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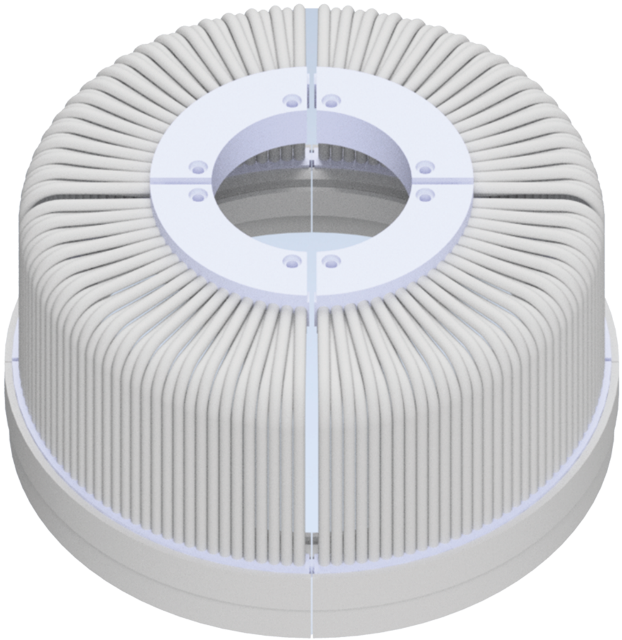

Manufacturability assessment of an additively manufactured heat exchanger

A case study of a heat exchanger in thermal energy storage systems

Master's thesis in Department of Industrial and Materials Science

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Department of Industrial and Materials Science
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2023

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Cover: Texel's current heat exchanger and the part of interest in this thesis.

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Abstract

Texel Energy Storage, a start-up based in Gothenburg, is collaborating with the US Department of Energy, Savannah River National Laboratory, and Curtin University in Australia to develop a revolutionary energy storage technology that competes directly with fossil fuels when combined with renewable energy sources. The goal of this thesis is to evaluate the feasibility of manufacturing Texel's future system's heat exchanger, while also enhancing our understanding of design for AM and the associated costs and time requirements.

This master thesis aims to explore the process of assessing the time and cost involved in designing and manufacturing the heat exchanger. However, it solely focuses on the redesign and assessment of one part of Texel's system and does not consider the entire product development process. The final model design will incorporate Design for Additive Manufacturing, and manufacturability assessment based on time & cost estimation for the newly designed heat exchanger in the case study, along with the base methods described in the theory chapter. This thesis will evaluate the degree of manufacturability based on the time and cost required for designing and manufacturing the heat exchanger in Texel's system, considering the economic aspects of AM. The theory for the method for the manufacturability assessment of the heat exchanger component will be described separately.

As per the thesis, the majority of costs associated with producing a metal additive manufacturing heat exchanger occur during the processing phase, which is consistent with previous research on metal AM part production.

Keywords: Additive manufacturing, Heat exchanger, Manufacturability

Preface

This master thesis was conducted from January to June 2023 as part of the mechanical engineering master programme, delivered and supervised under the Department of Industrial and Materials Science at Chalmers University of Technology in Gothenburg, Sweden.

I am especially indebted to my supervisors, Tina Hajali at the Industrial and Materials Science department of Chalmers University and Stefan Ewaldsson at Texel energy storage AB for their support and engagement throughout this thesis work.

I would also like to thank my examiner Assoc. Prof. Massimo Panarotto for his support during the entire Masters study. Lastly, I would like to thank my family and friends who supported me throughout my Masters studies.

Frej Perbo, Gothenburg, 2023-10-16

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1

Introduction

1.1 Background

Texel Energy Storage is a start-up based in Gothenburg currently working within a global co-operation, including the US Department of Energy, Savannah River National Laboratory, and Curtin University in Australia. The company is currently developing a new energy storage technology that moves beyond Lithium and competes head-to-head in combination with renewable energy technologies with fossil fuels[1].

Texel aims to establish itself on the market by providing an energy storage solution for storing excess energy. The energy may later be used in the case of a shortfall of energy. The current market-leading technology is Li-ion batteries [2]. To compete with this technology, Texel needs to create a battery that has high efficiency, long storage time, and battery longevity compared to Li-ion batteries[3]. Currently, Li-ion batteries have an efficiency above 90% [4]. Therefore, Texel desires to enhance the efficiency of its system as much as possible. Texel has developed a Thermal Energy Storage (TES) system, which stores excess energy when demand is low and releases it when demand is high.

The company is currently planning the manufacturing process for the TES system and its various components. Figure 1.1 shows a schematic view of the system, which consists of five subsystems: an electric heating element, the TES, a heat transfer (HT) system, a Stirling engine, and a generator. The HT system is particularly significant for this thesis as it facilitates the transfer of heat from the TES to the Stirling engine to produce electricity. The heat exchanger in the HT system is the focus of this thesis, as Texel aims to explore the possibility of manufacturing it using metal additive manufacturing (AM). Further details about the system will be provided in section 2.

This master thesis will explore the process of evaluating the time and cost involved in designing and manufacturing the heat exchanger. To refer to this process, we will use the term *Manufacturability*, which means the ease of manufacturing a product. This thesis will assess the degree of manufacturability based on the time and cost required for designing and manufacturing the heat exchanger in Texel's system [5].

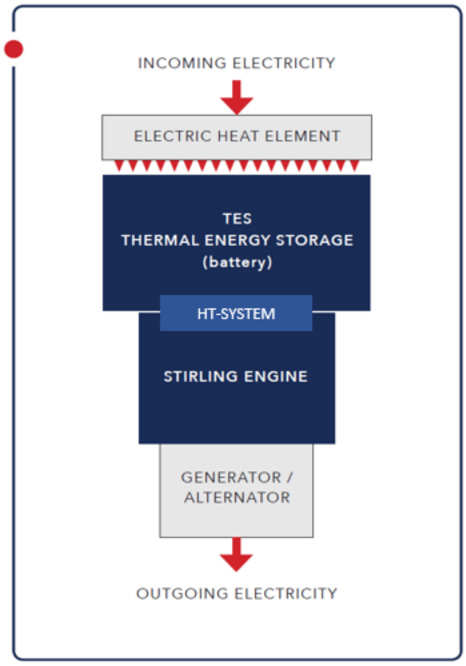


Figure 1.1: Schematic model of Texel battery (*Borrowed from Texel*)

1.2 Aim & Research questions

The thesis aims to investigate if AM techniques can be a viable alternative for developing and manufacturing different components in Texel's energy system. A suitable approach should be developed to investigate and identify the time and cost of manufacturing and designing the component with AM.

A case study of a heat exchanger in the energy system is conducted, and a design proposal for the heat exchanger will be put forward. The investigated heat exchanger is Texel's gas-gas heat exchanger which transfers heat between the Stirling engine and the hot gas from the thermal storage system, even at high temperatures and pressures.

The current version of Texel's heat exchanger is manufactured with conventional manufacturing (CM) methods. Texel seeks to investigate the possibility of manufacturing the next iteration of the heat exchanger with AM. To assess the feasibility of using AM for the heat exchanger, an investigation of different design and manufacturing parameters' effect on cost and time for AM to assess the manufacturability of the heat exchanger design for AM. The investigation aims to help the company assess the manufacturability of the heat exchanger and to use the case study of the heat exchanger to develop a general framework to evaluate other components. To evaluate the aim, three research questions are defined below. To evaluate the suitability of the heat exchanger to be manufactured with AM the heat exchanger needs to be redesigned for AM. Then a method for capturing the important parameters and principles for manufacturability needs to be assessed. Lastly, the method will be applied to the heat exchanger and discussed how it can be extrapolated more generally as a framework.

1. How to redesign the heat exchanger for AM?
2. How to assess manufacturability of the heat exchanger in Texel's system?
3. What is the general framework to assess manufacturability of a part for AM?

1.3 Scope & delimitations

This section describes the scope and the limitations set for the thesis in order to answer the research questions and reach the aim of the thesis.

1.3.1 Scope

This thesis assesses the cost and time consumed over the design and manufacturing process to produce a heat exchanger with metal AM when redesigning the component from its original design used for CM. A case study is conducted of the heat exchanger design for AM and a general framework will be discussed based on the case study.
The thesis started in January 2023 and is set to end in the summer of 2023. 30 credits are allocated to conduct a master's thesis over one term, which results in 1.5 credits/week for a study pace of 100%.
The thesis is conducted at the master program of Product Development (MPPDE). Therefore, it should have its starting point in product development and an academic focus on further knowledge in this area.

1.3.2 Delimitations

The thesis is focused on the component relevant to the case study and will therefore be an in-depth study of this type of component and the redesigning phase of a complex component. In this case, the case study component is a heat exchanger this could also be applied to other areas of interest when designing for AM.
The thesis focuses on the AM method L-PBF (Laser powder bed fusion) as a manufacturing method. It will not consider alternative manufacturing methods beyond eventual comparison with other methods.

To start with, the thesis has a limited timespan. Beyond that, the thesis will be limited by resources provided by Texel energy storage AB and resources available from Chalmers for students.

1.4 Stakeholders

The primary stakeholder for the thesis will be the student conducting the thesis, the company Texel Energy Storage AB, and Chalmers. As the provider of the thesis, Texel Energy Storage AB will therefore be interested in the outcome. As the educational institution, Chalmers keeps an interest in the student's final progress toward graduation, and Chalmers also has an academic interest in the outcome of the thesis. The company supervisor, the academic supervisor, and the examiner overlook the progress of the thesis to help and guide the student to produce a thesis with appropriate quality.

1.5 Overview of thesis

Chapter 2 will describe energy storage systems and the need for these systems, how Texel's system works, and the role of the heat exchanger of interest in this thesis.

Chapter 3 concerns the theory of metal additive manufacturing, design for additive manufacturing, and theory of manufacturability assessment.

In Chapter 4, the methodology of the thesis is explained, which methods are used to gather information and to generate the result. Research question 1 is answered in this chapter on how to redesign for AM.

The fifth chapter is the result. Here a design is proposed, and a manufacturability assessment method is suggested based on the theory established. In this chapter, the second research question is answered.

In Chapter 6, the result of the thesis is discussed as well as limitations and future improvements & opportunities. The third research question is also answered in this chapter by discussing how a general framework could be developed from the case study of the heat exchanger.

In the final chapter 7, the thesis is concluded and recommendation for future work is suggested.

2

Overview of energy storage and Texel system

This chapter briefly explains different concepts and systems that the reader might need to know to understand this thesis's project. In the following chapter, energy storage is described, and Texel's thermal storage system is also explained.

2.1 Overview of energy storage

According to the European Union (EU) [6], energy storage is defined as "Storing energy so it can be used later, when and where it is most needed, is vital for increased renewable energy production, energy efficiency, and energy security" [6]. Further, the EU states that to combat the current energy crisis, which started in the autumn of 2021, the energy sector needs to undergo a large-scale transformation to reduce carbon emissions. The world's energy consumption is projected to increase by 50% in 2050.[7] The projected energy consumption can be seen in the figure 2.1.

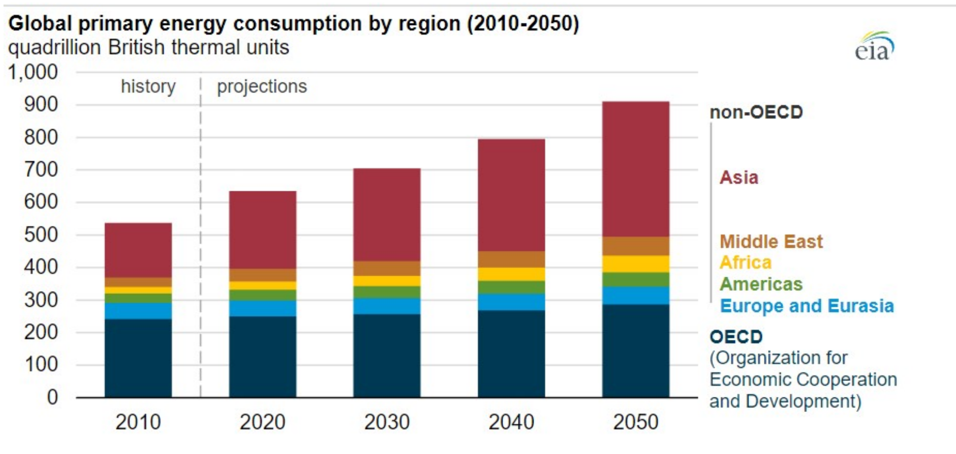


Figure 2.1: Projected global consumption of energy [7]

Electricity grids must be balanced and stable to generate a safe electricity supply. In other words, the electricity consumption must be perfectly matched with the electricity generation at any given time. With the increase in demand and the electrification process in Sweden, the rest of Europe, and the world at large, it is necessary for flexible solutions to reduce large fluctuations in electricity consumption or generation. Predictable volatility and the more unpredictable sources of change come from our increasing reliance on renewable energy, such as solar and wind. They rely on the sun and wind, which is out of our control.[8] European Union [6] The European Union models have shown that with the deployment of renewable energy comes an increased need for flexibility in energy systems. Energy storage will be an essential solution to achieve flexibility in energy systems as it can store energy when generation is high and consumption is low. It can output the stored energy when the situation is reversed. Aside from granting flexibility, energy storage solutions can reduce fluctuations in electricity prices and help consumers adapt their energy consumption.

By 2030, 69% of all EU countries energy system is estimated to come from renewable energy, and by 2050, the expectation is for the share to reach 80%. In EU nations, the demand for flexible energy systems rises considerably as renewable energy accounts for 74% of the overall capacity, on average.[9] The most prevalent energy storage solution often comes from chemical-based ones like Li-ion batteries or mechanical ones like pumped hydro storage. Aside from these two solutions, there is also thermal energy storage.

2.2 Thermal energy storage system

Thermal energy storage (TES) is as old as using water or ice to keep something cold. TES is a system that can store heat or cold to be used later under varying conditions such as temperature, place or power [10]. TES can be split into three categories: Latent, Sensible, and Thermochemical energy storage. The thermochemical energy system will be the only of the three to be discussed further in this thesis as it is the type of Texels system.

