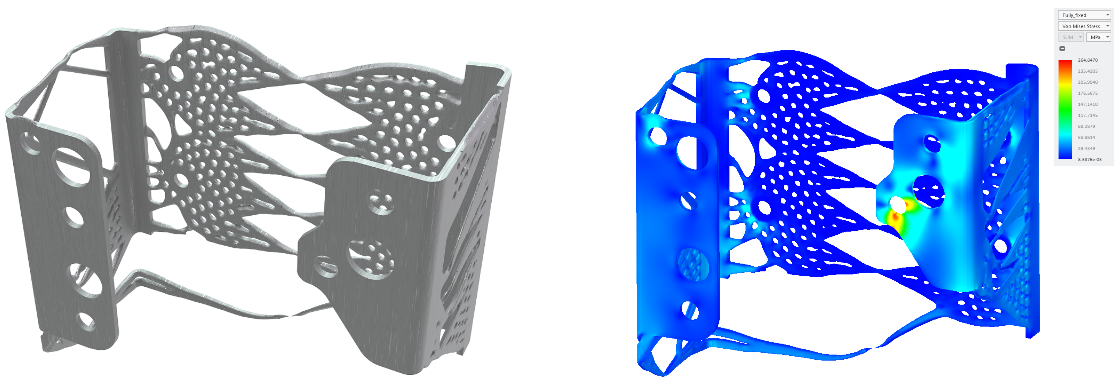


(a) The proposed solution **(b)** Stresses in the proposed solution

Figure 4.25: Proposed solution when freely generating the filter bracket while reducing material

4.4.3.2 Sheet Metal with Higher Resolution and Spread

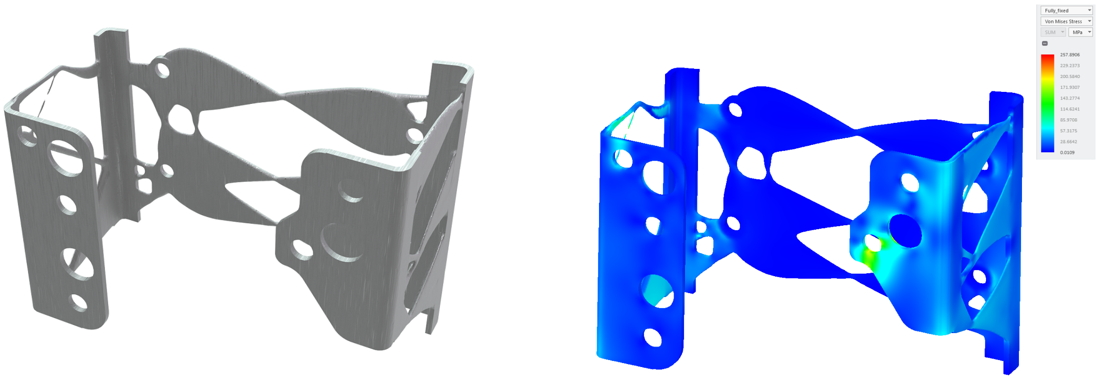
Seen in Figure 4.26 is a valid solution with most material connecting. Running with this increased resolution while the generation of the part takes multiple hours. This may be partly due to the number of load cases and constraints, however running a design study exploring how small changes would affect the part takes a prohibitively long time. The geometry generated is quite advanced, with many holes and large sections. The part did increase in mass to 0.733kg but decreased in max stress in the cutout area where the max value now is 60MPa. This solution even though possible with some post-processing would most likely be more expensive and rebut the assumption that manufacturing expenses would remain similar. This solution is approved for evaluation however further exploring the material spread constraint to a lesser extent would likely yield a better result.



(a) The proposed solution **(b)** Stresses in the proposed solution

Figure 4.26: Proposed solution when generating with higher resolution and more spread

4.4.3.3 Sheet Metal with Higher Resolution and Less Spread



(a) The proposed solution

(b) Stresses in the proposed solution

Figure 4.27: Proposed solution when generating with higher resolution and less spread

Using high resolution and less spread yields a part weighing 0.635kg. Its max stress in cutouts areas is 80MPa. This solution is more reasonable and is fully connected.

5 Discussion & Conclusion

Discussed and concluded In this chapter the result of the project along the lines of the two research questions is discussed and conclusions are found. Included are benefits, challenges and findings on the topic to implement Generative Design.

