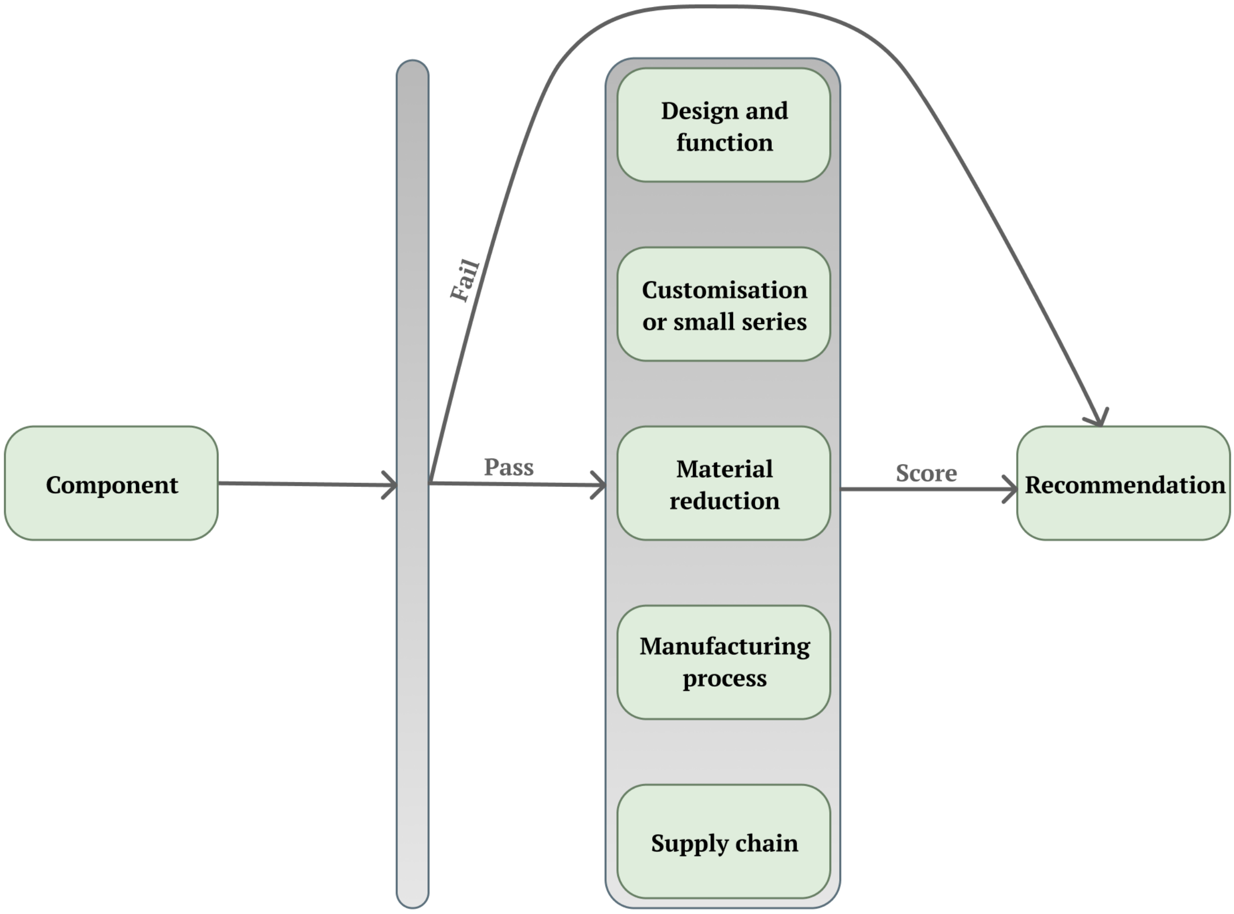

Development of a Recommendation Tool Identifying Environmental Sustainability Potential of Additive Manufacturing

Master's Thesis in Product Development and Industrial Ecology

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DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE

CHALMERS UNIVERSITY OF TECHNOLOGY
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Master's thesis 2023

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Cover: The structure of the recommendation tool visualising the different parts.

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Abstract

This master's thesis aims to support Volvo Penta in reaching their sustainability goals by exploring the environmental sustainability advantages of metal additive manufacturing (AM). This is achieved by creating a recommendation tool, which intends to identify the environmental sustainability potential of AM for components. The project methodology consisted of three phases: exploration study, development of the recommendation tool, and testing and evaluation. During the first phase, AM knowledge was obtained through a literature review and interviews. In the second phase, the structure, criteria, scoring and recommendations of the recommendation tool were developed. In the last phase, the usability and performance of the recommendation tool were tested.

The main result from the exploration study was the environmental sustainability advantages of AM identified for the product life cycle phases. Five component categories were created to capture these advantages, namely design and function, customisation or small series, material reduction, manufacturing process, and supply chain. The final recommendation tool consisted of three parts, one for briefly describing the components, one for eliminating non feasible components and one for evaluating the components. The elimination was based on requirements connected to AM buildability for binder jetting and powder bed fusion, while the evaluation criteria were based on the identified sustainability advantages divided into the component categories. The result of the recommendation tool is a mean score for each component category and corresponding recommendations. The usability test indicated that engineering judgement based criteria depend highly on the users' perception and experience of AM and the component. The evaluation indicates a strong correlation between AM expert opinions and the recommendation tool results.

The recommendation tool can educate the user and support discussions related to environmental sustainability and the use of AM. Thus, the recommendation tool incorporates sustainability in the centre of product development and can help Volvo Penta reach their sustainability goals.

Keywords: additive manufacturing, environmental sustainability, product development, recommendation tool, binder jetting, powder bed fusion

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This project was conducted in collaboration with Volvo Penta and the department of Industrial and Materials Science at Chalmers University of Technology. We want to thank our supervisors and examiner, Simon Carlsson from Volvo Penta, and Eduard Hryha and Mélanie Despeisse from Chalmers University of Technology for their support and guidance during the project. They have all encouraged us and provided valuable experience and feedback. Henrik Karlsson from Volvo Trucks Technology, Patrik Lindgren from Volvo Penta and Sven Bengtsson from Chalmers University of Technology have also shown great engagement in our project and supported us with appreciated knowledge in the field. We also want to thank Hans Olausson and the design engineers in the light duty engine platform department at Volvo Penta for welcoming us to the team and participating in our usability test. During the interviews Experts within the field of AM have shown an interest in the project and contributed with essential insights. Lastly, we want to mention our thankfulness towards our supporting families and friends.

Emma Karlsson and Alexandra Simonsen, Gothenburg, June 2023

List of Acronyms

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

AM	Additive Manufacturing
BJT	Binder Jetting
CM	Conventional Manufacturing
LDEP	Light Duty Engine Platform
MCF	Modified Complexity Factor
PBF	Powder Bed Fusion
PBF-EB	Powder Bed Fusion - Electron Beam
PBF-LB	Powder Bed Fusion - Laser Beam
RQ	Research Question
TOM	Trade-off Methodology Matrix

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1

Introduction

The fourth industrial revolution, Industry 4.0, implies a rapid transformation in design, manufacture, operation and service due to the utilisation of interconnectivity and smart automation. This can lead to many possibilities such as flexibility in production, mass customisation to adapt the products to customers and increased productivity. Additive manufacturing (AM) is considered one of the technical developments to enable these. However, there are still challenges to overcome in order to extract value for the organisations. In particular, the implementation of Industry 4.0 requires major investments and changes in the current production system (Davies, 2015).

Today, the world is facing a climate crisis. In the year 2015, 196 countries signed the Paris Agreement, a legally binding treaty on climate change. They agreed to limit the global warming to 2 °C above pre-industrial levels and to pursue efforts to limit the warming to 1.5 °C (United Nations, 2015). Thus, emissions need to be reduced by 45% until 2030 and reach net zero 2050 (United Nations, 2022). To achieve this, it is necessary to change to renewable energies, technology development and circular economy (UNCTAD, n.d.). An important part of creating a more circular economy is to follow the nine R's: refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle and recover (Kirchherr et al., 2017).

1.1 Background

Volvo Penta, a part of Volvo Group, delivers engines and complete power systems for marine and industrial applications such as drivelines for leisure and commercial boats, off-road industrial and power generation engines. Their vision is to *"become the world leader in sustainable power solutions"* (Volvo Penta, 2023a). To fulfil their vision, Volvo Penta joined the initiative science based targets. This master's thesis project focuses on reducing the climate impact and resource usage for Volvo Penta (Volvo Penta, 2023d). One step towards reaching the science based targets is to examine potential future sustainable manufacturing methods. Therefore, Volvo Penta is interested in exploring how AM technology can be implemented and its advantages, to understand when it is beneficial to utilise it. The project is conducted together with the light duty engine platform (LDEP) department, and will focus on the engines Volvo Penta D4 and D6.

The Volvo Penta D4 and D6 are inboard diesel engines designed exclusively for marine applications such as leisure boating. More than 100 000 engines have been sold since the launch year 2003. Both are characterised by having a high performance, unique marine torque, low fuel consumption, and long service intervals (Volvo Penta, 2019). In the technical description, it is stated that the two engines share lubrication systems, engine mountings, fuel systems, induction and exhaust systems, cooling system, and electrical systems. Therefore, they have many components in common. The main difference is the cylinder block and crankshaft, due to the D4 having four cylinders while the D6 has six cylinders. This leads to a difference in size that can be seen between figure 1.1 showing Penta D4, and figure 1.2 showing Penta D6 (Volvo Penta, 2023b; Volvo Penta, 2023c).

Figure 1.1: Penta D4 - Inboard Engine (Volvo Penta, 2023b)

Figure 1.2: Penta D6 - Inboard Engine (Volvo Penta, 2023c)

Within Volvo Group, AM has been practised for specific cases. In particular for Renault Trucks, the "Vulcan Engine Project" explored AM in which components in a DTi5 truck engine got redesigned to reduce weight. Thus, topology optimisation and integration were utilised to minimise the weight of the components while ensuring the fulfilment of the requirements. The project resulted in an engine with a 31% reduced weight of components and a 33 % reduction of the total number of parts (Volvo Trucks, 2018). Except for the Vulcan project within Volvo Group, another AM project has been performed. In this case, a tube bend for a Volvo Penta engine was printed in aluminium. In this case, AM was chosen because of the low volume and improved functionality by complex design. This project was especially interesting since the component is critical for the performance, and still got printed as a final component (Mattsson, 2019).

However, it is challenging to transfer new technology expertise, including AM, from the research to the industry. Moreover, the transfer of knowledge is crucial to unlock the full potential of the technology. Leutenecker-Twelsiek et al. (2018) describes the inherited implicit knowledge and guidelines utilised for conventional manufacturing (CM) require to be omitted to overlook their limitations. The implicit knowledge of AM is non existing in the industry, but it can be obtained by the designers over time by practising guidelines. However, existing guidelines for AM are challenging to implement due to their generality and scientific approach. Thus, there is a need for a method, that easily can be adopted by the design team, to support knowledge transfer to Volvo Penta and bring awareness to AM possibilities.

1.2 Aim and Research Questions

The master's thesis project aims at supporting Volvo Penta in reaching their sustainability goals and exploring the field of AM. The impact of the different phases of product life cycles should be identified to reduce emissions, resource use and waste. Moreover, the field of AM should be explored to investigate how an alternative production process to CM can be implemented to enhance environmental sustainability. The project intends to provide a way of analysing components, called a recommendation tool, to identify environmental sustainability potential for AM. This way of analysing components should substitute an expert within the field of AM, and provide guidance for less experienced designers.

To achieve the aim of the master's thesis the following research questions (RQ) will be answered:

> *RQ1: What environmental advantages can additive manufacturing bring along the life cycle of a component?*
>
> *RQ2: What are important criteria to consider when identifying environmental sustainability potential of additive manufacturing for a component?*
>
> *RQ3: How can an organisation implement the identified criteria in their product development process?*

1.3 Limitations

The master's thesis will have the following limitations:

- The recommendation tool will be adapted to suit a marine LDEP, a D4 or D6, thus criteria for these applications will be identified.
- Soley metallic components will be possible to evaluate in the recommendation tool.
- The user of the recommendation tool will be a design engineer at the LDEP department, and therefore it will be adapted to this circumstance.
- All data will be retrieved from existing databases.
- The recommendation tool will evaluate the components mainly from an environmental impact point of view.
- The recommendation tool will only evaluate the potential of AM for a component and give recommendations. Thus, the result will only provide guidance.

2

Theory

In this chapter, the theory necessary to develop the recommendation tool is presented. The first part includes a description of the two AM technologies, different redesign levels for AM and sustainability aspects of AM. The advantages and challenges of AM are also discussed. In the second part of the chapter, existing methods for component selection for AM are presented. These provide important inspiration for criteria and how a recommendation tool can be structured. The methods described more in depth are the trade-off methodology matrix (TOM), the three key attribute reference system and the scoring method.

2.1 Additive Manufacturing

AM, also known as 3D printing, is a production method where a product is produced by continuously adding layers of material until it is completed. Therefore, this method enables the possibility to manufacture a product having a complex design with efficient material usage. Moreover, the method can be used for a range of materials such as polymers, metals and ceramics. No part-specific tools or dies are needed, creating flexibility in production and shorter lead times. Currently, AM is widely used in fast prototyping, aerospace applications to minimise weight and medical applications to produce customised products. Two industrialised AM technologies are binder jetting (BJT) and powder bed fusion (PBF) (Bandyopadhyay and Bose, 2020).

2.1.1 Binder Jetting

Metal BJT is an AM technology using metal powder and a liquid binder in a multi-step process. A layer of powder is deposited on a building platform, thereafter an inkjet printhead applies a layer of binder guided by the CAD model to form a cross-section of each layer. A new layer of powder is then deposited and the process continues until the whole component is formed. See figure 2.1 for an illustration of the process. When the printing process is completed, the component is very fragile due to the binder being the only thing holding the powder together. At this stage, the component is called "green". The next steps are curing of the binder and depowdering of the component to remove the excess metal powder. Lastly, the product is sintered at a temperature below the melting temperature of the powder alloy to densify the component and reach the required material properties (Diegel et al., 2020).

There are two different types of metal BJT: infiltrated BJT and full sinter BJT. For infiltrated BJT, the green component is infiltrated with bronze during the sintering process. In the case of full sintering BJT, the component in the furnace is first heated to a lower temperature to completely burn out the binder, and thereafter the temperature is increased for the metal particles to bond (Diegel et al., 2020).

The density of the metal component increase when sintering as the porosities decrease, which is essential for the mechanical properties of the final component. An increased density also leads to the component shrinking, which is something that is of high importance to consider during the design process. The shrinking is usually from 3 to 20% but depends on the powder material and intended final density or properties. In addition, high-temperature sintering results in geometry distortion due to external forces as e.g gravity, shrinkage, etc. This is particularly present for components with complex geometry. Further knowledge of dimensional changes in complex shapes must therefore be developed to eliminate the risk of geometric accuracy issues (Diegel et al., 2020).

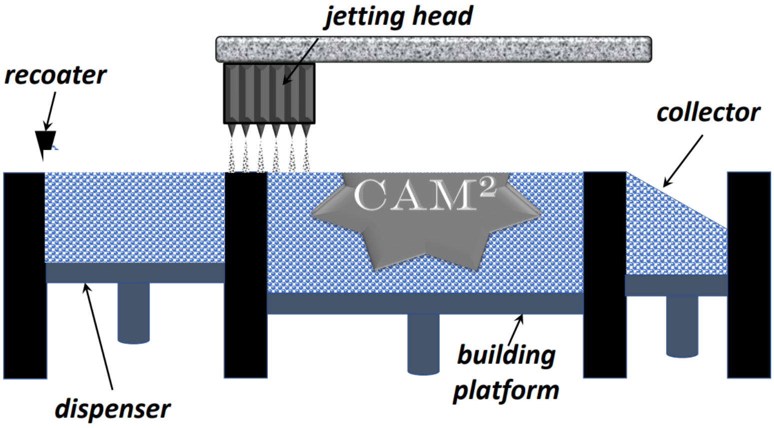


Figure 2.1: Schematic representation of the BJT process, courtesy of E. Hryha

When compensating for shrinking in the design process it is important to consider that large parts shrink more than thin parts. The level of shrinking also depends on the material and if the component is sintered or infiltrated. Holes must be large enough to not risk being clogged during infiltration or disappearing during shrinking. However, the main factor to consider when designing for BJT is the fragility of the "green" component. In order for it to be handled without breaking, a couple of design rules need to be followed. Large unsupported areas should be avoided or supported by geometrically stronger structures. Sharp corners and edges need to be rounded off, if sharp edges are required, they must be created during post-processing. The connections between different parts need to be thick enough, as well as the component walls. Overhangs or fine details need to be protected or made thick and short enough. Finally, salt shaker holes are required to allow the unbound powder to be removed (Diegel et al., 2020).

2.1.2 Powder Bed Fusion

PBF is an AM technology including a powder bed inside a chamber and an energy source. Similar to BJT a layer of powder is deposited on the building platform, but instead of a liquid binder, thermal energy selectively melts the powder. The fusion of powder is according to the description of the layer from a CAD-model. After each layer is finished, the building platform is lowered with a layer thickness and the recoater spreads a new powder onto the previous layer. This continues repeatable until the whole build is completed, resulting in a dense part. However, post-processing may be needed depending on the specific component and type of PBF method used (Diegel et al., 2020).

Two different types of metal PBF exist, where the chamber and the energy source is the main difference. The first type is primarily called powder bed fusion - laser beam (PBF-LB), which can be seen in figure 2.2. For this type, a laser is used to melt the powder together with a mirror to control where the laser directs. The chamber, in which the process takes place, consists of inert gas. The second type is called powder bed fusion - electron beam (PBF-EB), which can be seen in figure 2.3. As the name reveals the energy source is an electron beam managed by an electromagnetic coil. Moreover, a vacuum is created in the chamber to avoid interaction of the electron beam with the gas. In addition, the whole powder bed is heated to achieve an optimal temperature (EPMA, 2019).

The final metal parts produced by PBF are in general comparable to the equivalent part produced by casting, considering both the strength and the surface finish. However, the part needs, similar to casted parts, to be post-processed to reach a complete smooth or polished surface (Diegel et al., 2020).

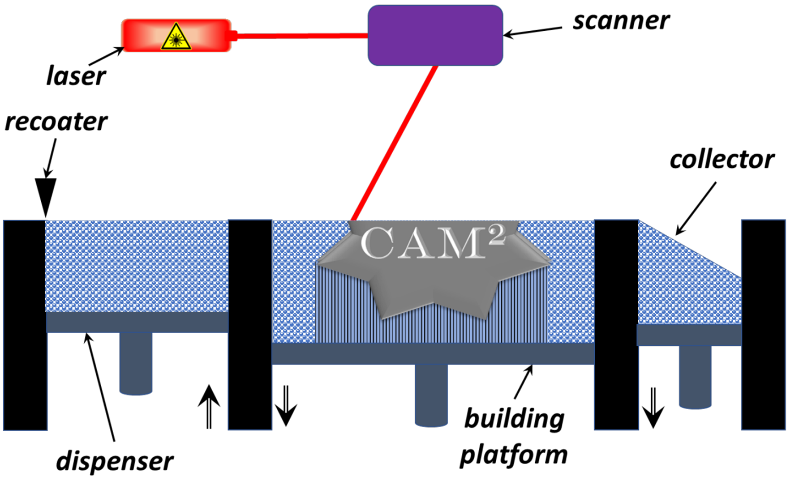


Figure 2.2: Schematic representation of the PBF-LB process, courtesy of E. Hryha

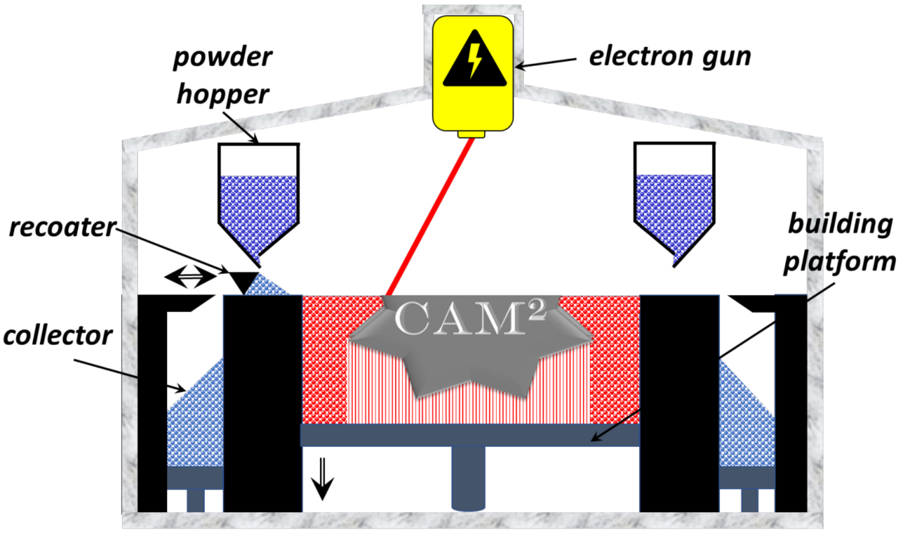


Figure 2.3: Schematic representation of the PBF-EB process, courtesy of E. Hryha

Several factors need to be taken into consideration when designing a component for either PBF-LB or PBF-EB. All factors, in combination with each other, will influence the selected design of the component. However, the precise guidelines will differ depending on the machine manufacturer and which method of PBF-LB or PBF-EB is used. To begin with, a combination of proper part orientation and support structures should be well balanced. The part orientation affects parameters highly connected to cost and quality, such as build time, number of supports and surface roughness to name some. Moreover, it needs to minimise post-AM treatment as e.g. removal of support structures, and lead to minimal residual stresses. The support structures can also serve as a strengthening, conduct the excess heat away from the component, and prevent the geometry from deforming during the building process. However, the support structure needs to be removed during post-processing, and thus it is desirable to minimise the usage considering both time and cost (Diegel et al., 2020).