In Figure 1.1, a schematic view of Texels system is shown. Thermochemical systems use reversible chemical reactions with high energy in the reaction to store energy. The method requires a high energy density of reaction material and for the reaction to be reversible. Generally, thermochemical storage systems have more performance efficiency than latent and sensible storage systems. Electricity is transformed into thermal energy through an electrical element. The heat starts the reactions in storage material, separating the reactants releasing one of the reactants as gas then storing the gas in a separate container. To discharge the TES, release the stored reactant back into the reactor, which reacts with other materials, resulting in energy release. The released energy is transferred via the HT system to the heat exchanger atop the Stirling engine, which heats the engine. A Stirling engine is a heat engine. A Stirling engine works by sealing a fixed amount of fluid in a closed system and changing the pressure by heating or cooling the engine [12]. The fluid moves between the hot and cold sides and expands and contracts. During expansion, pistons are pushed and, by doing so, transform heat to mechanical energy, which drives a generator giving the final output of electricity. In figure 2.2, a visualization of a Stirling engine is shown. The cold side is indicated with blue, and the hot side is indicated with red.

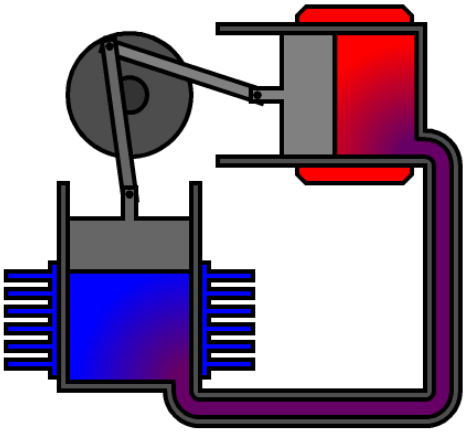


Figure 2.2: Stirling engine [11]

Texel's Stirling engine is visualized in figure 2.3. The important parts of the engine for this thesis are colored red and blue and can be seen at the top of the engine model in figure 2.3. The component colored red is the cylinders containing a piston each and is heated by the heat exchanger to create motion. The blue-colored area contains the cooler and the regenerator. This will be explained in more detail in the section 2.3.

The red area is where the heat exchanger is connected and will heat the Stirling engine, putting the piston in motion. The heat exchanger works with two gases as mediums. In this thesis, one gas is assumed to be hot air, heated up by the discharging TES. The working engine gas is assumed to be Helium. The placement of the heat exchanger in the system is shown in figure 2.4, and the heat exchanger will be further explained in section 2.3.

2.3 The current heat exchanger

The current heat exchanger prototype at Texel Energy Storage AB is designed with CM. CM refers to traditional manufacturing methods such as moulding, assembly, machining, cutting, and forging. Due to its complexity, the contemporary design is only viable to produce at a small scale. The prototype currently needs to be manufactured and assembled by hand. Further, the current iteration of the prototype still needs to be designed to work in the final system of the TES system. This thesis aims to propose a new iteration of the heater manufactured with AM and investigate the cost and time of design and manufacturing.

In figure 2.5, the three main parts of the old heat exchanger are visualized. The top of the old heater configuration is shown in figure 2.5a, the top part is mounted atop the middle part shown in figure 2.5b. The exhaust pipe on this part can also be seen in the figure. The middle part in figure 2.5b is the structural part to which all the other parts are connected. In this part, the inlet for air is located. The heat exchanger part fits within this part, where figure 2.5d fits. It is easier to see where it fits in figure 2.5c of the same part. The old design of the heat exchanger is designed

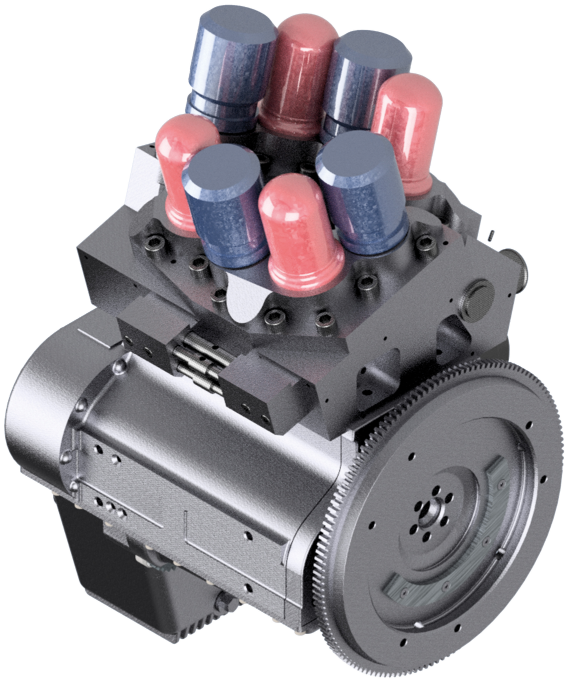


Figure 2.3: Texel's Stirling engine [1]

to be heated by a burner from within the heater construction. A burner would be located in the hollow space beneath the heater. Air would flow in through the hole seen on the front of figure 2.5b and be heated inside by the burner while the hot air vortex would heat the pipes of the heat exchanger in figure 2.5d. The gas in the pipes then flows back into the Stirling engine and drives the engine's pistons to create motion.

The old heater design needs to be redesigned to allow for an external hot air flow to heat the heat exchanger instead of the air being heated in the heater. The CM methods for the heat exchanger include casting, extruding, milling, and vacuum soldering among others. CM methods allude to established traditional methods of manufacturing. The design of the heat exchanger has a high level of complexity in its current form. The need to use CM methods in the past has resulted in complicated manufacturing and assembly processes that require the production and assembly of over 100 different parts. The resulting process is both expensive and time-consuming. Therefore, Texel intends to explore the possibility of using additive manufacturing (AM) as a manufacturing method for the heat exchanger in the energy storage system. For the heat exchanger to be manufactured with AM, it needs to be redesigned for AM.

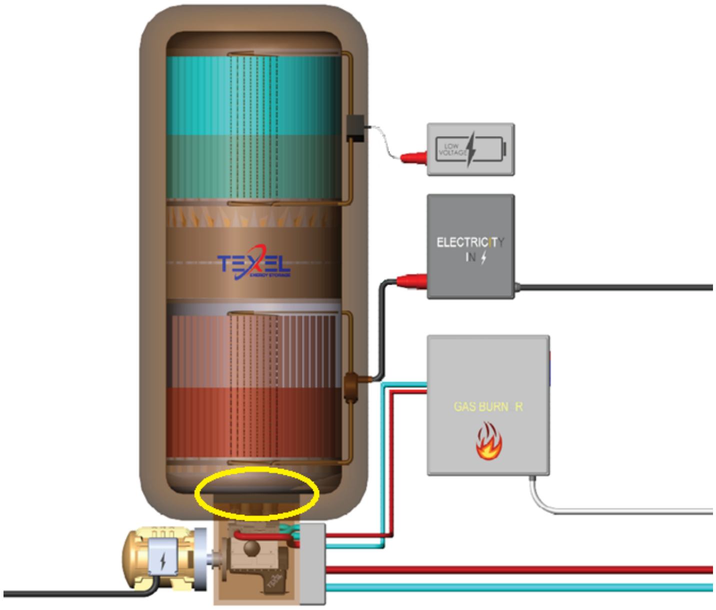


Figure 2.4: Visual representation of battery (*Borrowed from Texel*[1])

2.3.1 Design restrictions for the heat exchanger

Based on the requirements of the next iteration of the heater, it shall have an inlet and outlet for the hot air flow from the discharging TES. Each piston in the Stirling engine should have one inlet and outlet, meaning four inlets and four outlets.

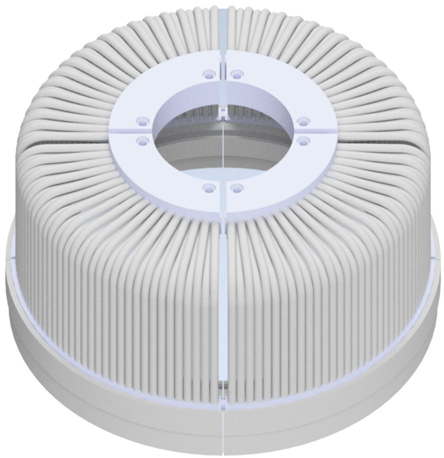
As seen in figure 2.6, The four pistons of the Stirling engine are interconnected. One piston's compression space is connected to an adjacent cylinder's expansion space. The pistons are series-connected in the order beginning with the expansion space, through the heat exchanger to the regenerator, then to the cooler, and lastly to the expansion space. The spaces are numbered in figure 2.6 as 1. Expansion space, 2. Regenerator, 3. Cooler, and 4. Compression space. The red area between the expansion space and the regenerator is where the heat exchanger will deliver the heat transferred from the hot air of the HT system. The working gas of the engine is then cooled in the cooler and flows to the compression space of the next adjacent piston. The pistons move in a sinusoidal reciprocating motion with a 90-degree phase shift between each adjacent piston. The red zone from each piston in figure 2.6 represents the four inlets and outlets in and out of the heat exchanger. The regenerator in the Stirling engine is a sort of heat exchanger that stores the fluid's heat in a solid medium. In this case, the regenerator stores heat as it cools the hot gas when the gas flows toward the compression space and heats it when it flows back toward the expansion space.

The maximum part volume is 251x251x140mm and preferably less, which will be highlighted further in the section 3.3.1 on the economics of AM.
The part should handle temperatures up to 900°C and a mass flow of 1000m^3/h of air. The airflow is illustrated in figure 2.6 as the hot air from the HT system flows

(a) Top part of the heater [1]

(b) Middle body of the heater [1]

(c) Bottom view of the middle body [1]



(d) The heat exchanger part of the existing heater [1]

Figure 2.5: Old heater design [1]

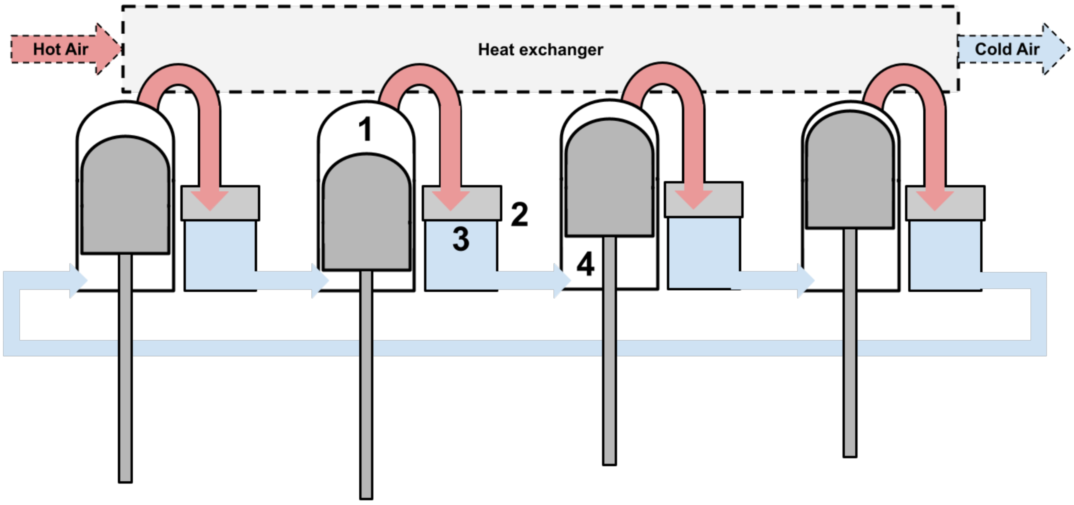


Figure 2.6: Schemaitc diagram of a 4-cylinder Stirling engine

through the heat exchanger. The heater should also transfer 177 kW of heat from the mass flow of air with an efficiency of at least 83%. These design restrictions are different for different manufacturing technologies and need to be adapted early in the design process and according to the chosen manufacturing methods.

3

Theory

This chapter describes the theory and the analytical concepts chosen in the thesis. First, AM is described with its pros and cons and the important concepts of how the technology works. Then the design method chosen to adapt to AM and the important concepts to adhere to is described. Lastly, the economics of AM and the method for the manufacturability applied from the literature is described, and the theory of the validation method.

3.1 Additive Manufacturing

Metal additive manufacturing is a layer-based manufacturing process to produce parts directly from a 3D model [13]. The process involves six steps: designing a digital 3D model of the part, creating an STL file, file manipulation, machine setup, building layer by layer, part removal, and post-processing.

Layer-based manufacturing is a process that builds an object layer by layer. The process starts with a digital model created using computer-aided design (CAD) software in metal AM. The software slices the model into thin layers and sends the data to the printer [13]. The printer then builds the object layer by layer by adding material until the final product is complete.

The process parameters such as laser power, scan speed, hatch spacing, and layer thickness significantly affect the microstructure and mechanical properties of the resulting part.

3.1.1 Laser powder bed fusion

Metal laser powder bed fusion (L-PBF) is a type of metal additive manufacturing (AM) that uses a high-power laser beam to selectively melt and fuse metallic powders layer by layer according to a 3D model. The manufacturing process can be viewed in the figure 3.1 It is also known as selective laser melting (SLM) or direct metal laser sintering (DMLS). L-PBF can produce complex and customized metal parts with high mechanical properties and reduced material waste [14]. L-PBF can be used for various applications in aerospace, automotive, medical, dental, and tooling [14].

