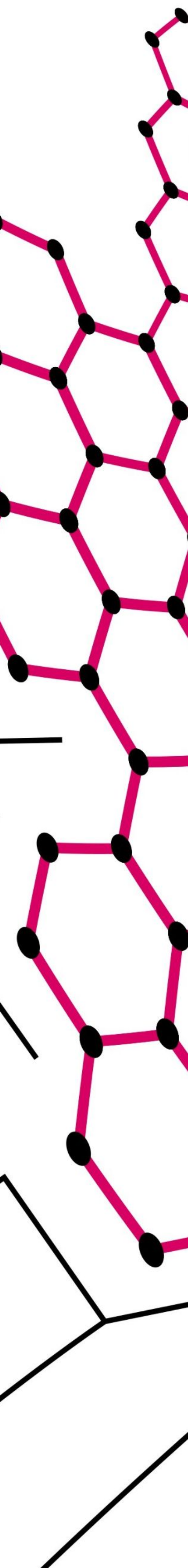

Financial viability of metal additive manufacturing in automotive industry for production of functional parts in high volume

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Abstract

Metal Additive Manufacturing (MAM) is a rapidly developing technology with the potential to revolutionise the automotive industry. MAM can be used to produce lightweight, high-performance, and customised automotive parts and components, as well as more efficient and sustainable manufacturing processes. This research aims to evaluate the viability and sustainability of applying MAM within the automotive sector for the production of $\geq$ 2500 parts / year. The study was conducted on the basis of the input of the automotive company Lightyear (Helmond, The Netherlands). A model has been developed to guide engineers in selecting a financially viable manufacturing method. It allows engineers to assess early in the design stage whether MAM is a viable option for high-volume metal-part production, requiring only rough estimates of the part. The model supports further integration of MAM into the manufacturing of automotive vehicles, highlighting the importance of designing parts to take advantage of the benefits that come with MAM, such as part consolidation and weight optimisation. One of the key findings underscores the importance of harnessing the design advantages offered by MAM to ensure cost efficiency. Furthermore, the research validates the viability of MAM, even at its current development stage, emphasising its potential for substantial cost savings throughout a product's life cycle. During the manufacturing phase, significant manufacturing cost reductions can be achieved. The cost estimation model developed enables engineers to make informed decisions in the early stages of design, promoting further integration of MAM into the automotive production landscape. In summary, this research reaffirms that MAM has significant promise and can be effectively applied within the automotive industry, showcasing its potential to drive substantial cost efficiencies throughout a product's life cycle.

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Thank you for being part of this academic adventure.

Declaration

I declare that, except where explicit reference is made to the contribution of others, that this dissertation is the result of my own work and has not been submitted for any other degree at the University of Twente or any other institution

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Reinoud Mulder

Nomenclature

- `AM` - Additive Manufacturing
- `CNC` - Computer Numerical Control
- `DfAM` - Design for Additive Manufacturing
- `DMLS` - Direct Metal Laser Sintering
- `HPDC` - High Pressure Die Casting
- `LCA` - Life Cycle Analysis
- `MAM` - Metal Additive Manufacturing
- `SEV` - Solar Electric Vehicle
- `SLM` - Selective Laser Melting
- `TO` - Topology Optimisation
- k - Mass reduction factor
- y^i - Overall yield factor
- m_p^{MAM} - Mass of part produced with Metal Additive Manufacturing
- m_p^{TM} - Mass of part produced with Traditional Manufacturing
- m_{raw}^i - Mass of raw input material
- m_p^i - Mass of finished product

Chapter 1

Introduction

This research is carried out as part of the Master's Degree in Mechanical Engineering at the University of Twente. This research started as an assignment for the automotive start-up Lightyear. Lightyear is a company that develops and manufactures electric vehicles. It was founded in 2018 and is based in Helmond, The Netherlands. The company's mission is to make electric vehicles accessible to everyone. Therefore, the company is developing a range of vehicles that are designed to be affordable, efficient, and sustainable. Lightyear also focuses on the development of innovative technologies to reduce the environmental impact of electric vehicles. The unique selling point of their first car is the addition of a solar panel to the roof of the car and its high aerodynamic efficiency. This generates electricity, which results in a longer range. Their first vehicle, the Lightyear 0, is shown in Figure 1.1. Unfortunately, the company filed for bankruptcy in January 2023, one month after the start of this research, in part due to the high price of their first car of more than €250.000. Therefore, it has been completed under the supervision of the University of Twente since then. The consequences will be discussed in Chapter 3.

Figure 1.1: Render of the Lightyear 0, the first car developed by Lightyear. The focus during development was on high aerodynamic efficiency and the integration of a solar panel in the roof.

This chapter provides an introduction to gain clear insight into the context of this research. First, in Section 1.1 more information is given on the background of the company and provides additional information on the context of the problem. Subsequently, Section 1.2 provides a description of the problem. This is followed by the research objective in Section 1.3 along with relevant sub-questions. Section 1.3.2 covers the scope of the research, and the last section of this chapter is Section 1.4 on the structure of the thesis.

1.1 Background information

Lightyear was founded in 2016 by former members of the Solar Team Eindhoven, a group that won the World Solar Challenge in Australia. The company aims to develop and produce Solar Electric Vehicles (SEV) that can be charged using solar power. Lightyear's vision is to create sustainable, energy-efficient cars that can run on renewable energy and reduce dependence on fossil fuels. One of Lightyear's notable achievements is the development of their first prototype, the Lightyear 0. This SEV incorporates advanced solar panels into its design, enabling it to recharge its battery using solar energy. Lightyear claims that the Lightyear 0 has a significantly extended range compared to other electric vehicles (625 km with a 60.0 kWh battery), making it suitable for long-distance travel. They also claim that the solar panel, depending on the climate, could yield between 6,000 and 11,000 km of free, effortless, and clean range every year. It also has a lightweight design (1575 kg) and efficient power management systems to maximise energy efficiency [1].

The Lightyear 0 received significant attention and received several awards for its innovative approach to sustainable transportation. In addition to its solar charging capabilities, the vehicle can be charged using the traditional electric vehicle charging infrastructure. Lightyear has also emphasised the importance of vehicle-to-grid integration, which allows the car to contribute excess energy back to the grid when not in use. Apart from the Lightyear 0, the company is actively working on the development of future models and aims to bring solar electric vehicles to a wider market. It wants to achieve this by setting the maximum purchase price of the new model at €40,000. They have plans to expand their product line and improve the technology behind their solar charging systems. Lightyear envisions a future where solar electric vehicles become mainstream, contributing to a more sustainable and eco-friendly transportation system. However, in part due to the high purchase price of Lightyear 0 of €250,000, the company filed for bankruptcy in January 2023. The purchase price increased during the production process, at the beginning of the design it was sold for €100,000. This led to low sales numbers, and even with an increase in price, the cars were sold at a loss. Since filing for bankruptcy, the company has made a restart in a scaled-down version to achieve its ambitious mission of clean mobility for everyone.

The goal of Lightyear 0 was to show everyone what the company could achieve. The company is also a start-up. This means that it cannot make use of the advantages that come with economies of scale in the way that large automotive companies can. However, to become a successful automotive company and achieve their mission, the price of their cars needs to be much lower. That is the goal of the second car that Lightyear is currently developing, called Lightyear 2. As mentioned above, the price should be below €40,000. To reach that goal, they want to produce many more of the second model. The plan was to produce about 250 cars of the first model. The plan for the second model is to scale up production to 10000 cars annually. Furthermore, less expensive materials need to be used for production. The Lightyear 0 frame is made of recaptured carbon fibre to decrease the weight of the car. This is an expensive material to use and requires a lot of manual labour.

Lightyear vehicles differentiate themselves from other vehicles, not only by using vehicle integrated photovoltaics for propulsion, but more than anything by their extreme efficiency. By creating a vehicle that has less air and rolling resistance and weighs less than all other cars in the same category, Lightyear ensures that its vehicles will make the most efficient use of energy while still ensuring customers a comfortable drive. With this extraordinary focus on efficiency, there is a need for new technologies, designs, processes, and materials. Additive Manufacturing (AM) is one of those emerging new processes and has numerous benefits, which Lightyear seeks to leverage, such as but not limited to: toolless manufacturing, fast design iterations, increased design freedom, strength-to-weight optimisation, increased complexity, local-for-local, and on-demand manufacturing. AM is a very promising technique, but comes with its own strengths and weaknesses which will be covered later in this research. To successfully implement AM within the Lightyear supply chain, more information is required. In this research, the main focus will be on Metal Additive Manufacturing (MAM), since there is not much knowledge within the company on how the technique can be applied to their advantage when compared to AM with plastics.