In addition to the previous factors, the geometry of features needs to be adapted to suit the manufacturing process and machine capability. The aspect ratio is important to consider since a thinner wall can be unstable for the recoater and thermal stresses, which will result in a distorted component. Furthermore, there are guidelines regarding wall thicknesses, overhang angles, gaps, holes and inner channels (Diegel et al., 2020).

2.1.3 Redesign for Additive Manufacturing

Diegel et al. (2020) describe the importance of redesigning a component specifically for AM to capture the advantages. In general, it is favourable to minimise printing time and cost by making some changes to the existing design. The specific component and its application will determine the suitable level of redesign.

There are three different approaches to redesign mentioned by Diegel et al. (2020). The first approach is called "direct part replacement", which implies no or incremental changes to the design. Thus, the component should be able to be produced with a design similar to the original design. For example, spare parts can be suitable to print with the original design to ensure its fit and reduce the lead time. The second approach is "adapt for AM", meaning that the form of the component should be redesigned to improve the additive manufacturability. However, the function of the component and the assembly remains the same as for the original component. The last approach is "design for AM", which is a completely redesigned component to maximise the benefits of AM, such as weight reduction or flow optimisation. Moreover, the design is created to result in an increased function and fit of the component in its assembly. This influences a lot of steps, and therefore it should be performed early in the process.

2.1.4 Life Cycle Perspective of Additive Manufacturing

To determine the possible environmental sustainability benefits of AM, it is important to use a life cycle perspective, where all the processes required for obtaining the function of a product can be included. The concept is inspired by biology and aims at identifying all used resources and emissions released during the "life" of a product. The life cycle of products consists of five phases: resources, manufacturing, distribution, use and end of life, as illustrated in figure 2.4. The main advantage of using a life cycle perspective is to identify the total impact of a product. This prevents shifting any environmental burden from one life cycle phase to another, and thus potentially even worsen the total impact. When considering the advantages and challenges of AM, it is thus important to evaluate if the sustainability advantages are major to the challenges. In addition, using a life cycle perspective gives a clearer view of which phases the challenges belong to and thus support the process of preventing these (Hauschild et al., 2018).

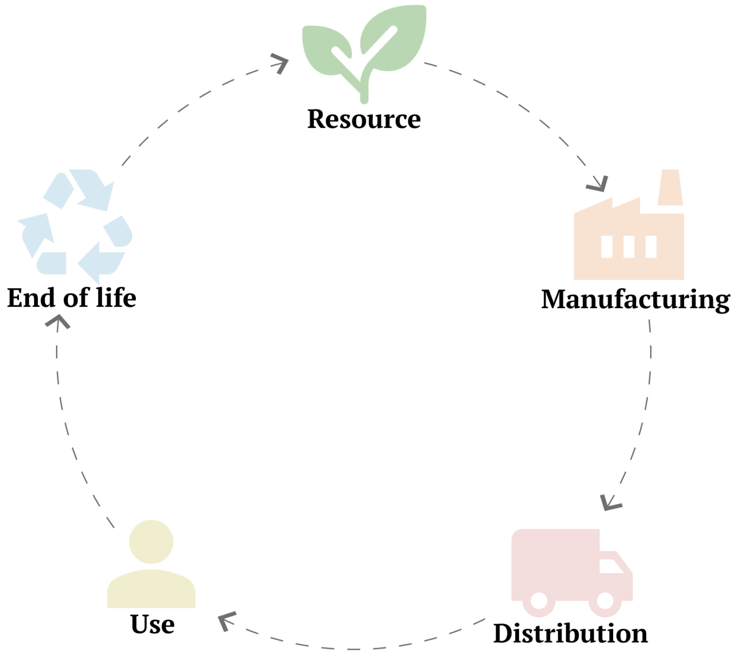


Figure 2.4: The life cycle of a product and the phases

2.1.5 Advantages of Additive Manufacturing

AM can contribute to reducing the product life cycle impact in multiple ways. The technology allows for improved resource efficiency, both in the production and use phase. With AM, it is possible to produce designs with complex shapes, such as hollows, cavities and mesh structures. The advantage of creating optimised designs leads to less material needed and creates lighter products consuming less fuel in the user phase. Furthermore, it is possible to consolidate numerous parts to make the assembly of the end product easier and to reduce material variety. The technical performance can also be improved and thus extending the product life (Diegel et al., 2020).

In addition to the decreased material content of each product, the additive principle of the technology decreases waste during manufacturing compared to subtractive, CM methods (Ford and Despeisse, 2016). If the end of life phase includes recycling, it is possible to close the loop since the recycled materials can act as resources in another life cycle (Hauschild et al., 2018). According to Ford and Despeisse (2016), the estimated recyclability of metal powders is 95 to 98%. One challenge with recycling materials is to separate different materials, such as alloys or metals welded together. Therefore, products that can be disassembled easily or are made of one material support a more circular economy. However, it is also important that circular material flows and logistics exist, so all the processes can be done as efficiently as possible (Stahel, 2016). Furthermore, AM allows for remanufacturing and refurbishing as it is possible to reprint a damaged part of a component or produce new spare parts.

Another important advantage of AM is the flexibility that AM offers. This allows for a reconfiguration of the value chain, creating shorter, more localised supply chains where the production is done closer to the end customers. These chains require less shipping and thus decreased the environmental impact of the distribution phase. Shorter supply chains also significantly decrease the lead time which allows the use of a make-to-order business model and reduced inventories. As small batches or the production of only one item is economically feasible, customisation of products is enabled (Ford and Despeisse, 2016).

2.1.6 Challenges with Additive Manufacturing

There are still several challenges to overcome with the technology. This is mostly due to AM being in an early development phase, and therefore the potential for the technology can change as it evolves.

While AM offers great design freedom, designing a component for AM requires the right skills. Most engineers are used to designing for conventional methods and hence miss capturing the benefits of AM. Support structures, which is material needed to support the component during printing, are needed in most cases. This material creates waste and requires post-processing work to be removed for PBF. Therefore, skills are required regarding designing a component to minimise support structures by optimising its orientation on the build plate. Despite an optimised design, the need for post-processing and support structures is difficult to eliminate, which is a disadvantage of AM (Ford and Despeisse, 2016).

Moreover, there are new design limitations that need to be considered when designing for AM. The technical requirements of the product, such as stresses, surface quality and dimensional accuracy need to be considered early in the design process. This requires detailed knowledge of the product in an early stage of the development. Often, the whole life cycle needs to be considered to optimise the design for AM (Lindemann et al., 2015).

Since the unit price and time for AM is relatively independent of production volume, the speed and cost of production pose problems for high volumes and is rarely economic in these cases. Printers and materials are also expensive to invest in. Although, the development of printers has evolved fast in the last years lowering the prices. Moreover, the printer's limited build volume creates size restrictions for components (Ford and Despeisse, 2016).

The energy consumption is significantly higher for AM methods compared to conventional methods. For example, PBF-EB consumes 61 to 177 MJ/kg of material while machining of stainless steel only consumes about 0.3 to 1.1 MJ/kg (Kellens et al., 2017). As AM is very energy intensive, the manufacturing process itself generally leads to a larger carbon footprint than CM. In a case study from the Manufacturing Technology Center, the largest contributors to carbon emissions for the AM method L-PBF were identified to be the electricity in the production and the primary production of the metal powder (MTC, 2023).

The usage of metal powder also leads to health risks. Due to the microscopic size of the powder, most metal powders are reactive, combustible and highly toxic for humans to inhale. Dangerous dust clouds can be formed by accident during manufacturing. Therefore, it is of high importance to use safe machines and protective equipment (Balakrishnan, 2019).

Another challenge when using AM for end products is the lack of standardisations for the materials used and the limited supply of powders (Ford and Despeisse, 2016). There is also a lack of standardisation for AM processes, which inhibits the implementation of AM in the industry. Developing standards requires large investments of time, effort and capital. However, standards are needed for quality assurance of products and processes. Without standardisations, manufacturing slows down and there is resistance to use specific materials and processes as they are not already approved (Swerim, 2020). There are a number of ISO-standards available for AM, but they are currently under development (ISO, 2023).

2.2 Existing Methods for Selecting a Component

Based on the advantages and challenges of AM, it is clear that AM may offer great value to some components if used in the right applications and with an optimised design. Lindemann et al. (2015) state that it rarely is beneficial to produce a component with AM while still keeping its design for a CM method. This makes the selection of which part to additively manufacture more complicated as it is necessary to foresee the possible benefits of using AM for a component. To see the full benefits, it is necessary to redesign the component for AM, choose a suitable material and method. This requires a lot of knowledge about the product, AM and time to perform a redesign using the necessary software. Therefore there is a big need for methods to identify beneficial component candidates.

2.2.1 Trade-off Methodology Matrix

One approach to identify a suitable component, even for inexperienced designers, is discussed by Lindemann et al. (2015). The approach consists of a three phase method to reduce the effort of information collection before the appropriate component is selected.

The phases are:

1. **Information phase** - obtain knowledge about AM to be able to select a large number of components to evaluate.

2. **Assessment phase** - evaluate each component in a trade-off methodology matrix (TOM) to identify the most promising components for AM.

3. **Decision phase** - collect data and document the component requirements to find the most suitable component for AM.

The TOM in the assessment phase is an important part of this method. It consists of three sections, the top, the first and the second. The top section consists of a description of the component, typically including a brief description of their function, typical product quantities, production cost, dimensions, mass, material and a picture of the part. In addition, an initial estimation of the number of components possible to produce in one building volume is included (Lindemann et al., 2015).

The first section includes criteria, definitions and ratings. These differ depending on the industry in which the component is used and are defined according to the company's strategy or business area. The section is structured into main categories with corresponding sub-criteria, for which each component will receive a rating. The highest rated will be taken into further consideration by having discussions with AM experts. This is to identify the three components with the most potential, which will be included in the last phase (Lindemann et al., 2015).

In the second section, the three most promising components will be evaluated to determine whether they are preferably manufactured by conventional or additive methods. It is evaluated how well the components meet their performances with the best suitable AM material and an estimation of the necessary post-processing. Moreover, the material consumption, processing time and economic aspects of AM and CM will be compared (Lindemann et al., 2015).

The result from the TOM is the identified components and the possible benefits from additive manufacturing, as well as identified requirements needed towards the redesign process. This information is thereafter used in the decision phase. Lindemann et al. (2015) claims this method is possible to adapt to the knowledge of the designer and the industry to which it will be applied. Moreover, AM experts have used this approach independently of each other and ended up with the same components selected in 90% of the cases. The methodology can be utilised by companies as an initial screening, and then the applicable AM candidates can be further evaluated by experts.

2.2.2 Reference System Based on Three Key Attributes

The reference system is based on three attributes: production volume, customisation, and complexity. These attributes represent the sides of a cube, creating eight regions describing all types of manufactured products as seen in figure 2.5. Each product or component is then categorised based on these three attributes (Conner et al., 2014).

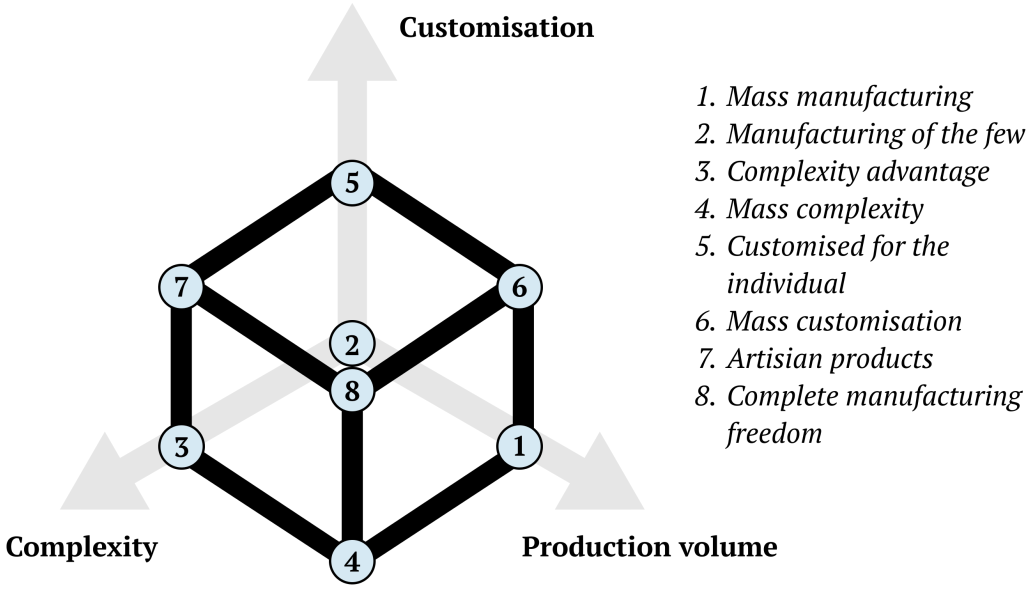


Figure 2.5: Attributes combined into a cube with marked regions

The **production volume** is the number of components produced in a given timeframe, which depends on the lot size and order quantities (Conner et al., 2014).

The **level of complexity** of a component is defined according to a number of parameters. The value called modified complexity factor (MCF) can be calculated as seen in equation 2.1 to 2.4. AM is likely to be cost effective for components with an MCF value greater than 44 (Conner et al., 2014).

$$MCF = w_0 + w_1 * C_{CR} + w_2 * C_{AR} + w_3 * C_{NH} \tag{2.1}$$

C_{CR} is the component volume ratio, calculated as 1 minus the volume of the final component divided by its bounding box volume.

$$C_{CR} = 1 - \frac{V_c}{V_b} \tag{2.2}$$

C_{AR} is the area ratio, calculated as 1 minus the surface area of a sphere with equivalent volume to the manufactured component divided by the surface area of the component.

$$C_{AR} = 1 - \frac{A_s}{A_c} \tag{2.3}$$

C_{NH} is the number of cores parameter. It is determined by the number of holes or slots that would require a core in the case of casting.

$$C_{NH} = 1 - \frac{1}{\sqrt{1 + N_H}} \tag{2.4}$$

The weights, w, determine the importance of each parameter and can be seen in table 2.1. They were calculated using multiple regression analysis of 40 cast components of varying complexity (Conner et al., 2014).

Table 2.1: Parameters for the complexity equation

Parameters	
Weight	Value
w_0	5.7
w_1	10.8
w_2	18.0
w_3	32.7

The **level of customisation** is divided into 5 different levels in this method. The levels are based on literature and online search of different customised products. Conner et al. (2014) state the levels and the related descriptions included in table 2.2.

Table 2.2: Levels of customisation for a product

Levels of customisation		
Level	Name	Description
0	No customisation	Components where the customer has no input on the design, such as commodity products.
1	Pre-defined options	The customisation is limited to a few pre-defined options, such as the choice between a few colours for the components.
2	Limited customisation	The components have only one feature that is customisable.
3	Greater freedom of customisation	For components for which a number of features can be defined by the customer.
4	Random customisation	Components in this category are truly unique, such as personalised human implants.

A component is assigned to a region of the cube based on the production volume, level of complexity and customisation. Conner et al. (2014) mentions eight regions where AM or CM is recommended to different extends, these are described in table 2.3.

Table 2.3: Regions of the cube

Regions of the cube		
Region	Name	Description
1	Mass manufacturing	Non-customised, simple components produced in large volumes. CM is preferable, but AM can still be used to produce tooling to reduce lead time.
2	Manufacturing of the few	Components with limited complexity and customisation but produced in small volumes. A cut-off volume can be calculated to determine when AM is economically beneficial.
3	Complexity advantages	Components that are more complex. If the component consists of multiple welded parts, AM might be beneficial to reduce the number of parts and hence reduce welding time and increase component quality.
4	Mass complexity	Complex products, produced in large volumes.
5	Customised for the individual	Components produced in low volumes with low complexity but high customisation.
6	Mass customisation	Components that are produced in large volumes but each component is customised
7	Artisan products	Components that are highly complex and customised.
8	Complete manufacturing freedom	Components are highly complex, customised and produced in large volumes. AM enables the customisation and complexity, but it is still problematic with the large volumes.

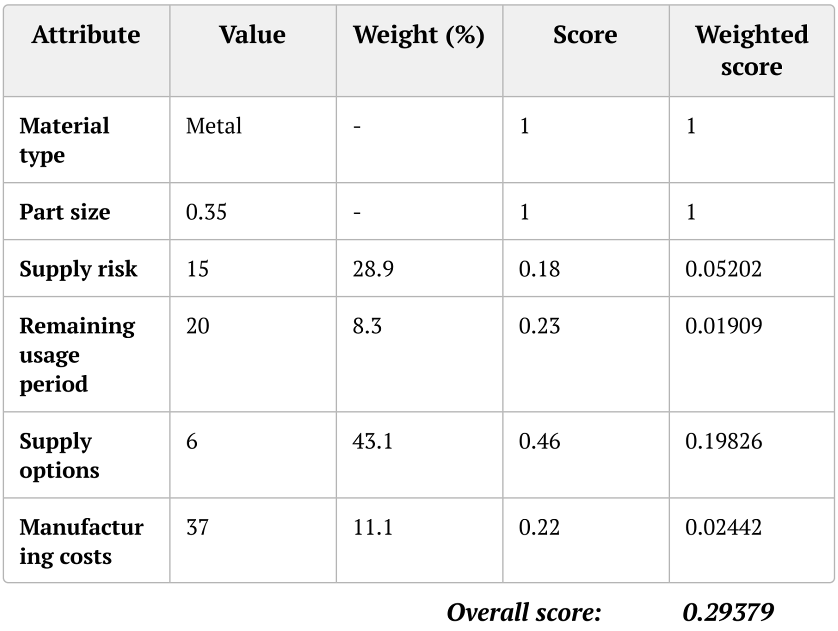
If a component is redesigned for AM and becomes more complex, it might change to a "higher" region and hence it will probably be more beneficial to utilise AM. Regarding region 1 CM is recommended, while AM is recommended for region 5 to 8. For the other regions, each case has to be further investigated. The accuracy of the method can be improved with even more levels of complexity and customisation (Conner et al., 2014).

2.2.3 Scoring Method

Knofius et al. (2016) have created a scoring method, which uses a top-down approach to identify promising spare parts from a large collection of possible options. The method is easy to use since it solely requires information typically found in the standard information system. Depending on the available information in the databases the attributes included in the method can be adapted. However, the potential benefits from design changes are not included. Instead, it is proposed to combine this method with other procedures to capture the performance from the design change.

The scoring method mainly consists of an assessment including specific attributes, for which the spare parts get evaluated. The spare part receives a score for every attribute, given by the obtained information from the database. There are two different kinds of attributes, the Go or No-Go attributes and the spare part attributes. Go or No-Go attributes are crucial AM technical constraints, such as part size. The resulting score for these attributes is binary, either a 1 meaning the value is within the feasible range or a 0 if not. Moreover, the spare part attributes are used to assess the performance of using AM from a spare part management perspective. For example, the number of supply options and manufacturing per-order costs are attributes included. The score resulting from the spare part attributes is created by linear scoring in the range from 0 to 1, which is normalised depending on the best (1) and worst (0) values of the other spare parts. To account for the company goals, the spare part attributes have been assigned a weight that represents their importance in relation to others (Knofius et al., 2016).

Lastly, the overall score of the spare part is calculated. Firstly, a singular is given by multiplying all scores of the Go or No-Go attributes. Secondly, each spare part attribute is multiplied by the corresponding weight and later all attributes are summarised. To get the final score the singular from the score of Go or No-Go attributes is multiplied by the sum from the score of spare part attributes. These final scores can be used for ranking components (Knofius et al., 2016). Figure 2.6 shows an example including all attributes and the score.



Attribute	Value	Weight (%)	Score	Weighted score
Material type	Metal	-	1	1
Part size	0.35	-	1	1
Supply risk	15	28.9	0.18	0.05202
Remaining usage period	20	8.3	0.23	0.01909
Supply options	6	43.1	0.46	0.19826
Manufacturing costs	37	11.1	0.22	0.02442

Overall score: ***0.29379***

Figure 2.6: Example illustrating the attributes and the score for the scoring method

2.2.4 Other Existing Methods Including Evaluation Criteria

There are several other existing methods containing criteria for selecting suitable components for AM. Klahn et al. (2014) state four selection criteria connected to design for identifying promising components. Each criterion implies a potential improvement of the overall system when redesigning the component for utilising AM. Moreover, a specific component can get assigned to several criteria. The first criterion is integrated design, meaning several functions are unified in a design. The second criterion is individualisation, which is a customised design implying minor variation among components. The third criterion is light-weight design, where the material usage is reduced to only cover necessary parts. The fourth criterion is the efficient design, improving the efficiency of the product while in operation.

Senvol (2022) lists seven beneficial scenarios to utilise AM, which can be used as criteria for evaluating the suitability of a component. These scenarios are connected to possible achievable supply chain benefits and hence try to capture the advantages by using AM. The scenarios are: expensive to manufacture, long lead times, high inventory costs, sole-sourced from suppliers, remote locations, high import or export costs and improved functionality.