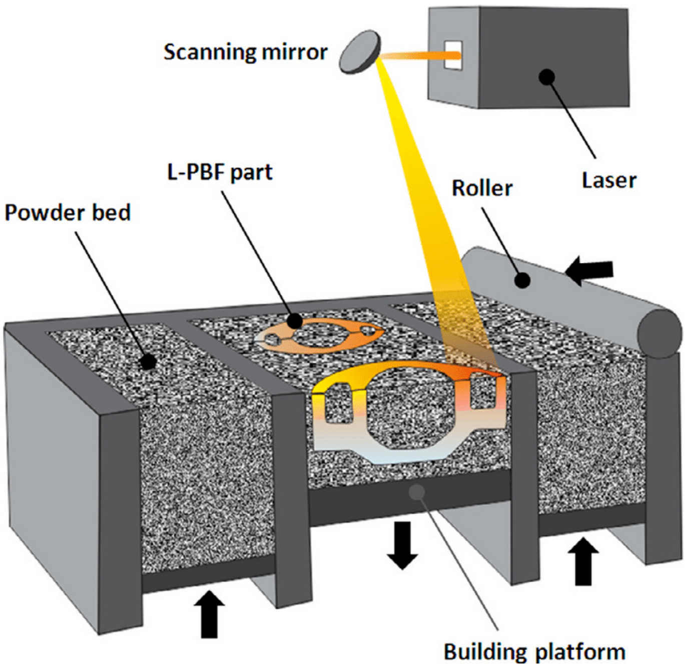


Figure 3.1: Schematic setup of L-PBF [13]

The L-PBF process consists of several steps and the most important are listed here [15]:

- The 3D model of the part is sliced into thin layers and converted into a machine-readable format.
- A thin layer of metal powder is spread over a substrate plate by a recoater blade or roller.
- A laser beam scans the cross-section of the part and melts the powder according to the 3D model.
- The substrate plate is lowered by one layer thickness and a new layer of powder is spread over the previous layer.
- The process is repeated until the part is completed.
- The part is removed from the powder bed and subjected to post-processing steps such as heat treatment, machining, polishing and coating to improve its surface finish, dimensional accuracy and mechanical performance.

Various factors, such as the material properties, the powder characteristics, the laser parameters, the scanning strategy, the built environment, and the part geometry, influence the L-PBF process. These factors affect the quality and performance of the L-PBF part, such as its density, porosity, microstructure, residual stress, distortion, and surface roughness. Therefore, optimizing the L-PBF process for each specific application and material is essential. There are different methods for process optimization, such as experimental design, numerical modeling, and machine learning. When applied, The metal AM method, like L-PBF, comes with advantages and disadvantages that must be considered to successfully design a part with the technology.

3.1.2 Advantages & disadvantages of AM

AM technologies inherently have several advantages and disadvantages compared to CM methods. According to Diegel, Nordin, and Mott [16] there are 7 main advantages gained by applying AM methods to produce a product. In table 3.1, the main seven advantages of AM are listed. The advantages and disadvantages described in this section consider specifically AM with metal as the material used for manufacturing.

Table 3.1: List of AM advantages

Number	Advantages of AM
1.	**Part complexity**
2.	Instant Assemblies
3.	**Part Consolidation**
4.	Mass Customization
5.	**Freedom of Design**
6.	**Light-Weighting**
7.	On-Demand Manufacturing

In metal AM, part complexity refers to the level of intricacy and variation in a metal part's geometry and features that can be produced using AM processes [17]. Compared to CM methods, AM offers more design freedom and allows for the creation of intricate and flowing designs that would be challenging or impossible to achieve otherwise. This design freedom can be leveraged to incorporate features like lattice structures, internal cavities, and topology-optimized designs, resulting in material savings and weight reduction while maintaining high-performance levels [17].

With additive manufacturing, intricate parts can be pre-assembled and emerge from the machine already assembled. In contrast, traditional manufacturing often requires complicated assembly processes for basic items. However, if additive manufacturing is used for entire assemblies, a small gap must be left between the moving components. While this gap may not meet, tight engineering fits, it is still significant by engineering standards [16].

Part consolidation refers to replacing multiple simpler parts with a single, more complex AM part. This approach can help to reduce assembly and inventory costs by minimizing the need for necessary tools, procurement of these tools, labor costs, and time spent on assembly operations and transportation [18].

With the help of additive manufacturing, parts can now be produced on demand, eliminating the need for long wait times for tooling in mass manufacturing. This speeds up the time-to-market and allows for seamless product alterations. Moreover, it minimizes stock control by enabling the manufacturing of components on the spot. Additive manufacturing also facilitates cost-effective mass customization, particularly in industries such as hearing aids, dental crowns, and high-end design [16].

The additive manufacturing process provides designers with a unique opportunity to create without limitations. Unlike traditional manufacturing, which restricts creativity due to cost and feasibility concerns, additive manufacturing allows for the precise creation of almost anything as envisioned. This improves product quality and encourages innovation [16]. The freedom of design is tightly linked with part complexity as AM allows for almost any design no matter the complexity however, liberties taken can result in costly post-processing.

Lightweighting is an advantage gained through the freedom to design at greater complexity than for CM. Lightwiegthing refers to the strategy of reducing weight and material usage by exploiting the capabilities of metal AM. This strategy can be applied to reduce emissions and environmental impact and improve performance and functionality [19].

On-demand manufacturing has emerged as a progressive and pioneering practice that challenges the traditional supply chain established during the industrial revolution. This fabrication methodology entails producing goods only when necessary, resulting in substantial cost savings as it eliminates the need to maintain vast inventories. This approach is remarkably efficient and allows for rapid and seamless product iterations. By harnessing AM technology, enterprises can fabricate parts locally, thereby mitigating risks and enhancing flexibility [20]. In figure 3.2, the traditional supply chain is shown, and in figure 3.3, the more compact and flexible on-demand supply chain of AM is shown. As AM technology grows, this simpler supply chain for AM will be more prevalent as it cuts out middlemen and increases flexibility [16].

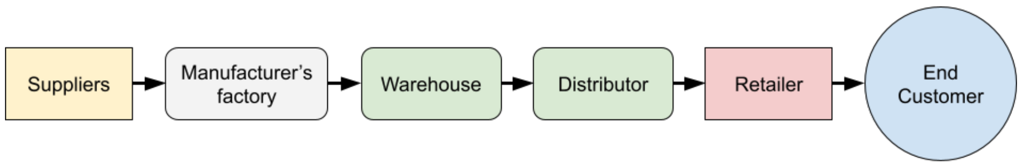


Figure 3.2: Traditional supply chain of today

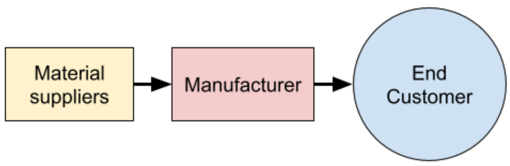


Figure 3.3: On-demand supply chain for AM

Metal AM is a technology that offers many advantages over conventional manufacturing methods, but it also has some disadvantages that must be considered. The main disadvantages of metal AM are listed in the table 3.2 explained below in more detail.

Table 3.2: List of AM disadvantages

Number	Disadvantages of AM
1.	High cost
2.	Limited materials
3.	Uncertainty in material properties
4.	Post-processing requirements
5.	Specific design constraints

High cost: Metal AM comes at a high cost, particularly for large-scale mass production, compared to traditional manufacturing methods. The major factors contributing to this cost include material expenses, the high maintenance and depreciation costs of AM machines, and the need for skilled designers and operators who incur high labor costs [19].

Limited materials: Metal AM can use various metal alloys, but the selection is slim compared to materials available for CM methods. beyond the meager availability of the feedstock material for AM, the quality and compatibility of these materials are also lacking. This is mainly due to the challenges of producing feedstock material such as powder for metal AM which obtain the suitable qualities of flowability, chemical composition, density, and melting point [19].

Uncertainty in material properties: Metal AM material characteristics and functionality are uncertain due to a range of factors. These include inconsistent metal feedstock, complicated AM procedures, and the absence of standardized testing techniques [19].

Post-processing requirements: Metal Additive Manufacturing can create parts nearly finished in shape, but they often need further processing to enhance their quality and functionality. The post-processing stage involves removing supports, heat treatment, machining, polishing, coating, testing, and inspection to address imperfections and defects [21].

Specific design constraints: Regarding metal additive manufacturing, certain design limitations exist due to the process capabilities and restrictions. These include minimum feature size, overhang angle, support structure, build orientation, and thermal management. These constraints can ultimately impact the quality and feasibility of the produced parts, affecting accuracy, roughness, porosity, stresses, and distortion [19].

It is important to acknowledge that there are certain drawbacks associated with metal AM technology, which can be attributed to its relative novelty as a manufacturing technology. The first machine concepts for AM were developed in the 1960s as experimental setups. Stereolithography was invented in the 1980s, and the first metal AM technology was developed in the early to mid-1990s [22][23]. L-PBF is currently the most advanced metal AM technology, which has started serial production in some industries [22]. In figure 3.4, the metal AM's Technology readiness level (TRL) in different key industry sectors. TRL is used to measure the level of technology implementation in the industry and was first developed by NASA [24]. As indicated in figure 3.4 the TRL of metal AM has reached full-rate production in some industry sectors, except for the medical industry, there is still some way to reach full-rate production.

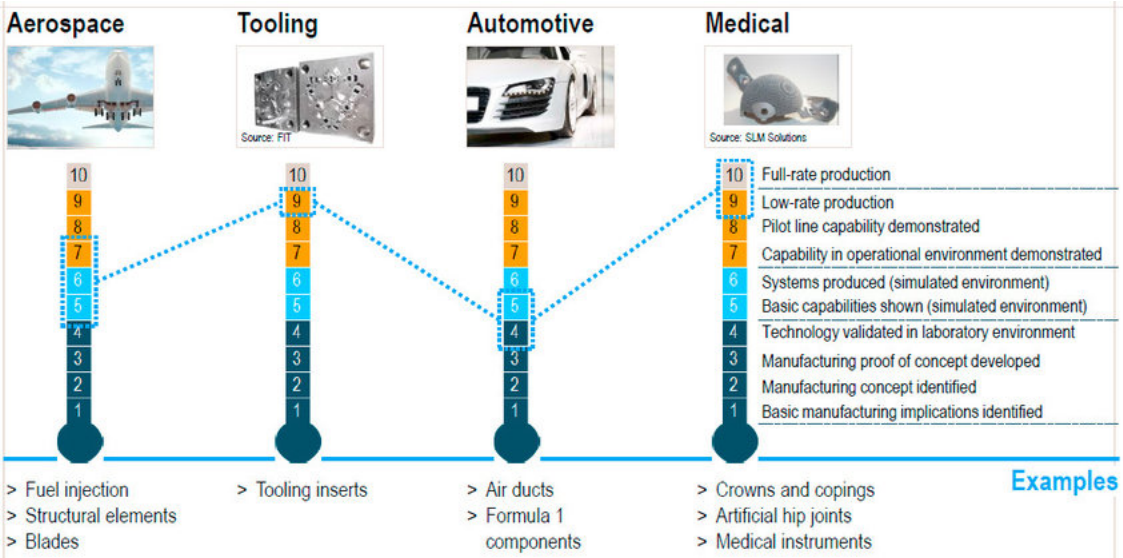


Figure 3.4: TRL of metal AM in different key industries [24]

The automotive and aerospace sectors face challenges causing the lower TRL rating. This is due to various application issues. High part costs, low productivity, lack of standardization, insufficient technical knowledge, and designing skills equivalent to traditional metals are all hindering its complete implementation [24][21]. Standardization, education of designers & machine operators to further knowledge & experience of AM tools and machinery, and development of new materials will improve with time [21][25]. More material will be made available, but it takes time as the material composition for AM needs to be designed specifically for metal AM to be usable [25]. However, some drawbacks are inherent in the technology and are related to metal AM's design limitations and post-processing requirements. These will be further discussed in section 3.2, and how to address them during the design process by following design guidelines is described in section 3.2.1.

metal AM processes and applications have not been fully explored or established, leading to uncertainty regarding the quality of the final part. In general, the intricate traits of L-PBF and the multitude of factors that need to be optimized to minimize or eradicate defects like surface roughness, porosity, and residual stress are significant challenges and computationally inefficient. Recent research suggests that it remains uncertain how most of these defects are connected to the various L-PBF variables and their actual characteristics [21]. Mitigation of this issue can be achieved to a certain extent through proper design considerations, but it also relies on the capabilities of the particular machine, the proficiency of the operator, and the selection of appropriate materials. The uncertainties related machine specific parameters are not considered in this thesis as there are a large variety of machines available and no specific machine is chosen from Texel's point of view.

3.2 DfAM

Design for additive manufacturing (DfAM) seeks to create designs based on the advantages of AM capabilities. Diegel, Nordin, and Mott [16] states, "AM can be an expensive process, so for its use to be profitable as a production method, it must bring added value to a product". According to Diegel, Nordin, and Mott, there are several ways to add value and use the advantages of AM. The following section will describe the main advantages of using AM and how it will be applied in this thesis.

3.2.1 Metal AM guidelines and considerations

When designing a part for AM, there are some guidelines to consider based on the technology restriction; these six guidelines are listed in this section [16]. Important to note that these guidelines vary between different machines. As no specific machine is defined for manufacturing the heat exchanger, general values for these features will be considered.

Metal AM guidlines	
Guideline	Guideline description
Minimum wall thickness	Should be more significant than 0.2mm, with a fillet of one-fourth of the minimum wall thickness.
The overhang angle	Should be less than 45 degrees to avoid excessive amounts of the support structure.
Clearance between moving parts	More than 2mm in the horizontal direction, and vertically there should be room to remove supports.
Vertical slots and circular holes	Should be at least 0.5mm.
Vertical bosses and circular pins	Should be at least 0.5mm.
Built-in external screw threads	Should always be built vertically.

Besides these considerations, it is also essential to consider build orientation when designing the part and the volume of the metal AM machine. These guidelines need to be considered from the beginning of the design and through the whole workflow.

3.2.2 Computer-aided design

Computer-aided design (CAD) is the use of computer systems to aid in creating, modifying, analyzing, or optimizing a design. It is used in many fields, such as architecture, engineering, and product design [26]. CAD software creates 2D and 3D models of products and structures. The software allows designers to create detailed drawings and models that can be used for manufacturing or construction. CAD tools of different kinds will be used throughout the design process and applied sensibly with the guidelines in mind.

3.2.3 Design tools and workflow

This section overviews the tools used to design the heat exchanger for AM. The 3D model has been executed through an iterative design process. To begin with, create the heaters heat-conducting volume and shell with inlets and outlets for the fluid flow. During this thesis, several software has been used to design the heat exchanger. The workflow can be separated into four main steps: Design of basic geometry, generate design suitable for AM, validation through simulation, and print preparations.

First, the basic geometry of the part was designed in traditional CAD software. In this case, Autodesk Inventor was used. A design space for the heat transfer volume was defined, and other essential functions of the heater, such as the shells, inlets, and outlets, were defined in this step.