1.2 Problem description

The concept of on-demand manufacturing is revolutionising the automotive industry, and AM plays a vital role in its realisation. Traditional manufacturing methods often involve maintaining substantial inventory levels to meet anticipated demand. However, with on-demand manufacturing enabled by AM, parts can be produced as needed, reducing inventory costs and the risk of obsolete stock. This lean approach streamlines the supply chain, improves product availability, and minimises lead times, all contributing to greater operational efficiency. It also allows to bring back the production from lower wage countries back to Europe. Parts can be manufactured in close proximity to the assembly location, offering several advantages such as:

- Reduction of transportation distances which saves cost
- Shorter lead times
- A more agile and responsive supply chain
- Mitigation of environmental impact caused by transportation

MAM has multiple advantages when applied in the automotive industry. By making use of these capabilities, manufacturers can make use of design freedom, enabling the production of complex geometries and lightweight structures that were previously unattainable with traditional manufacturing methods. This not only enhances the overall performance of the product but also contributes to improved fuel efficiency and reduced environmental impact. One of the key advantages of AM in the automotive industry is toolless manufacturing. Unlike conventional methods that require costly and time-consuming tooling and fixturing, AM allows direct production of parts from digital designs. This eliminates the need for tooling expenses, reducing lead times, and enabling rapid prototyping. Manufacturers can now engage in iterative design processes, accelerating product development cycles and facilitating design optimisation. This is one of the focus points of Lightyear, in order to achieve their goals of providing clean and affordable mobility for everyone. The outcome of this research aims to help them achieve that.

AM also has disadvantages, where cost is an important one. This is because the technique is relatively new and many improvements can be achieved. An area in which improvements can be made is the production of the metal powder used for the production of parts. Currently, metal powder is around five times more expensive per kg than a billet of the same material. The evaluation of the cost competitiveness of MAM compared to traditional manufacturing methods is a critical aspect of this research. A comprehensive cost analysis is dependent on various factors, such as material expenses, labour costs, and equipment investments [2]. By carefully considering economies of scale and volume production capabilities, the research aims to provide insight into the cost effectiveness of MAM for high-volume (>2500 parts annual) production scenarios. Long-term costs and return on investment will also be evaluated, ensuring a better understanding of the financial viability of incorporating AM into the automotive industry. In addition to cost considerations, the thesis provides information on the life cycle assessment of automotive parts and the influence of MAM on the automotive industry. Environmental effects are taken into account when determining how MAM can be used in a cost-competitive way in the automotive industry. This will give Lightyear the capability to make a good trade-off between e.g. environmental impact and cost when choosing the production process for a part.

By exploring these topics and conducting a comprehensive analysis, this thesis aims to provide a deeper understanding of the application of MAM in the automotive industry. Research will provide valuable information on the advantages, cost competitiveness, and environmental implications of producing a larger volume of parts, helping to pave the way for the further adoption of MAM in the automotive industry.

1.3 Research objective

The objective of this study is to assess the feasibility, cost effectiveness, and environmental impact of applying MAM in the automotive industry to produce high-volume functional parts. Specifically, the study aims to investigate the current state of the art of MAM and its application in the automotive industry, analyse the life cycle of metal additively manufactured parts in the industry, and develop a comprehensive cost estimation model to compare the costs throughout the entire life cycle of additively manufactured parts with conventionally manufactured parts. By addressing these objectives, the research seeks to provide valuable information on the trade-off between the potential benefits and challenges as well as the environmental impact of adopting MAM in high-volume automotive production and to support informed decision making in the industry.

The main research question of this research therefore can be formulated as follows:

"Can metal additive manufacturing be applied in the automotive industry to produce functional parts in high volume when comparing costs throughout the life cycle?"

1.3.1 Research questions

A number of research sub-questions has been formulated in order to answer the main research question:

- What are the key advances and recent developments in metal additive manufacturing technology and how have these innovations been adopted and applied within the context of the automotive industry?
- What is the life cycle of additively fabricated metal parts in the automotive industry?
- How can the costs for the entire life cycle of additive and conventionally manufactured parts be calculated?

A case study will be used to validate the outcome of the different applied models. It will also give more insight into the influence of different parameters related to the research question. A comparison will be made between an additively manufactured vehicle part and a part manufactured with traditional methods. The part that will be produced with AM is optimised according to the methods of design for additive manufacturing, taking advantage of the design freedom that comes with AM.

1.3.2 Scope definition

This research is conducted with Lightyear as the background context, although the company filed for bankruptcy during the study, and the research was completed without direct input from the company. The determination of the annual production quantity of parts is based on the initial input provided by Lightyear. Additionally, environmental considerations play a significant role in the selection of the recommended production method for each part. While the research is specific to Lightyear's circumstances, it still holds broader significance for the automotive industry as a whole. The global emphasis on reducing carbon emissions, driven by regulators such as the EU and growing public interest, underscores the relevance of this research. Furthermore, the scope of the study focuses solely on metal parts, excluding additive manufacturing of polymers.

1.4 Thesis structure

The six chapters of this thesis are structured as listed below.

- Chapter 1 - This chapter serves as an introductory section for the research, offering a comprehensive overview of the covered topics. Its purpose is to establish the context for the specific research topic and provide background information on the relevant company involved in the assignment. Additionally, the chapter defines the research scope and outlines the main research questions and sub-questions.

- Chapter 2 - This chapter centres around the relevant literature concerning MAM and its research objectives. It presents a comprehensive overview of different MAM technologies, cost models, and their historical evolution. Additionally, the chapter investigates the implications of AM on supply chains, its influence on the automotive industry, and provides information on the current state of the field, offering valuable information in a dynamic and evolving domain.

- Chapter 3 - This section outlines the methodology employed in the research, specifically focussing on the logic behind the developed models for cost estimation and inventory cost. It elaborates on the data collection process and provides details on how the collected data are used. Furthermore, the section discusses the validation of the results obtained from the models, ensuring their reliability and accuracy in the research findings. It also provides an explanation of the model development process and the selected parameters used for cost estimation. It describes in detail the functioning and characteristics of the developed models. This section also outlines how these models are used to make cost estimates and highlights the specific parameters and variables involved in the estimation process.

- Chapter 4 - This section covers the results and discussion of a case study conducted using the developed models. The case study involves selecting an automobile component that is optimised for AM and comparing it with the original part based on various criteria. The study examines the performance and characteristics of the optimised AM part compared to the original part, providing information on the benefits and advantages of using AM in this context. The chapter also focusses on the findings of the case study and their significance for similar cases within the research area. Offers an analysis of the results, provides insight into their interpretation, and compares them with existing research. The chapter further explores the broader implications and limitations of the findings and their relevance to advance knowledge in the field.

- Chapter 5 - The concluding chapter of the thesis comprises two sections. The first section presents the conclusions drawn from the research carried out and provides a summary of the key findings. The recommendations aim to bridge these gaps and offer potential solutions to guide future actions and further research in the field.

Chapter 2

Literature review

This chapter discusses the theory behind AM and cost models in a review of the literature. It begins with a general introduction to AM with a particular focus on MAM. Additionally, it presents a state-of-the-art showing how MAM is currently applied in the automotive industry. Section 2.1.1 addresses the practical limitations and obstacles that arise when implementing AM in real-world manufacturing scenarios. The section examines the challenges associated with factors such as material properties, process reliability, design constraints, and scalability. Section 2.2 describes the literature on the development of AM cost models and the different cost classification techniques that are applied. The effect of AM on supply chains is covered in Section 2.3. Furthermore, Section 2.4 delves into the specific applications of AM in the automotive industry. It examines the current utilisation of AM techniques within automotive manufacturing processes, highlighting the benefits and challenges faced in this sector. Finally, the last section of the chapter discusses the implications derived from the literature review conducted in the preceding sections. Summarises key findings and offers concluding remarks on the theory behind AM and cost models, as well as highlighting current gaps in research.