Reiher et al. (2017) describe that the decision of when to utilise AM should be based on a systematic selection process to decide the best combination of the design, material and manufacturing technique. This can be done by a two-stage process in which the listed components are first narrowed down based on criteria such as size, cost, and demand properties. The TOM by Lindemann et al. (2015) is mentioned as one example to achieve the first stage. Thereafter, the suitability of AM for the remaining components is evaluated based on the costs and benefits by AM experts. In addition to these stages, there is a template which captures the necessary information about the component. It includes the key characteristics such as a picture, the name, number for the CAD-model, and the main function.

Materialise (n.d.) is the creator of the tool "3D Print Barometer" available for everyone at their website. This is used to quickly evaluate the suitability of producing a component with AM. The components are assessed based on the size, design, project value, series size and purpose. For each criterion, there is a set of predefined possible alternatives to answers, from which the user can choose. All alternatives have a clear description of the definition and a reference to compare your component with. For example, the alternatives to choose from regarding the component size are a ping pong ball, tennis ball, football or space hooper. When the user has filled in all criteria, the tool calculates both the suitability percentage of each criterion and in total. Moreover, a recommendation for the assessed component is given.

3

Methods

The method for performing the master's thesis project is inspired by the generic product development process described by Ulrich et al. (2019). In this method, steps are performed to conceive, design and commercialise a product. However, this method has been adapted to meet the needs of this project and the particular circumstances. Thus, this method has been transformed into three phases: exploration study, development of the recommendation tool, and testing and evaluation. Together they cover all relevant steps needed for completing this project.

The first phase **exploration study** is about exploring the field through research, and collecting all of the required information for the development of the recommendation tool. The second phase **development of the recommendation tool** consists of the actual development and creation of the recommendation tool. The third phase **testing and evaluation** is about testing the recommendation tool to understand possible improvements regarding usability, and thereafter evaluating the performance of the recommendation tool. All phases and the performed activities can be seen summarised in figure 3.1. The phases have been overlapping and thus worked on concurrently as the project proceeded. Moreover, the second phase required many iterations before reaching a pre-final version for testing and evaluation. Thereafter, the recommendation tool was refined into the final version, which is the one presented in this report.

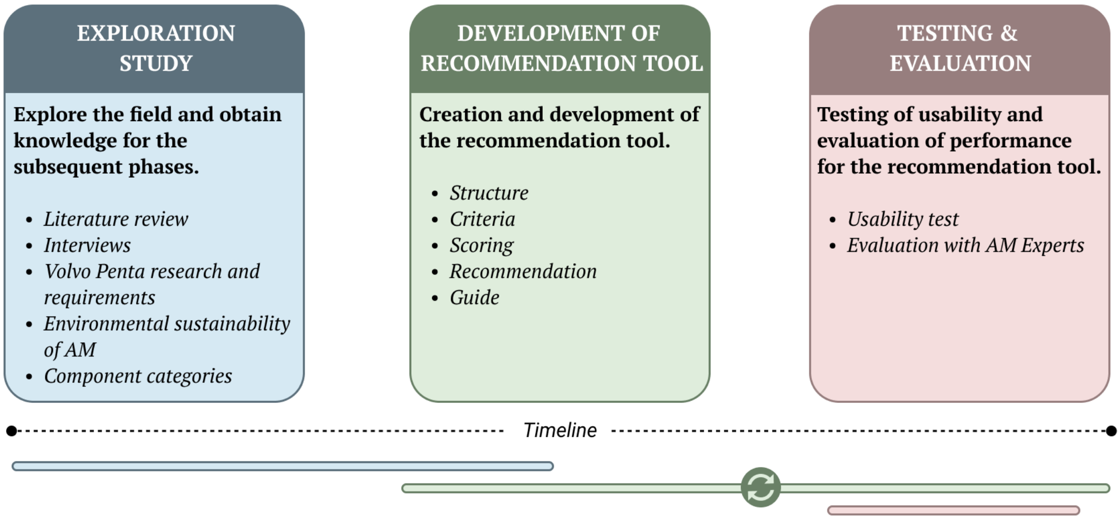


Figure 3.1: The phases in the master's thesis project

3.1 Exploration Study

First, an exploration study was conducted to obtain the necessary knowledge required for the further procedure. A bottom-up approach was used to identify relevant articles to read and to start exploring the field. Therefore, the initial approach was to perform the research from a broad perspective, and later narrow it down to identify more specific fields. Moreover, the exploration study consisted of several activities, which were performed to obtain the necessary knowledge. To begin with, a literature review about AM was carried out together with interviews with experts within the field of AM. Concurrently, research about Volvo Penta was accomplished to understand the company, and decide upon the requirements and wishes for the recommendation tool. Lastly, environmentally sustainable advantages of AM were assigned to phases of a product life cycle. Based on this the component categories, that later were used in the recommendation tool, could be created.

3.1.1 Literature Review About AM

In the beginning, a literature review was performed to explore existing knowledge within the AM field. Therefore, general keywords such as "additive manufacturing", "3D printing" and "advantages and challenges with AM" were used in the databases Scopus and Google scholar. The aim of this phase was to get the basic knowledge of the AM technology, possible applications, advantages and challenges, to understand the possibilities of AM. Concurrently to this search, AM technologies and the industrial applicable machines were studied. This was done to explore the possibilities in the current state of AM technology. After obtaining experience within the broad field, sustainable applications of AM were explored. During this phase, the focus was to understand how AM can be used to reduce the environmental impact of products. Different possibilities were identified along the product life cycle.

The next phase was to focus more on a specific field, and thus articles about existing guidelines for part selection for AM were studied. Initially, articles summarising multiple guidelines were read, and from these sources more specialised articles could be found. Moreover, keywords such as "part selection for AM", "AM guidelines", "methods for selecting guidelines" and "identify parts for AM" were used. This was explored to get inspiration for the development of the recommendation tool. At the end of this phase, interesting parts from relevant sources were summarised into a mind map to collect the obtained knowledge.

3.1.2 Interviews

In addition to the literature review, several interviews were held with experts to further explore the field of AM. All the participating experts work in areas related to AM, although they have different perspectives and experiences. Information about each of the participants is presented in table 3.1. The variety of perspectives enables capturing a broader area and getting dispersed insights. Since the interviews were focused on different areas, each one was prepared separately and contained unique questions. However, all interviews were semi-structured due to the ability to obtain answers to existing questions while still exploring the field. Thus, questions were prepared as a base, but the interview was not limited to only these questions. As the interviews progressed additional questions were asked to build on to the answers.

Table 3.1: Information about the held interviews

Interviews		
Participant	**Title**	**Topic**
AM Researcher	Professor in Powder Metallurgy and Additive Manufacturing	Current industrialised AM technologies, machines on the market and requirements for a component to be produced with AM.
AM Expert	Doctor in Surface Technology and Principal Materials Engineer	General advantages of AM and applications of AM in the industry.
AM Designer	Doctor in Materials Chemistry and AM Specialist	Process of evaluating a component for AM, criteria to consider in the process, designing for AM and applications of AM in industry.
AM Powder Expert	Adjunct Professor in Materials Science	Recycled material in powder production, environmental impact in powder production and data from the production.

A total of four interviews were held in person with the participants. The first interview was with the AM Researcher, which focused on the current industrialised AM technologies and the requirements necessary for the component to fulfil in order to be possible to produce with AM. The second interview was with the general AM Expert, and thus it focused on the experienced advantages and applications of AM. The third interview was with the AM Designer to understand how the components get selected from the design perspective. Lastly, an interview was held with the AM Powder Expert to understand the relationship between environmental sustainability and powder production. During the interviews notes were taken to document the answers, but these have been excluded from the report due to confidential reasons. Instead, the main insights from each interview were summarised.

3.1.3 Research About Volvo Penta and Requirement Specification

In parallel to these previously described phases, research about Penta was conducted through different activities. Several courses from Volvo Penta were attended which included information about the available products and the organisation structure. Moreover, meetings were held with Volvo Group employees at different departments. For example, a meeting was held with an employee at purchasing to get insights about the supply chain at Volvo Penta. The Volvo Penta workshop was visited to have a look at a dissembled engine, to identify all existing components and integrated systems in the engine. All of these activities were performed to partly obtain knowledge about the Volvo Penta D6 and D4 engines, and partly to understand the current use of AM within the organisation. In addition, it was also important to understand the needs of the company as well as its visions regarding sustainability.

To collect Volvo Penta's needs and expectations regarding the recommendation tool a requirement specification was created. In this, all requirements and wishes of the recommendation tool were listed together with a description of how each will be fulfilled. The requirement specification list was iteratively improved until the final version got approved by Volvo Penta. The list was further used as a guide during the development of the recommendation tool, mainly to identify essential features and to distribute resources. All of the requirements were crucial to fulfilling, while the wishes would add value to the recommendation tool.

3.1.4 Potential Environmental Sustainability Advantages of AM During the Product Life Cycle

All potential sustainability advantages of AM were collected during an idea generation session. This session was based on the knowledge obtained during the literature review. Thus, it started with listing all advantages of environmental sustainability that could be identified based on the general advantages, or that were already mentioned in the literature. After that, these were divided into different phases in the product life cycle, to highlight in which phase each advantage can have a positive impact. To organise the list and to easily differentiate among the advantages, each phase got assigned a specific letter and then the respective advantage in each phase got named after the letter and an additional number.

3.1.5 Component Categories

The previously identified advantages of environmental sustainability during the product life cycle were used as inspiration to create the main criteria for the recommendation tool. Thus, a set of component categories were identified as the main criteria for identifying environmental sustainability potential of AM. Moreover, each component category got a description to define which components belong to each. As a final step, the listed advantages were assigned to the component categories to ensure all advantages were included in at least one category.

3.2 Development of the Recommendation Tool

The development of the recommendation tool was performed in an iterative process, in which inspiration from the existing methods, requirement specification and component categories were used as the base for building the recommendation tool. The structure was created together with a system for handling data. To identify if there is an environmental sustainability potential of AM, different filters were created to first eliminate non feasible components, and thereafter evaluate the remaining ones. Therefore, a scoring system was developed together with some recommendations based on the identified potential. Lastly, a guide was created to support the user during the usage of the recommendation tool.

3.2.1 Creation of the Recommendation Tool

The tool was created in Excel and consisted of four sheets. A main sheet was created as a form, where data should be filled in by the user. This sheet was divided into three steps, from 0 to 2. Step 0 was created to briefly describe the component, step 1 acted as a first filter with elimination criteria and step 2 was a second filter for evaluation. For step 1 and 2 criteria were needed for the elimination and evaluation of the components. Step 2 was divided into the component categories, from the exploration study, with belonging sub-criteria for each. The sub-criteria were created to capture the associated sustainability advantages of each component category. Moreover, the sub-criteria were further developed in collaboration with Volvo Penta to adapt the recommendation tool to their design engineers, products and processes. Each criterion was assigned a scoring range, generating a score as the user fills in the form. The main sheet was thereafter programmed so that a mean score for each category will be displayed together with a recommendation. To improve the usability of the fill in form, the cells that need to be filled in were marked in light green while the other cells were kept white. The mean scores for the different categories were coloured from red to green to support the interpretation of the result.

To perform elimination and evaluation, data were needed for the different criteria. Therefore, all required data were collected in a second sheet. The process specific data was based on the interview with the AM researcher and the material specific data was obtained from the database Granta EduPack. To ease the understanding and programming of the recommendation tool, another sheet was created to extract the data specifically need for the material filled in by the user. A last sheet was created to act as a support containing information about eligible levels for some criteria.

3.2.2 Scoring

For all criteria, the possible scores are integers from 0 to 5. The score 0 will not be a part of the evaluation and is equal to the score the user receives when not filling in data for one criterion. The score 1 means that there is no identified potential for AM and 5 means that there is high potential for AM. The scores in the range between these extremes are equally distributed, hence the score 3 is neutral. The scoring was set in different ways depending on the criteria being answered by engineering judgment or with a numerical value.

For criteria with numerical values or where the user has to decide upon a level of a certain statement, a scoring range from 1 to 5 was applied. For the numerical values, the values required for the different scores were set based on discussions with Volvo Penta employees, on existing methods, and by benchmarking comparing values for different components. For the statement criteria, the Likert scale was used. The Likert scale is a way to assess the user's view by using the two most extreme cases and having intermediate options in between, with a neutral option in the middle (Joshi et al., 2015).

For criteria that were displayed as questions, the answer options were either yes or no, or with three different statements. For the yes or no options, the scores were set to 5 for yes and 0 for no. When three statements were eligible, the scores were set to 5 for the option resulting in the largest AM benefits, the middle option was scored 3 and the worst one 0. These questions evaluate "bonus"-possibilities with AM such as the possibility of improving the performance, using topology optimisation or part integration. If any of these applies to the investigated component a significant "bonus" should be added to the score as these features can bring large value. However, the absence of one possibility should not reduce the total score as no component will have all of these "bonus"-possibilities. For the questions with three statements, the middle option add a lower value to the score as it is not certain that this AM possibility will be possible to benefit from.

For the manufacturing processes, a more complex scoring was developed. Each process was evaluated based on four criteria; the amount of scrap created during manufacturing and due to quality issues, the energy intensity of the process, if any complex special tools are needed, and the existence of emissions from gases or liquids. The scoring was done in collaboration with Volvo Penta, and thus based on their knowledge about their currently used processes. Moreover, the number of manufacturing processes used for an investigated component influenced the score.

3.2.3 Recommendation

A recommendation of how to proceed based on the mean score of the different component categories will be provided to the user. To get an overview of the result the user should analyse the mean scores for component categories both individually and together. Therefore, a table was created where the interpretations for different ranges of mean scores are given. From this, the user can analyse the mean scores for each component category to identify the potential for AM. Thereafter, guidelines are listed regarding analysing all component categories together. Moreover, to support the further step in the development of the component, design recommendations are provided for component categories receiving a high mean score. For some component categories, it is crucial to redesign the component to capture the benefits, while in others redesigning a component may require more work than the provided benefits. The purpose of the recommendations is that the user should be able to understand the result and take a well informed decision.

3.2.4 Guide

A guide was created to improve the usability of the recommendation tool. The objective was to include all necessary information about the recommendation tool to support the user. Therefore, the guide should prevent the user to interpret the criteria individually when those are not clear. Moreover, the guide should show the user where the data can be retrieved, to ensure that the same type of data is used for a criterion. The main reason for this is to obtain a similar result independent of the user and to enable comparison between different components.

The guide was created during a session where the recommendation tool was filled in for a specific component. Thus, each criterion was analysed regarding how to interpret the description, what each answer means, and where the data can be found. The findings during the session were documented and later refined into the guide.

3.3 Testing and Evaluation

Several tests were performed to examine the usability of the tool and to evaluate its performance. In this chapter, the processes of planning, executing and analysing both tests are presented.

3.3.1 Testing Usability

To investigate the usability of the recommendation tool, the design engineers at LDEP department were requested to participate in a user test. In particular, the understanding of the questions and the ease of accessing the data requested were of interest to evaluate. During the user test, the participants tried out a pre-final version of the recommendation tool by filling in data for two different components. Each component was part of a predefined case with a project description, to simulate a real situation. However, these cases were not based on reality. In addition, the guide was attached which described the overall usage of the recommendation tool, how to interpret the questions and where to find the requested data. Moreover, the participant was requested to answer a couple of questions in a question form about themselves, the user experience of the tool and the guide.

There were in total four participants with different experiences regarding the product, design and AM. Two participants filled in the recommendation tool independently and sent the result without any communication during the process. This captures the actual future situation, where it is necessary for the user to interpret the information without support from the developers. To discover hidden problems and get an understanding of the process, the two other participants were observed while filling in the data.

The combination of user tests implies an overview of the usability, from which the result could be analysed. Mainly, the filled-in data in the recommendation tool was compared among the participants to detect differences and similarities. This was done together with a comparison of the question forms as well as the observations. Everything was organised together in documents to ease the comparison. From the analysis of the result, it was possible to identify problematic criteria and formulations as well as possible improvements. Thus, both the tool and the guide got improved based on this feedback.

3.3.2 Evaluation of the Recommendation Tool

To determine the accuracy of the results obtained from the recommendation tool, they were compared with the opinions of the experts in three evaluation sessions. The AM Researcher, AM Expert and AM Designer were asked to bring a component to an evaluation session. During each session, the expert filled in the recommendation tool for their chosen component. This was done during an observation in which the expert was allowed to ask questions to prevent any misunderstandings and ensure the recommendation tool was filled in correctly. Once the tool was filled in, the expert explained their opinions regarding the components' suitability for AM and this was compared with the mean score for the different component categories of the tool. A discussion was held regarding the reasons that the expert thought the component was suitable or not for AM and how they correlated to the result of the recommendation tool. By comparing the three results of the recommendation tool with the expert opinions, it can be evaluated whether the recommendation tool reflects an AM expert opinion.

4

Results

In the previous chapter, the methodology is described, which consists of the three phases: exploration study, development of the recommendation tool, and testing and evaluation. Each phase includes different activities, and thus several results are given from performing these. Figure 4.1 shows a summary of the results for the phases, which are presented further down in this chapter.

EXPLORATION STUDY

- *Summary of existing methods*
- *Insights from experts*
- *Requirement specification*
- *Identified potential sustainable advantages of AM*
- *Component categories*

DEVELOPMENT OF RECOMMENDATION TOOL

- *The recommendation tool: Information about the component, elimination and evaluation*
- *Scoring*
- *Recommendations based on the scoring*
- *Guide*

TESTING & EVALUATION

- *Insights from potential users*
- *Comparision between recommendation tool and experts*

Figure 4.1: Summary of the result from each phase

4.1 Exploration Study

The result of the exploration study covers several areas of interest. Firstly, a summary of the existing methods from the research is presented, which were later used as inspiration for the recommendation tool. Thereafter, follows the insights from the held interviews with experts within the field. Moreover, a requirement specification states the identified requirements and wishes. Finally, the potential environmental sustainability advantages found in the research have been assigned to the different phases in the life cycle. In addition, the component categories are identified based on these advantages.

4.1.1 Existing Methods

The exploration study regarding the existing methods resulted in a summarised mind map, seen in figure 4.2, covering all of the relevant existing methods for selecting components. The following mentioned sources, do all contribute with important insights to the creation of the recommendation tool. To begin with, the **TOM** by Lindemann et al. (2015) gives inspiration regarding how the criteria can be divided into primary main criteria containing several sub criteria with more detailed questions. Moreover, the structure of the evaluation sheet with several sections makes it easier to get an overview and find information. In addition, the template from Reiher et al. (2017) includes key characteristics about the component in the upper section, which concisely collects all basic information needed for the quick evaluation.

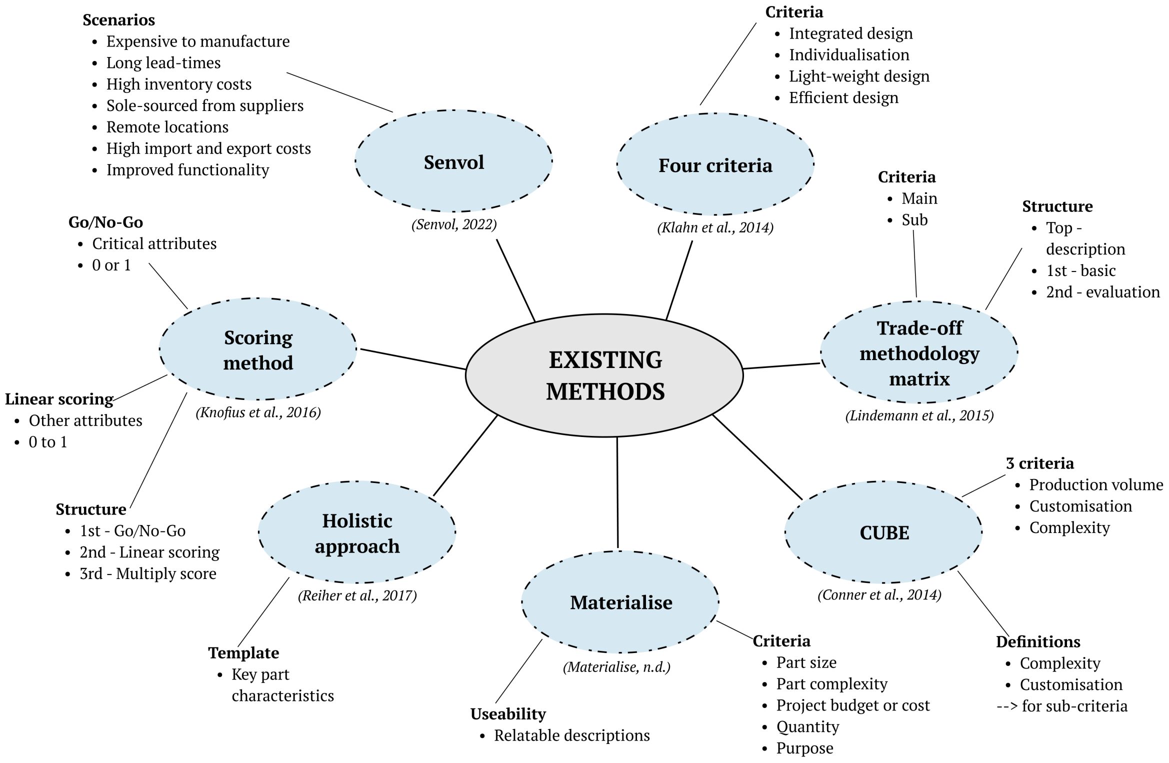


Figure 4.2: Mind map of the sources contributing with insights to the development of the recommendation tool

The **three reference system** created by Conner et al. (2014) shows how the relation between the attributes customisation, complexity and volume can affect the recommendation. For this article, the different ways of measuring the attributes are especially interesting for the further development of the recommendation tool. The complexity equation provides the possibility to decide the design complexity by using numerical input. Thus, the user will not need to determine it based on experience and engineering judgement.