Secondly, The CAD model was exported to nTopology, a CAD software using implicit modeling to create AM-friendly designs. to utilize the nTopology software ability to adapt a design to AM. nTopology can create structures optimized for AM given parameters defined by the user in the created 3D model from Inventor.

To validate the design, the third design tool, the simulation software, was used to evaluate the design. A mesh is exported from nTopology to the simulation software Ansys Discovery. A workflow can be seen in figure 3.5. The workflow is an iterative process, designing, refining design for AM, and validating with simulation. Finally,

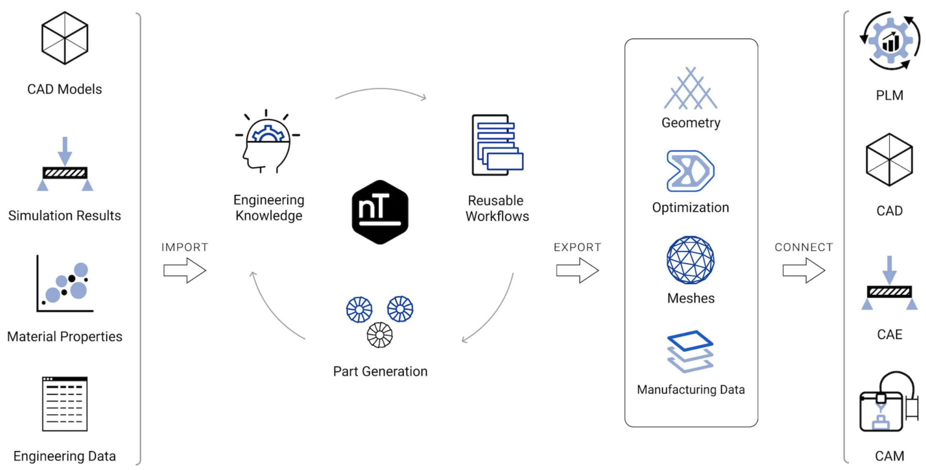


Figure 3.5: Work flow with nTopology [27]

after the design is deemed ready, the design is exported as an STL file to Autodesk Netfabb. This print preparation software determines support generation and optimal print orientation. With this information, the build time and support volume can be calculated. When the design is ready and all important parameters are gathered, the manufacturability of the design will be assessed.

3.3 Manufacturability assessment

This section establishes the theory for the method for the manufacturability assessment of the heat exchanger and the general consideration of the economic aspects of AM. The section also includes a detailed description of the input, outputs, and how the assessments are conducted. The manufacturability assessment will include two methods devised to calculate the cost of producing AM parts and will be described separately in the following sections.

AM is layer based method where the material is deposited in one thin layer at a time directly from a 3D model layer-wise until the whole 3D model is manufactured [28]. Compared to CM, where 2D drawings with specifications for the desired CM method are needed. This means AM method can easily produce complex parts compared to CM methods. It also means that cost and time assessments based on CM methods are invalid due to their significant differences [21].

The manufacturability must be assessed to evaluate if a part is appropriate to manufacture with AM. This is done by evaluating the time and cost to design and manufacture the part with AM. It is essential to do this evaluation in the product development phase to identify if a part is feasible to produce and to be able to make the correct decision when deciding on manufacturing methods [28][29]. It is important to proceed with this investigation early in the development phase as an AM-produced part needs to be designed differently from a part produced with CM methods [29].

3.3.1 Economics of AM

General cost and time considerations for AM and the design of a HEX from the A Practical Guide to Design for Additive Manufacturing and other sources. In the 2018 Wohlers Report[30], service providers of AM were asked which processes possed the largest share of the part cost when manufacturing in AM [16]. The result from the query shows the on-average value for all providers and can be seen in Table 3.3. Printing and post-processing represent 86.8% of the total costs for metal AM. Therefore, it makes sense to focus the design on improving these areas.

Table 3.3: Printing, Pre- and postprocessing cost shares [16]

Process phase	Metal (%)
Pre-processing	13.2
Post-processing	31.4
Total pre and post	44.6
Printing	55.4

Part geometry, i.e. the parts shape and size, is the primary way to affect cost and time from a design point of view[31]. To reduce the part cost, the main factor the designer controls is to reduce print time by creating a part geometry suitable for printing. This can be done by following the previously mentioned guidelines for metal AM and reducing the part's total volume, i.e. less material to print and reduced printing time.

Another critical factor is to minimize the contour area meaning the surface area of each layer that the laser needs to hatch (or scan) to melt the metal powder. The heater is shelled to utilize this, and an internal self-supporting lattice structure is generated with the help of previously mentioned design tools. The lattice structure reduces the parts mass and generates an internal structure with a suitable surface area-to-volume ratio. The principle can be seen in Figure 3.6. An AM machine takes

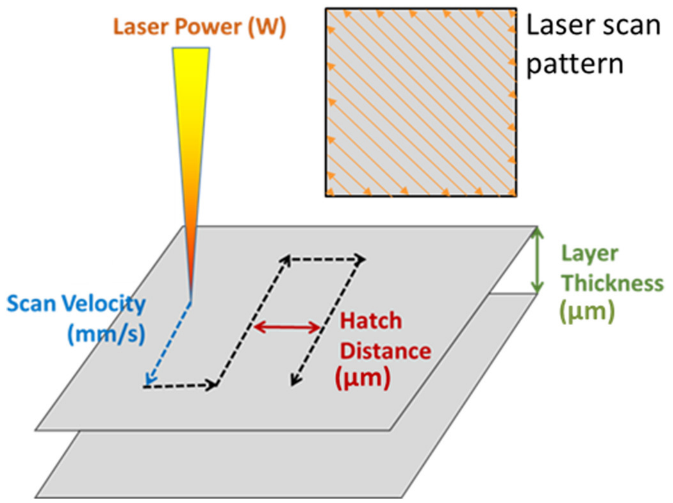


Figure 3.6: Contour and hatch pattern[16]

consumes much time and leads to more costs. There are several aspects, such as layer preheating time and recoater time (the time it takes the recoater of the machine to apply the new layer of metal powder). These aspects are machine specific and can only be improved by design by reducing the number of layers, which results in fewer actions for the machine. Another factor to consider is the height of the part [16].

Design to reduce the number of supports for the heater is done by deciding the build orientation and ensuring guideline 2 is upheld, i.e., the overhang angle of the part is less than 45 degrees. The lattice structure, as mentioned before, is created to be self-supported.

3.3.1.1 Design parameters affecting build time and cost

From the informal interview with the expert in AM software at Chalmers and the training of the new software *nTopology*, the significant parameters to design around for AM could be identified. In the previous section, 3.3.1 machine-dependent parameters and how they affect the build time and cost are identified. It was found that the total volume and height of a designed part have the greatest effect on cost and time by utilizing the *nTopology* software to generate an optimal geometry that preserves the part's functionality while minimizing the total volume. The minimized volume means less material used & less area to deposit material, and therefore lower material cost & build time. Lower height of a designed part results in less downtime between layers, meaning lower build time. The third and final design consideration is the part orientation which minimizes the amount of support, leading to less post-processing work needing to be conducted.

3.3.2 Parameters for AM

This section explores the indirect cost attributed to a part manufactured with metal AM. The previous section 3.3.1 and section 3.3.1.1 discuss the design parameter directly impacting the cost of manufacturing a part with metal AM. This section describes the indirect cost of manufacturing a part with AM. The indirect costs are traditionally calculated with a process-oriented model [28]. The indirect cost can be sorted according to the process in which the cost occurs. The literature found that the process could be separated into the three categories of pre-processing, Processing, and post-processing [**thompson2016design\autocite {kadir2020additive}**].

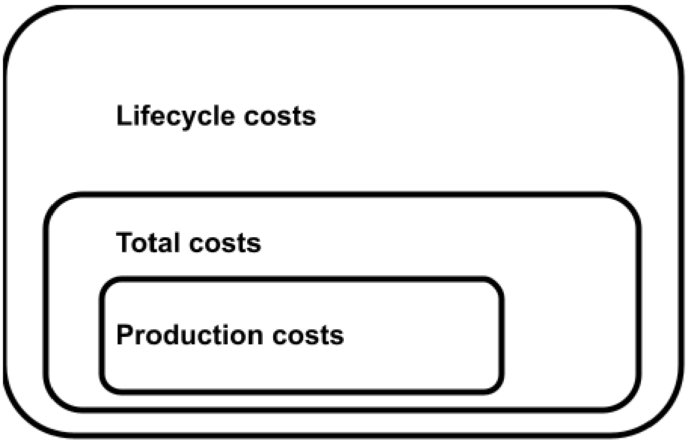


Figure 3.7: Cost components [28]

To further widen the manufacturability scope and consider the total cost as seen in figure 3.7, the cost is considered on the process level [28]. The total cost considers the material, pre-processing, production post-processing, and administrative costs [32][33]. This adds two more process inputs the manufacturability assessment, administration overhead, and material costs. This is summarized in figure 3.8 showing a black box of the manufacturability assessment and the inputs and outputs connected to it. All the inputs will be further described in the following sections. The sources defining the parameters are noted for each input in these sections.

3.3.2.1 Design parameters

The design parameters greatly affect the end result of the manufacturability assessment. In figure 3.8, the process step affected by the design parameter is shown. The

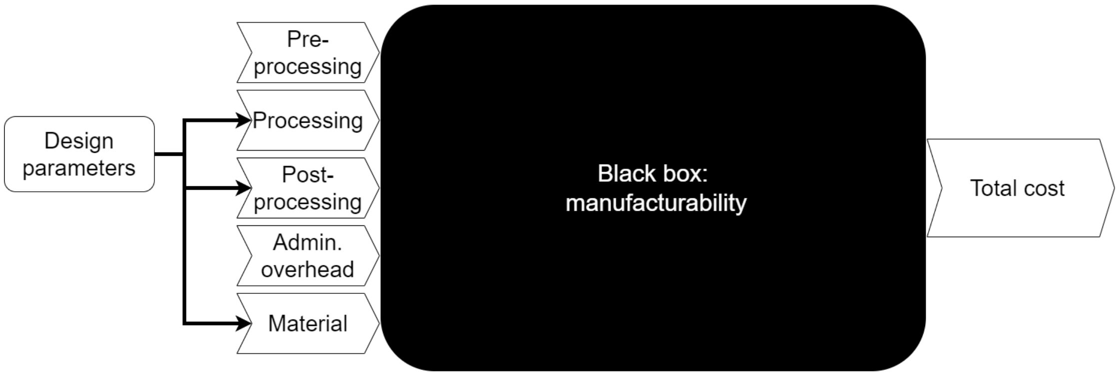


Figure 3.8: Black box for manufacturability

design parameters of importance are shown in table 3.4. These can be changed in the design phase to create an optimized part. The output of this step is build time and part orientation.

Table 3.4: Material cost

Cost parameter	**Parameter function**	**Source**
Part volume	affects material costs and build time	[33]
Part height	affects build time	[34]
Part geometry	Affects support volume and part volume	[34][35]
Part orientation	affects support volume	[34][35]

3.3.2.2 Material

This section describes the material input of the black box in figure 3.8. The material cost needs the design parameters of volume to be evaluated. The output from this step is the total cost of material.

Table 3.5: Material cost

Cost parameter	**Parameter function**	**Source**
Material cost per kg	To define the material cost of part	[33][34]
Density	Material specific	[34][33]
Mass of material	The mass based on the volume	[34][33]

3.3.2.3 Pre-processing

The administration overhead cost considers surrounding costs such as hardware and software costs. The Total overhead cost is calculated as a cost per hour depending on the cost of the software & hardware and the salary of the operator or designer. This step is not directly affected by design parameters.

Table 3.6: Administration overhead cost

Cost parameter	Source
Hardware cost	[33]
software cost	[33]
Salary of operator	[33]

3.3.2.4 Processing

The processing step refers to the actual AM process of layer-wise building a component. It can also be viewed as the main step of AM production. This step depends on the design parameters that govern the build time. The output of the processing step is the cost per part produced.

Table 3.7: Processing cost

Cost parameter	Parameter function	Source
Build time	Build time (dependent on Design parameters)	[33][36]
Operation hours	Machine specific	[36]
Machine price & maintenance	Used to approximate machine cost	[37]

3.3.2.5 Post-processing

The post-processing step considers all activities and tasks performed after the 3D model is fully formed. The cost considered here is heat treatment, Hot Isostatic Pressing (HIP), and support removal with wire EDM. The post-processing step must consider the design parameters that govern part orientation and geometry, which decide the support amount needed [38][16]. The support removal is the parameter primarily dependent on the design parameters.

Table 3.8: Pre-processing cost

Cost parameter	Source
Heat treatment cost	[37]
HIP cost	[37]
Salary of operator	[33]
Support removal	[36]
Lifetime of post-processing machines	[37]

3.3.2.6 Pre-processing

The pre-processing step consists of a constant set-up time for a build and the salary of the CAM engineer & the machine operator. This step is not directly affected by design parameters and will not change much, no matter the design choices. The output of the step is the total cost for pre-processing.

Table 3.9: Pre-processing cost

Cost parameter	Source
Set-up time	[36]
Salary of operator	[33][39]
Hours CAM programming	[39]

3.3.3 Validation method of manufacturability assessment

The manufacturability assessment applies methods from articles gathered during the literature review. To validate the method proposed for the manufacturability assessment built on the methods investigated, this thesis proposes to compare the result of the proposed method with external software.

Etteplan is a company that provides Technology Services, specializing in software and embedded solutions, engineering solutions, and technical communication solutions. The goal is to help customers create a better world through engineering, innovation, and digitalization [40]. Etterplan has developed a tool called AMOTool which provides a risk-free early estimation of part cost for metal AM.

The AMOTool has a unique feature that minimizes the risk of 3D model leakage to unauthorized persons. It does not require a 3D model as input to calculate the manufacturing cost. Instead, it only needs specific data such as part height, part volume, complexity estimation of the part, machine type, material, number of parts per build area, layers of stacked parts, support volume, an approximation of post-processing cost, and annual production volume. With these inputs, the AMOTool can accurately estimate the cost of manufacturing the part.