2.1 Additive manufacturing techniques

AM, by definition, is a manufacturing technique that builds three-dimensional objects by adding multiple layers of a material from a computer-aided design (CAD) file with minimal human interaction. Today, modern AM machines can manufacture functional parts from various materials, such as metals, ceramics, polymers, and composites. AM is defined by the American Society for Testing and Materials (ASTM) and the International Standards Organisation (ISO) as the official industry name, while recognising 3D printing as a commonly used synonym. They developed the following standard 52900:2018 [3] as the process of joining materials to make parts from data from 3D models, usually layer by layer, as opposed to subtractive manufacturing and formative manufacturing methodologies. The first versions of AM were developed in the late 1980s [4]. Since then, market penetration and quality have steadily increased. The technology started as a production technique for the rapid production of prototypes. It has developed as a technology that allows mass production of end-use parts [5]. BMW reported in 2018 that it had produced its millionth component with AM [6]. Another example is that Volkswagen achieved a 650% cost reduction in VW Tiguan production tooling using the MetalFAB G1 from Additive Industries (Eindhoven, The Netherlands) [7].

In a study by Deloitte, it is stated that AM is implemented within the industry to increase perceived value in any of the following areas: risk, profit, and time [8]. They developed an AM framework that identifies the paths companies can take as they seek business value using AM; it is shown in Figure 2.1. The four paths that have been identified are listed below.

Figure 2.1: Framework for understanding AM paths and value, Graig et al. [8].

- Path 1: It describes companies that do not want to radically change their products or supply chains, but want to improve their value proposition using AM. Examples are using AM for prototyping and manufacturing tooling and fixtures.
- Path 2: Companies want to use AM as an enabler for supply chain transformation and want to take advantage of the scale economics offered. Examples are the production of spare parts or problematic production locations like space and on the maritime industry.
- Path 3: Companies take advantage of AM by developing new products with improved performance. Design products with lattice structures or using part consolidation. An example is a fuel nozzle developed by General Electric [9].
- Path 4: Describes new business models that are based on AM by altering both the supply chain and products. Examples are 3D scanning or printing custom glasses or shoes in retail stores [10].

The described tactical paths deal with the design of the product within an AM-based supply chain. It is required, both for the realisation of enhanced product performance and when printing more standard designs, that these designs have been optimised for specific AM process opportunities and constraints. The aim is to ensure that they are produced reliably, on time, and cost-efficiently. DfAM describes methodologies used to optimise product design with the goal of improving all the life-cycle stages of a product. A framework that links the different aspects of AM design is presented in Figure

2.2, it is based on the insights of Graig et al. [8]. As shown, part of DfAM is implementing Topology Optimisation (TO) or making use of lattice structures in the design, among other options. TO is developed to answer mechanical design problems. The question is how to place the right material in the correct location in a predefined design space [11]. The goal is to design parts that meet mechanical requirements with minimal material use. The method is based on numerical analysis. Guided by gradient computation or non-gradient discrete approaches, it provides design solution update steps in an iterative way [12]. Traditionally, TO is driven by an objective function, minimising or maximising while being subjected to a set of predefined constraints,such as mass, deformation, vibration frequency, etc. Usually, continuous design variables are used to solve the TO problem in a discrete way. During this iterative optimisation process, segments of the predefined initial design space are removed step by step to arrive at the minimal volume or mass of the part. More advanced methods use genetic algorithms that both add and remove material. This is called a bidirectional TO scheme. Another technique that can be used to design parts with minimal material use is generative design. Generative design is a powerful technique that focusses on creating parts with minimal material usage while still meeting specific design requirements. The general concept behind generative design involves a multi-step process that begins with the conversion of 2D sketches into detailed 3D CAD models. These models serve as the starting point for the subsequent design iterations. Once the CAD models are in place, various constraints and properties are defined to guide the generative design process [13]. These constraints can include factors such as weight limitations, performance requirements, manufacturing constraints, and desired design objectives. By setting these parameters, the generative design algorithm has clear guidelines to follow during the iterative optimisation process. The core of generative design lies in the iterative process of generating multiple design iterations. This iterative approach plays a central role in exploring and refining design solutions to achieve optimal outcomes. The algorithm explores a wide range of design possibilities, evaluating and refining them on the basis of the defined constraints and objectives. Each iteration generates a design option that represents a potential solution. Through these iterations, the algorithm fine-tunes the designs, adjusting parameters, and exploring different geometries and configurations to achieve optimal outcomes. The generative design process is not limited to the generation of a single design solution. Multiple optimised solutions can be generated, each with its own unique attributes and trade-offs. This provides designers with a range of options to choose from, allowing for further analysis and decision-making based on specific project requirements.

There are many different processes for MAM. In this research, the main focus will be on Laser Powder Bed Fusion (LPBF). This is because this is one of the first metal MAM techniques invented and, hence, the most mature. For this technique, there are the most machines on the market that can produce products on an industrial scale. Due to the relative maturity of the process, a broader range of materials is available, offering better resolutions than electron beam melting and direct energy deposition. Other names for LPBF that one comes across when researching this topic are Selective Laser Melting (SLM) and Direct Metal Laser Sintering (DMLS). SLM was launched in 1995 and was commercialised by a German company called SLM Solutions [14]. Like SLM, DMLS was also developed in 1995 and is a trademark of EOS. In contrast to what the name DMLS suggests, the metal is fully melted during the process and is not only sintered. In Figure 2.3 an overview of the inside of an LPBF machine is given. The process involves melting metal particles with a heat source. In this case, a laser is used. The more advanced LPBF machines employ multiple lasers to speed up the production process. The build chamber is filled with an inert gas (nitrogen or argon) to prevent oxidation of the molten metal. The product is built with layers ranging from $20 - 200\ \mu m$ [15]. The thin layers of metal powder are evenly spread across the powder bed with a powder spreader, also known as a recoater. After each layer, the metal powder is melted at the predetermined locations to create the product. Subsequently, a new powder layer is spread evenly; this is repeated until the product is finished. After each layer, the powder bed moves in the negative z-direction by the same distance as the thickness of the previous layer, as shown in Figure 2.3. If support structures are required to manufacture the product, they are built from the same material and are then removed

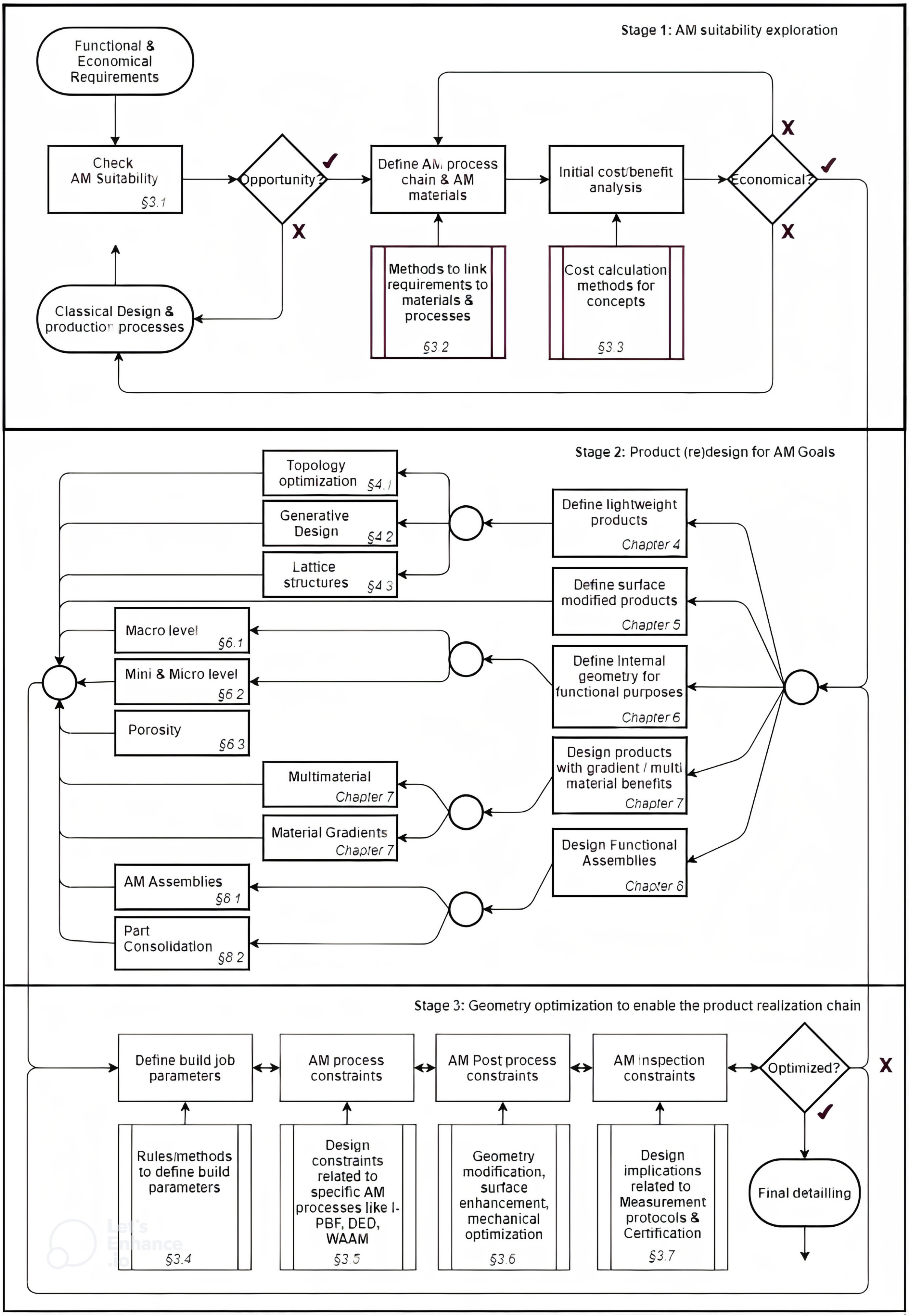


Figure 2.2: Design framework linking DfAM stages, actions and goals. Showing the steps involved when designing for AM [11].