Another inspiring method to identify promising parts is the **scoring method** created by Knofius et al. (2016). Especially the structure, including different kinds of attributes and having an overall score, was of interest. The division by having Go or No-Go attributes for elimination, and part attributes for evaluation is a good approach to deciding the suitability of a component for AM. This since the scoring between them differs according to their importance, and thus will affect the total score in various ways. However, the user needs to fill in all information before getting a result, which could be a waste of time in the case of components not passing the elimination.

Several sources include interesting criteria for part selection within different areas. The seven stated scenarios from Senvol (2022) give inspiration related to either the manufacturing process or supply chain. Criteria in these areas can be extracted based on the scenarios. In the same way, the four criteria described by Klahn et al. (2014) can be the base for criteria related to design. Moreover, the tool created by Materialise (n.d.), includes a mix of important criteria for several categories. In this case, the clearly defined ranges of values and pictures visualising the different alternatives to answer improve the usability of the tool.

4.1.2 Interviews

From each interview, insights regarding the different fields could be retrieved, which are summarised and presented below.

In the interview with the **AM Researcher**, insights were obtained about the current industrialised AM technologies and limitations when producing a component. The AM Researcher states that the two main AM technologies applied in the industry are BJT and PBF. However, there are other technologies in development that may be interesting in the future. In addition, the AM researcher points out that not all machines available on the market have the same maturity.

Further, the researcher describes the compatibility with AM of a component will highly depend on its size and the material, which both must be printable. In the case of PBF the building chamber can be a limiting factor, which differs among materials. However, the build chamber is not necessarily the limiting factor when the laser cannot cover the whole space. Then it is the field of vision for the laser that limits the component size. For now, the most common size of build volume for steel, titanium, brass, bronze, copper and nickel alloys is 250 x 250 x 350 millimetres, and 600 x 600 x 600 millimetres for aluminium. The differences in size are due to that aluminium is less prone to residual stresses. In the case of Binder Jetting the building chamber is not the limiting factor, instead the fragility of the "green" component and the post processing will limit the size to 50 x 50 x 50 millimetres for all metals.

The interview with the **AM Expert** gave insights regarding the different advantages and applications of AM within the mobility industry. At first, the AM Expert discussed that the experienced advantages of AM are related to energy saving, optimisation, material utilisation, functionality, and small series. Energy can be saved due to the on-off technology since the AM machine does not have to be operating all the time, like a furnace. Moreover, energy can be saved during the user phase if the vehicle weighs less and thus consumes less fuel. To reduce the weight, improvements in the design such as topology optimisation can be implemented for each component. In addition, material waste can be reduced during manufacturing by solely using material where it is necessary. Since it is possible to print complex designs, this allows the designer to create a design with improved functionality. For example, it is possible to create internal channels for cooling or measuring. The AM Expert further describes how AM has been an advantage for small series. Especially, when there is a desire to receive them quickly, or when the required tools are not available.

Thereafter, several examples of applications for AM were given by the AM Expert. The first application is a bracket for a cooling pipe, which fractured for the customers using the product in a certain environment. A containment action was needed to deliver an equivalent bracket with improved performance in a short amount of time. Thus, AM was used to iterate a new design with better functionality, and a shorter lead time compared to CM. Another application was a component for which the scenario created an opportunity to use AM. Initially, the component was presumed to be casted, but since there were no tools available and delays in production, AM was considered as the better alternative.

The interview with the **AM Designer** gave insights regarding when to select AM instead of CM and the subsequent design process. The AM Designer describes that in the beginning a technical evaluation is needed to ensure no safety critical components are produced by AM. These components require extensive tests, which are expensive. Thereafter, the supplier delivers cost approximations for the components since these calculations are complex due to the many factors to consider. In addition, data from different departments at the company is collected to decide the suitability of AM. Some important parameters to consider are the lead time, annual quantity, material and performance. In the end, the AM Designer will use the result from this together with experience to decide if the component can be beneficially produced with AM.

For now, the AM Designer mainly experiences the utilisation of AM as a temporary solution. For example, when the company runs out of spare parts and a new supplier is needed, or when the lead time needs to be reduced for a specific project. However, when a decision is made that a component should be produced by AM the AM Designer usually experience a dilemma regarding redesign. In general, a component already has a certain design and a fit in the assembly. Therefore, it is desirable to preserve this design to avoid further quality tests. On the other hand, if the component is not redesigned it takes a long time to print which will affect the cost. In the case of a redesign, the work time can span from days to weeks depending on the component.

During the interview with the **AM Powder Expert** several insights were obtained regarding the environmental sustainability of powder. Firstly, it was discovered that there is no usage of recycled material when creating powder for AM for a mentioned producer. The expert stated this is due to the small amount of powder used within the AM industry in combination with the costs for analysing the powder composition to ensure quality. In addition, the current common applications for AM require alloys, that are both expensive and complex. Mostly because of the rich variation of compositions existing.

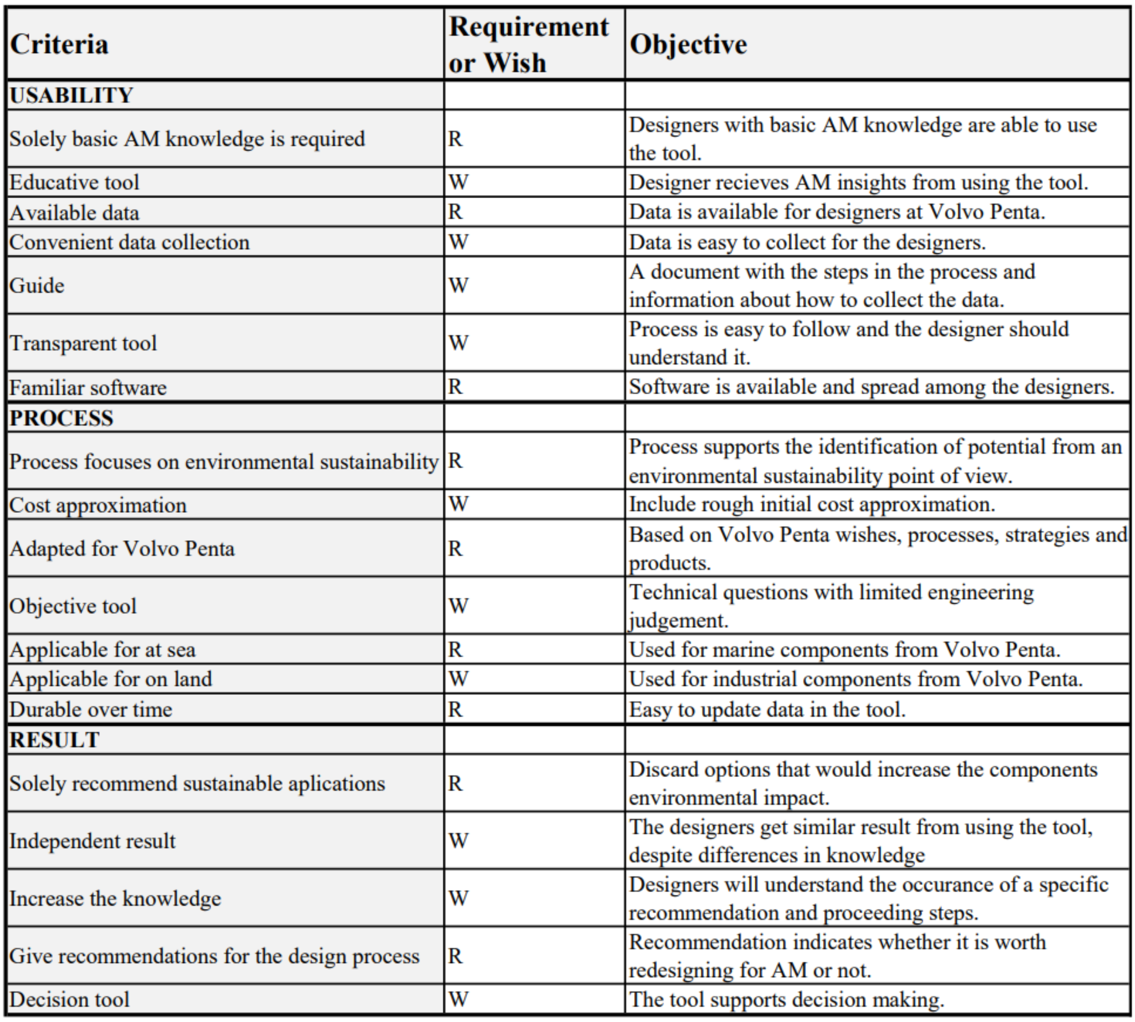
However, the AM Powder Expert claims it is possible to use solely recycled material to create the powder, which is already done in other manufacturing processes like pressing. Thus, the expert believes there are possibilities to close the loop of the material flow, if there are economic incentives making it more profitable to use recycled materials. Moreover, the development of administration for the system and material chain is necessary to enable an efficient recycling process. This is to reduce the cost of analyses and the amount of waste during the cleaning process. Potentially, the material can be recycled over and over again. The expert describes that the present greatest environmental impact depends on the electricity mix and the mining industry. Further, the AM Powder Expert discusses the difficulty of finding relevant and reliable data about the powder and the production process. This is due to that producers are unlikely to share data, and risk revealing confidential information.

4.1.3 Requirement Specification

The requirement specification, seen in figure 4.3, contains in total nineteen requirements and wishes for the recommendation tool. These are divided into three different categories: usability, process and performance.

In the first category, the criteria are focusing on how the usability of the recommendation tool should be measured. The requirements regarding usability are that the recommendation tool should be easy to use with basic knowledge of AM, all data needed should be available and the design engineers should be familiar with the software. It is also appreciated if the data can be found conveniently and if the design engineers get educated while using the recommendation tool. Moreover, a guide can help to improve usability, and transparency can lead to an increased understanding of AM.

In the second category, the criteria are related to the process of filling in the recommendation tool. Therefore, it focuses on what is included in the recommendation tool and how it should be applied. The requirements in this category are that the recommendation tool should focus on environmental sustainability, be adapted to Volvo Penta, applicable for products at sea and durable over time. It is also desirable if the recommendation tool includes a rough cost approximation, using limited engineering judgement, and can be applied to products on land.



Criteria	Requirement or Wish	Objective
USABILITY		
Solely basic AM knowledge is required	R	Designers with basic AM knowledge are able to use the tool.
Educative tool	W	Designer recieves AM insights from using the tool.
Available data	R	Data is available for designers at Volvo Penta.
Convenient data collection	W	Data is easy to collect for the designers.
Guide	W	A document with the steps in the process and information about how to collect the data.
Transparent tool	W	Process is easy to follow and the designer should understand it.
Familiar software	R	Software is available and spread among the designers.
PROCESS		
Process focuses on environmental sustainability	R	Process supports the identification of potential from an environmental sustainability point of view.
Cost approximation	W	Include rough initial cost approximation.
Adapted for Volvo Penta	R	Based on Volvo Penta wishes, processes, strategies and products.
Objective tool	W	Technical questions with limited engineering judgement.
Applicable for at sea	R	Used for marine components from Volvo Penta.
Applicable for on land	W	Used for industrial components from Volvo Penta.
Durable over time	R	Easy to update data in the tool.
RESULT		
Solely recommend sustainable aplications	R	Discard options that would increase the components environmental impact.
Independent result	W	The designers get similar result from using the tool, despite differences in knowledge
Increase the knowledge	W	Designers will understand the occurance of a specific recommendation and proceeding steps.
Give recommendations for the design process	R	Recommendation indicates whether it is worth redesigning for AM or not.
Decision tool	W	The tool supports decision making.

Figure 4.3: The requirement specification

In the last category, the criteria focus on the result from using the recommendation tool. Hence, it states how to measure the fulfilment of the desired outcome from utilisation. In this category, the requirements are that solely environmentally sustainable components should be recommended for production by AM and that the recommendation tool will state the need for redesign based on the outcome. In addition, it is preferred if the result is similar among design engineers with different experiences, gives a clear background leading to the outcome and supports the decision making process.

4.1.4 Potential Environmental Sustainability Advantages of AM During the Product Life Cycle

Based on the advantages and challenges of AM, it is clear that AM can offer great sustainability values in the different life cycle phases of components. During the idea generation session, the potential sustainability advantages of AM were identified and listed in the boxes A to E in figure 4.4. The following five phases reperesent the life cycle of a component: resource, manufacturing, distribution, use and end of life.

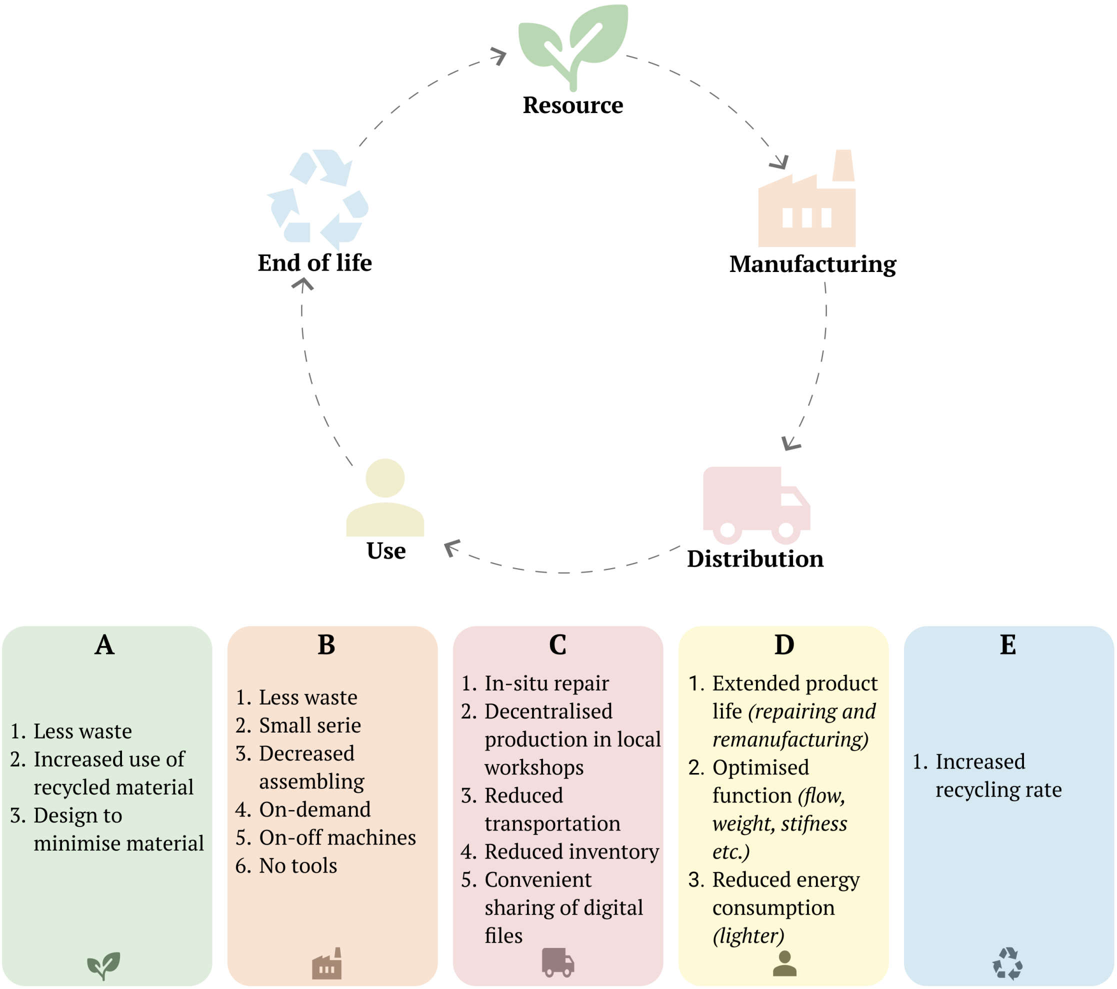


Figure 4.4: The identified environmental sustainability advantages of AM assigned to phases of the product life cycle

In the **resource** phase (A), AM can add value by reducing the need of new material resources. By redesigning for AM to make a lighter design, the amount of material needed can be reduced. As AM is an additive process, less material waste is produced compared to conventional methods. Moreover, the metal powder can be produced from recycled scrap and hence increase circularity. Since additive manufacturing allows the usage of less raw material, the benefits are most significant for components produced with energy and resource demanding materials or for conventional methods generating a lot of waste. The major advantages of AM in this phase are summarised to be: less waste, increased use of recycled material and design to minimise material.

The **manufacturing** phase (B) is where AM could have the most negative impact due to the high energy use per kilogram of final product. However, AM may still add some value in this phase. In cases of small series, the high energy consumption of AM may be compensated for by the absence of tooling and thus the energy required for the tool production. In CM, the production of tools is often necessary. Moreover, by printing all the parts at once or integrating components, the need for assembling decreases. This leads to shorter manufacturing processes, which may result in less energy being consumed. AM allows on-demand production which can reduce the need for inventory and hence the risk of overproduction. Furthermore, the AM machines are only using energy while producing products, unlike many furnaces consuming energy for maintaining a high temperature over time. To summarise this phase, the major advantages of AM are for small series production, decreased assembling, on-demand production, on-off machines, no tools and less waste.

Regarding the **distribution** phase (C), there are significant advantages. On-demand production decreases the need for inventory, which affects the number of warehouses and steps in the value chain. This leads to reduced transportation related to inventories. As AM allows small series, it is possible to decentralise the production to minimise the distance to customers. Files with CAD models can be sent digitally, and components can be printed on-site. This also allows for in-situ repair and more localised sourcing for the metal powder. However, it is important to consider whether decentralised production and localised sourcing are beneficial or not. They can pose inefficiency in the system causing larger total environmental impacts. The major advantages of AM for this phase are in-situ repair, decentralised production in local workshops, reduced transportation, reduced inventory, convenient sharing of digital files and localised sourcing.

The impacts from the **use** phase (D) can be decreased with AM if the product is designed to be lighter or if the life length is prolonged. Lightweight designs for moving parts can decrease energy and fuel usage. As AM can improve the technical performance of a component it can extend its use phase. Remanufacturing and repairing with AM are also two ways of prolonging the life of a product. The possible advantages of AM for this phase are thus extended product life, optimised function, and reduced energy consumption.

For the **end of life** phase (E), AM may offer an increased possibility of recycling. As mentioned before, metal powder can be produced from waste, and therefore it is possible to recycle the component to produce new powder again. By integrating parts, it is possible to make the whole component of the same material and hence facilitate recycling. However, the integration of parts may be negative as the whole component would have to be changed in case of failure, instead of just the affected part. Therefore, is it important to not integrate parts with different life expectancies that cannot be repaired.

In conclusion, the main advantages of AM are found in the resource, distribution, use and end of life phase, while the manufacturing phase could cause higher environmental impacts.

4.1.5 Component Categories

The five component categories identified are design and function, customisation or small serie, material reduction, manufacturing process, and supply chain as illustrated in figure 4.5. In each component category, the related sustainability advantages listed in figure 4.6 are assigned. Moreover, criteria within these component categories determine the possibilities of AM.