4

Methods

This chapter describes the methodology for conducting the thesis and answering the research questions. The methodology is based on the theory gathered in the literature review and how the theory is applied to Texel's heat exchanger for the case study. The methodology section initially outlines the research methodology and subsequently details the application of DfAM theory. Following this, the method for the manufacturability assessment is clarified, and the articles used as the basis of the method are described and how a validation method for the manufacturability is applied.

4.1 Research methodology

This is a preliminary method that is intended to be followed but can be revisited to be revised for further clarifications and additions as the thesis proceeds. This thesis focuses on further product development by redesigning a component and creating a manufacturability framework. The thesis will be both parts of a larger development project at the company and develop a product (the manufacturability framework and CAD designs) that is suitable to use [41] research methodology. In figure 4.1 the main steps in the methodology are shown.

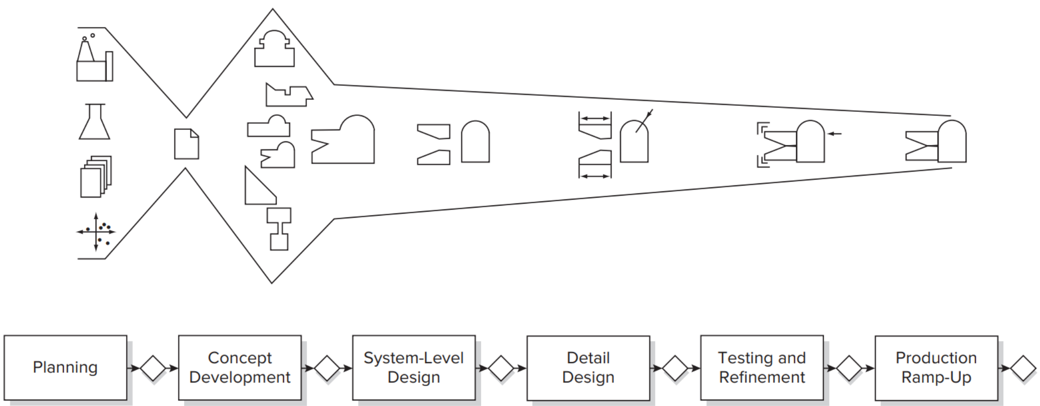


Figure 4.1: Research methodology from [41]

The research methodology of *Product Design and Development* [41] spans the whole product development process, from idea and design to ramp-up to full production. This process can be separated into six steps: Planning, Concept development, System-level design, Detail design, Testing and refinement, and Production ramp-up. These are shown in figure 4.1. This thesis focuses on the redesign and manufacturability assessment of one part of Texel's system and will, therefore, not consider the whole product development process of the methodology. The six steps are summarized in the list below.

1. **Planning:** Planning involves identifying opportunities, assessing technology and market objectives, and creating a project mission statement with the target market, business goals, assumptions, and constraints.

2. **Concept Development:** In the concept development phase, identify of target market's needs and evaluate different product ideas. The most promising concepts are selected for further development and testing, with detailed descriptions and economic justifications.

3. **System-Level Design:** During system-level design, the product is broken down into subsystems and components, and key components are designed. Production and final assembly plans are established, resulting in a geometric layout, functional specs for each subsystem, and a preliminary process flow diagram.

4. **Detail Design:** In the detail design phase, the product's geometry, materials, and tolerances are specified, along with identifying standard parts and creating a process plan. The outcome is control documentation, including drawings or computer files, specifications for purchased parts, and fabrication and assembly process plans. Materials selection, production cost, and robust performance are crucial issues in this phase.

5. **Testing and Refinement:** Multiple pre-production product versions are created and evaluated. Alpha prototypes use production-intent parts to test functionality and meet customer needs. Beta prototypes use parts from intended production processes to test performance and reliability and identify necessary engineering changes.

6. **Production Ramp-Up:** During the production ramp-up phase, the product is manufactured, and a workforce is trained while addressing any issues. Products are evaluated, and flaws are identified. The launch is gradual, and a post-launch review is conducted to improve future projects.

Out of these six steps, steps 2-4 will be applied in this thesis. Step 1 *Planning* will be applied to a degree in this thesis. Still, as the thesis project is conducted with Texel, they already have established the parameters, such as target markets and business goals.

Step 6 *Production Ramp-Up* will be the only step not applied in the thesis project. This thesis will investigate the manufacturability of the heat exchanger and propose a manufacturability method. A design proposal will also be developed, which will not be ready to be taken into production. Therefore, the thesis will end in steps 4 & 5 *Detail Design & Testing and Refinement.* The thesis will follow the Spiral product development process illustrated in figure 4.2 as the product, in this case, the heat exchanger, will be developed to work in an existing system. For this thesis, the testing will be mainly conducted with simulations, and the manufacturability assessment will be tested for the heat exchanger and further developed iteratively.

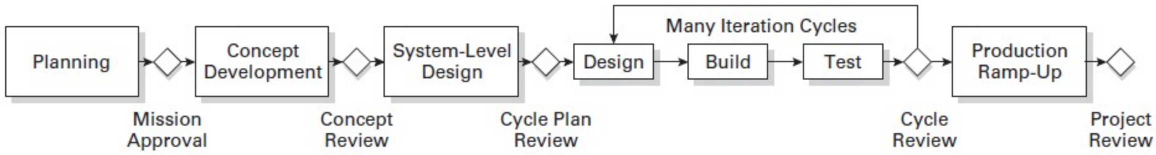


Figure 4.2: Product development process flow [41]

4.2 Re-design with DfAM

The method is adapted from the book *A Practical Guide to Design for Additive Manufacturing* [16]. The strategies applied, and guidelines used are described in section 3.2. From the advantages in table 3.1, four advantages are of more interest for the heat exchanger design with metal AM.

Part consolidation will be used as the existing heat exchanger manufactured with CM methods consists of around 160 different components. Using metal AM, the heat exchanger can be consolidated into only one part, so over 100 assembly operations can be avoided. All this while the heat exchanger keeps its original function and the possibility of compressing the size of the heat exchanger. Part complexity is closely related to part consolidation and **freedom of design**, as AM allows for the freedom of almost infinite **part complexity** of the design. This freedom allows for designing the heat exchanger as one part and creating complex geometries that would be impossible to manufacture with CM methods. A complex geometry used for the heat exchanger generates gyroid lattice structures that are self-supporting and are modeled in such a way that the thin wall of the lattice structure only separates the two fluids of the heat exchanger. The final advantage utilized is creating a **lightweight** part resulting from the lattice structure, as the heat exchanger will keep its structural integrity while maximizing the heat transfer between the two fluids. Lastly, the last advantage mentioned in the 3.1.2 of **on-demand manufacturing** will, if Texel wishes to produce the heat exchanger in-house, allow them to reduce the inventory space needed and a shortened supply chain which comes with AM methods.

The section 3.1.2 describes possible disadvantages of using AM as a method for producing parts in metal. Some of these disadvantages come from the relative novelty of the metal AM technology, but to lessen the impact or avoid them, guidelines are outlined in section 3.2.1. By following the six guidelines, faulty parts can be avoided, and the support structures needed can be minimized by applying the guideline of overhang angles and having the build orientation in mind throughout the design process.

4.3 Manufacturability assessment

This section describes the methodlogy of manufacturability assessment. How the manufacturability assessment was generated and what methods were used. Literature was reviewed and screened to sort out relevant articles. From the relevant articles, the two most suitable articles were applied to the case study of the heat exchanger and used as a basis for the manufacturability framework generated for the heat exchanger. Several other articles with complementary and relevant methods were used to enhance the base methods from the two articles.

The literature gathering for the manufacturability assessment was conducted with the following steps:

1. Understanding the importance of keywords.
2. Finding articles through various academic search engines
3. Evaluate articles based on suitability for thesis
4. Describe and apply the method of the articles

The article search began with identifying relevant keywords, including: *AM, LPBF, cost, framework, economics, manufacturability, time, metal, cost assessment, cost estimation, cost model, design, and heat exchanger*. These keywords were then utilized in various combinations to search for the most pertinent articles for the thesis project. All literature searches always included the keywords *Metal and AM*.

The second step was to use reliable platforms to find the literature on. Search platforms like ScienceDirect, Google Scholar, Scopus, Connectedpapers, and Springer Link were utilized to conduct the search.

The 20 most relevant for each search result were then screened based recency of the article, the article's title, and the article's abstract and conclusion. Articles older than 2003 were discarded immediately, and articles between 2003 and 2013 were kept as maybes. Articles were then screened based on the relevance of the title. The abstract and conclusions were read for all the articles with relevant titles to sort out the most relevant articles. The most relevant articles were sorted out from the abstracts, and the conclusions were fully read. The theory for manufacturability was then established based on the most relevant articles.

The information gathered from the most relevant articles was then processed and analyzed to find any knowledge gaps and the key parameters for a manufacturability framework.

From the articles analyzed, two articles were selected as a foundation for the proposed method of this thesis, the manufacturability framework. Additional relevant articles found during the literature review were used to supplement these two methods with missing parameters.

4.3.1 Expert knowledge & software utilization

An informal interview with an expert on additive manufacturing software was conducted, and specialized software for additive manufacturing was learned to complement the information gathered in the literature review. The informal interview was used to gather expert knowledge and ease learning new software.

By learning the software and using it to design a new proposal for the heat exchanger, important design parameters affecting the manufacturability assessment could be gathered.

4.3.2 Cost model validation of the manufacturability assessment

To validate and evaluate the result of applying the methods from Article A, Article B, and the final proposed method for manufacturability, a comparison with Etterplan's AMOTool is conducted. The tool is an early estimation and, therefore, can not be regarded as the absolute correct answer but works well to indicate if the proposed methods' calculations are in the right region.

In order to make a comparison with the proposed method, the inputs required for the AMOTool will be inputted using the same values utilized in the proposed method. This will be displayed in the following Result chapter.

5

Results

In this chapter, the results of this thesis will be accounted for. The result of the thesis is separated into three sections: the final model design with DfAM, a cost and time estimation based on the newly designed heat exchanger in the case study, and the base methods described in the theory chapter. Then the result of the proposed method combines selected parts of the methods after comparing the two and other literature. Lastly, the proposed methods cost calculations are compared with another method to evaluate, and validate the result.

5.1 Design proposal

The final design of the heater has utilized the methods of DfAM. The existing heater was deemed suitable for redesign as several advantages when designing for AM could be gained. The most obvious benefit of this design is utilizing part consolidation. The original design was constructed with 156 different parts, and when redesigned for AM, the heat exchanger consisted of only one part. The original prototype for the heater is designed to work in a system only containing the Stirling engine. The heater in that system needed a free internal space for a burner to heat the heater pipes directly. As mentioned earlier, when designing the new proposal for the heat exchanger, a hot flow of air should transfer heat to the Stirling engine from the TES instead.

A new, more compact design is possible with the use of AM by adding self-supporting manifold lattice structures with a gyroid pattern that also separates the hot air fluid and the gas flow of the engine. These lattice structures were meshed and exported to a CFD simulation. From the simulation, data was attained to refine the lattice structure to improve the flow and heat transfer of the heater. This was done with nTopologys field-driven design and by creating baffles and plenums to improve the flow. This process can be iterated repeatedly until a satisfactory result is reached. The geometrical complexity of the heater can be fully utilized when designing for AM.

The Final proposed design can be seen in figure 5.1. The design visualized shows the hot flow of air (red), the helium flow from the engine (blue), and how they flow through the lattice structure. The final design is, to a degree, simplified. The hot air inlet is only the open lattice structure, but the future design might need an inlet compatible with the HT system. The design only represents a quarter of the heat

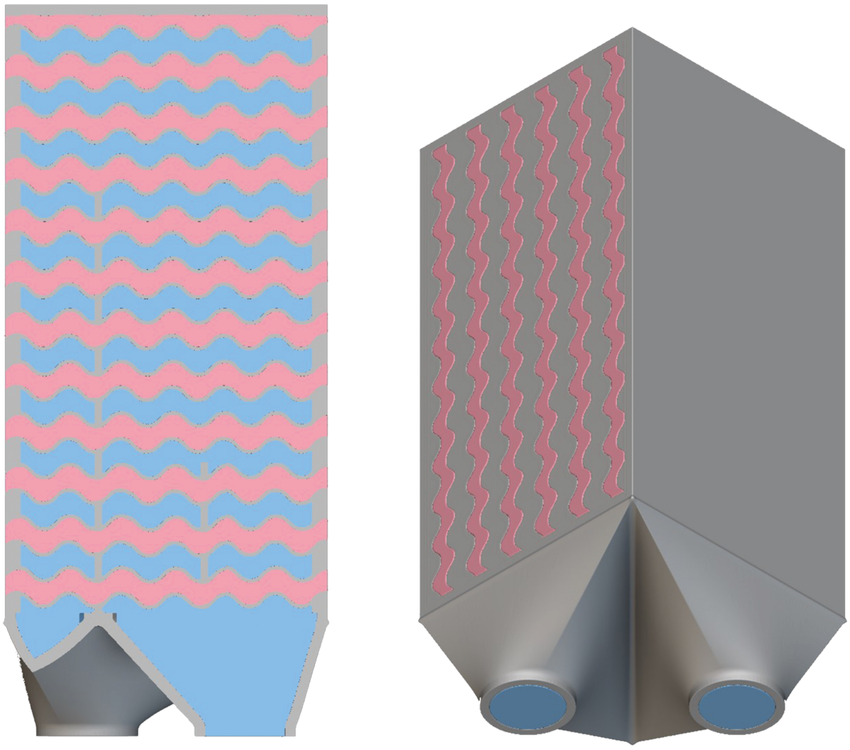
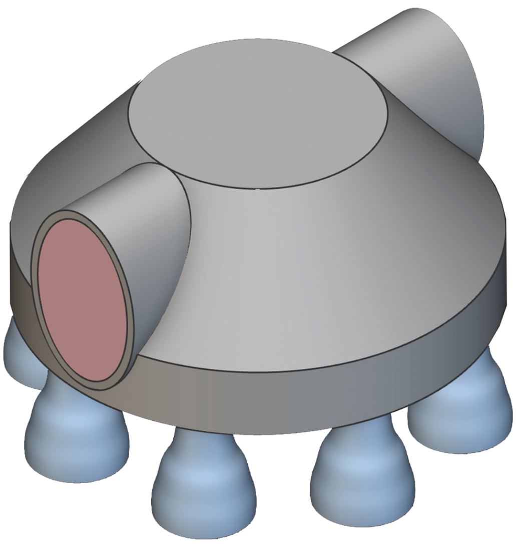
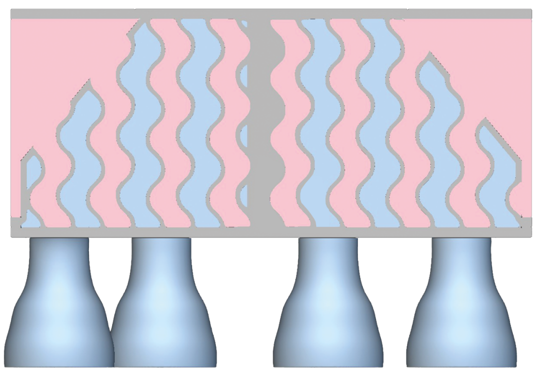


Figure 5.1: Final design proposal with cross-section & bottom side view

exchanger, which was done due to a lack of computational power. In figure 5.2, an earlier iteration of a possible design for the full heat exchanger is shown.