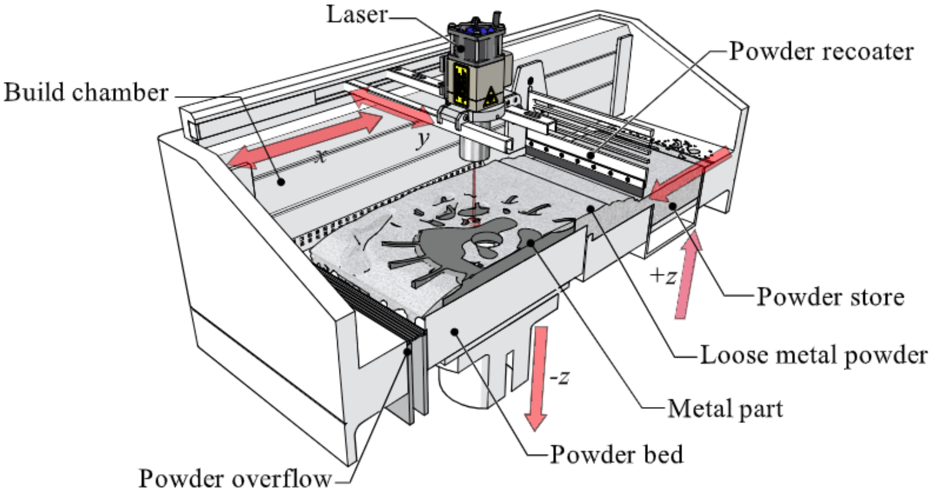


Figure 2.3: Schematic of a typical LPBF machine [15].

during post-processing. Support structures are essential in additive manufacturing to provide stability and prevent deformations during the printing process. They are necessary to support overhangs, dissipate heat, maintain material stability, ensure surface quality, and improve print bed adhesion. Although support structures are important, they are designed to be removable after printing to facilitate post-processing and achieve the desired final product [16]. When the build is complete and the product has cooled to room temperature, parts are removed from the powderbed, and excess powder is manually removed and recycled. Often, before parts are removed from the build plate, internal material stresses are relieved and parts are heat treated.

2.1.1 Additive manufacturing challenges

As mentioned in the previous section, there are many advantages that come with MAM. However, there are some drawbacks that can make MAM application challenging in real-world applications. In this section, some of the challenges and limitations are described.

Armstrong et al. [15] gave an overview of AM technology. In this overview, the current state of MAM is described, and a summary is shown in Table 2.1. It is estimated that more than fifty parameters can affect the final properties of a built part. They can be divided into three categories: pre-processing, printing, and post-processing. Together, they form the main challenges within MAM. Challenges include residual stress, surface roughness, and porosity. Together, they contribute to problems related to consistency, repeatability, and process stability[17]. Surface roughness can influence fatigue strength by up to 60% [18] and affect corrosion resistance, wear, and geometric accuracy. High surface roughness can be caused by multiple factors. Examples include the staircase effect, the adhesion of partially melted powder to the product, and partially melted regions of powder in the product. Multiple studies have predicted the effect of surface roughness on overhanging regions [19, 20]. However, a root cause could not be sufficiently defined. In addition, high porosity and the appearance of voids negatively influence MAM characteristics. It can influence fatigue strength, corrosion resistance, stiffness, mechanical strength, and fracture toughness [17]. Porosity can be caused by insufficient laser power, resulting in incomplete fusion of powder particles [21]. Another problem that causes defects is the appearance of residual stress in builds. The problem is related to high thermal gradients and rapid cooling rates during the building process [22]. Residual stresses can influence mechanical properties, such as geometric accuracy and fatigue resistance. There are multiple options for (partially) mitig-

Advantages	**Disadvantages**
Relatively high accuracy	Relatively poor surfaces finishes
Near net-shaped production	Relatively high porosity
High material utilisation factor	High residual stresses
High specific strength and stiffness	Typically require post-processing
Ability to recycle powder	Support structures are required
High geometrical complexity	Powder handling health and safety issues
A broad range of feedstock materials	Low productivity
	Limitations on build envelop
	Complex process-structure- property relationship

Table 2.1: Summary of the advantages and disadvantages of LPBF [15].

ating the effects of residual stress during post-processing. It can be done with laser shock peening, thermal control of the buildplate, and heat treatment [23]. However, these methods are not always economically viable [24]. Due to the numerous parameters involved, much research is still needed to better understand the process-structure-property relationships of the defects mentioned above.

As mentioned above, it becomes possible with MAM to produce complex geometries that are not achievable or are very expensive to produce with traditional manufacturing techniques. Examples of these complex structures are lattice structures or TO geometries. These optimisations in geometry can be used to improve mechanical properties or decrease weight. Since MAM allows for the production of complex geometries, a trade-off needs to be made whether MAM is a viable option for the production of the parts. One factor that has a large influence on this trade-off is the cost aspect.

2.2 Cost models

To help in the decision on whether MAM is a viable option compared to traditional manufacturing techniques, cost models have been developed. To gain an overview of MAM cost estimation opportunities, an overview of the main existing models is presented to provide an overview of MAM cost estimation opportunities. Cost estimation for MAM is complex. Due to this, current studies are limited in their scope, according to Thomas D [25]. The literature showed that even with the rapid growth of reported studies, knowledge of MAM cost models is still limited in many aspects. A cost model is a quantitative tool used to estimate and analyse the costs associated with a particular process, activity, or project. It provides a systematic approach to understanding and evaluating the various cost components involved in a given situation. Cost models are commonly used in business, finance, engineering, and other fields to assess the financial implications of different scenarios. A cost model is a quantitative tool used to estimate and analyse the costs associated with a particular process, activity, or project. It provides a systematic approach to understanding and evaluating the various cost components involved in a given situation. Cost models are commonly used in business, finance, engineering, and other fields to assess the financial implications of different scenarios. In the context of this research on MAM, the focus is on determining the cost per part produced using MAM. The model takes into account various factors that contribute to the overall cost. As new MAM technologies are developed, cost models become obsolete and are still bound with uncertainties. Production overheads also seem to have increased, and costs such as maintenance, quality control, material handling, inventory, environmental aspects, and safety issues should be studied discretely to achieve a complete and accurate MAM cost model. Furthermore, the models are scattered into many applications and technologies and are discussed using different viewpoints based on diverse perspectives, such as finance, management, and production. As a result, there is a missing link in terms of

Classification techniques		Definition
Method-based	Qualitative: Intuitive	Based on the experience of the estimator
	Qualitative: Analogy	Based on historical data. A comparison is often made between old parts and new parts during estimation
	Quantitative: Parametric	Based on statistical regression expression where variables are referred to as cost drivers
	Quantitative: Analytical	Based on product decomposition into units, operations, or activities that relate to how to manufacture the product
Task-based	Design-oriented	Based on design-related activities
	Process-oriented	Based on the process of commissioning the product development activities covering production-related and post-processing costs
Level-based	Process-level	Based on the production cost, which involves entire product development phases (pre-processing, production and post-processing)
	System-level	Based on product life cycle that covers supply chain, operation management and system-level services

Table 2.2: Definition of cost classification techniques [26].

how to use them in various manufacturing technologies for the benefit of many levels of users, such as customers, manufacturers, managers, or service providers [26]. Studies examine individual parts rather than assemblies, or they tend not to include the effect on the supply chain. The effects of the supply chain can include reduced inventory and transportation costs, as well as a lower risk of interruptions in the supply chain. It is stated that in the research conducted by Thomas D [25], until the article was published in 2016, MAM was cost effective to produce small batches in a centralised way. However, since then, there have been many developments in this area. With increasing levels of automation and distributed production, increased batch sizes may become more cost-effective or already are. Furthermore, the main cost drivers for MAM are material costs and the cost of a MAM system. Increasing levels of adoption of MAM have reduced the cost of MAM raw materials as a result of the effects of economies of scale. The average price of the MAM systems also decreased by 51% between 2001 and 2011, after adjustment for inflation [25].