5.1 Benefits and Challenges

The parts evaluated have to different extents proved their potential for development through generative design as shown in the results. They are for the structural models used stronger and lighter than the original part. Some parts are with the manufacturing cost model used even competitive in the aspect of manufacturing cost. Considering this, a Volvo Penta engine using parts developed through generative design would add value through stronger more reliable parts while lowering the cost of operating the vessel due to the parts being lighter. The lighter parts would due to factors described in Chapter 2.3.1 decrease the fuel consumption. Decreasing fuel consumption during operation is not only good for the customers, but it is also in line with Volvo Penta's aim of becoming a leader in sustainable power solutions [30] and global goals to reduce the use of fossil fuels [31].

Some disadvantages can also be argued to be shown in the results. The structural model used in the generation process is intended to reflect reality. However, complex dynamic systems are hard and time-consuming to model. Transferring loads and constraints of an assembly system model to a part-level model may be hard or impossible. As discussed in the results some assumptions and simplifications are implemented to make it possible to optimise to a satisfactory part. However, doing this is discarding parts of how the part would interact in reality and may make the generated part not reflect all the aspects it is required to comply with. This could result in everything from a sub-optimal part to a defective part. A topic for future study is ways to enable good and fast modelling, minimizing the challenges found and ensuring the benefits are maintained.

Modelling accurately capturing reality is in some cases becoming a challenge due to the limited selection of load and constraints available in creo. A wider selection of options for the structural model is available in some other tools for design optimisation. One such option is a point load seen missing in Chapter 4.3.1, where instead the moments are manually calculated. The tool is further limited by only being able to handle static loads. For many components developed at Volvo Penta, vibrations and thermal loads are of concern which can't be modeled using generative design in creo. A suggestion for future studies and the development of generative design tools is the inclusion of point loads, thermal loads and constraints for sheet metal manufacturing.

Another aspect of modeling found in some of the parts investigated had to have their model adjusted to achieve a satisfactory convergence into a realistic part. Determining whether it is a realistic part is not among the capabilities of creos tool generative design. The judgment and actions to achieve a satisfactory convergence to a realistic part may only be determined by the designer. Found for parts investigated is the trade-off between making a realistic part and reducing the amount of material. In these cases, the optimiser may neglect a fixture point or contact surface that may be determined to be essential. There may be solutions to this such as more extensively defining a structural model and inputting why the surface or fix point is important to include. However such considerations add additional time and may even be impossible with limited information, constraints and loads available.

The time of extensively modeling the structure is only one part of the total time of development. It is stated by PTC in [5] as a selling argument that using generative design could provide a faster time to market. Without questioning the truthfulness of this argument, it was found throughout the project that a large amount of time is needed to create and validate the inputs to generative design. Shown in the results are multiple iterations of each part some of which are invalidated. Some iterations are usually needed to achieve satisfactory output and that is using already developed parts to validate against. All this results in a long time to get a first design proposal. However, achieving a final design is likely how PTC argues that the generative design process would provide a faster time to market.

5.2 Implementing Generative Design

The benefits found are discussed in Chapter 5.1, one of which is faster time to market. The circumstances where faster time to market can be speculated on is when looking at how generative design could be implemented. The conventional design process including verification illustrated in Figure 5.1 includes redesign when failing verification. When a part is verified a structural model is defined by CAE engineers and aspects of manufacturing are considered by production engineers. When considering that the work is already to some extent being done as part of the conventional development process, the additional time needed to define the inputs may not be as significant. It should also be included that failing verification is less likely when verifying against similar or the same requirements as inputted to generative design. This would require less re-work in all stages of the development process making it probable that a faster time to market can be achieved and a cheaper development process.

With the inputs to different extents already being defined within the company.