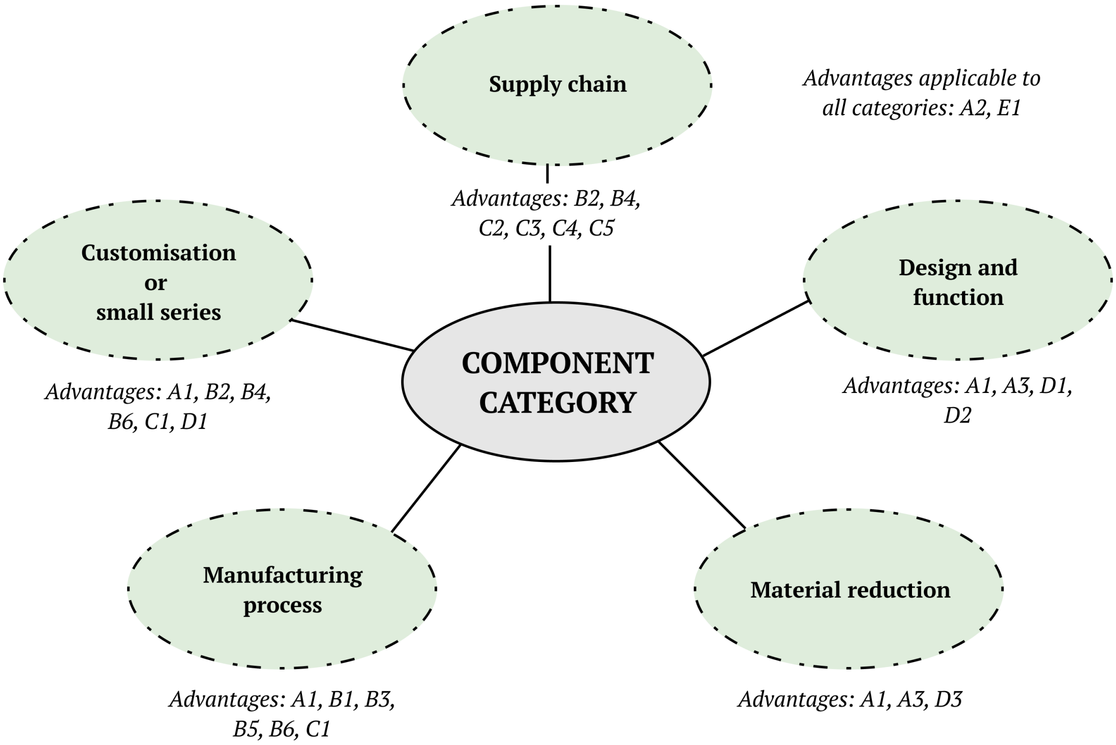
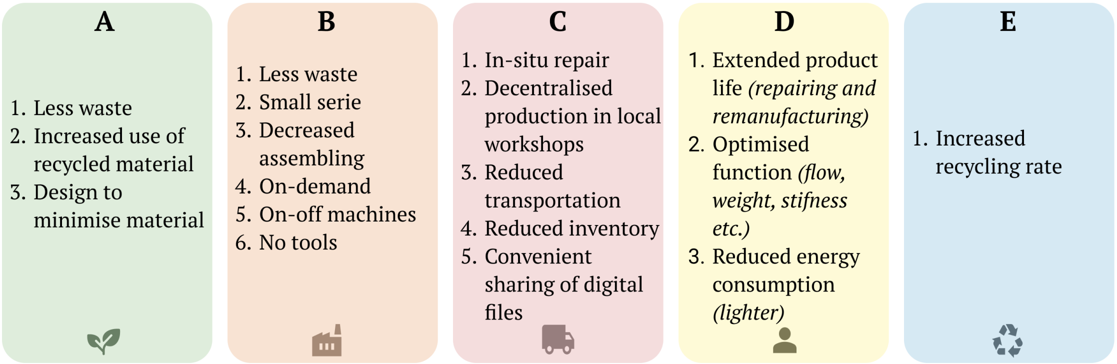


Figure 4.5: The five identified component categories



A

1. Less waste
2. Increased use of recycled material
3. Design to minimise material

B

1. Less waste
2. Small serie
3. Decreased assembling
4. On-demand
5. On-off machines
6. No tools

C

1. In-situ repair
2. Decentralised production in local workshops
3. Reduced transportation
4. Reduced inventory
5. Convenient sharing of digital files

D

1. Extended product life *(repairing and remanufacturing)*
2. Optimised function *(flow, weight, stifness etc.)*
3. Reduced energy consumption *(lighter)*

E

1. Increased recycling rate

Figure 4.6: The identified environmental sustainability advantages

The **design and function** category aims at identifying components currently having a complex shape or can be redesigned with increased complexity in order to improve their functionality. The design can be optimised in several ways to achieve improved functionality, such as topology and flow optimisation. Also, the possibility of integration for several components with similar functions is important in this category.

The **material reduction** category should identify components for which the design can be changed to reduce the material usage and create a lighter design. This can be dense original parts, due to the limitations in opportunities within CM, which are not required to consist of all material. The usage of lattice structures, hollows or other cavities can reduce the amount of material and thus a lower weight of the component can be achieved. This is especially interesting when the material used for a component has a high embodied energy.

The **customisation or small series** category aims at identifying components that Volvo Penta manufactures in small quantities. Customisation of components may lead to smaller series of a relatively large scaled produced components since each variant is manufactured in a smaller quantity. Moreover, spare parts that need to be produced in small quantities will be identified in this category. Components that require very complex tools in combination with being manufactured in small quantities are extra interesting from an AM point of view.

The **manufacturing process** category aims at identifying components having a complex manufacturing process, consisting of many steps during production and assembling. Components using more resource demanding manufacturing processes or producing a high level of scraps will be identified. The complexity of reaching a certain level of quality can lead to variations among components and thus more scraps in the production is important.

The **supply chain** category aims at identifying components with complex or uncertain supply chains. Suppliers that outsource a part of their production or are located far away from the production site, generally make the supply chain more uncertain. This since more and longer transports are needed and more partners are involved. In cases where a product is no longer in production or newly developed, the supply chain may not exist. The lead time is also an important part of this category.

4.2 Development of the Recommendation Tool

In this chapter, the resulting recommendation tool will be presented. First, the structure of the recommendation tool and the criteria are described. Thereafter the scoring related to each criterion is motivated, followed by the recommendations associated with the different scores. The final part explains the guide, which aims to support the user.

4.2.1 Creation of the Recommendation Tool

The recommendation tool consists of an Excel document with four sheets in total. The main sheet "fill in", the second sheet "level information", the third sheet "all data" and the final sheet "specific data". The "fill in" sheet is the form where the user fills in data and gets the final score. This sheet is divided into three major steps:

- **Step 0** - Information about the component
- **Step 1** - Elimination criteria
- **Step 2** - Evaluation criteria

The three different steps are presented in figure 4.7, which also visualises the structure of the recommendation tool. Tables with included criteria and possible answers for each step in the recommendation tool can be seen in appendix A. Figures for all steps showing the different criteria and fill in column are seen below. In addition to the fill in column, step 1 and step 2 have a result column to the right where calculations and scores will be generated as data is filled in. This result column is not shown, since no data is filled in.

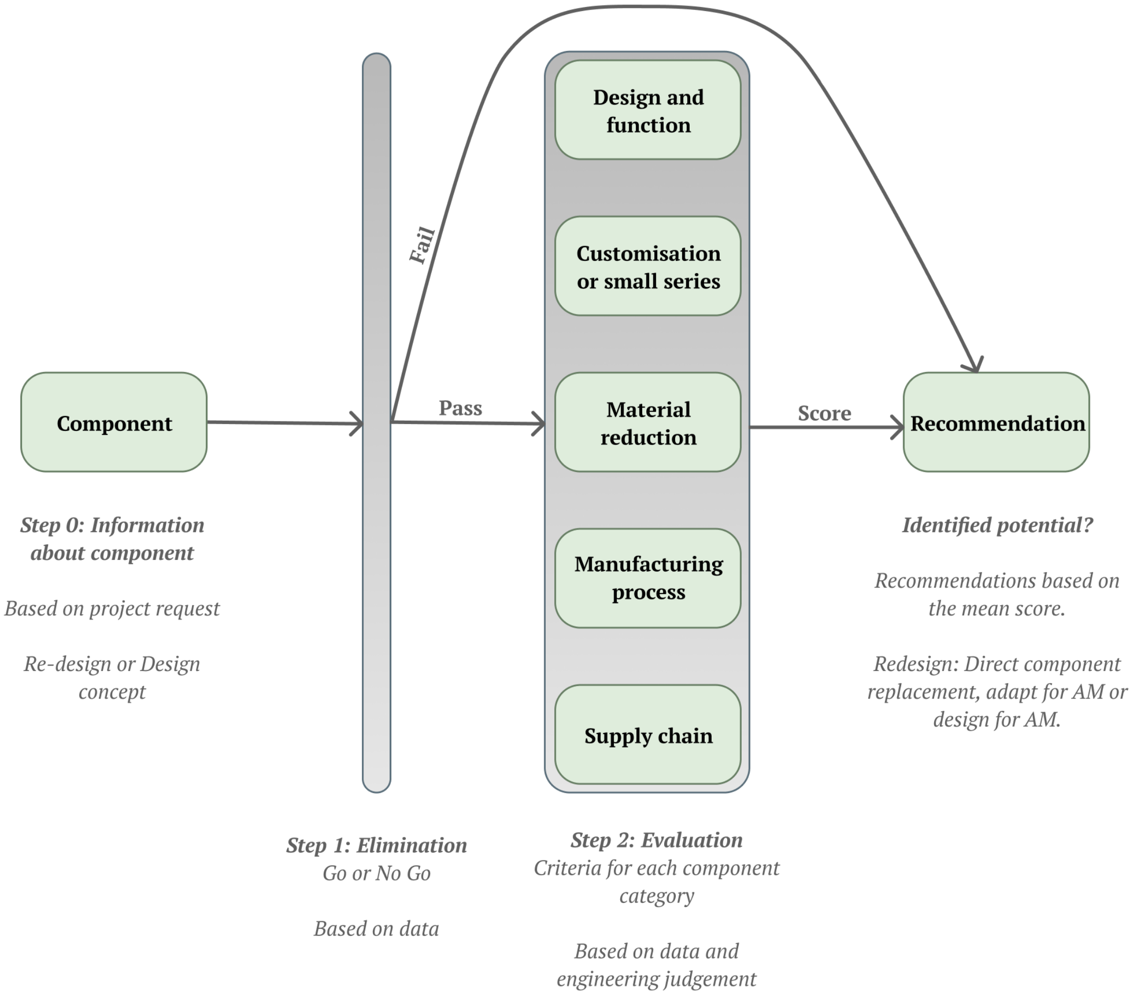
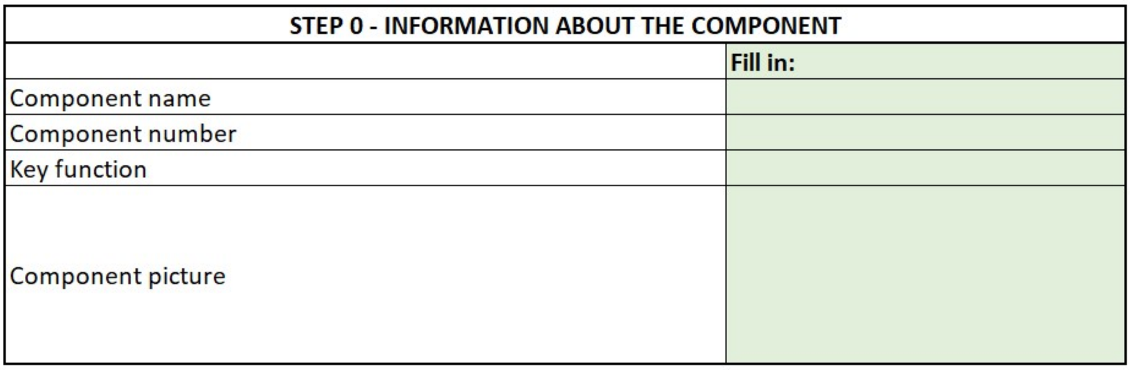


Figure 4.7: The process for deciding the potential for AM of a component

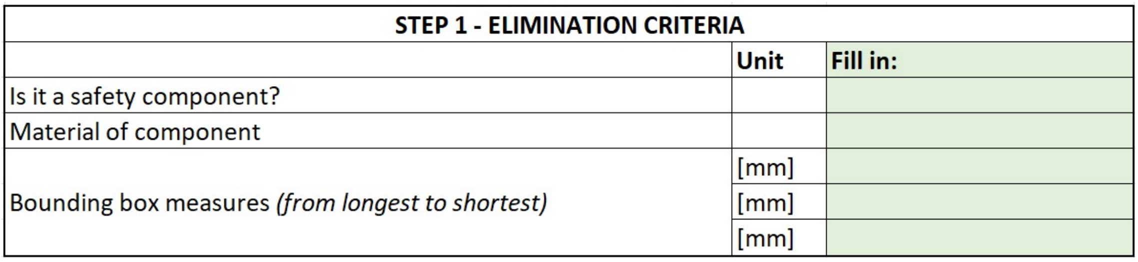
In step 0, the user is asked to fill in information about the component. This information does not count towards the final score, it is solely for the user experience and documentation. By filling in the component name and number, its key function and a picture, the user gets a clearer view of the component. It will also facilitate for others accessing the document and for communication, once the recommendation tool is filled in. Figure 4.8 shows the appearance of step 0 in the tool.



STEP 0 - INFORMATION ABOUT THE COMPONENT	
	Fill in:
Component name	
Component number	
Key function	
Component picture	

Figure 4.8: Step 0 - Information about the component

Step 1 with elimination criteria is the part of the recommendation tool where non feasible components for industrially available AM machines get eliminated. First, the user is asked to fill in if the component is a safety component. If it is a safety component, more extensive verification work will be required and hence a note about this will appear to the user. Thereafter, the user is requested to fill in the main material used for the component and its bounding box sizes. The eligible materials are different alloys of aluminium, steel, titanium, brass, copper, nickel and zinc. See appendix B for exact materials. For each of these materials, data about possible building dimensions for BJT and PBF have been collected. It will be visible to the user if a bounding box measure is exceeding the limits, as each measure generates a pass or fail in the result column. If the component passes all elimination criteria the user gets the recommendation to proceed with the next step. See figure 4.9 for the appearance of step 1 in the tool.

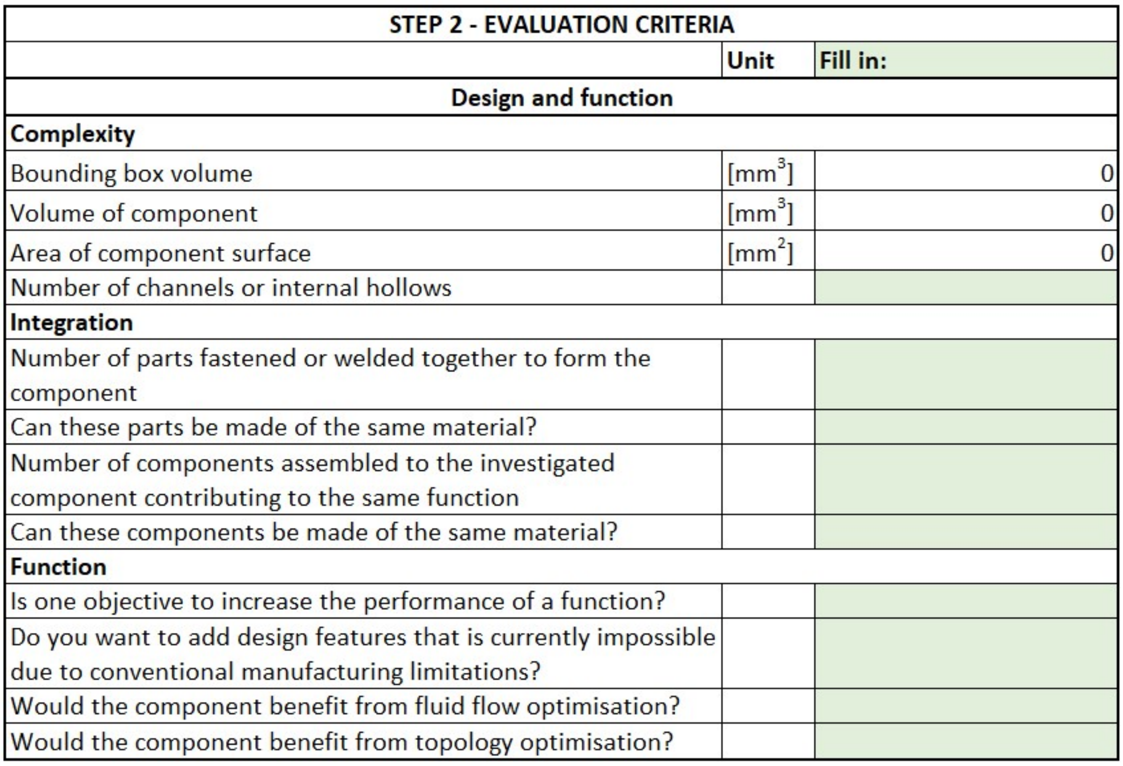


STEP 1 - ELIMINATION CRITERIA		
	Unit	**Fill in:**
Is it a safety component?		
Material of component		
Bounding box measures *(from longest to shortest)*	[mm]	
	[mm]	
	[mm]	

Figure 4.9: Step 1 - Elimination criteria

Step 2 with evaluation criteria is the part of the tool where the component is evaluated in depth. This part is divided into the five component categories identified in the exploration study.

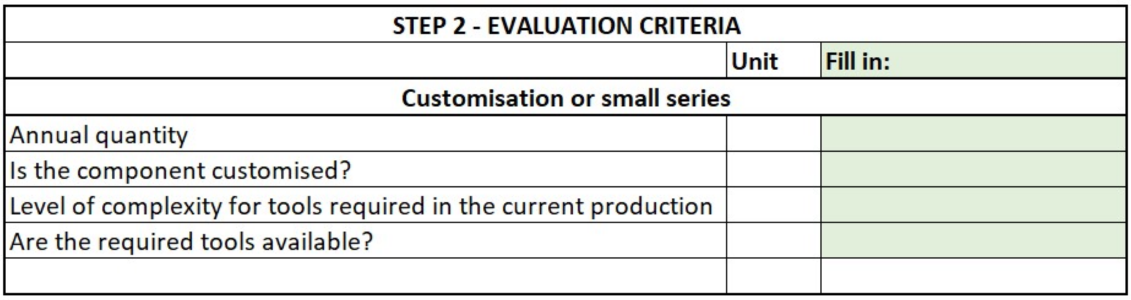
The **design and function** category is, as seen in figure 4.10, divided into three categories: complexity, integration and function. The complexity of the component is evaluated using the MCF equation from Conner et al. (2014) which is described more in detail in the theory chapter 2.2.2. The possibility of integrating several parts of the component, to reduce the need for assembling, is evaluated based on the number of parts of the component and their materials. To be able to produce the whole component in one print, all the parts need to be made in the same material. It is also evaluated if other components assembled to the investigated component can be integrated to reduce the number of components of the final product. This can further reduce assembling time, component weight and material. The possibilities of improving the function of a component with AM are evaluated based on four criteria. These are about the objective of redesigning the component and the possibility to optimise the design.



STEP 2 - EVALUATION CRITERIA		
	Unit	**Fill in:**
Design and function		
Complexity		
Bounding box volume	[mm^3]	0
Volume of component	[mm^3]	0
Area of component surface	[mm^2]	0
Number of channels or internal hollows		
Integration		
Number of parts fastened or welded together to form the component		
Can these parts be made of the same material?		
Number of components assembled to the investigated component contributing to the same function		
Can these components be made of the same material?		
Function		
Is one objective to increase the performance of a function?		
Do you want to add design features that is currently impossible due to conventional manufacturing limitations?		
Would the component benefit from fluid flow optimisation?		
Would the component benefit from topology optimisation?		

Figure 4.10: Step 2 - Design and function

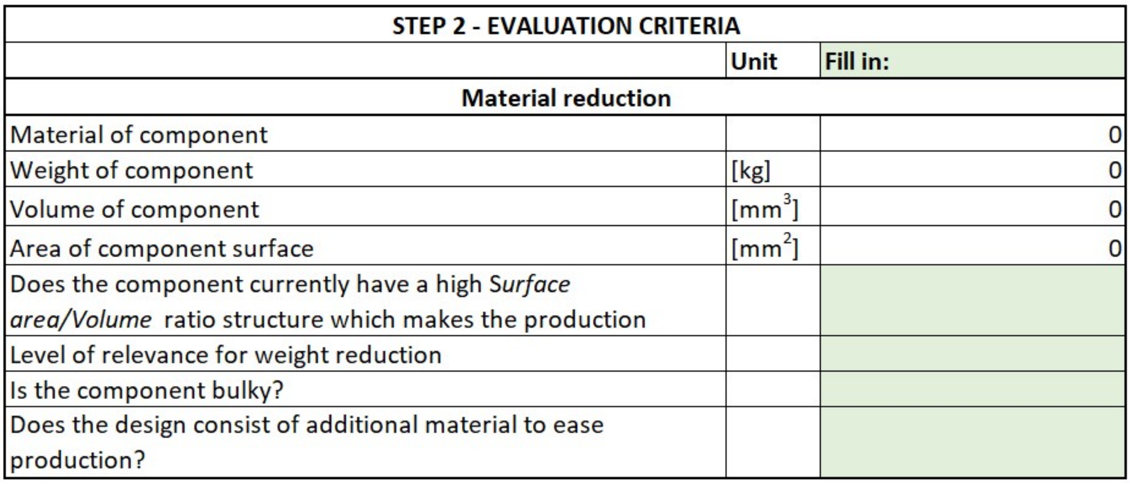
To evaluate the category **customisation or small series**, the criterion annual quantity, is of great interest as AM generally is more beneficial for small quantities. Furthermore, it is asked if the component is customised. AM allows a high degree of customisation without significant cost increases compared to CM. Other criteria are the level of complexity of the currently required tools and their availability. If the required tools are available, AM is less beneficial as the resources for producing the tools are already consumed. See figure 4.11 for the appearance of this category in the tool.



STEP 2 - EVALUATION CRITERIA		
	Unit	**Fill in:**
Customisation or small series		
Annual quantity		
Is the component customised?		
Level of complexity for tools required in the current production		
Are the required tools available?		