In some cases, the cost per unit can be higher when a product is produced with MAM compared to traditional manufacturing. However, the company that designed the product becomes more flexible. There is no need for expensive moulds that must be used for longer periods of time to become cost-effective. If a part is produced and an unforeseen design iteration is required to make it more reliable, it can be easily done with MAM at no extra cost.

Thomas D [25], also states that MAM has an influence on the cost during the entire use phase of a product. It is not only about the cost of production, but also about allowing for the production of products that might not have been possible using traditional manufacturing methods. With MAM, it is possible to design products that have new capabilities, such as extended useful life, which require less natural resources or the time required during the production phase of a product. The example given in the research is that automobiles might be lighter to increase the range of electric vehicles. Another example often given is the reduction in the weight of aircraft parts. Empirical analysis shows that it takes on average 0.2 kg of fuel to transport 1 kg of weight over a distance of 1000 km. It also requires an additional 0.02 to 0.03 kg of fuel per 1000 km for every kg of weight added [27].

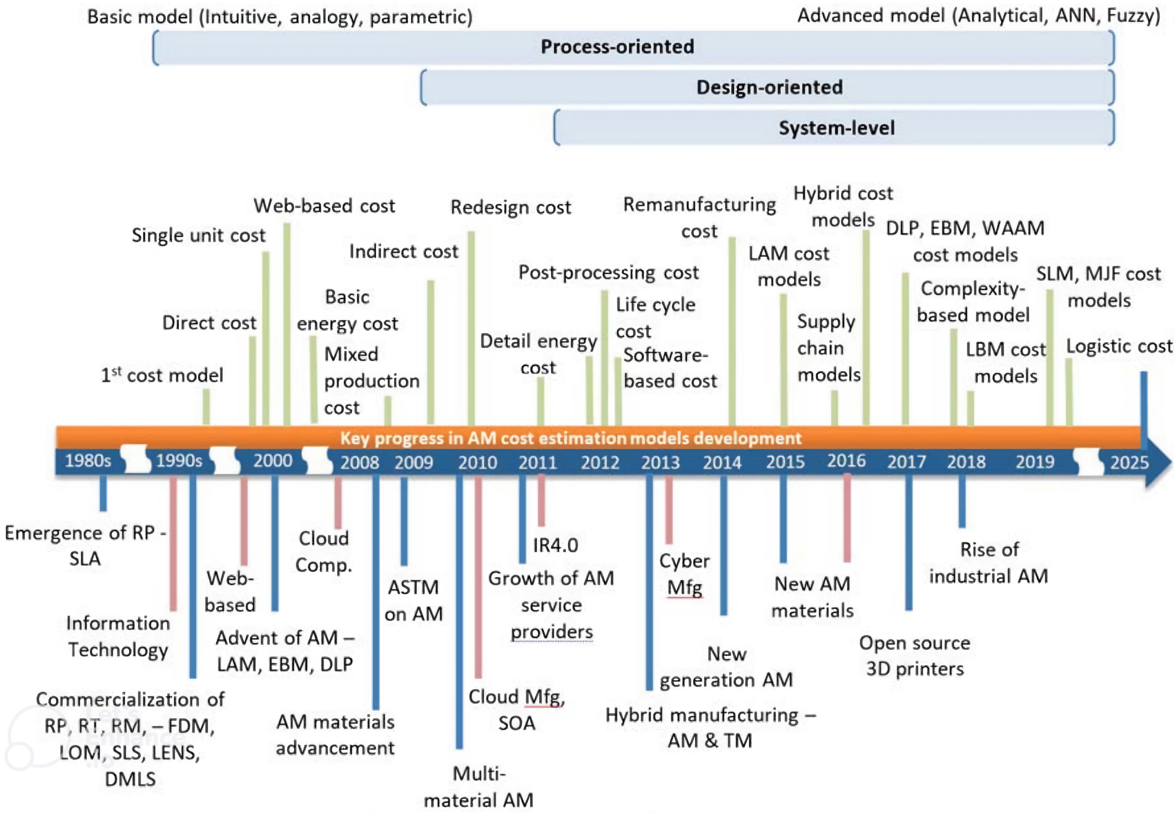


Figure 2.4: Evolution of MAM cost estimation model development adopted in various manufacturing technologies [26].

Research on MAM cost estimation has evolved a lot since its emergence. In Figure 2.4 a timeline is given for the development of MAM cost estimation models. Zuhra et al. [26] state that there are four cost classification techniques. An overview is depicted in Figure 2.5. It can be categorised into the following areas: intuitive, analogous, parametric, and analytical. According to the research, there are three different perspectives for cost estimation: finance and accounting, manufacturing and management. Different classification techniques are stated to be employed from different perspectives: method-based, task-based, and level-based, respectively. The definition of each is given in Table 2.2.

There are two research papers on MAM cost models that have received significant attention: Hopkinson and Dickens [28] and Ruffo et al. [29] in the early stages of cost estimation for MAM. This was due to a different cost estimation technique, which led to conflicting results. Both applied the intuitive technique to compare injection moulding with different MAM techniques to produce polymer-based parts, namely stereolithografy, fused deposition modelling, and selective laser sintering. Hopkinson and Dickens made three assumptions on which to base their research. The first was that the system produces a single-part type for one year. The second assumption is that the entire build volume is used. The last assumption they made is that the utilisation factor is 90%. Labour, material, and machine costs were included in the analysis. The average cost per part is calculated by dividing the total cost by the total number of parts produced in one year. The result is a flat line independent of the number of parts produced, as shown in Figure 2.6.

Ruffo et al. estimated the costs with a task-based cost model. Hopkinson and Dickens used the same product. In a task-based cost model, every cost is associated with a particular activity. Ruffo et al. assumed a machine utilization of 57%, based on the premise that the equipment operates for 100 hours per week over 50 weeks annually. This assumption was considered realistic during their research period. However, advancements in the technology suggest that achieving higher utilization percentages is now feasible. Even with current technological developments, the utilization factor of

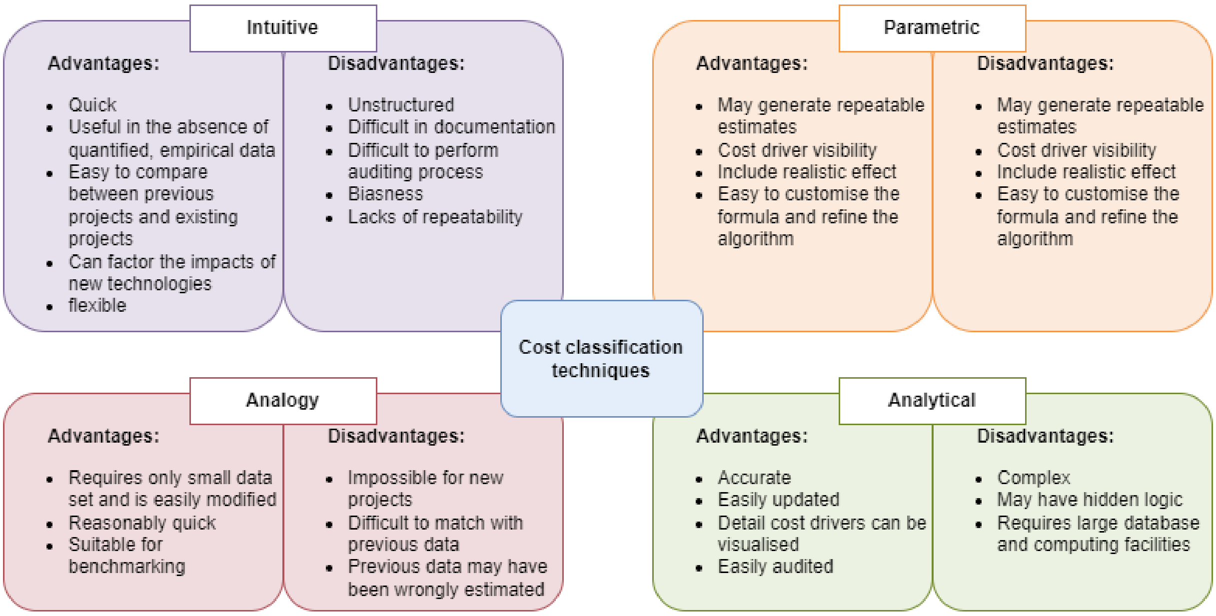


Figure 2.5: Advantages and disadvantages of various cost classification techniques, adapted from [26].