(a) Side top view of heat exchanger



(b) Cross-section of heat exchanger

Figure 5.2: Design iteration of the whole heat exchanger

The gyroid lattice structure created a compact, relativity lightweight heater with an excellent surface-to-volume ratio. The increased surface area will result in a more significant convective heat transfer. The thickness of the lattice structure is another parameter essential to the heat transfer. Depending on the thickness of the solid medium transferring heat, it should be designed to be as small as possible due to heat conduction.

5.2 Manufacturability assessment

This section applies the cost and manufacturability assessment methods to the heat exchanger in the thesis. The application of the two chosen articles will be described, then the methods of the two articles will be reflected upon, and both methods demand the need to choose an AM machine. Both articles originally assumed the EOSINT m270 model. Since the EOSINT m270 is no longer in production, the EOS m290 has been assumed for this thesis. It shares many similarities with the m290 model but has a slightly larger build area.

Several related articles were studied for the manufacturability assessment. The critical elements were to use relatively recent articles. Input for methods should be related to the design process, preferably articles that study heat exchangers in the context of cost analysis. To establish a method for the manufacturability assessment, more general methods of assessing metal AM were looked at to build a manufacturability method that encompasses the whole process of AM. It is important for the base on which the method will be built to consider cost in all process stages and for all activities conducted using AM technologies.

5.2.1 Result of articles

There were several articles focusing on one or a few process stages of AM like *Enabling Cost-Based Support Structure Optimization in Laser Powder Bed Fusion of Metals*, which only looked at how to design for cost optimization of support structures [42]. Another article makes a comprehensive cost assessment for the aerospace industry. Still, it focuses on cost saving enabled by AM through fuel saving during end use of the manufactured parts [37]. This article considers some important factors, especially in the post-processing stage, which will be incorporated into the proposed method of this thesis. Still, as a base for the method, the article focuses too much on the end use.

In the article *Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints*[38], the author emphasizes the significance of DfAM in cost modeling. The article explains how cost models are subsets of DfAM, and highlights the importance of redesigning a part to suit AM technologies. If a part is originally designed for CM methods, it might not be feasible to manufacture it with AM. Thompson, Moroni, Vaneker, *et al.* [38] classifies cost models for AM into two categories: well-structured production costs (including labor, material, and machine cost) and ill-structured costs related to transportation, inventory, build failure costs, and more. In the past, cost models have been more focused on well-structured costs to identify the best manufacturing processes for the product cost and compare CM and AM methods with other methods. However, recent work has shifted towards ill-structured costs, focusing on the life-cycle perspective.

The article *Additive manufacturing cost estimation models a classification review* goes further with the classification of cost models for AM and classifies the models as method-based, task-based, and level-based [28]. In this thesis, we will not delve into the method-based techniques, as they only estimate costs from an accounting perspective. Instead, we will focus on task-based techniques, which can be categorized into two sub-groups: design-oriented and process-oriented. Design-oriented techniques concentrate on various phases of product development and manufacturing tasks, such as part design, process planning, and redesign, which are typically carried out before full production takes place [28]. When evaluating the cost of manufacturing, process-oriented techniques take into account both direct costs (such as labor, machine, and material) and indirect costs (such as administrative and pre- and post-processing operations). This comprehensive approach allows for a more accurate assessment of the overall cost directly related to the manufacturing process.

Typically, strategies based on levels adopt an economic management approach and categorize into two types: process-level and system-level [28]. When it comes to techniques, level-based ones tend to cover more ground than task-based ones. Within the level-based category, there are two subgroups: process-level and system-level. Process-level techniques take into account all production-related costs, including production costs and total costs. System-level techniques go even further and consider other factors like surrounding services, the supply chain, and the product's entire life cycle. In Figure 3.7, it is shown how different techniques factor in the cost components. The task-based approach primarily considers the production component, as depicted in Figure 3.7, while the level-based approach takes into account multiple components.

This research paper focuses on the Texel heat exchanger's design and manufacturability for AM. As the heat exchanger is not yet in production, the evaluation of its manufacturability must consider the manufacturing tasks and product development phase's production costs. The thesis will also broaden the cost components to the total cost, assessing the manufacturability. However, the models used in the study will not consider the system level as it encompasses several costs throughout the product life cycle, such as loans, insurance, disposal, and salvage value. The wide scope of these costs does not directly relate to design and manufacturing decisions. Therefore, this thesis's model used for the manufacturability assessment will only consider relevant literature.

The article *Connecting part geometry and cost for metal powder bed fusion*[43] mainly applies the cost model developed in the article *Metal Additive Manufacturing: Cost Competitive Beyond Low Volumes*[37] but adds the focus of scarp and reject rates of the processes. The article also uses generative design to generate several designs of the same part and compare the geometry impact on the cost. The part used in the article has a rather simple complexity, and the way to apply the model from the article by Budinoff and Shafae [43] would be difficult to apply for a heat exchanger, and the model builds on the article by Laureijs, Roca, Narra, *et al.* [37] so it suffers the same drawbacks as that article.

The article *The economics of additive manufacturing: Towards a general cost model including process failure*[44] strives to create a general cost model for all different AM methods. In the article, the process method used is binder jetting; the parts produced are small medical tablets. The further develops an earlier model, including the process failure or part rejection. As the cost model in the article Ding, Baumers, Clark, *et al.* [44] is general, other sources would be needed to apply the model in order to fill in the blanks of the model when specifying AM process, material, and part. Therefore this article will not be used more than an inspiration for the cost to consider.

The article *Economic sustainability of additive manufacturing: Contextual factors driving its performance in rapid prototyping* uses questionnaires to gather information from companies on the economics of AM. This article was rejected as it focused on AM in rapid prototyping (RP), and the material considered in the article was only plastics.

The article *Systematic manufacturability evaluation using dimensionless metrics and singular value decomposition: a case study for additive manufacturing*[45] poses an interesting case as it takes a systemic view and uses machine learning to create a dimensionless decision model to rank different components' suitability for AM. The model considers cost as one of twelve metrics and incorporates design rules from DfAM as metrics [45]. It evaluates the feasibility of the part to be produced with metal AM beyond costs and will therefore not be considered for this thesis. As a result, the article named Article A & B was filtered out to be the most suitable.

5.2.2 Article A: Economics of additive manufacturing for end-usable metal parts

In this section, the article Economics of additive manufacturing for end-usable metal parts, henceforth called Article A, will be described, and its cost model will be explained [36]. One key assumption in Article A is that the whole build volume of the AM machine is used to produce copies of the same part [36]. The direct consequence is that AM production cost is considered at a constant overproduction volume [36]. Therefore, the only aspects to be considered are the ones directly affecting the cost of the parts. The cost items for AM considered in this article can be sorted into the following two categories: material and processing costs. Article A does not take into account administrative overhead costs, as well as energy, rental, and ancillary equipment outlays. These costs will be approximated to 10% of the total cost instead. Furthermore, labor costs are considered when the AM machine requires an operator to monitor or perform operations. The labor cost varies depending on the manufacturing location; Article A has assumed Western Europe as the location. Lastly, if assembly operations are required, they can be assumed to be manual.

To go into more detail about the part cost, the material costs are calculated as the mass of the part times the material suppliers price per kilogram with the addition of a surcharge of 10% for support and waste. The processing cost is split into three sub-categories: pre-processing, post-processing, and processing. Figure 1 shows a table of the cost parameters considered in Article A and the final equation used to evaluate the total part cost. The processing cost is given by the ratio of the machine rate multiplied by the build time per job divided by the number of parts produced per job. The build time and height of the build are calculated by the machine software (In this article, EOSs machine EOSINT m270 and EOS software were used) with an STL file as input. The machine cost encapsulates interests and full-service maintenance to each part, a lifespan of 5 years is assumed, and a straight-line depreciation technique is assumed. To estimate machine cost per hour, Article A assumes utilization of 60% of the total hour per year, which is 5000 h per year.

The only operations the operator conducts are setting up and monitoring the machine during the pre-processing and post-processing. Operations during post-processing include cooling, cleaning parts, support removal, finishing operations, and heat treatment. In Article A, an additional cost is considered to heat treatment aside from the labor cost. This applies well to the heat exchanger in this thesis, as the method developed in the article is also used for a redesign project.

Furthermore, the cost analysis does consider build time but only for a specific machine (EOS). It does not consider the importance of how surface area per layer and volume affect build time and, by extension, the cost. It is possible to use the method from Article A to evaluate cost depending on design parameters such as volume, build orientation, and surface area, Still, it relies on the reliability of the machine software.

In table 5.1, the cost model of Article A is shown. The table details all the parameters considered in Article A and how the parameters are applied to calculate the final total cost. Finally, it should be noted that this article is from 2012, and the rapid development of AM during the last decade might render some points of the article unactual.

5.2.2.1 Result of the method of Article A

In Article A, the case study in question is from the aerospace industry and considers a landing gear for an airplane with an existing design for CM methods. The landing gear is redesigned using of principles of DfAM. It applies part consolidation and lightweighting to reduce the volume of material and optimize for the highest strength-to-weight ratio. In contrast to the heat exchanger, the landing gear needs to consider integrated moving parts for the design, and the performance-to-weight ratio considers tensile strength instead of heat transfer and, heat flow as in the case of the heat exchanger.

The utilization of 5000 hours yearly is based on a 60% utilization rate of the total lifetime approximated in Article A. The article states the utilization rate to be conservative, and a rate of 80% can be achievable. Texel is a smaller company and would not be able to fully utilize the machine to a 60% rate as Texel currently does not have set up production of the TES system. This thesis aims to evaluate the manufacturability of the heat exchanger for Texels future system. Therefore, it is

Number of parts produced per job	(−)	*N*	*Magics RP software*
Material cost per kg	(EUR/kg)	*M*	Given by supplier
Part volume	(mm^3)	*V*	Magics RP software
Density of the sintered material	(g/mm^3)	*D*	
Mass of material per part	(kg)	*U*	$D \times 1.1 \cdot V$
Material cost per part	*(EUR)*	*MP*	$U \times M$
Machine operator cost per hour	(EUR/h)	*O*	
Set-up time per build	(h)	*A*	
Pre-processing cost per part	*(EUR)*	*AP*	$O \times A/N$
Depreciation cost per year	(EUR/year)	*C*	Given by supplier
Hours per year	(h/year)	*H*	5,000
Machine cost per hour	(EUR/h)	CH	C/H
Build time	(h)	*T*	EOS machine software
Machine cost per build	(EUR)	CB	$CH \times T$
Processing cost per part	*(EUR)*	*CP*	CB/N
Machine operator cost per hour	(EUR/h)	*O*	
Post-processing time per build	(h)	*B*	
Heat treatment cost per build	(EUR)	HT	
Post-processing cost per part	*(EUR)*	*BP*	$(O \times B + HT)/N$
Total cost per assembly	**(EUR)**	**P**	**MP+AP+CP+BP**

Table 5.1: The cost model applied in Article A [36]

assumed that a utilization rate of 60% will be achieved for the total production of the heat exchanger and the system.

Table 1 shows the variables and equations used to calculate the total cost of one heater. Article A considers four main areas, material, pre-processing, processing, and post-processing, where the main part of costs comes from the processing. Articles A and B take the machines purchase price and necessary equipment and give an hourly cost for using the machine based on the assumed years of usefulness and operation hours. The cost increases due to the build time approximated with CAD software. The other large cost sources are from the material and postprocessing, which comes in at 1778 and 1610 respectively. The material costs are based on the metal powder's supplier price and the part's volume. The method in Article A also accounts for 10% of extra material for support and other material wastes. The heat treatment cost is an average of the typical cost for post-processing in additive manufacturing. The setup time was assumed to be around the same as for the old model

EOSINT M270 as the same machine supplier is assumed. The post-processing time is approximated from the supports generated in the CAD software and times stated for support removal time per cubic millimeter of support.

Article A was deemed a suitable method to use as a base because the method was developed for laser additive manufacturing with metal as a material and considers the critical parameters of production through the three phases (pre-processing, processing, post-processing) with a clear methodology. The method is also applied in the article *Design and development of a novel additively manufactured geothermal heat exchanger*[35] for a heat exchanger, which makes it a good candidate to evaluate Texel's heat exchanger.

When the method is applied, the total cost of producing one heat exchanger with this method would be around 6430 euro per part, and the full calculations can be viewed in appendix A.1 in figure A.1.