Figure 4.11: Step 2 - Customisation or small series

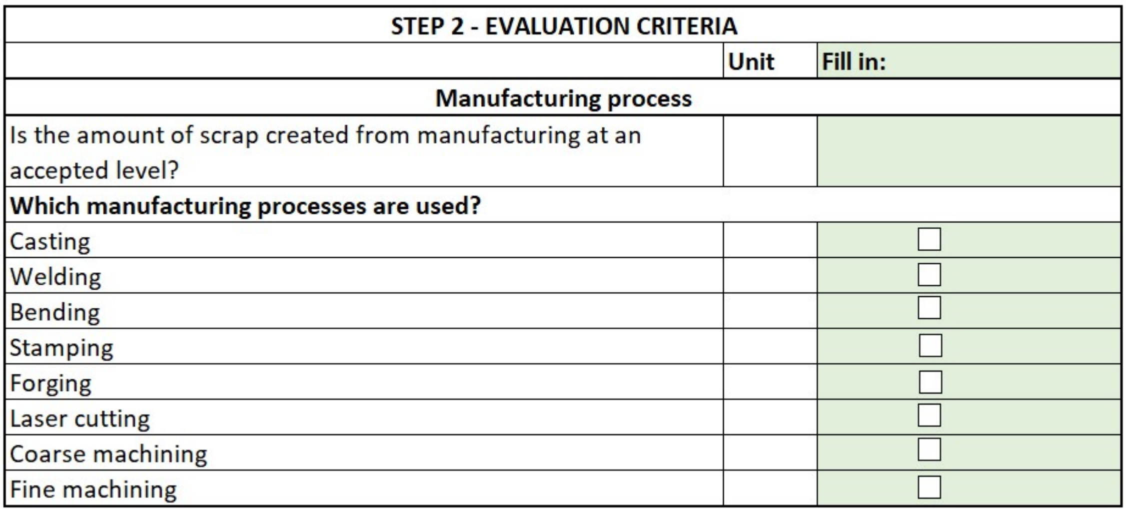
For the **material reduction** category, the material, weight and volume of the component are retrieved from the earlier step. These are used to calculate the embodied energy of the component and its surface area to volume ratio. A high embodied energy of the current component leads to greater possible energy savings with AM through design for minimised material use. The embodied energy is automatically calculated using data for the embodied energy of the material per kilogram multiplied by the component weight. Regarding the surface area to volume ratio, a low value indicates that the component probably has a bulky structure and hence there is more to gain with an AM redesign. For example, a bulky structure can be redesigned into a lattice structure and thus obtains a high surface area to volume ratio. However, for some components that already have a high surface area to volume ratio, such as heat exchangers, AM may be beneficial as it could ease production. Therefore, the user should fill in if the component currently has a high surface area to volume ratio structure. It is also asked if the component is bulky or consists of additional material to ease production. If extra material and bulky parts can be removed when redesigning for AM, the potential is significantly higher. See figure 4.12 for the appearance of this category in the tool.



STEP 2 - EVALUATION CRITERIA		
	Unit	**Fill in:**
Material reduction		
Material of component		0
Weight of component	[kg]	0
Volume of component	$[mm^3]$	0
Area of component surface	$[mm^2]$	0
Does the component currently have a high *Surface area/Volume* ratio structure which makes the production		
Level of relevance for weight reduction		
Is the component bulky?		
Does the design consist of additional material to ease production?		

Figure 4.12: Step 2 - Material reduction

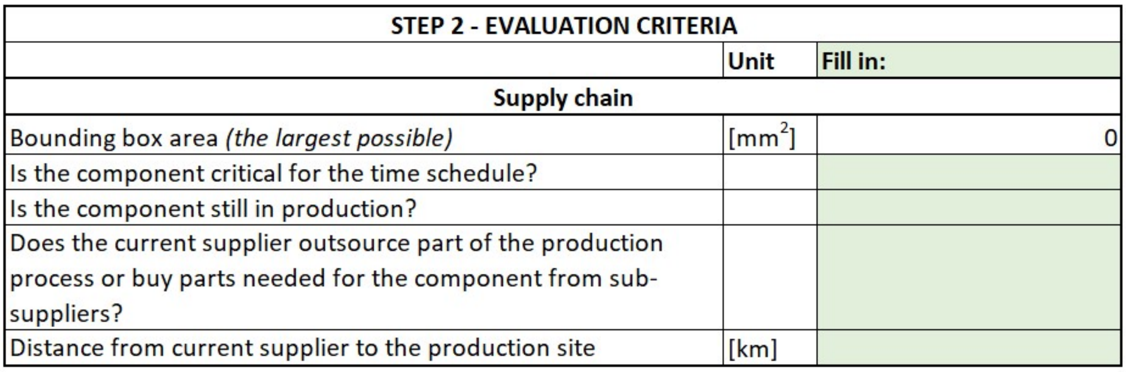
For the **manufacturing process** category, the first criterion clarifies if the amount of scrap created from manufacturing is at an acceptable level. If this is not the case, AM could be used to decrease scraps. Thereafter, the user can fill in all manufacturing processes currently used by ticking in boxes. The eligible manufacturing processes are casting, welding, bending, stamping, forging, laser cutting, coarse machining and fine machining. These have been selected based on discussions with Volvo Penta, and are the most common processes. See figure 4.13 for the appearance of this category in the tool.



STEP 2 - EVALUATION CRITERIA		
	Unit	**Fill in:**
Manufacturing process		
Is the amount of scrap created from manufacturing at an accepted level?		
Which manufacturing processes are used?		
Casting		☐
Welding		☐
Bending		☐
Stamping		☐
Forging		☐
Laser cutting		☐
Coarse machining		☐
Fine machining		☐

Figure 4.13: Step 2 - Manufacturing process

The criteria in the **supply chain** category can be seen in 4.14. This category is less extensive due to the recommendation tool being developed for design engineers, and their difficulty of retrieving information in this area. However, the category is of great importance since AM offers several advantages for components in this category. The criteria used are the ones possible for the design engineer to retrieve. First, the bounding box measure is filled in to calculate the number of components fitting on a single building plate. This value is not scored but given as information to the user. It can be of interest for the planning of the future supply chain, as it gives an indication of the minimum order quantity. Another criterion is if the component is critical for the time schedule, which can be the case when the current component needs to be exchanged immediately. The next criterion is about if the component is still in production, to determine if a supply chain is established. If not, there are no limitations for optimising a new supply chain with minimised transportation. The next criterion is if the current supplier outsources any of the production processes for the component, by using a sub-supplier, making the supply chain longer and less certain. Finally, the distance from the current supplier to the production site should be filled in. Generally, a longer distance results in uncertainty for the supply chain as the transports are longer and the communication harder to maintain. In addition, longer distances result in more fuel being consumed.



STEP 2 - EVALUATION CRITERIA		
	Unit	Fill in:
Supply chain		
Bounding box area *(the largest possible)*	[mm^2]	0
Is the component critical for the time schedule?		
Is the component still in production?		
Does the current supplier outsource part of the production process or buy parts needed for the component from sub-suppliers?		
Distance from current supplier to the production site	[km]	

Figure 4.14: Step 2 - Supply chain

The "level information" sheet contains supporting information for the user to read when filling in criteria with level options. These are the level of tool complexity and level of relevance for weight reduction. Examples of the different levels are presented to clarify the differences among levels. The "all data" sheet contains data about building box measures for BJT and PBF for the different materials. The embodied energy per kilogram for the materials is also found on this sheet. The "specific data" sheet retrieves data from "all data" and only contains data valid for the material that the user has chosen in the "fill in" sheet. The "fill in" and the "level information" sheets are the only two which are supposed to be accessed by the user, the two others are solely for retrieving data.

4.2.2 Scoring

For criteria where the answer is a numerical value, the scoring is based on the magnitude of the value. The first criterion resulting in a numerical value is connected to the MCF equation, which originates from Conner et al. (2014). In the article, it is mentioned that AM is likely to be cost-effective for parts with an MCF value greater than 44, and thus the value 44 was scored with 5. Thereafter the score is reduced by 1 for each decrease of 5 in the equation, which results in every MCF value below 24 having a score of 1. The other criteria, which are scored based on their numerical value, are the number of parts of the component, the number of components assembled to the investigated component, the annual quantity, the embodied energy, the surface area to volume ratio and the number of manufacturing processes used. The scoring of these was based on benchmarking by using a number of Volvo Penta components. For example, the score for surface area to volume ratio was set based on the ratio for ten different components with different design complexity and properties.

Criteria for which the answer is a level in the Likert scale, the scoring corresponds to the levels. These criteria are the level of complexity for the tools needed in the current production, and the level of relevance of weight reduction. In these cases, the score of the highest level is 5 respectively 1 for the lowest level.

Moreover, there are criteria with binary answers, yes or no, for which the score is either 5 or 0. These criteria are all based on engineering judgment, and thus they should only affect the score if applicable to the component. Therefore, these can be considered as "bonus" possibilities, which have an important impact on the final score for applicable components. The criteria with binary scoring are: if one objective is to increase the performance of a function, if the user wants to add a design feature currently impossible, if the required production tools are available, if the component have a high surface area to volume ratio, if the amount of scrap from manufacturing is above the accepted level, if the component is critical for the time schedule, if the component is still in production and if the current supplier outsources parts of the production or buy any required parts from sub-suppliers.

However, there are two special criteria for the binary scoring: if all of the parts in the component can be made in the same material, or if the components assembled to the investigated component can be made in the same material. The responses to these criteria will result in a score that is also based on the criteria above each of these, which are about the integration of parts and components. If the user answers yes, the score for the combination of the two questions will be based on the generated numerical value. If the user answers no, the combination will result in a 0 since it is not possible to benefit from the integration possibilities. Machines for BJT and PBF can only print components consisting of a single material.

In addition to the previous criteria, three statement scoring is used for four criteria where a middle option was required due to the availability of multiple levels of yes. For some components, the main reason to use AM is to create a flow or topology optimised design, and thus it would result in an evident yes. Regarding other components, such optimisation may still be beneficial but not as important. Therefore there was a need to not only have yes and no but also include a neutral option: possibly but not necessary. This type of scoring follows the principles of the Likert scale by assessing the user's view, with two extreme and a neutral option. In these cases, five levels are considered too detailed making it difficult for the user to determine the differences. The three statement scoring is also used when the user fills in if the component is bulky and if it consists of additional material to ease production. In these cases, the answer no gives the score 0, minor part gives the score 3, and major part gives the score 5.

The scoring for the different included manufacturing processes is shown in table 4.1. Each manufacturing process is scored based on the categories: scraps, energy intensity, special tools and emission. If a manufacturing process has a major impact in one category, it is marked in the table. As can be seen in the table, bending does not have a major impact in any of the categories, thus it receives the score 1. Stamping and laser cutting have a major impact in two categories and are scored with a 3. Casting, welding, forging and coarse machining receive a score of 5 due to having a major impact in three categories or a particularly high impact in one category. Moreover, fine machining is one of the manufacturing process options, but it will not count towards the final score. In general, equivalent fine machining is used for components produced with either AM or CM. However, it is still included in the form to reduce the risk of confusing coarse for fine machining.

Casting generates scrap both due to quality issues, and due to additional material required to fill all parts of the moulds. Moreover, casting is a very energy intense method due to the need of melting the metal. Special tools are needed as moulds and cores are required. Welding is energy intensive due to the equipment using heat and pressure. In addition, welding usually requires special tools for holding the parts of the component in the correct position during the process. The process also generates hazardous fumes and emits nitrogen oxide and carbon dioxide gases. Stamping is energy intense since pressure is used to form the components, special tools are also required such as fastening devices. Forging is very energy intensive as both heat and high pressure are applied to form the components. In addition, forging requires moulds. In case of laser cutting, the laser makes the process energy intense and causes hazardous fumes. Coarse machining generates a massive amount of scrap due to its subtracting process. It is also energy intensive, due to the high amount of energy needed to remove all the material to form the part.

Table 4.1: Scoring of each manufacturing process in the recommendation tool

Scoring of manufacturing process					
Process	Scraps	Energy intense	Special tools	Emission	**Score**
Casting	x	x	x		**5**
Welding		x	x	x	**5**
Bending					**1**
Stamping		x	x		**3**
Forging		2x	x		**5**
Laser cutting		x		x	**3**
Coarse machining	2x	x			**5**
Fine machining					**0**

For each component category, a mean score is calculated based on all scored criteria. The mean scores in the different component categories are the final results of the recommendation tool. Based on the value of each mean score, recommendations will be generated for how to proceed.

4.2.3 Recommendation

After completing the usage of the recommendation tool, the mean score of each component category will be given. These mean scores should be analysed both individually and together in order to determine the potential for AM. From this analysis, a recommendation is given for the component. The interpretation of the mean score individually for each category can be seen in table 4.2. As listed there is no identified potential for AM in a category if the mean score is lower than 2.5. However, there is possible potential if the mean score in a category is from 2.5 to 3.5.

Potential for AM is clearly identified in categories where the mean score is above 3.5, and certainly high potential if the mean score is above 4.5.

Table 4.2: Interpretation of mean score for each category

Interpretation of the mean score for each component category	
Mean Score	**Interpretation**
< 2.5	No identified potential for AM.
2.5 - 3.5	Possible potential for AM.
3.5 - 4.5	Potential for AM.
> 4.5	High potential for AM.

As the tool is a first step in evaluating components for AM, it is only of value to give the user indications of how and when to investigate the component further. It is important to look both at each component category separately and all together to understand in what way the component would be suitable for AM or not. The recommendation tool does not have any weight on the scores nor provide a total mean score as this is not of interest. The idea is that the user will most likely be part of a project with aims, therefore the weighting of the scores will vary among users. However, the recommendation tool can provide recommendations based on all of the scores received in the different component categories. By combining the different scores, different recommendations will be obtained according to table 4.3.

Table 4.3: Recommendation for mean score

Recommendation for mean score	
Mean Score	**Recommendation**
< 2.5	Only evaluate further if the component has received a score greater than 3.5 in any other category.
2.5 - 3.5	Evaluate the specific drivers identified in the category to determine if potential exists.
3.5 - 4.5	Evaluate further and investigate whether the criteria with the lower scores within the category can be improved.
> 4.5	Evaluate further, focus on if the benefits captured for the high scoring category can compensate for any low scoring category.

If one or more component categories get a score below 2.5, it is not recommended to proceed based on these categories. Though, it will still be recommended to proceed with a further evaluation if any other category has received a score above 3.5. If the component only gets scores below 2.5 and 3.5, it will therefore not be recommended to proceed with a further evaluation. A component with no potential and solely possible potential should not receive additional resources. On the contrary, if the component does not get any score below 2.5, and all scores are between 2.5 and 3.5, it is recommended to proceed and further evaluate the criteria increasing the score. If these criteria are important for the project, it is worth continuing the evaluation. If not, there is no need of evaluating the component further for AM.

If the component scores 3.5 to 4.5 in any category, it is recommended to evaluate the AM possibilities further. If there are any lower scoring categories, the criteria decreasing the scores in these categories should be investigated further. If low scoring categories are important for the project and cannot or will not change over time, AM should not be considered. It is also important to ensure the accuracy of this data, especially if it is based on engineering judgement.

If the component gets a score above 4.5 in any component category, a further evaluation for AM should always be done. This is due to the benefits captured in this category can be high enough to motivate the usage of AM, despite the scores in other categories. However, it should be further evaluated whether this high scoring category is important and if its benefits really do compensate for any other low scoring categories.

The next step, if the user has decided to proceed with AM for the component, is to evaluate the level of redesign required. Redesigning guidelines will also be provided by the recommendation tool. As written in chapter 2.1.3, there are three approaches: direct part replacement, adapt for AM and design for AM. For the two last approaches, redesigning the component for AM is necessary. Depending on which component category the high score is received in, the recommendation differs according to table 4.4.

Table 4.4: Recommendations regarding redesign for component categories

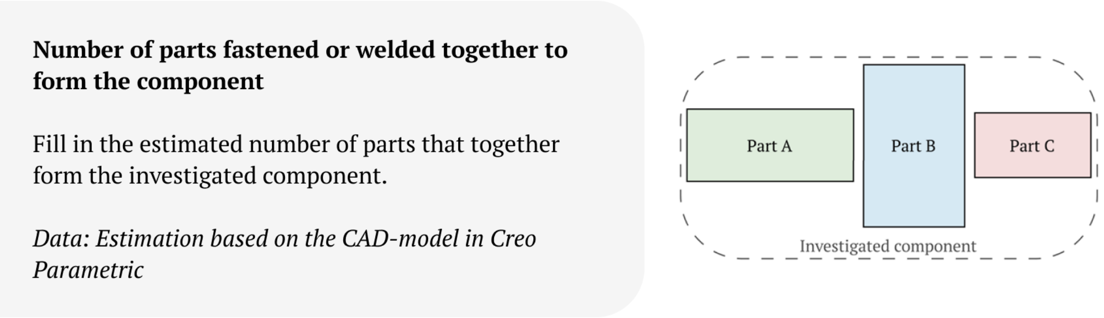
Recommendation for redesign	
Category with the highest score	**Recommendation** *(Note: Redesigning for AM may be time-consuming but is generally beneficial to improve the function and save printing time and material)*
Design and function	Redesigning the component is crucial to benefit from the AM advantages.
Customisation or small series	Redesigning is not required, but may give benefits if the component has a high score in the categories "Design and function" or "Material reduction".
Material reduction	Redesigning the component is crucial to benefit from the AM advantages.
Manufacturing processes	Redesigning is not required, but may give benefits if the component has a high score in the categories "Design and function" or "Material reduction".
Supply chain	Redesigning is not required, but may give benefits if the component has a high score in the categories "Design and function" or "Material reduction".

For the design and function category, the recommendation tool gives a scoring based on the potential advantages that can be achieved with designing for AM, which enables increased complexity and integration of parts. For the material reduction category, redesigning the component for AM is required to reduce the amount of material used or create lattice structures. For the remaining categories, AM redesign is not directly linked to their advantages. However, components with the highest score in these categories can still benefit from material reduction and the possibility to increase the function. Generally, redesigning for AM is advantageous, but there are cases where it is not. For small component volumes or when the lead time is of importance, the time that redesigning requires may not be worth its benefits. Furthermore, for some spare parts, it might be important that the weight and design are the same in order for the product to operate properly. Therefore, these other categories need to be evaluated further to determine if it is more suitable to perform a direct part replacement or adapt for AM.

4.2.4 Guide

The guide is a document summarising all required knowledge to use the recommendation tool. Thus, the first section starts with general information that the user should be aware of before starting to use the recommendation tool, together with the recommended approach for filling in data. For example, it describes that solely the green cells should be filled in with data and that a cell should be left empty in case the data cannot be found. Moreover, the guide encourages the user to fill in approximations when the exact data is not existing, since the tool should be used as a fast evaluation. This section also contains information about what the user needs to have open, in terms of software and databases, to find all information related to the component.

The next section shows information regarding all of the criteria and data needed to fill in the recommendation tool. Therefore, this guides the user during the actual usage. For each criterion, the user gets a description and explanation of how it can be interpreted. Thereafter, the possible answer options are stated together with some further explanation of what each means. In addition, each criterion has a description of where to find the data in the database and software. Figure 4.15 shows an example of a specific criterion in the guide with belonging information. The last section of the guide consists of information regarding how to interpret the result from using the recommendation tool. It describes the different ranges of mean scores, and whether or not it should be recommended to further evaluate AM for this component.



Number of parts fastened or welded together to form the component

Fill in the estimated number of parts that together form the investigated component.

Data: Estimation based on the CAD-model in Creo Parametric

Figure 4.15: A part of the guide showing two criteria

4.3 Testing and Evaluation

In this chapter, the results from the tests are presented. Firstly, the result from the usability test gives insights from potential future users. Thereafter, a comparison between the recommendation tool and experts' opinions evaluates the performance of the recommendation tool.

4.3.1 Testing Usability

As previously mentioned two different fictional cases were created and handed out to the participants. The first case involves a project about the component "Ball Valve", which contributes to fulfilling the international convention for safety of life at sea. This was stated to be a cost down project in which the manufacturing tools must be exchanged to produce any future components. The second case was a project for the component "Exhaust Pipe Elbow", that needs to be redesigned due to a problem regarding corrosion and leakage between the component and the connected turbo. Both components can be seen in figure 4.16.

Figure 4.16: The components used for the usability test, the Ball Valve to the left and the Exhaust Pipe Elbow to the right

The recommendation tool with the filled in data from the participants for the first case, can be seen in appendix D. In this case, all participants completed the test, and this resulted in the four columns. Designers A to C filled in the form individually, while Designer D got observed. The data from the second case is in appendix E. In contrast to the first case, solely three participants had the opportunity to complete the test, and thus only three columns with data are presented. Designers A and B performed the testing individually, while Designer C got observed.

When analysing and comparing the data from the usability test, the two cases resemble. As can be seen in appendix D and appendix E there is a combination of similarities and differences regarding the data filled in by the participants. For some of the criteria, the data even varies among all of the participants. In general, it can be seen that data collected from a software source, such as the measures from the CAD model or data received about the supplier, do not vary a lot between the participants. In this case, the differences can be due to rounding of the values or that the data was collected from different features in the available software at Volvo Penta. This since information about the component can be found in several places, and sometimes it differs slightly between the software. For example, the weight can be either estimated from the CAD model or received from the database, which may contain the value from actual weighting. Moreover, this type of information does not require a lot of previous experience with the component, which can also be a reason for similar data.

However, the result and filled in data vary highly for the criteria where engineering judgement is required. For the first case, only 2 out of the 20 criteria based on engineering judgement have a common answer among the participants, while it is 5 criteria for the second case. The marked questions in the appendices are those that are especially difficult to answer according to the test, and where the differences lead to separate outcomes. The question "Do solid structures exist?", for the second case, is an example where the designers have different perceptions about the component. The answers to this question differ completely and are even contradicting. Considering this variation in answers, it seems like the previous experience in designing and knowledge in AM may lead to different results for this test. However, it may also be due to interpreting the criteria differently, which further affects the answer.

When comparing the answers to the question form it can be seen that the experience of designing and knowledge about AM differs among the participants. They have experience from 2 to 12 years as designers, and some have previously worked with AM, while it is a completely new area for another. However, it is difficult to tell if the result differs due to this, or if there is another pattern connected to the filled in data. The time to fill in the recommendation tool spans from 20 to 40 minutes, when the participants were using it for the first time. The second time using the tool was generally faster than the first time.