90% assumed by Hopkinson and Dickens remains challenging to attain. The total cost is the sum of indirect costs and raw material costs. Indirect costs are dependent on the total build time. This results in the jagged saw tooth shape that can be seen in Figure 2.6. Each time an additional build cycle is needed to produce the parts, the cost increases due to the increased amount of time required.

MAM was poorly understood around 2006, leading to inadequate cost factors, such as energy and system-level costs. These factors were thought to have a small impact on MAM cost. Later, sustainability effects were taken into account by incorporating energy use into cost models. This was first done by Baumers et al. [30] who analysed the energy consumption of a DMLS process. They showed that the average production cost depends on the capacity of the building volume. Lindeman et al. [31] were the first to realise that post-processing costs are an important part of the operation. They used a time-driven ABC approach to include pre-processing costs such as the preparation of CAD data, the creation of support structures, and the placement of parts on the buildplate. Time-driven ABC is a costing method that uses the time required to complete each step in a process to produce a product or deliver a service. The cost of a product or service is determined by multiplying the total time required to complete a series of process steps by the capacity cost rate, while the capacity cost rate (expressed as a cost per unit of time) is determined by the total cost of the supplied capacity. Part of the post-processing costs are quality control, removal of support structures, and possible heat treatment. T. Vaneker [11] presented a general overview of post-processing costs for metal MAM; an overview is given in Table 2.3.

Yim and Rosen [32] developed a design-orientated cost model. This model focused on the selection of a suitable MAM process in the early stages of the design process based on the estimated build time. With the help of an approximation of the geometric data of the part, specifically the bounding box and volume, a first estimate can be made, so that the user can identify and compare potential manufacturing processes. The research by Atzeni and Salmi [33] was the first to present a comparison of two metal production processes. From an economic point of view, they compared and demonstrated the suitability and cost effectiveness of MAM compared to high-pressure die-casting for medium-volume production of metal parts.

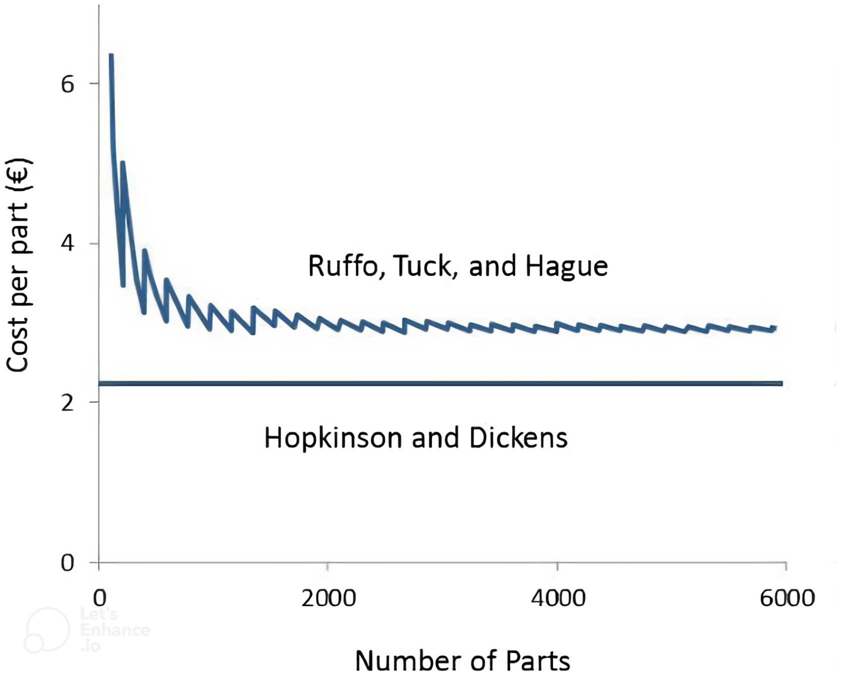
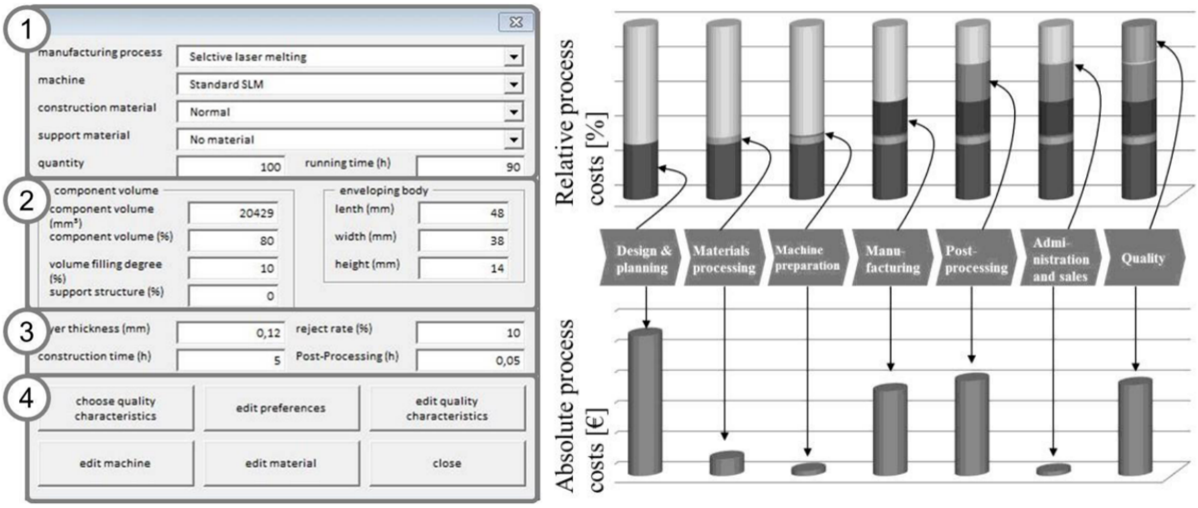


Figure 2.6: Cost model comparison showing different estimations for cost per part (Ruffo, Tuck, and Hague vs. Hopkinson and Dickens) [25].

Technique	**Improvement goal**	**Cost indication**
Stress relief	Reduction/removal of thermal residual stress	$\$500-600$ per build plate
Part removal	Remove part from the build plate wire-EDM	$\$200-300$ per build plate
	Remove part from the build plate - Band saw	Low cost
Heat treatment	To improve microstructure and mechanical properties	$\$500-2,000$ per batch
Hot isostatic pressing	To reduce porosity and improve fatigue live	$\$500-2,000$ per batch
Machining	To improve accuracy of mating interfaces, surfaces, add threads and/or remove supports	Cost depends on geometry and material and fixture needs
Surface treatments	Improve surface finish/quality/surface roughness	$\$200-2,000$ per batch
Inspection and testing	Process qualification and part validation & certification	10 - 20% of total cost per part [34]

Table 2.3: Indication of cost for post-processing operations for MAM [11].



manufacturing process: Selctive laser melting
machine: Standard SLM
construction material: Normal
support material: No material
quantity: 100
running time (h): 90

component volume
component volume (mm³): 20429
component volume (%): 80
volume filling degree (%): 10
support structure (%): 0

enveloping body
lenth (mm): 48
width (mm): 38
height (mm): 14

yer thickness (mm): 0,12
reject rate (%): 10
construction time (h): 5
Post-Processing (h): 0,05

Figure 2.7: Input (left) and output (right) area of a cost model developed by Schröder et al. [35].

In the work of Schröder et al. [35] MAM production costs were evaluated with an Excel tool. The outcome evaluated costs and performed a sensitivity analysis. The input and output screens of the cost model are shown in Figure 2.7. Based on the results of their work, they state that:

- The most cost-influencing factors are the investment costs of the machine and its load factor.
- Post-processing of products with high quantities and small bodies has great potential for process optimisation.
- Economies of scale exist only for small products; products with large bodies are nearly independent from the ordered quantity.

They suggest that a cost model should include waste material recycling, support structures, printing time, the maximum number of products that can be printed simultaneously, the level of complexity, post-processing time, and quality management methods to protect and monitor the quality of the product and process. In addition to the goal of reducing costs, MAM also has advantages on a societal level. This level concerns the reduction of resource consumption and maximisation of utilisation. Thomas D [25] states that there are two approaches to examine MAM at the societal level. It is discussed from a monetary cost and from a resource consumption perspective.