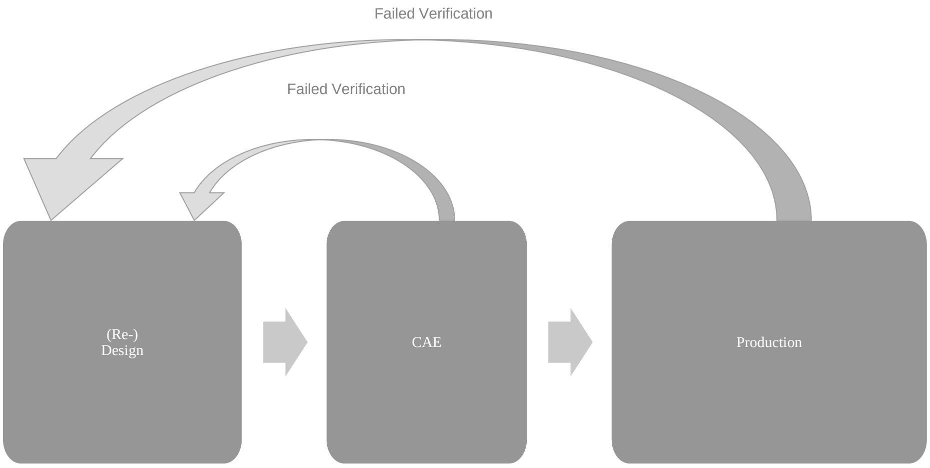


Figure 5.1: Conventional development process

Instead of using them to find and remedy where the design is lacking, the already-to-be-defined inputs could be used to find an optimal design (as defined by the inputs). A collaborative effort between departments illustrated in Figure 5.2 may be introduced to achieve a faster time to market, save money and create a better design. Such a collaboration would create new challenges and highlight challenges currently being addressed. Future studies on this topic should include generative design as part of how departments would collaborate.

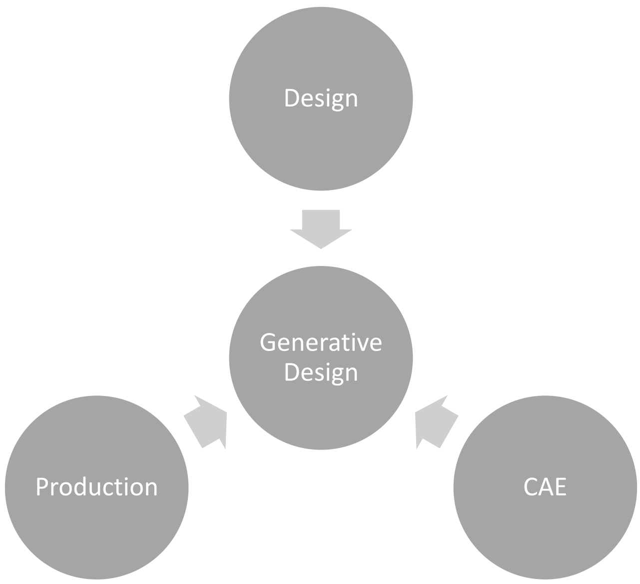


Figure 5.2: Interdepartmental collaboration into generative design

Bibliography

[1] S. Junk and L. Burkart, "Comparison of cad systems for generative design for use with additive manufacturing," *Procedia CIRP*, vol. 100, pp. 577–582, 2021, 31st CIRP Design Conference 2021 (CIRP Design 2021), ISSN: 2212-8271. DOI: 10.1016/j.procir.2021.05.126.

[2] D. Vlah, R. Žavbi and N. Vukašinović, "Evaluation of topology optimization and generative design tools as support for conceptual design," *Proceedings of the Design Society: DESIGN Conference*, vol. 1, pp. 451–460, 2020. DOI: 10.1017/dsd.2020.165.

[3] K. Bhadani and J. Skön, *Balancing of wheel suspension packaging, performance and weight*, 2016. DOI: 20.500.12380/238598.

[4] H. Helmfrid and J. Larsson, "Topology optimization of electric motor installation," M.S. thesis, Chalmers University of Technology, 2021. DOI: 20.500.12380/302754.

[5] PTC. (2022). "What is generative design? | generative design software | ptc," [Online]. Available: https://www.ptc.com/en/technologies/cad/generative-design (visited on 27/05/2022).

[6] A. Kobetski and M. Fabian, "Time-optimal coordination of flexible manufacturing systems using deterministic finite automata and mixed integer linear programming," *Discrete Event Dynamic Systems*, no. 19, pp. 287–315, Sep. 2009. DOI: 10.1007/s00158-007-0217-0.

[7] P. Y. Papalambros, "Design optimization practice in product development," *DS: Proceedings of EDIProD*, no. 29, pp. 79–90, 2002. [Online]. Available: https://www.designsociety.org/publication/27324/.

[8] K. Murota, "Linear programming," in *Computer Vision: A Reference Guide*. Cham: Springer International Publishing, 2019, pp. 1–7, ISBN: 978-3-030-03243-2. DOI: 10.1007/978-3-030-03243-2_648-1.

[9] G. Rozvany, "A critical review of established methods of structural topology optimization," *Structural and Multidisciplinary Optimization*, no. 37, pp. 217–237, Jan. 2009. DOI: 10.1007/s00158-007-0217-0.