In the question form comparison, it can also be detected that the participants did not understand every criterion. All of these difficult criteria are based on engineering judgement and are marked as questions for which the answers differ a lot. However, the participants were able to fill in all data and when they had difficulties the guide supported them. In general, the participants are satisfied with the content of the guide and only proposed some smaller changes for the final version. One of the participants further explains that it will not be a problem to fill in the questions in a real situation, in which they have more information about the project and knowledge about the component. In addition, it is mentioned that engineering judgment is difficult, and thus they regularly have discussions among colleagues in the department to support each other. These discussions create an opportunity to decide upon what to fill in for the criteria requiring engineering judgement, to get a common perception and hence the most accurate result.

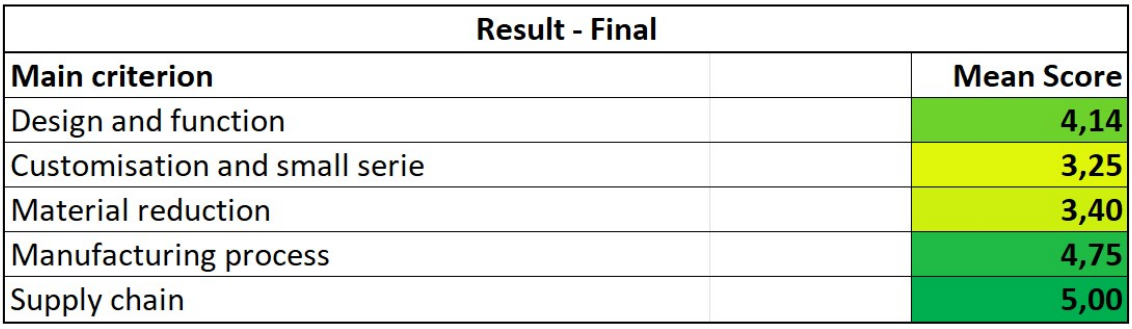
During the observation, it could be seen that the participant was eager to start filling in data without paying any attention to the guide. Therefore, the participant filled in data retrieved from another source than the one described in the guide. However, when the participant encountered a difficulty, the guide was used and this helped to solve the problem. One example of this is that the participant filled in the information about the manufacturing process without noticing the supplier. Thus, this data later had to be changed when the participant realised the manufacturing process was not compatible with the current supplier. On the other hand, it was discovered that the data in the recommendation tool easily can be changed if needed.

As a result of the usability testing the recommendation tool was modified in order to increase the usability. Thus, the final version got refined according to the identified difficulties. All of the marked criteria in appendix D and appendix E got either reformulated or a more clear explanation in the guide. For example, "Number of cores or holes" was troublesome, and this got changed to "Number of channels or internal hollows".

4.3.2 Evaluation of the Recommendation Tool

To evaluate the accuracy of the recommendation tool sessions were held together with the AM Researcher, the AM Designer and the AM Expert. Moreover, they were asked to choose one component they considered suitable for AM, potentially suitable for AM or not suitable for AM. One evaluation session was performed with each expert, in which the tool was filled in for their chosen component. The result from the recommendation tool was then compared to the experts' opinions.

The first evaluation session was performed together with the **AM Researcher**. The component evaluated was a separator that the AM Researcher had previously worked with and considered suitable for AM. The result from the recommendation tool was consistent with the AM Researcher's opinion. As can be seen in figure 4.17, the highest potential can be found in the component categories manufacturing process and supply chain, which both got a score greater than 4.5. These are closely followed by the design and function category which got a score in the range 3.5 to 4.5, meaning that there is potential for AM. No categories got a score below 2.5 so there is potential for AM in all of the categories according to the tool. For this component, the AM Researcher considered the component suitable for AM due to its complex internal channels and the difficulties to manufacture these.

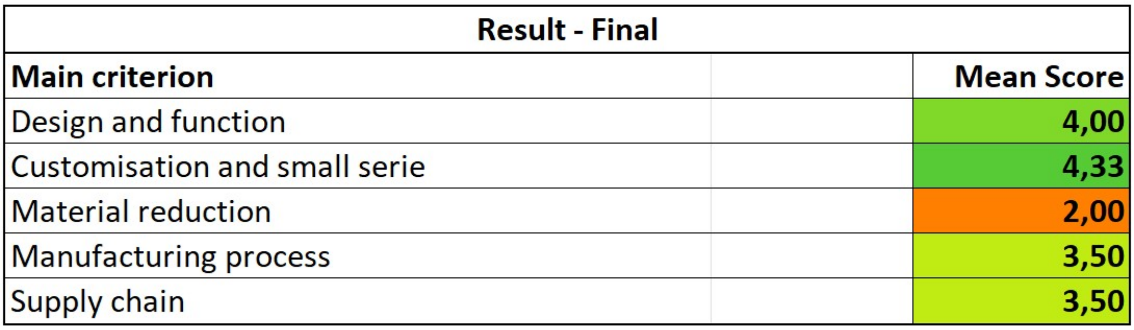


Result - Final

Main criterion		Mean Score
Design and function		4,14
Customisation and small serie		3,25
Material reduction		3,40
Manufacturing process		4,75
Supply chain		5,00

Figure 4.17: The final score from the recommendation tool for a component suitable for AM

The second evaluation session was performed together with the **AM Designer**. The component evaluated was a water pipe which had been previously considered for AM due to identified potential, but in the end, the final decision was to produce it conventionally. The main reason that the AM Designer had investigated the component was due to the small volumes. This is reflected in the tool as the score for customisation and small series is close to 4.5 as seen in figure 4.18. There are also three other categories where the score is 3.5 or above. However, the component scores 2 in the material reduction category, which indicates that the component must be investigated further to determine if it would still be beneficial to use AM in total.

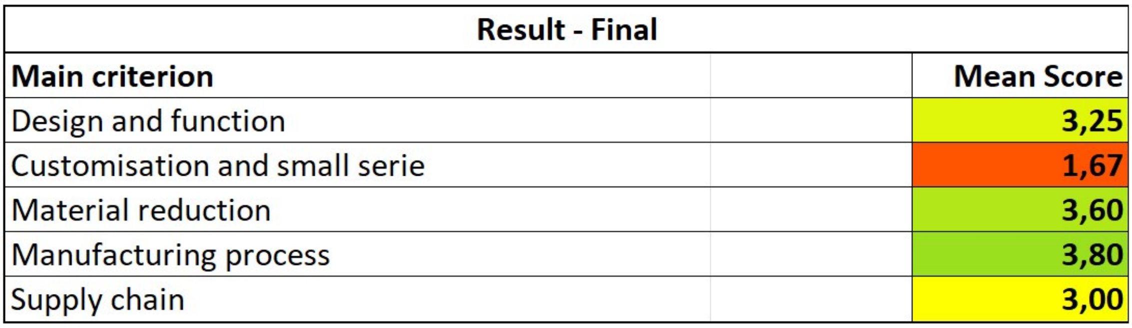


Result - Final

Main criterion		Mean Score
Design and function		4,00
Customisation and small serie		4,33
Material reduction		2,00
Manufacturing process		3,50
Supply chain		3,50

Figure 4.18: The final score from the recommendation tool for a component potentially suitable for AM

The third evaluation session was performed together with the **AM Expert**. The component evaluated was a bracket, which the AM expert considered unsuitable for AM. This is due to it being a standard component produced in a high annual quantity. The component got a low score in the category customisation or small series, as seen in figure 4.19, which correlated with the AM Expert's perception. However, the score for material reduction and manufacturing process is greater than 3.5 and thus the tool has identified potential for these categories. The AM expert thought this was very interesting and pointed out how the result would change in the future when the component will be a spare part and the annual quantity will be significantly smaller.



Result - Final

Main criterion		Mean Score
Design and function		3,25
Customisation and small serie		1,67
Material reduction		3,60
Manufacturing process		3,80
Supply chain		3,00

Figure 4.19: The final score from the recommendation tool for a component not suitable for AM

The evaluation sessions gave promising results since the results given from the recommendation tool corresponded well with the experts' perceptions. As the AM Expert remarked, the recommendation tool is also a good instrument to evaluate different scenarios. It is easy to change and experiment with the parameters to see how the result changes. If one category gets a very high score, it is of interest to look more into each criterion in the category to understand how to maximise the potential of AM. On the contrary, if one category gets a very low score, the user should investigate which parameters contribute the most to the low score. Investigating this makes it possible for the user to see what needs to be changed, now or in the future, for the component to be suitable for AM.

During the evaluation sessions, the formulations of the criteria were also discussed. Some criteria were reformulated to improve the understanding and to ensure the correct data was requested. One example is the criterion considering the surface area to volume ratio. The AM Designer recommended adding a criterion about the current surface area to volume ratio. The manufacturing process for components with a high surface area to volume ratio can be beneficial with AM.

5

Discussion

This master's thesis project intends to answer in total three research questions, which are the following:

> *RQ1: What environmental advantages can additive manufacturing bring along the life cycle of a component?*
>
> *RQ2: What are important criteria to consider when identifying environmental sustainability potential of additive manufacturing for a component?*
>
> *RQ3: How can an organisation implement the identified criteria in their product development process?*

The first research question (RQ1) can be considered answered in chapter 4.1.4, in which all of the possible advantages are stated during the product life cycle. The second research question (RQ2) can be answered through the criteria included in the created recommendation tool in chapter 4.2, which indicates the environmental sustainability potential of AM for a specific component. All criteria are summarised in appendix A. These are identified based on the interviews in chapter 4.1.2, existing methods in chapter 4.1.1 and component categories in chapter 4.1.5. All of the answers to the mentioned research questions are considering the current circumstances and the possible development of the technology. Therefore, the list of advantages, requirements and criteria can emerge over time depending on the development. The third and last research question (RQ3) corresponds to the created recommendation tool in chapter 4.2, which an organisation can utilise to implement the requirements and criteria in the product development process. However, it would be possible to implement these in other ways as well.

5.1 Exploration Study

In this chapter, the method and result from the exploration study will be discussed.

5.1.1 Existing Methods

From the literature review of AM, and especially regarding the existing methods, it can be discovered that most of the component selection is based on engineering judgement. Several of the methods require an expert to contribute with AM knowledge during at least one part of the selection. In general, it seems like it is difficult to select the components without the presence of an engineer with AM knowledge, who can give an opinion. However, as the research is in progress there may arise methods independent of engineering judgement or experts and be based on numerical values. Although different methods of component selection exist, these are often specified to an application and can be difficult to apply directly to a specific industry or organisation. Thus, resources may be required to first understand the method, and then adapt the method to the application. Moreover, this can hinder the knowledge transfer from the research to the industry. This report can contribute to the research, as the recommendation tool can demonstrate how existing knowledge can be combined and adapted in order to be applicable to the industry.

5.1.2 Interviews

The interviews were necessary to include to discuss the available information about AM, and to clarify the current possibilities. Several insights from the interviews resulted in knowledge difficult to obtain through other available sources. Furthermost, the interesting insight from the AM Powder Expert regarding the absence of recycled material in AM powder production. This is surprising considering powder for other applications mainly is produced from recycled material. Moreover, the existence of machines and technologies that are not sufficiently developed for the industry, was discovered through the interview with AM Researcher. During the interview with the AM Designer it was also possible to get insights from the industry, and the procedure in practice. As previously stated, all of this information would have been difficult to receive without the interviews. However, the interviews could have included more participants in order to include more areas and be more comprehensive. For example, it would have been interesting to include a participant evaluating AM from the environmental sustainability point of view. To make the results from the interviews more reliable, it would have been of value to interview multiple experts within the same area. This would give a broader perspective and prevent the result to be sensitive to a single expert's opinion or perception.

5.1.3 Requirement Specification

Several of the requirements listed in the requirement specification are perceived as fulfilled for the final version of the recommendation tool. In the usability category, all requirements are fulfilled since it is proven from the usability test that the recommendation tool can be used by a designer with basic AM knowledge, all data is available, and the designers are familiar with the software. The usability test also indicates the requirements in the process category are fulfilled regarding adaptation for Volvo Penta, applicability for at sea and durability over time. Moreover, the requirement about the process supporting the identification of potential from an environmental sustainability point of view can be considered fulfilled since the component categories are used, which are based on this. In the result category the requirement about how the generated result indicates the need for redesign, is fulfilled. The need for redesign will depend on the mean score and be a part of the recommendations, which are presented more in detail in chapter 4.2.3. However, it is difficult to determine if the requirement is achieved stating that solely environmentally sustainability potential for AM should be recommended and how the opposite should be discarded. Extensive additional tests are required to be performed for a set of components to prove this requirement is fulfilled. In that case, the results from the recommendation tool could be compared to the result from another sustainability analysis, such as a life cycle analyses.

In addition to the requirements, some wishes from the requirement specifications were fulfilled. The result from the usability test shows the data is easy to collect for the designer. Moreover, the guide was created with the purpose to support the user, which got positive reviews during the testing. It also appears that the recommendation tool can be applied to products on land from Volvo Penta, as the included criteria are not formulated to only cover the products at sea. However, some additional criteria may be included to capture the full potential.

5.1.4 Potential Environmental Sustainability Advantages of AM During the Product Life Cycle

The potential sustainability values of the different life cycle phases of a component were identified as possible advantages with current AM technology. It is important to underline that these are only possibilities and do not necessarily reflect reality. Redesigning the component is crucial for capturing the advantages: minimisation of materials, optimisation of the function and extended product life. This also requires designers with the knowledge to perform designing for AM, which is a deficiency in many companies today. A non redesigned component produced with AM will not embrace these sustainability values.

Furthermore, to reduce waste and increase recycling, it is important that material flows exist, which the components can follow at the end of their life. These flows will have to be created and the necessary infrastructure and collaborations will need to be established. It is also important that processes for producing AM powder use scraps. This can be achieved when the demand, and hence production volumes of AM powder increase. Political incentives might also be needed to further make it more economically beneficial to use recycled material.

For the main sustainability disadvantage of AM, electricity consumption in the manufacturing phase, the future evolution of sustainable energy can solve this problem. If the electricity mix is 100% renewable, the manufacturing phase of AM components will be more environmentally sustainable, and hence the total impact of components produced with AM will be significantly lower. Moreover, as AM technology evolves, it is probable that more sustainability advantages will appear, which are difficult to identify for the existing technologies.

5.1.5 Component Categories

In chapter 4.1.5 component categories were identified based on the identified potential sustainability. These component categories are believed to be of high importance when considering components for AM. Even if the technology evolves, they probably remain important criteria for component selection for AM. However, the specific advantages included in each component category can change depending on the future research and development of areas connected to AM. Moreover, other component categories may be discovered if other environmental sustainability possibilities arise, which do not belong to any of the stated ones. In addition to the usage of component categories in the recommendation tool, these can be used to raise awareness of AM potential in case of deficiencies for an existing component.

5.2 Development of the Recommendation Tool

In this chapter, the method and result from the development of the recommendation tool will be discussed.

5.2.1 Creation of the Recommendation Tool

The recommendation tool is based on Volvo Penta's organisation, products and design engineers. However, it is most probably applicable to other industries and companies as well. To make it more general, the scoring could be refined to be based on all types of components from different industries. Moreover, some criteria could be modified or added depending on other attributes that do not apply to Volvo Penta products. For example, additional manufacturing technologies and materials could be included. It would also be interesting to evaluate if the recommendation tool could be used for plastic or ceramic components, or how it would have to be refined to achieve this. As the technology develops, the recommendation tool will have to be upgraded and the scoring may change. Probably, the levels for a higher score will be decreased as the technology improves and it will generally be more beneficial to use AM. New "bonus" features may arise, and thus criteria for capturing those will have to be added. In addition, the maximum component sizes possible to build should be edited as the AM machines become larger and more advanced.

The elimination criteria were inspired by the scoring method from Knofius et al. (2016). However, in the scoring method, the user still has to fill in all of the criteria before receiving the result. In this recommendation tool, the user will not have to spend time evaluating a component that will not suit in the limiting measures. By placing the elimination criteria in a separate, first section, the user will only proceed if a component is feasible to produce. The advantage of this is the time saving, while the disadvantage might be that some components being slightly above the size limits will not be further investigated. It is possible that non feasible components could have been redesigned to be smaller, and thus be feasible for AM. One way of preventing this would be to increase the limits for maximal building sizes, but that could be misleading.

The maximum building sizes are based on a combination of AM technologies and the material the component is produced in. Thus, it can be possible to change material for a non feasible component to make it feasible. This is difficult for the user to know, and requires the user to try different possible materials. Therefore, the guide includes information about possible actions to take for eliminated components. The user could also read the "all data" sheet to get information about the feasible sizes. The data for the eligible materials are retrieved from the database Granta Edupack, and thus the material names are stated as in the database. These names are not necessary equal to what company uses, and this requires the user to know the corresponding material. However, this should not be a problem as they generally do have good material knowledge, or can retrieve the information. In addition, the data for the materials do not differ considerably as long as the correct metal group is chosen. For example, all types of steel have similar values for maximum building sizes and embodied energy.

The evaluation criteria are divided into the component categories, which are based on the identified sustainability advantages along the product life cycle. One difficulty was to ensure all criteria needed were included, while each advantage is only counted once. However, it was decided to include two criteria in the manufacturing process category that partly measures the same advantage. There is one criterion asking if manufacturing scrap is at an accepted level and another one asking for the manufacturing processes used. The scoring of the manufacturing processes is partly based on the level of scraps produce. Thus, if the user tick the box for coarse machining or casting and fill in a yes on the level of scrap criteria, the high level of production scraps contributes twice to the final score. Therefore, a consideration had to been made whether the criteria of scrap level should be included or not. The decision was to include it, to capture components with problematic scrap levels despite the manufacturing method. Furthermore, counting it twice in the case for coarse machining and casting would just enlighten the problem. The double counting could have been solved by excluding the score from the scrap level in case of these manufacturing processes. However, this would make the recommendation tool less transparent and understandable.

Another example of preventing double counting is the customisation criteria in the customisation or small serie category. In the early development of the recommendation tool, the component selection method by Conner et al. (2014) was included to decide the level of customisation. However, this was removed since high customisation automatically meant a low annual quantity for Volvo Penta. They produce small quantities of special components, rather than customising large series components. Thus, it was problematic that a special component would have a low annual quantity, while the user also would fill in that it was not customised. Therefore, the high score from the low quantity would be evened out by the low score received for a low customisation level. Instead, a criterion with a binary scoring of 5 or 0 was formulated for the customisation to make sure that it will not lower the mean score, but still add a value if the component is customised.

The equation MCF is used to determine the component complexity directly as presented in Conner et al., 2014. This equation has shown a very high accuracy according to AM experts and thus it is integrated into the recommendation tool. In the original methodology by Conner et al. (2014), it was created for casted components but in the recommendation tool it is used for all types of components. To adapt the equation to all manufacturing processes the "number of channels or internal hollows" is used instead of the "number of cores needed for casting". This does not change the equation but does reduce confusion when the user fills in the recommendation tool.

The supply chain component category is less comprehensive due to the recommendation tool being developed for design engineers. Thus, criteria requiring data they could not retrieve are excluded. For example, lead time would have been an interesting criterion to include if possible. To develop the recommendation tool further, it would be of value to extend this category to include more numerical value based criteria. On the other hand, the recommendation tool aims to identify potential from the designer's perspective. Another recommendation tool could be developed for the supply chain department focusing more on criteria connected to their work.

5.2.2 Scoring

The scoring is one part of the recommendation tool that would benefit the most from continued development. To improve the scoring of the numerical values, benchmarking with a wide range of components assessed by experts would be necessary. First, a distribution of numerical values for the components would be needed. Thereafter, AM experts would determine the scores for the numerical values. It could also be of interest to explore the usage of machine learning for scoring, by exploring a large variety of components with different properties and their corresponding AM potential, to identify for what values the different scores should be set. Furthermore, the scoring of the recommendation tool is currently solely based on Volvo Penta Products. It is therefore difficult to say if the scoring is applicable to other types of components with other properties and requirements. To increase the range of application areas for the recommendation tool and make it useful for other companies as well, the scoring should be refined using components from different industries.

Another way the scoring can be improved is through collecting more data of the different manufacturing processes. Currently, the scoring is based on knowledge and general practice from Volvo Penta. It would be of value to further support the scoring with data about the processes from the suppliers. However, collecting data can be problematic due to the risk revealing confidential information. Using data from previous studies would be another way to support the scoring, but this was unfortunately difficult to retrieve. In this project, the approximations were considered accurate enough, due to the recommendation tool being used for the first identification of AM potential.

Furthermore, the criteria based on engineering judgement would be interesting to further develop. Making the recommendation tool more objective and thus less dependent on the user's AM experience, would increase its performance. Therefore, it would be of interest to further investigate if it is possible to use any numerical values to evaluate these criteria. In the current recommendation tool, these criteria are scored 0 if the user does not see any potential for the component. This is partly due to no component fulfilling all of these "bonus" possibilities, and partly to avoid a low score caused by a user not imagining the AM possibilities. For example, this could be the case when a user does not know when topology or fluid flow optimisation can be applied.