First, from a monetary cost perspective, as discussed by Young et al. [36], there are two ways to categorise the production cost. The first involves well-structure costs. These are costs related to labour, material, and machines. The second involves ill-structured costs. This is related to the costs associated with machine setup, build failure, and inventory costs. Many of the studies covered so far in this research mainly focus on the first category, the "well-structured" costs. They account for a significant portion of the costs associated with MAM. Thomas D, also states that the studies tend to focus on the production of single parts, and studies that examine assemblies tend to neglect supply chain effects. These effects can be related to inventory and transportation costs. But this is an area where benefits may be hidden. It states: "For instance, a dollar invested in automotive assembly takes 10.9 days to return in revenue. It spends 7.9 days in material inventory waiting to be used. It spends 19.8 hours in production time and another 20.6 hours in downtime when the factory is closed. Another 1.3 days are spent in finished goods inventory. Moreover, of the total time used, only 8% is spent in actual production". From a lean philosophy perspective, this is a significant source of waste. In addition, all these parts need to be transported from the production location to where they are assembled. The research of Thomas D, states that transportation of manufactured equipment travels

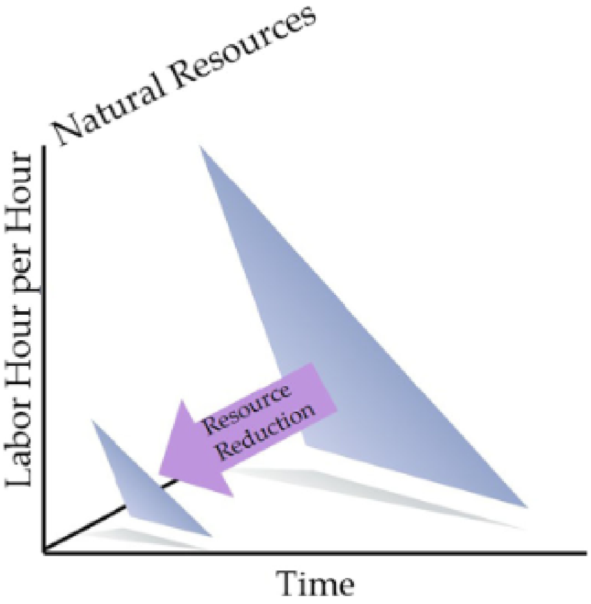


Figure 2.8: Time, labor, and natural resources needed to produce a manufactured product [25].

1298 km on average. There were 605 billion dollars worth of manufactured goods in inventories in 2013 in the United States of America. This is equal to 10% of that year's total revenue. If inventory can be reduced by MAM, this can lead to significant savings. The potential to produce assemblies in one build can also lead to reduced inventory and transportation costs.

Currently, there is quite a good understanding of the production costs of MAM. This is not the case for other costs in progress. As stated before, the major advantage of MAM is the combination of multiple parts of an assembly into a single part that is produced with MAM, this is called part consolidation. Also, parts can be made lighter, more reliable, and last longer. This is because the design is not limited by the design constraints of traditional manufacturing. The cost models previously mentioned did not take into account part consolidation. Therefore, a so-called cradle-to-grave analysis is required. In research by Thomas D [25], an example of a generic 100 dollar steering/suspension component made in the USA is given. If the component were produced using additive manufacturing, it might reduce some of the intermediate part costs. For example, it may not require screws, bolts, or intermediate assemblies. This reduction might subsequently eliminate some wholesale and transportation costs, which together amount to 12.1% of total costs. Gathering all the required data is time consuming, but gives good insight into what costs contribute to the total cost of a generic part.

The second perspective for MAM on a societal level is from the perspective of resource consumption. This considers the basic elements of production, namely: labour, land, entrepreneurship, human capital, and time. In Figure 2.8 shows the relation between labour, time, and natural resources. The example given is that the use of a machine can reduce the labour and time required to produce a product, but it can increase energy consumption. The ideal shift would result in a reduction in all three components in Figure 2.8. The research states that "the total advantage of an MAM manufactured good is the difference in the use of land, labour, and time expended on production, utilisation, and disposal combined with the utility gained from the product compared to that of traditional manufacturing methods". In the case of the same $ 100 dollar steering/suspension component as mentioned before, it can lead to a significant saving. When additive manufacturing was used for this product, the resulting product can exhibit reduced weight and lower maintenance requirements, leading to enhanced fuel efficiency and decreased maintenance needs. For example, by achieving a modest 0.1% increase in fuel efficiency and a 0.1% reduction in maintenance for the production of 100,000 cars with an average fuel consumption of 11.3 L/km, potential savings of up to 22,900 labour hours can be realised. Additionally, the conservation of natural resources results in more than 5,600,000 kg of CO_2 equivalents saved. These considerations encompass the concept of life-cycle costs, encompassing all expenses incurred by the product user, including purchase and usage costs. (plant, machinery, equipment, apparatus, and product life) [37]. In addition to the cost aspect of implementing MAM in the automotive industry, MAM has influence on the entire supply chain. This influence contributes to the trade-off between MAM and traditional manufacturing methods. The research can be further extended by incorporating the effects of MAM on transport costs and related emissions. For instance, a component that requires less frequent replacement can lead to reduced transport-related emissions and lower costs associated with supplying garages with this part. This further highlights the environmental and economic benefits of adopting MAM.

2.3 Effect on supply chain

In order to evaluate the impact of MAM on the supply chain, Scott and Harrison [38] conducted a study in which a manufacturing company is considering the development of a new production line. The study aimed to compare the viability of using MAM versus traditional manufacturing methods such as injection moulding or subtractive methods to manufacture the product. By analysing the end-to-end supply chain, the study sought to determine the most suitable option for the company's manufacturing needs. A strategic optimisation model is built with a wide variety of stochastic elements. They, along with others, observe that demand is the most critical factor in deciding which method to adopt. They also argue that a decrease in material costs can increase MAM adoption in supply chains. The results of the study are depicted in Figure 2.9, showing how much raw material and machine costs influence the probability of MAM adoption. Material prices have changed a lot since the time of the research. At that time, MAM machine manufacturers had adopted the "razor blade business model," where profits are generated by the sale of expensive raw materials [39]. Currently, there are more raw material manufacturers on the market. Leading to a reduction of raw material cost. The research model has some limitations. Although the model is strategic in nature and considers inventory carryover from year to year, it does not include inventory management on a tactical level. It has been assumed that MAM will reduce inventory levels because production can occur in small batches on demand. In general, including this effect is advantageous for MAM. It may lead to production in smaller batches, reducing inventory, and possibly the amount of safety stock. Manufacturers with high inventory holding costs will, therefore, be impacted differently from manufacturers with lower holding costs.

An advantage of MAM is that it allows production in smaller batches based on demand, allowing lower inventory levels and less safety stock. The model Scott and Harrison [38] developed in their research does not take this into account. Another advantage that is not taken into account is that the machines can produce other products in "downtime" when demand does not allow for full utilisation of the machines. Furthermore, tooling and moulding costs are not included in the variable costs per unit for traditional manufacturing. The final thing they mention that is not included is that MAM allows for customisation of products according to the needs of every customer. In a study by Chan A et al. [40], industry experts from China are interviewed. An interviewee gave the following example of the application of MAM in the production of car headlights. There could be six variations of the headlights, which means that the company needs to stock up on inventory for six stock keeping units. This is expensive and it is also time consuming to design and manage the corresponding moulds, MAM on the other hand, does not need expensive moulds. A summary of key benefits of MAM use is given in the list below [41].