[10] G. Rozvany , “Aims, scope, methods, history and unified terminology of computer-aided topology optimization in structural mechanics,” *Structural and Multidisciplinary Optimization*, no. 21, pp. 90–108, Apr. 2001. DOI: 10.1007/s001580050174.

[11] Z. Zuo, “Topology optimization of periodic structures,” eng, Ph.D. dissertation, RMIT University, 2009. [Online]. Available: https://researchrepository.rmit.edu.au/esploro/outputs/9921861974801341.

[12] N. van Dijk, K. Maute and M. Langelaar, “Aims, scope, methods, history and unified terminology of computer-aided topology optimization in structural mechanics,” *Structural and Multidisciplinary Optimization*, no. 48, pp. 437–472, Sep. 2013. DOI: 10.1007/s00158-013-0912-y.

[13] X. Duan, X. Qin and F. Li, “Topology optimization of stokes flow using an implicit coupled level set method,” *Applied Mathematical Modelling*, vol. 40, no. 9, pp. 5431–5441, 2016, ISSN: 0307-904X. DOI: 10.1016/j.apm.2015.12.040.

[14] S. Castagne, R. Curran and P. Collopy, “Implementation of value-driven optimisation for the design of aircraft fuselage panels,” *International Journal of Production Economics*, vol. 117, no. 2, pp. 381–388, 2009, ISSN: 0925-5273. DOI: 10.1016/j.ijpe.2008.12.005.

[15] E. B. Barbier, A. Markandya and D. W. Pearce, “Environmental sustainability and cost-benefit analysis,” *Environment and Planning A: Economy and Space*, vol. 22, no. 9, pp. 1259–1266, 1990. DOI: 10.1068/a221259.

[16] S. Pagerit, P. Sharer and A. Rousseau, “Fuel economy sensitivity to vehicle mass for advanced vehicle powertrains,” in *SAE 2006 World Congress Exhibition*, SAE International, Apr. 2006. DOI: 10.4271/2006-01-0665.

[17] J. J. Corbett, “Marine transportation and energy use,” in *Encyclopedia of Energy*, C. J. Cleveland, Ed., New York: Elsevier, 2004, pp. 745–758, ISBN: 978-0-12-176480-7. DOI: 10.1016/B0-12-176480-X/00193-5.

[18] Freightos. (2022). “Air freight air cargo shipping: Air freight charges, rates, costs quotes,” [Online]. Available: https://www.freightos.com/freight-resources/air-freight-rates-cost-prices/ (visited on 28/05/2022).

[19] Freightos . (2022). “Ocean freight: Ocean sea freight shipping: Rates, quotes and charges (2022),” [Online]. Available: https://www.freightos.com/freight-resources/ocean-freight-explained/ (visited on 28/05/2022).

[20] JET-A1-FUEL.COM. (2022). “Jet a-1 price on fuel,” [Online]. Available: https://jet-a1-fuel.com/ (visited on 10/05/2022).

[21] C. Hueber, K. Horejsi and R. Schledjewski, “Review of cost estimation: Methods and models for aerospace composite manufacturing,” *Advanced Manufacturing: Polymer & Composites Science*, vol. 2, no. 1, pp. 1–13, 2016. DOI: 10.1080/20550340.2016.1154642.

[22] Ansys, *Granta edupack*, version 18.1, 27 May 2022. [Online]. Available: https://www.ansys.com/products/materials/granta-edupack.

[23] J. Liu and Y. Ma, “A survey of manufacturing oriented topology optimization methods,” *Advances in Engineering Software*, vol. 100, pp. 161–175, 2016, ISSN: 0965-9978. DOI: 10.1016/j.advengsoft.2016.07.017.

[24] K. G. Swift and J. D. Booker, *Manufacturing Process Selection Handbook : From design to manufacture*. Elsevier Science Technology, Apr. 2013, ISBN: 9780080993607.

[25] E. Toyserkani, D. Sarker, O. O. Ibhadode, F. Liravi, P. Russo and K. Taherkhani, *Metal additive manufacturing*. Wiley, 2021, ISBN: 9781119210832. [Online]. Available: https://search.ebscohost.com/login.aspx?direct=true&db=cat07472a&AN=clec.ybp17498850&site=eds-live&scope=site&authtype=guest&custid=s3911979&groupid=main&profile=eds.