5.2.3 Article B: Cost Estimation of laser additive manufacturing of stainless steel

In the article Cost Estimation of laser additive manufacturing of stainless steel (Heidi Piili et al. 2015) a cost estimation is calculated, and the article will be called Article B from here on [33]. The article expresses the total cost of additive manufacturing as shown in equation 5.1 [34].:

$$C_{build} = m_{material} * C_{material} + T_{build} * C_{indirect} \tag{5.1}$$

The direct cost represents the costs directly related to part mass and raw material costs. The indirect cost considers the whole platform build time and machine cost rate. Furthermore, it should be noted that to achieve a cost per part, the total cost of C_{build} should be divided by the number of parts produced in the same build. Heidi Piili et al. (2015) go further than in equation 5.1 and propose a more detailed calculation about environmental aspects and decide to consider electricity consumption separately. This more detailed version of the model can be seen in eq 5.2.: [34]:

$$C_{build} = m_{material} * C_{material} + w * Price_{material} + E_{build} * Price_{energy} \tag{5.2}$$

Equation 2 considers energy expenses separate from the machines upkeep and day-to-day business costs. These costs were found to be less than 10% of the total cost [34]. It should be mentioned that this model applies to the production of multiple instances of the same part, and the shielding gas cost is accounted for in the machine cost itself. For this thesis, equation 5.1 will be the preferred choice over equation 5.2 as the thesis focuses on how cost can be affected during the design phase. To determine the build time T_{build} equation 5.3 is used [34].

$$T_{build} = T_{job} + (\alpha_{Time} * l) + T_{voxel} \tag{5.3}$$

$$T_{voxel} = \beta_{Time} * 5^2 * 5/l_t * RO_i + (\alpha_{Time} * l) + T_{voxel} \tag{5.4}$$

$$RO_i = V_{P_i}/V_{A_i} \tag{5.5}$$

Equation 5.3 calculates the total build time (T_{build}) in equation 5.1. There are three components to calculate the time: a constant time for the setup of the machine (T_{job}), and a time for each layer (α_{Time}) which is then multiplied by each layer (l). T_{voxel} is calculated with equation 5.4 and represents the time it takes to scan $1mm^2$ (β_{Time}) for each of the $5mm^3$ voxels into which the model is divided. Equation 5.5 defines the rate of occupancy of each voxel, i.e., how much of the volume of the part occupies each voxel of the build. The model gives a cost estimation of a whole build, i.e., a build can contain more than one part depending on how many parts that fit the build volume. The model approach only considers the costs of a laser additive manufacturing process. For this model, it is argued that the largest contributor to cost is the investment cost of the machine, and to reduce the cost of the part, more importance should be focused on minimizing build time. It should be noted that the model does not consider post-processing cost as it may vary according to the user [33]. To apply the model, an AM machine must be defined to assess laser diameter, build volume, and machine cost [34].

5.2.3.1 Result of the method of Article B

Article B applies two different ways to calculate the total cost of the production of the part [33]. The first one from equation 5.1 does not consider energy cost as a separate cost, while for environmental reasons, equation 5.2 does. This thesis focuses on how the design process affects manufacturability, and according to Article B, the energy cost only accounts for 10% of the cost. Therefore, there is no need to go into more detail about electricity ex, which cannot be affected by design choices, as it is mostly affected by the energy price. On the other hand, as energy prices have rocketed (doubled in prices between January 2021 and January 2023 for industrial producers in the EU), the importance of minimizing energy usage might affect the total cost considerably more than 10% today [46].

As described in the theory section 5.2.3 for the cost assessment, this method from Article B first calculates the direct cost of material and the total material used. It combines direct costs with all the indirect costs times the total build time; however, it does not consider post-processing. Based on the geometry of the part to be produced, such as the average surface area, part volume, and part height, the part is divided into layers based on the layer thickness of the powder used for EOS machines. The equations used to calculate are described in the Theory section 3.3. The equation uses a voxel approximation for how much of the build volumes is occupied based on transforming the volume of the part to $5mm^3$ voxels and how much of the voxel space is occupied by the actual volume of the part. The scan speed is the same for the EOS m290 as for the older model EOSINT m270, and the idle time was also assumed to be the same.

After the build time is calculated, the indirect costs affected by the build time need to be calculated. The rent is approximated for the space occupied by the necessary machinery, space recommended by EOS, and the m^2 price for industry spaces in Gothenburg. The rent cost assumes that Texel intends to rent new space for production. The total indirect cost is calculated from the four categories: production overhead, administration overhead, production labor, and machine costs. Yearly costs include software, hardware licenses, maintenance, and consumables.

Article B describes the pre-processing and processing in more detail but do not consider the post-processing at all. The method was applied as it considers the production in more detail and applies a different method for calculating the build time which can be of interest to evaluate.

When the method is applied, the total cost calculated with this method was about 6540 and the full calculations can be viewed in appendix A.1 in figure A.2 and A.3.

5.2.4 Comparison of the methods from articles A & B

There is quite a small difference between the total cost when the methods from the two articles are applied to the heat exchanger. The second method is slightly more expensive, even if it does not consider the post-processing cost. The difference comes to 113. This is mainly because the second method considers more cost aspects in detail and applies another way to calculate the build time. Beyond just the cost of purchasing the EOS machine, it also considers the separate cost of the wire erosion machine in contrast to the first method using an approximation of the combined cost for the whole system. The first method does not consider the prices for administration overheads, just the salary for the operator during the pre-processing, and hardware and software costs are considered in method two. Article B considers the rent for the approximated space for the AM machine and utilizes its needs, while Article A does not consider rent at all. As Texels strategy to produce their TES system is undecided, the cost of rent will not be considered for the proposed method in this thesis.

When comparing the two methods, the impact of the build time estimation on the final total cost is also clear. To get an accurate total cost, the build time estimation must be accurate as it affects most large cost contributors. It is also clear that the post-processing segments of the two methods need to be further developed. The method from Article A considers heat treatment cost, HIP, and removal of supports for the post-processing. In contrast, Article Bs method only considers the removal of supports but considers the wire-cutting machine cost and salary for the operator. Article A only uses averages for HIP and heat treatment, and for support removal, only considers the salary of the operator into consideration. This needs to be further explored to get an accurate estimate of the manufacturability of the heat exchanger.

One clear indication from both methods is that cost can be significantly reduced when several parts can be manufactured per job/build, as the processing cost can be minimized further with more parts per build.

5.2.5 Proposed manufacturability method

This section will outline the proposed methodology for applying the heat exchanger. The approach is based on Article A, but with additional insights from Article B and other relevant sources. One notable advantage of Article A is its reliable build time estimation, which was determined using Autodesk Netfabb software to calculate support volume and build time. This is significant because build time estimation is closely tied to cost. To use Netfabb, we need to input information such as laser power, the component to be printed, the additive manufacturing machine, the powder particle size, and the layer height. For the manufacturability assessment, we will rely on Article A, supplemented by Article B and other sources, to fill in any gaps.

The primary drawback of Articles A and B is their lack of recent information. Article A overlooks the administrative overhead cost and fails to consider the modeling and design of costs in the pre-processing stage. On the other hand, the administration overhead of Article B will be utilized in the proposed method. As the DfAM section outlines, post-processing costs are among metal AM's most significant cost contributors. Therefore, obtaining an accurate calculation of post-processings impact is crucial, aided by other references. While Article B provides a more detailed analysis of the machine costs, it does not account for all the necessary tools required for post-processing. The calculations and costs for the post-processing phase are applied from the article Metal Additive Manufacturing: Cost Competitive Beyond Low Volumes, where the post-processing is further detailed for a more accurate estimation [37]. There is also Computer-aided manufacturing (CAM) programming during the pre-processing phase, which has been added as it is a necessary step before the setup of the AM machine and preparing the 3D model of the part for AM. The addition is applied from the article Design for Additive Manufacturing: Cost Evaluations [39]. The article otherwise applies a similar methodology as seen in Article A.

Furthermore, the article Design and Development of a novel additively manufactured geothermal heat exchanger has applied the method of Article A for the cost estimation of a heat exchanger, indicating that the method from Article A is applicable to heat exchangers [35]. To calculate the cost per part using the proposed method, please refer to the table labeled [REF IN overleaf] for the necessary inputs. The estimation is divided into five categories based on the production phase in which the cost arises - material cost, pre-processing cost, administration overhead cost, processing cost, and post-processing cost. Figure 5.3 displays a pie chart that breaks the cost into these categories, highlighting that the processing phase incurs the highest cost.

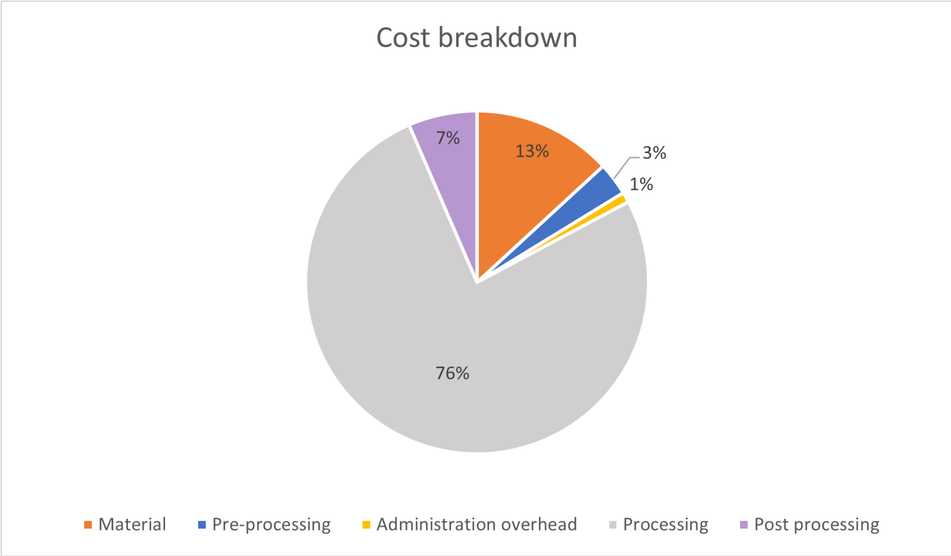


Figure 5.3: Cost breakdown based on which phase of production

The total cost calculated with this method was about 5360 euros, and the full calculations can be viewed in appendix A.1 in figure A.4.

5.2.6 Comparison with AMOTool

In this section, a comparison with the result from the AMOTool will be accounted for. The input values employed in the proposed method are used as inputs for the AMOTool. Subsequently, the outcome of the proposed method will be evaluated by utilizing the resulting output of the AMOTool.

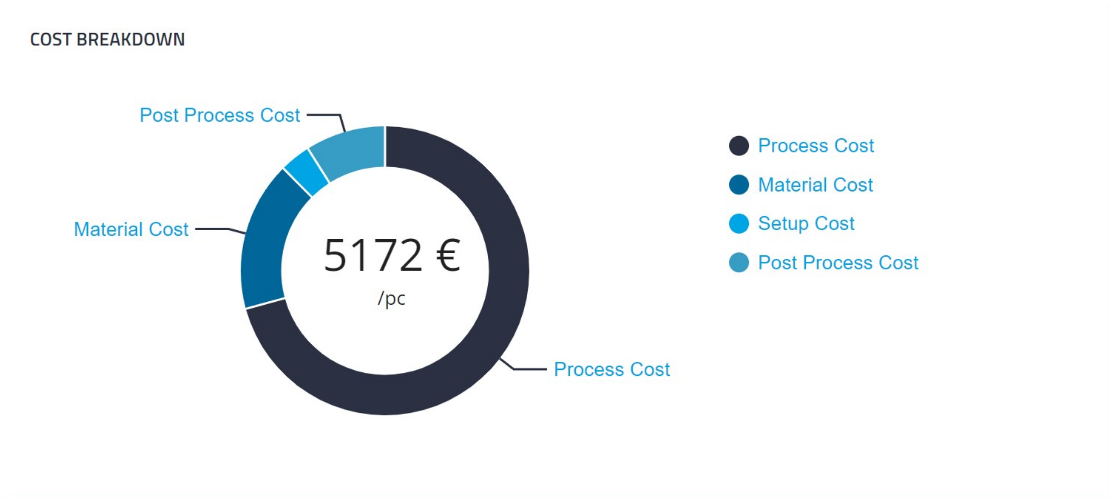


Figure 5.4: Result of the AMOTool

According to the cost estimate generated by the AMOTool, the total cost is estimated to be 5172 euros, while the proposed method's final cost per part is calculated to be 5360 euros. As stated in the theory section discussing the tool's validity, the estimation is not precise and only serves as a rough estimate. However, the costs fall within a similar range, indicating that the resulting cost is within a valid cost segment.

6
Discussion

A new design for the heat exchanger has been proposed. The design utilizes metal AM, and a case study was conducted to assess its manufacturability. Guidelines were applied to take advantage of the benefits of metal AM and suggest an improved design that estimates the cost and time it takes to manufacture the heat exchanger. A manufacturability assessment was created that evaluated the total cost of production under specific parameters. The thesis found that the heat exchanger's processing phase had the most significant impact on cost. This includes the cost of the machine, maintenance, and auxiliary systems. The number of parts produced per build and build time were the most critical factors affecting these costs. Maximizing the build area and reducing the volume of the part will reduce the cost per part. It is recommended to optimize the design further to minimize each part's area on the build plate to allow more parts to be printed simultaneously. However, due to computational power constraints and time limitations, only a quarter of the final design was analyzed, which can be assumed to represent the whole adequately. It would be interesting to evaluate the whole part in the future, especially since developing a complex design like the lattice structure and creating a meshed form could take several days of simulation or generation.

During the manufacturability assessment, relevant literature was reviewed to inform the analysis. The oldest article used as the basis for the assessment dates back to 2012. The other articles used date from 2015 to 2023 and were used to enhance the proposed methods' relevance. All of the articles applied cost assessments for metal AM, but there is a need for more literature on cost estimations or evaluations of additively manufactured heat exchangers. This area could benefit from further exploration as AM technology advances and grows.

It's worth noting that the manufacturability evaluation is centered on Texel's heat exchanger case study. Specifically, this assessment aims to determine the heat exchanger design's suitability for metal AM production. Although the method is currently tailored for heat exchangers, it can be tweaked to fit the production of other metal AM parts. Additionally, the cost approximations assume that the heat exchanger will be produced in-house and that the AM machine will be utilized at a rate of at least 60%. However, since Texel is a small company without any production, achieving such a high utilization rate may be challenging. Therefore, it may be advisable to outsource manufacturing to a supplier with suitable technology capabilities.

The potential environmental impact of using metal AM for heat exchanger manufacturing would be worth exploring, which was not considered in the thesis. As the use of AM technology can significantly reduce material use and material waste and shorten supply chains, as noted in the thesis, it may also positively affect transportation emissions, minimize delays, and lower the demand for spare parts inventory.