One identified difficulty with the binary scoring of 5 or 0, is that component categories with mostly engineering judgement criteria will more likely get a high score. For these categories, there are only a few criteria that could get a score lower than 5. This is most problematic in the supply chain category where only one of the criteria is scored based on a numerical value, making the mean score highly dependent on this value. Hence, it can be concluded that some categories are less evaluated, and thus their result should be seen as less reliable. While for other categories, like the design and function category, the category mean score will be based on more than twice as many criteria with a variety of scoring methods. To improve the recommendation tool, all categories would have to be comprehensive. Moreover, it has been prioritised to make the tool as understandable and transparent as possible. If the user understands the scoring and what it is based on, it will still provide useful information about the potential. However, it is important to evaluate the less comprehensive categories more in depth before it is decided to produce a component with AM.

The engineering judgement criteria with the binary scoring will only increase the component category mean scores. This can be considered problematic, but it is preferred that more components will be further investigated than potential being unidentified. Despite the scoring being precise or not, the recommendation tool can still be used to compare components. The main uncertainty with the current scoring system is whether it results in too high or low mean score. However, this will apply to any component and thus the difference between two components can be used to rank components on their AM potential.

5.2.3 Recommendation

To avoid misinterpretations of the scoring, neither a total mean score nor criteria or category weights have been used. The importance of different criteria can vary depending on the project scope. Therefore, it is of value to understand the scores received and to interpret them in an accurate way for the specific project. Furthermore, the importance of the different criteria can be dependent on the component, and therefore it has not been possible to determine weights for the criteria. However, it could be of interest to further investigate if weights could be applied for some criteria with significant importance for AM. For example, if the annual quantity would be 1, this could be enough reason to produce the component with AM despite any other scores. This is partly addressed in the recommendations, stating that only one component category with a mean score above 4.5 is sufficient to further evaluate the component for AM. However, if the component category receives a low mean score despite the low annual quantity, the potential can be missed. A solution could be to include a weight on the criterion annual quantity, which only applies if the quantity is small or large. It is solely in these cases that the criterion is of great importance. For medium annual quantities, the criterion will not determine if a component should be produced with AM. On the other hand, this would create a very complex scoring difficult to understand for the user.

5.2.4 Guide

As previously stated, the guide in chapter 4.2.4 was created to support the user during the process. Users interpret the criteria differently, and thus it is necessary to have a guide acting as a common foundation. This guide is specifically created for Volvo Penta regarding the retrieval of data from the available software but the description of criteria and the answer options are general. Currently, there are no educative inclusions in the guide except for required explanations for some criteria. However, this could be included to improve the AM knowledge transfer to the organisation. On the other hand, that can make it overwhelming, which reduces its usability.

5.3 Testing and Evaluation

In this chapter, the method and result from the testing and evaluation will be discussed.

5.3.1 Testing Usability

The usability test was a good approach to exploring the usability of the recommendation tool and understanding the interaction with the designers. However, the result showed a lot of variation among the participants, which could partly be affected by the design of the test. Thus, there are several identified improvements. In the testing, two fictional cases were used to simulate projects. These were explained briefly to reduce time consumption ensuring higher participation. On the other hand, the brief descriptions can have caused differences in interpretation among the participants. This could affect the result since several criteria are connected to the scope of the project. In future testing, a clarified case description would be required, and the participants should have more knowledge about the included component. It would be even better if the recommendation tool could be applied to a project to test it in a real scenario.

Moreover, the AM experience of the designers and attitudes can limit the imagination of possible AM potential. Depending on if the designer has the approach direct part replacement, adapt to AM and design for AM the result can differ highly. Thus, it is proposed to fill in the recommendation tool together among the designer, and then continuously discuss the criteria and answers. Another alternative would be several designers filling in the recommendation tool individually, and then comparing the results during a discussion. Regardless, including multiple designers can contribute to a fair representation of the project scope and capture all advantages and challenges of AM. Thus, the source of error connected to the difference in results for criteria based on engineering judgement can be avoided.

The usability test was performed for the pre final version of the recommendation tool to receive proposals about improvements for the criteria. Therefore, it would be interesting to test the final version of the recommendation tool and to make a comparison to the previous version. This could reveal if the final version got improved by the feedback and if the result is more similar among the participants. In this case, both previous and new participants could participate to get both perspectives.

5.3.2 Evaluation of the Recommendation Tool

The evaluation of the accuracy of the recommendation tool was based on three experts and components. To improve the reliability of the evaluation, more components and experts would be needed. However, as the results were very aligned with the experts' opinions, it can still be concluded that the performance was good during these sessions. The recommendation tool evaluates the components based on environmental sustainability potential, which is a new perspective of component selection for AM. Hence, the suitability for AM of components that the experts brought was based on other factors than environmental sustainability. Therefore, it is difficult to evaluate whether the recommendation tool succeeds to identify environmental potential. This could be investigated by conducting life cycle analyses for a range of components produced with CM and evaluating these components in the recommendation tool. Thereafter, the components need to be redesigned for AM, and new life cycle analyses have to be conducted. The recommendation tool is proven to identify sustainability potential if there is a correlation between the reduced environmental impact of the AM component and the identified potential from the recommendation tool. However, this would require a considerable amount of work. It would be necessary to conduct a large number of life cycle analysis reports and redesign the components for AM.

5.4 Volvo Penta and the Recommendation Tool

In the future, Volvo Penta can use this recommendation tool as an initial step to quickly determine if a component has environmental sustainability potential for AM. This first step is from the design engineer's point of view for all component categories. Thus, the next step should involve other perspectives such as purchasing and supply chain, to further evaluate the potential. It would be interesting if these departments had their own recommendation tool with criteria specifically adapted for their perspectives. Moreover, the recommendation tool can build knowledge within the organisation, as it makes the designers reflect on the criteria and result. This is important since there is a lot of knowledge about CM, but limited experience regarding AM. Potentially, the recommendation tool can be transferred directly without adaptation to all engine design engineer departments in the organisation.

The ethical aspects of this project focus on environmental sustainability. The aim of the project is to help Volvo Penta to reach their sustainability goals, and thus the recommendation tool is based on sustainability and not economic profit. All criteria are based on the potential sustainability advantages identified along a product life cycle. It is believed that this is the way forward, because if the world shall meet the climate goals every company needs to prioritise sustainability. Hopefully, this recommendation tool will help to guide the engineers of Volvo Penta to take more ethical decisions to decrease the environmental impact of the company's products. This reduced environmental impact can contribute to a huge difference, considering the large amount of Volvo Penta D4 and D6 being produced. Moreover, the recommendation tool aims to educate the user and can contribute to a new way of thinking and making decisions, where sustainability is at the centre of product development. It is also believed that other companies can find inspiration in this, and that Volvo Penta can act as a role model for how to use AM to enhance sustainability. As the AM technology is in an early development state it is important to create a sustainable working practice associated with the technology.

6

Conclusions

The aim of the Master's Thesis project is to support Volvo Penta in reaching their sustainability goals and exploring the field of AM. This is achieved by creating a recommendation tool, which intends to identify the environmental sustainability potential of AM for components. The recommendation tool is divided into three parts, one for briefly describing the component, one for eliminating non feasible components, and a final one for evaluating the feasible components. In order for a component to pass the elimination, it needs to fulfil requirements connected to material and size limitations. These are identified based on the existing industrial machines for BJT and PBF. Thereafter, the component is evaluated based on criteria connected to different component categories, which are design and function, customisation or small series, material reduction, manufacturing process, and supply chain. Finally, the component receives mean scores for each component category and corresponding recommendations regarding the interpretation of the score and the redesign.

The component categories are based on environmental sustainability advantages of AM during the product life cycle, which are generated from an exploration study. The life cycle perspective is used to ensure that the total environmental impact of a product is included. The main advantages of AM are found in the resource, distribution, use and end of life phases. Efficient material utilisation can be achieved by increased use of recycled material, design for minimising material, repairing and increased recycling. Transportation can be avoided in many cases through in-situ reparation, decentralised manufacturing and reduced inventory since on-demand production is possible. However, the manufacturing phase can cause a higher environmental impact due to the significant energy consumption of AM machines.

Usability tests and evaluation sessions are used to determine the performance of the recommendation tool. The result from the usability test shows that criteria based on engineering judgement are dependent on the users' perception and experience of the component and project. To avoid differences in these affecting the final result, multiple users can fill in the recommendation tool together or individually for comparison. In each of the three evaluation sessions, the result from the recommendation tool is compared to an AM expert's opinion regarding a component. The result from all evaluation sessions indicates a strong correlation. However, because of the low number of evaluations, it is not possible to conclude its overall performance. Furthermore, the AM experts do not consider environmental sustainability when selecting components for AM, which results in the sustainability potential identification not being evaluated. This would require comprehensive tests including more AM experts and the conduction of life cycle analyses confirming the environmental sustainability potential for AM identified by the recommendation tool.

There are possible improvements for the recommendation tool regarding scoring and criteria. The numerical value scoring can be improved by basing it on a wider range and an increased number of components. The criteria of each component category can also be revised to explore the possibilities of changing engineering judgement criteria to numerically value based criteria. Moreover, as the AM technologies develop, the criteria and scoring require continuous updating to ensure the potential for AM is identified for the current situation.

This project has resulted in a recommendation tool with criteria important for identifying environmental sustainability potential of AM for components. While there are still areas of improvement for the recommendation tool, it can be used to educate the user and support discussions related to environmental sustainability and the use of AM. Volvo Penta can use the recommendation tool as an initial step for developing a way of working with sustainability in the centre of product development. If the indications of the evaluation sessions can be proven correct, the recommendation tool provides support for Volvo Penta selecting components profiting from the environmental sustainability advantages of AM. This will move the company toward their sustainability goals.

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A

Recommendation Tool

The recommendation tool consists of three steps as previously stated, and each of these has criteria. In table A.1 is the information requested about the component. The criteria and answers connected to the elimination are shown in table A.2. Lastly, the criteria and answers for the evaluation are divided into Part A in table A.3 and Part B in table A.4.

Table A.1: Step 0 in the recommendation tool

Step 0: Information about the component	
Criteria	**Answer**
Component name	
Component number	
Key function	
Component picture	

Table A.2: Step 1 in the recommendation tool

Step 1: Elimination criteria	
Criteria	**Answer**
Is it a safety component?	Yes or No
Material of component	Materials stated in appendix B
Bounding box measures	Numerical value [mm]
Volume of component	Numerical value [mm^3]
Area of component surface	Numerical value [mm^2]
Weight of component	Numerical value [g]

Table A.3: Part A of step 2 in the recommendation tool

Step 2: Evaluation criteria	
Design and function	
Criteria	**Answer**
Bounding box volume	Numerical value [mm^3]
Volume of component	Numerical value [mm^3]
Area of component surface	Numerical value [mm^2]
Number of channels or internal hollows	Numerical value
Number of parts fastened or welded together to form the component	Numerical value
Can these parts be made of the same material?	Yes or No
Number of components assembled to the investigated component contributing to the same function	Numerical value
Can these components be made of the same material?	Yes or No
Is one objective to increase the performance of a function?	Yes or No
Do you want to add design features that are currently impossible due to conventional manufacturing limitations?	Yes or No
Would the component benefit from fluid flow optimisation?	Yes, Possibly but not necessary or No
Would the component benefit from topology optimisation?	Yes, Possibly but not necessary or No
Customisation or small series	
Criteria	**Answer**
Annual quantity	Numerical value
Is the component customised?	Yes or No
Level of complexity for tools needed in the current production	Level
Are the required tools available?	Yes or No or No tools needed
Material reduction	
Criteria	**Answer**
Annual quantity	Numerical value
Does the component currently have a high Surface area/Volume ratio structure which makes the production complicated?	Yes or No
Level of relevance for weight reduction	Level
Is the component bulky?	Major part or Minor part or No
Does the design consist of additional material to ease production?	Major part or Minor part or No

Table A.4: Part B of step 2 in the recommendation tool

Step 2: Evaluation criteria	
Supply chain	
Criteria	**Answer**
Is the component critical for the time schedule?	Yes or No
Is the component still in production?	Yes or No
Does the current supplier outsource part of the production process or buy parts needed for the component from sub-suppliers?	Yes or No
Distance from current supplier to the production site	Numerical value [km]

B

Materials Included in the Recommendation Tool

Table B.1 contains the eligible materials and their related data.

Table B.1: The materials included in the recommendation tool

Material			**Age-hardening wrought Al-alloys**	**Cast Al-alloys**	**Non age-hardening wrought Al-alloys**	**Stainless steel**
Machine Data - Binder Jetting	x	[mm]	50	50	50	50
	y	[mm]	50	50	50	50
	z	[mm]	50	50	50	50
Machine Data - Powder Bed Fusion	x	[mm]	600	600	600	350
	y	[mm]	600	600	600	250
	z	[mm]	600	600	600	250
Primary material production	Embodied energy	[MJ/kg]	196,5	192,5	199,5	72,2

Material			**High carbon steel**	**Low alloy steel**	**Low carbon steel**	**Medium carbon steel**
Machine Data - Binder Jetting	x	[mm]	50	50	50	50
	y	[mm]	50	50	50	50
	z	[mm]	50	50	50	50
Machine Data - Powder Bed Fusion	x	[mm]	350	350	350	350
	y	[mm]	250	250	250	250
	z	[mm]	250	250	250	250
Primary material production	Embodied energy	[MJ/kg]	32,4	31,05	31,05	32,4

Material			**Cast Iron**	**Titanium**	**Brass**	**Copper**
Machine Data - Binder Jetting	x	[mm]	50	50	50	50
	y	[mm]	50	50	50	50
	z	[mm]	50	50	50	50
Machine Data - Powder Bed Fusion	x	[mm]	350	350	350	350
	y	[mm]	250	250	250	250
	z	[mm]	250	250	250	250
Primary material production	Embodied energy	[MJ/kg]	32,4	621,5	56,05	59,1

Material			**Nickel**	**Nickel-based superalloys**	**Titanium alloys**	**Zinc die-casting alloys**
Machine Data - Binder Jetting	x	[mm]	50	50	50	50
	y	[mm]	50	50	50	50
	z	[mm]	50	50	50	50
Machine Data - Powder Bed Fusion	x	[mm]	350	350	350	350
	y	[mm]	250	250	250	250
	z	[mm]	250	250	250	250
Primary material production	Embodied energy	[MJ/kg]	167	236,5	621,5	52,55

C

Summary of the Question Form

Q1: For how long have you worked as a design engineer?
The participants have work experience as a designer in the range of 2 to 12 years.

Q2: Do you have any previous knowledge about additive manufacturing (AM)?
The participants have varying knowledge about AM and previous experience.

If yes, what is your previous experience?
Two participants have previously worked on projects related to AM and design, while another has experience in rapid prototyping and hobby projects. The last participant has no previous experience but has started to gain an interest in the field.

Q3: How long did it take to use the recommendation tool?
For each participant, the time to fill in the for each case took around 20 to 40 minutes. The second time filling in the tool was generally faster than the first time.

Q4: Did you understand all of the questions?
No, all of the participants did not understand all questions.

If no: Which questions were problematic to understand and how did you interpret those?
The following questions were difficult to understand according to the participants:

- “Number of cores or holes”
- “Number of components assembled to the investigated component contributing to the same function”
- “Would the component benefit from fluid flow optimisation?”
- “Is the component used for a vehicle in motion?”
- “Is the amount of scraps from manufacturing a problem or above the accepted level?”

Q5: Did you find the relevant data to all questions?
Yes and No. The participant found all data for the criteria but struggled with some of them.

If no: Which questions were problematic and why? Did the guide help?
The following questions were difficult to understand according to the participants:

- “Which manufacturing processes are used?”
- “Is the amount of scraps from manufacturing a problem or above the accepted level?”

The guide did help all of the participants looking for information and guidance. One participant states that the problem with answering the questions will probably not be the case in a real project situation. Because then they have more knowledge about the component and project. In that case, they also have a dialogue with the suppliers.

Q6: Is there anything else you wish to be included in the refined version of the tool?
In the refined version, one of the participants wants to include if the component is a safety critical component since that can lead to additional costs for compliance and failure modes and effects analysis. Moreover, a participant suggested including if the component should be aesthetically appealing, tooling cost, price per part and surface finish requirements.

Improvements suggested for the usability is to collect all of the data needed to be filled in from a specific software in a common place. Also, the arrows for the list should always be visible if possible.

Q7: Did you use the guide?
All of the participants used the guide.

If yes: Was there any unclear information? Do you have any suggestions about where to find data that should be included in the guide?
Most of the participants were satisfied with the content. One participant wanted clarification for the description regarding the criterion “Number of cores or holes”. Another participant mentioned that assessments of engineers are always difficult, but they usually discuss it with colleagues, which will probably make it easier In the future.

If no: Were you able to fill in the form and find all data?
-

Q8: Is there anything else you wish to be included in the refined version of the guide?
One participant refers to the things mentioned previously in Q6. Another participant mentions that one of the software should be the master in case the data can be collected from different sources.

D

Usability Test for the First Case

The filled in data from test participants for the Ball Valve can be seen in table D.1.

Table D.1: The recommendation tool for the Ball Valve

INFORMATION ABOUT THE COMPONENT	Designer A	Designer B	Designer C	Designer D	Marked questions
	Individually	Individually	Individually	Observation	
Component name	Exhaust Pipe Elbow	Exhaust Pipe Elbow	Exhaust Pipe Elbow	Ball Valve	
Component number	-	-	-	-	
Key function	-	-	-	-	
Component picture					

STEP 1 - ELIMINATION CRITERIA					
Material of component	Aluminium	Aluminium	Aluminium	Aluminium	
Bounding box measures *(from longest to shortest)*	108	110	108	108	
	89	90	89	74	
	49	50	49	37	

Volume of component	83145	83145	83144	83144	
Area of component surface	33297	28551	33296	33297	
Weight of component	294	294	300	294	

STEP 2 - EVALUATION CRITERIA					
Design and function					
Complexity - Casting					
Bounding box volume	470988	495000	470988	295704	
Volume of component	83145	83145	83144	83144	
Area of component surface	33297	28551	33296	33297	
Number of cores or holes	2	2	0	1	x
Integration					
Number of parts fastened or welded together to form the component	3	0	1	3	x
Can these parts be made of the same material?	Yes	Yes	Yes	Yes	
Number of components assembled to the investigated component contributing to the same function	2	2	0	3	x
Can these components be made of the same material?	Yes	No	No	Yes	x
Function					
Is one objective to increase the performance of a function?	Yes	Yes	No	No	x
Do you want to add design features that is currently impossible due to conventional manufacturing limitations?	No	Yes	Yes	Yes	
Would the component benefit from fluid flow optimisation?	Possibly but not necessary	No	No	Possibly but not necessary	x
Would the component benefit from topology optimisation?	Yes	Possibly but not necessary	No	Possibly but not necessary	x
Customisation or small series					
Annual quantity	125	175	175	125	
Is the component customised?	No	No	No	No	
Level of complexity for tools needed in the current production	Level 3	Level 1	Level 3	Level 3	x
Do the required tools already exist?	No	No	Yes	Yes	x
Material reduction					
Material of component	Aluminium	Aluminium	Aluminium	Aluminium	
Volume of component	83145	83145	83144	83144	
Area of component surface	33297	28551	33296	33297	
Weight of component	294	294	300	294	
Is the component used for a vehicle in motion?	Yes	No	Yes	Yes	x
Do solid block structures exist?	Minor part	Major part	Major part	Minor part	x
Does the design consist of additional material to ease production?	Minor part	No	Major part	Minor part	x
Manufacturing process					
Which manufacturing processes are used?					
Casting					
Welding					

E

Usability Test for the Second Case

The filled in data from test participants for the Exhaust Pipe Elbow can be seen in table E.1.

Table E.1: The recommendation tool for the Exhaust Pipe Elbow

INFORMATION ABOUT THE COMPONENT	**Designer A** **Individually**	**Designer B** **Individually**	**Designer C** **Observation**	**Marked questions**
Component name	Exhaust Pipe Elbow	Exhaust Pipe Elbow	Exhaust Pipe Elbow	
Component number	-	-	-	
Key function	-	-	-	
Component picture				

STEP 1 - ELIMINATION CRITERIA				
Material of component	Stainless Steel	Stainless Steel	Stainless steel	
Bounding box measures *(from longest to shortest)*	228	178	240	
	161	161	185	
	145	145	156	

Volume of component	543705	543705	543705	
Area of component surface	305694	436291	305694	
Weight of component	4300	4300	4000	

STEP 2 - EVALUATION CRITERIA				
Design and function				
Complexity - Casting				
Bounding box volume	5322660	4155410	6926400	
Volume of component	543705	543705	543705	
Area of component surface	305694	436291	305694	
Number of cores or holes	1	4	1	**x**
Integration				
Number of parts fastened or welded together to form the component	4	2	4	**x**
Can these parts be made of the same material?	Yes	Yes	Yes	
Number of components assembled to the investigated component contributing to the same function	0	2	2	**x**
Can these components be made of the same material?	Yes	No	Yes	**x**
Function				
Is one objective to increase the performance of a function?	Yes	Yes	Yes	
Do you want to add design features that is currently impossible due to conventional manufacturing limitations?	No	Yes	Yes	**x**
Would the component benefit from fluid flow optimisation?	Yes	Possibly, but not necessary	Possibly, but not necessary	
Would the component benefit from topology optimisation?	Yes	Possibly, but not necessary	Possibly, but not necessary	
Customisation or small series				
Annual quantity	525	483	500	
Is the component customised?	No	No	No	
Level of complexity for tools needed in the current production	Level 3	Level 1	Level 3	**x**
Do the required tools already exist?	Yes	Yes	Yes	
Material reduction				
Material of component	Stainless steel	Stainless steel	Stainless steel	
Volume of component	543705	543705	543705	

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