[26] PTC. (Mar. 2022). “Creo generative design,” [Online]. Available: https://support.ptc.com/help/creo/creo_pma/r8.0/usascii/index.html#page/generative_design/generative_design.html (visited on 28/05/2022).

[27] I. R. M. Junior, A. Ogliari and N. Back, “Guidelines for reverse engineering process modeling of technical systems,” in *Complex Systems Concurrent Engineering*, G. Loureiro and R. Curran, Eds., London: Springer London, 2007, pp. 23–30, ISBN: 978-1-84628-976-7. DOI: 10.1007/978-1-84628-976-7_3.

[28] X. Jiang, H. Wang, Y. Li and K. Mo, “Machine learning based parameter tuning strategy for mmc based topology optimization,” *Advances in Engineering Software*, vol. 149, p. 102 841, 2020, ISSN: 0965-9978. DOI: https://doi.org/10.1016/j.advengsoft.2020.102841.

[29] *Eos of north america, inc. material pricing*, v13, EOS, Mar. 2014. [Online]. Available: https://engineering.cmu.edu/next/_files/documents/eos-materials-price-list_06-19-14.pdf.

[30] (2022). “Sustainability - we want to lead the way | volvo penta$_2$022,” [Online]. Available: https://www.volvopenta.com/about-us/toward-sustainability/ (visited on 01/07/2022).

[31] (2022). "Breaking up with fossil fuels | undp," [Online]. Available: `https://feature.undp.org/breaking-up-with-fossil-fuels/` (visited on 01/07/2022).

[32] I. N. Brown and M. F. Aldridge, "Power models and average ship parameter effects on marine emissions inventories," *Journal of the Air amp; Waste Management Association*, vol. 69, no. 6, pp. 752–763, 2019. DOI: `10.1080/10962247.2019.1580229`.

[33] P. Mohazzab, "Archimedes' principle revisited," *Journal of Applied Mathematics and Physics*, vol. 05, no. 04, pp. 836–843, Apr. 2017. DOI: `10.4236/jamp.2017.54073`.

A

Appendix 1

A.1 Drag Resistance in Marine Vessels

The equation describing drag in for a marine vessel found in [32] is shown in equation A.1. Resistance model of a ship as a function of mass, where ρ, C_T,$V_{Reported}$ and η_T are constants such that does not vary such as salt water density, hull resistance coefficient and engine efficiency. The variable that affects the drag is S, which is the hulls wetted surfance area. The hulls wetted surface area will be a function dependent on the hull shape and the amount of water needing to be displaced in order to achieve buoyancy in accordance with Archimedes' Principle described in [33]. The equilibrium equation of a floating marine vessel is described in Equation A.2. Where m is the mass of the ship, g is the gravity acceleration, ρ is the density of the displaced fluid and V is the displaced fluid volume.

$$P = \frac{\rho C_T \frac{1}{2} S V_{Reported}^3}{\eta_T} \tag{A.1}$$

$$F = 0 = mg - \rho g V \tag{A.2}$$

The wetted surface area is the area that is wetted and can be described by the circumference C and the height h as Equation A.3. Assuming the change in circumference is small and can be treated as a constant for proportional small changes in height. A new equation for the change in wetted surface area can be formulated as Equation A.4. With the same assumption, the change displaced volume, ΔV can be expressed as Equation A.6. Here instead of circumferance C, hull area A used.

$$S = \int_0^h C(h)dh \tag{A.3}$$

$$\Delta S = C\Delta h \tag{A.4}$$

$$V = \int_0^h A(h)dh \tag{A.5}$$

$$\Delta V = A * \Delta h \tag{A.6}$$

With Equation A.4, Equation A.1 can be expressed as Equation A.7 describing change of drag. Using Equation A.2 and A.6, the change in mass, Δm can be used to describe as the change in height, Δh in Equation A.8. Combining Equation A.7 and A.8 into Equation A.9 defining relationship of how the drag of a boat is affected by a change in mass.

$$\Delta P = \frac{\rho C_T \frac{1}{2} V_{Reported}^3}{\eta_T} C \Delta h \tag{A.7}$$

$$\Delta h = \frac{\Delta m}{\rho A} \tag{A.8}$$

$$\Delta P = \frac{C \rho C_T \frac{1}{2} V_{Reported}^3}{\eta_T \rho A} \Delta m \tag{A.9}$$

DEPARTMENT OF INDUSTRIAL AND MATERIAL SCIENCE
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
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