Exploring the potential cost savings of metal AM parts in their end use is a fascinating topic worthy of further study. The aerospace industry, for instance, has conducted numerous studies on how AM's lightweight designs can reduce fuel consumption and costs. Similarly, we could investigate whether an additive-manufactured heat exchanger can effectively minimize the amount of fluid required for energy transfer or improve the efficiency of an energy storage system's energy-to-electricity conversion. Examining cost efficiency throughout the heat exchanger's life cycle would also be a valuable area of research.

The proposed method for the manufacturability assessment employs different aspects of various other cost assessments and evaluations. The proposed method aims to approximate the total cost of producing a part with metal AM and help in the decision-making when metal AM is of interest to apply. Compared to similar assessments researched in literature during the thesis, the manufacturability assessment considers the same or more factors than many other assessments. It should be mentioned here that this manufacturability assessment only evaluates a theoretical case, and fine-tuning the assessment experiments with manufactured prototypes of the heat exchangers would be useful. There appears to be a lack of similar assessments conducted for heat exchangers, and this thesis can be a good benchmark to compare other similar studies of heat exchangers. The lack of studies on heat exchangers to compare with means uncertainties with conclusions can be difficult to eliminate. But this thesis identifies important design and manufacturing parameters and how these parameters interact to result in a final design & manufacturing cost.

The importance of considering this early in the product development phase can also be highlighted as the decision to use either CM or AM methods means radical differences in the design as the manufacturing methods differ. This could be an opportunity to investigate the possibility of finding a hybrid version of AM methods and CM methods that could harness AM's flexibility & allowed the complexity of design with the simpler & cheaper CM methods which aren't as time-consuming, possibly leading to a hybrid method which allows for the flexible medium complex part to be serially produced.

It is interesting to compare the manufacturability assessment of the heat exchanger with the validation result from AMOTool. These two results are quite similar regions of cost. The AMOTool does not use a 3D model as input. Instead, it uses the average surface area of each layer and the total volume of the part to make an approximation. The manufacturability assessment of this thesis uses build time generated in build preparation software; as this software uses the 3D model, it probably calculates a more accurate build time and does not use an average but instead the actual surface area of the part for each layer. This probably results in a more accurate assessment of the total cost.

As for generating a framework for manufacturability, I would suggest that this thesis is a solid start to developing a general framework. The most important parameters for design and manufacturing are defined in this thesis and translated into a manufacturability assessment of the heat exchanger. The parameters should be more or less the same for the heat exchanger as any other part to be produced with AM. The assessment considers all costs surrounding the process of adding layer upon layer, such as the machine cost, salaries, post- and pre-processing parameters, and material and administration overheads. By substituting the 3D model for another, changing the part volume, the number of parts per build, part geometry, part height, and part orientation, an estimate for another part would probably be possible and give a fair estimate. Further, the material can be adjusted to the preferred for each part desired to be manufactured. It should be mentioned that for the framework to work at all, the part needs to be designed by the principles of DfAM, and therefore, designs for CM methods are not applicable. The last consideration for a general framework is design optimization. As the heat exchanger optimizes for maximum heat transfer for the minimum volume part, other parts might want to maximize other features such as the part's strength. Therefore, the framework might need further development to consider different optimization goals. The framework could probably function for other heat exchangers and similar parts optimized for heat transfer.

During this thesis, one of the most significant realizations for me has been the steep learning curve to learning the whole process of producing a part for AM, from designing the part for AM to additively manufacturing the part with all the knowledge needed to handle the AM machine and all post-processing activities. The design process of nTopology used for this thesis significantly differs from the design process with more conventional tools like Solidworks or Catia. The designer relies more on setting up the limits and aims for the algorithms that solve the problem than a design for CM methods with conventional software, which relies more on the design's problem-solving to find the best solution. This made me realize the metaphorical mountain of knowledge which needs to be climbed for AM to take a more prominent role in the manufacturing industries.

To further improve the outcome of this thesis, it would be beneficial to carry out experimental prints of the heat exchanger using metal AM. This will enable a comparison of actual costs and time spent, leading to an improved manufacturability assessment.

7

Conclusion

The thesis suggests that most costs associated with manufacturing a metal AM heat exchanger occur during the processing stage, consistent with previous research on metal AM part production. About 75% of the cost of the heat exchanger occurs during processing, mainly due to the depreciation of the AM machine. This highlights the high initial cost of using AM as a manufacturing method. Since the lifespan of the AM machine is only approximately five years, the machine needs to be in constant production to reduce costs. Printing multiple parts during one job/build is an effective way to maximize the AM machine's value and improve the part's manufacturability. Build time heavily depends on design parameters such as part volume and geometry. It is, therefore, essential to consider DfAM early in the product development phase if a part is desired to be manufactured with AM. Suppose Texel decides to pursue AM manufacturing for heat exchangers. In that case, it will be essential to explore methods of reducing the part size to fit multiple parts on the build plate and consider larger AM machines with a greater build area. The manufacturability assessment is validated through external software to appreciate the feasibility of the result, and in the future, I recommend further validating the result with experimental results.

CM and AM methods deviate early in the product development process, making it clear the vitality of DfAM for a good manufacturability result. Using the methodology of DfAM, the design proposed could be successfully analyzed and the manufacturability was assessed for the heat exchanger. The design was successfully sliced and prepared in printing preparation software, consolidating over 100 parts assembly of the CM design into one part with minimal support structures. Further optimization and iteration could enhance the design proposal as the software demands a lot of computational power when designing complex parts. This would be interesting to continue with before a prototype could be additively manufactured.

7.1 Ethics

In this section, we will discuss the ethical considerations that were taken into account for the thesis. The primary ethical concerns that needed to be addressed in the thesis revolved around the collection and handling of information and the disclosure of the thesis results.

The purpose of this thesis is to expand understanding of design for AM, as well as the costs and time involved in the manufacturing process. Additionally, the aim is to enhance Texel's product by sharing this knowledge. To maintain scientific ethics, it is crucial to properly reference authors and give credit where it is due, as information will be obtained from various sources.

For students working on their thesis, it is important that they uphold any agreements made with both the company and Chalmers unless otherwise discussed with these parties. It is crucial that the student maintains originality in their work and avoids any involvement in plagiarism.

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A

Appendix 1

A.1 Manufacturability assessment methods

Parameter	variable	Unit	Describtion	Reference
N	1		Number of parts produced	3D-model
m	120,198	EUR/kg	Material cost per kg	Given by supplier
V	630868	mm3	Part volume	3D-model
D	8,44	g/cm3	Density	
U	5,856978512	kg/unit	Mass of material per part	D*1.1*V
MP	703,9971032	EUR	Material cost per part	U*M
A	1,2	h	Set-up time per build	
AP	7,34925312	EUR	Pre-processing cost per part	O*A/N
C	140000	EUR/year	Depreciation cost per year (Assume 5 years of usefulness)	https://3dprintingindustry.com/news/eos-launches-m-300-4-industrial-metal-3d-printer-with-ten-times-productivity-139463/
H	5000	h/year	Hours per year	Article
CH	28	EUR/h	Machine cost per hour	C/H
T	146	h	Build time	3D-model
CB	4088	EUR	Machine cost per build	CH*T
CP	4088	EUR	Processing cost per part	CB/N
O	6,1243776	EUR/h	Machine operator cost per hour	
B	3	h	Post-processing time per build	Article
HT	1610	EUR	Heat treatment cost per build	https://www.additivemanufacturing.media/articles/postprocessing-steps-and-costs-for-metal-3d-printing
BP	1628,373133	EUR	Post-processing cost per part	(O*B+HT)/N
P	**6427,719489**	**EUR**	**Total cost**	**(P=MP+AP+CP+BP)**

Figure A.1: Article A: cost assessment

Costs				
Label	Name	parameter	Unit	Sourc
Production overhead				
	Rent, building area cost	17,12799014	EUR/h	Sour
Administration overhead				
	Hardware purchase	1920,8105	EUR	
	Software purchase	1920,8105	EUR	
	Hardware cost/year	384,1575	EUR	
	Software cost/year	384,1575	EUR	
	Consumables per year	1280,548	EUR	
	Total administration overhead	0,3521484	EUR/h	
Production labor				
	Technician annual salary	30813,2748	EUR	a
	Employer contributions	22	%	
	Total production labor	7,518439051	EUR/h	
	Total indirect cost per machine hour	**43,00576519**	EUR	
	Direct cost for inconel 625 powder/ k	120,198	EUR/kg	https
	Direct electricity cost / MJ		EUR	
Utilization				
	Utilization rate	57,04	%	
	Annual machine operating hours	5000	h	
Equipment				
	AM equipment and wire eroder	8	years	
	Hardware and software	5	years	
Machine costs				
	Machine purchase	419067,82	EUR	
	Machine purchase cost per year	52383,4775	EUR	
	Maintenance cost per year	25338,985	EUR	
	Machine consumables per year	2923,7255	EUR	
	Wire erosion machine purchase	63250	EUR	
	Total wire erosion costs per year	9389,75	EUR	
	Total wire erosion costs per year	90035,938	EUR	
	Total machine costs	18,0071876	EUR/h	
Total	**Total cost**	**6541,377213**	**EUR**	

Figure A.2: Article B: Cost assessment

Geometry and time				
Name	Equations variable	Unit	Describtion	Source
RO	0,122739726		Rate of occupancy	
Beta_Time	0,0125	s	Time to scan 1mm2 during build	COMBINED
S_A	9720,00539	mm2	Surface area	3D model
l_d	0,1	mm	Focus diameter of selected machine	https://www
N	3500		Number of layers	
l_t	0,04	mm	Layer thickness, depends on the laser focus diame	
Alpha_Time	13,88572199	s		https://www
S_vel	7	m/s	Scan speed	https://www
VP	1120000	mm3		
VA	9125000	mm3	Voxel volume of used height of build volume	
T_voxel	350000	s		COMBINED
T_job	63	s	Fixed time for start-up of machine	COMBINED
T_build	**110,7397297**	**h**	**Total build time**	
h	140	mm	Part height	CAD model
LF index	1,15		A index to ensure there is no lack of fusion between layers	Printability c
Voxels	73000		Total number of voxels	
Mass of part	14,8	kg		

Figure A.3: Article B: Geometry and time variables

Parameter	variable	Unit	Describtion	Reference
N	1		Number of parts produced	3D-model
m	120,20	EUR/kg	Material cost per kg	Given by supplier
V	630868	mm3	Part volume	3D-model
D	0,00844	g/mm3	Density	Given by supplier
U	5,86	kg/unit	Mass of material per part	D*1.1*V
MP	704	EUR	**Material cost per part**	U*M
A	1,2	h	Set-up time per build	Article A
O	29,21	€/h	Salary for technician/engineer	https://www.ratsit.se/lonestatistik/maskiningenjor-lon
At	4,5	h	Hours for CAM programming	Design for Additive Manufacturing: Cost Evaluations
Ec	0,28	%	Employer contribution	https://www.verksamt.se/alla-e-tjanster/rakna-ut/rakna-ut-vad-en-anstalld-kostar
AP	166,50	€	**Pre-processing cost per part**	O*Ec*(A+At)
Q	1920,81	€	Hardware purchase	Article B
W	1920,81	€	Software purchase	Article B
AQ	384,16	€	Hardware cost/year	Article B
AW	384,16	€	Software cost/year	Article B
AT	1280,55	€	Consumables per year	Article B
AoP	51,41	€	**Total administration overhead**	T*((AQ+AW+AT)*Lt+(Q+W))/(H*8)
T	146	h	Build time	Netfabb
H	5000	h/year	Hours per year	Article A
Lt	5	years	Assuming 5 years of usefulness	Article A
C	604500	€	Machine price	Metal Additive Manufacturing: Cost Competitive Beyond Low Volumes
Ca	60450	€	Auxiliary equipment price	Metal Additive Manufacturing: Cost Competitive Beyond Low Volumes
Cm	34540	€	Maintenance cost (During lifeti	Metal Additive Manufacturing: Cost Competitive Beyond Low Volumes
CH	27,98	€/h	Machine cost per hour	(C+Ca+Cm)/(H*Lt)
CB	4085,02	EUR	Machine cost per build	CH*T
CP	4085,02	EUR	**Processing cost per part**	CB/N
HTP	56125,5	€	Heat treatment (HT) machine c	Metal Additive Manufacturing: Cost Competitive Beyond Low Volumes
HTL	24960	h	Lifetime of HT machine	chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.energimyndigheten.se/4a9556/globalassets/energieffektivisering_/jag-ar-saljare-eller-tillverkare/dokument/produkter-med-krav/ugnar-industriella-och-laboratorie/annex-b_lifetime_energy.pdf
HT	2,25	€/h	Cost per hour of HT	HTP/HTL
BH	6,3	h	Time for HT	Metal Additive Manufacturing: Cost Competitive Beyond Low Volumes
PH	2325000	€	HIP machine price	Metal Additive Manufacturing: Cost Competitive Beyond Low Volumes
PHa	102300	€	HIP auxiliary tool price	Metal Additive Manufacturing: Cost Competitive Beyond Low Volumes
PHL	20000	Cycles	Lifetime of wire HIP (cycles)	Hot Isostatic Pressing: Improving quality and performance in AM (metal-am.com) och https://quintustechnologies.com/hot-isostatic-pressing/products/hot-isostatic-presses/
HIP	121,37	€/build	Total cost of HIP per build	(PH+PHa)/PHL
EP	202104,113	€	Wire EDM cost (including auxiliary and maintenance)	
BL	24960	h	Lifetime of wire EDM	https://edmproud.com/wire-edm-what-makes-a-wedm-last-and-how-long/
EDM	8,10	€/h	Cost per hour of wire edm	EP/BL
Vs	5457	mm3	Support volume	Approximation from Netfabb
Sp	103,23	mm3/min	Wire EDM removal speed	Waterjet Cutting vs EDM Cutting | Techniwaterjet
BE	0,88	h	Time for wire EDM	Vs/Sp
BP	352,43	EUR	**Post-processing cost per part**	(O*B+HT)/N
P	**5359,37**	**EUR**	**Total cost**	**(P=MP+AP+AoP+CP+BP)**

Figure A.4: The proposed manufacturability assessment method