- Shortening the lead time
    - Due to the possibility of parts consolidation
    - Decreasing the number of manufacturing operations per item/part

- Production on location
  - Manufacturing facilities relocate to countries where parts are developed (for example, USA or Germany, etc.)
  - New opportunities for the production of spare parts on site.
  - A decrease in transportation cost
- Allows for development and production of customer-specific, complex items
- A change in the relation between manufacturers and retailers. The role of inventory and retailers may decrease, due to implementation of on-demand manufacturing (also, named agile manufacturing)
- Possibility of launching low volume products at costs comparable to mass manufactured products
- The reduction of weight and volume parameters, a lower buy-to-fly ratio
- Improvement of decision making processes (agility)

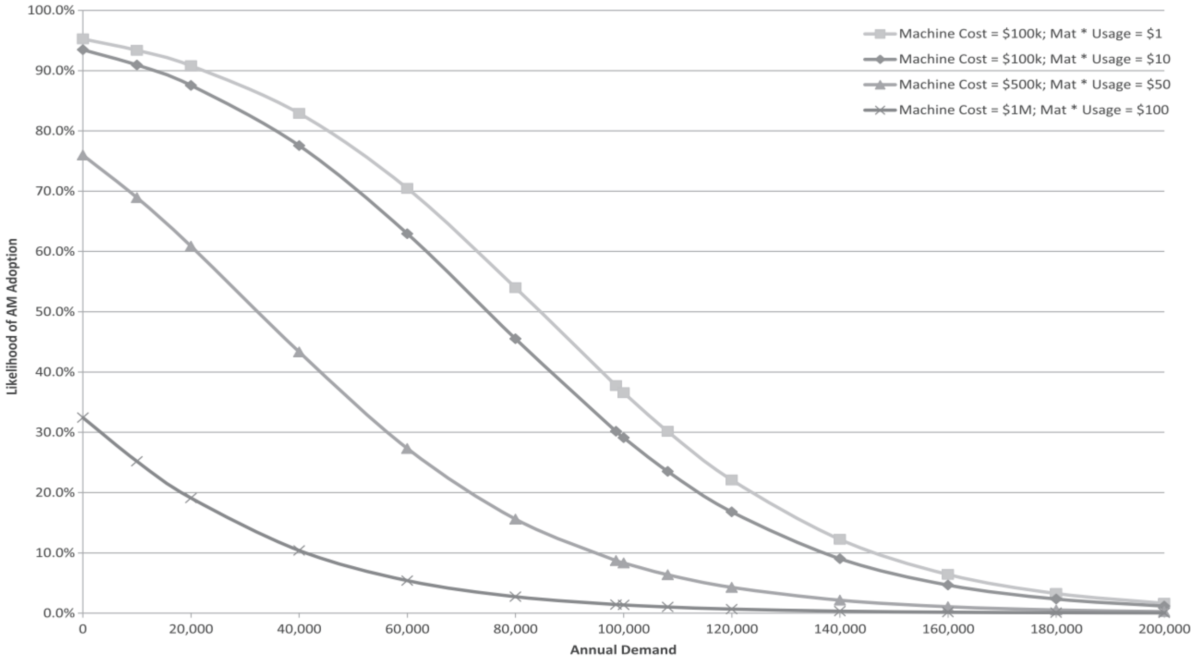


Figure 2.9: Shows how much raw material and machine costs influence the likelihood of MAM adoption depending on varying annual demand [38].

All the effects mentioned apply to the automotive industry. Vehicle manufacturers have been at the forefront of implementing MAM. One of the most prolific MAM applications in the automotive industry is in rapid prototyping. This is among the oldest uses of the technology, with some large auto manufacturers having prototyped parts with 3D printers for more than 20 years [42].

2.4 MAM in the automotive industry

The automotive industry is a highly competitive business where time to market is important, as is unit cost. To achieve this, a decrease in tooling time is valuable. This requires new production techniques and approaches, such as flexible manufacturing systems. MAM allows flexible production of products without a significant impact on costs and lead time [43]. New models and facelifts of older models are developed every day, driven by new design trends and the evolution of technology in terms of safety, aerodynamics, and weight reduction. MAM has proven to be one of the most promising responses to meet the fast-changing market demand. In particular, MAM provides freedom of design along with suitable materials for demanding applications. Currently, MAM in the automotive industry is used mainly for prototyping, tooling production, and expensive performance cars.

In a case study by Volkswagen together with the manufacturer of MAM machines, Additive Industries (Eindhoven, The Netherlands), a 650% cost reduction in production tooling was achieved using MAM [7]. The case study concerns a tooling nozzle used in the Volkswagen vehicle assembly process. Each car model has its own unique nozzle, and this case study focuses on the tool used during the assembly of the VW Tiguan. During the car assembly process, the tooling nozzle is attached to a robot arm that sprays a liquid PVC rope on the flanges of the front and rear doors of the car. The rope is applied to protect the door against water-induced corrosion. Conventionally, the nozzles are made of two titanium machined parts that are bent and welded together. Many different manufacturing and post-processing steps are required in the manufacturing process, making it a costly tooling part. From a technical perspective, the accuracy of the nozzle outlet is a critical requirement to ensure the quality of the PVC-deposited rope. More than 1000 nozzles per year are required for VW Tiguan car production in Wolfsburg. Previously, VW outsourced the manufacturing of these nozzles, which impacted both the cost and the lead time of production. The 650% cost reduction has been possible for multiple reasons. The first is part consolidation. The previous part consisted of two parts and required multiple manufacturing steps; the redesigned nozzle is printed as one part. The second factor that contributed was the reduction in material use. A third factor that contributed is the use of cheaper materials. Previously, the nozzle was made of titanium using traditional manufacturing methods. The nozzle can be made of a cheaper stainless steel alloy using MAM. The fourth factor is the reduction in lead time to two days instead of multiple weeks, with a much lower risk of disruptions in the supply chain.

MAM has allowed Ford to prototype designs in four days instead of four months, at 1% of the original costs [8] and Joe Gibbs Racing to reduce the time required for design and machining from 33 to 3 days [8]. In the research carried out by Leal et al. [43] a case study on the production of stamping inserts for the production of body panels showed that MAM was suited for this purpose. The stamping tools produced were tested by an automotive company to determine the behaviour of the tool under real operating conditions. A comparison was carried out, considering relative costs and manufacturing time, as well as overall behaviour under production conditions. DMLS technology was used with the intention of eliminating steps in the original production process. Creating a more streamlined production process with decreased manufacturing complexity. The comparison was made between three production processes: traditional manufacturing from laminated steel, a lost foam process, and MAM. Figure 2.10 shows what the manufacturing costs and the production time are for different manufacturing techniques. MAM costs are significantly higher as a result of the costs of metal powder and processing equipment. On the other hand, the lead time gain is significant, approximately 35% less than the fastest traditional manufacturing technique. Shorter lead time can provide an economic and technical advantage. The cost breakdown for MAM according to Leal et al. [43] consists of raw material and processing (84,2%), 3D scanning of the original part (9,3%), thermal treatment (0,3%) and finishing operations (6,2%). The application did not make use of DMLS capabilities, which allow the production of complex geometries. In addition, they did not take into account the entire life cycle of the stamps. The tools were monitored to compare their performance. The results show, compared to traditional tooling, similar mechanical performance achieving more than a million cycles.

There is a difference in the cost structures of different products and in the level to which they contribute to the life-cycle costs. This can be seen in Figure 2.11 where a comparison is made in the cost structure of three different types of products. As MAM can lead to a lighter car, the operating cost of the user can be reduced, maintenance costs can be reduced, and there can be environmental benefits. It is important to note that when evaluating the life cycle cost of vehicles in relation to MAM and to recognise the multifaceted impact it has, not only on the manufacturer but also on the end-user.

In the traditional manufacturing model, the upfront production cost significantly influences the selling price of a vehicle. MAM, while initially potentially costly in terms of part production, can lead to long-term cost efficiencies. However, these efficiencies are often operational costs rather than affecting the vehicle's sell price. For example, parts produced through MAM are typically lighter due to optimised design and material use. This reduction in weight directly impacts the fuel efficiency of the vehicle, potentially leading to lower fuel consumption over the lifetime of the car. While this significantly benefits the end-user in terms of operational cost, it does not directly affect the initial selling price of the vehicle, which is primarily determined by production costs.

The difference between the cost of production and the cost of operation is made clear by the advantages of additive manufacturing, which are more noticeable in the latter. Manufacturers may initially invest more in producing MAM parts, but these parts contribute to fuel savings and improved efficiency throughout the vehicle's life. In future automotive pricing models, considering the life cycle cost and operational savings resulting from MAM-produced parts could become essential. Including these operational efficiencies in the vehicle value proposition could better align with the overall goal of providing sustainable and cost-effective transportation solutions for everyone. It is important that this concept is understood by both manufacturers and consumers. Manufacturers must strategically integrate MAM to improve efficiency and reduce operational costs. Simultaneously, consumers need to appreciate the long-term benefits of MAM-produced vehicles, not only in terms of sustainability but also in potential fuel savings and overall cost-efficiency during the vehicle's lifetime. The examples given in this section show that MAM is currently used within the automotive industry mainly for prototyping and tooling. However, research about functional parts is still limited. This is a gap in the research that needs to be adressed.

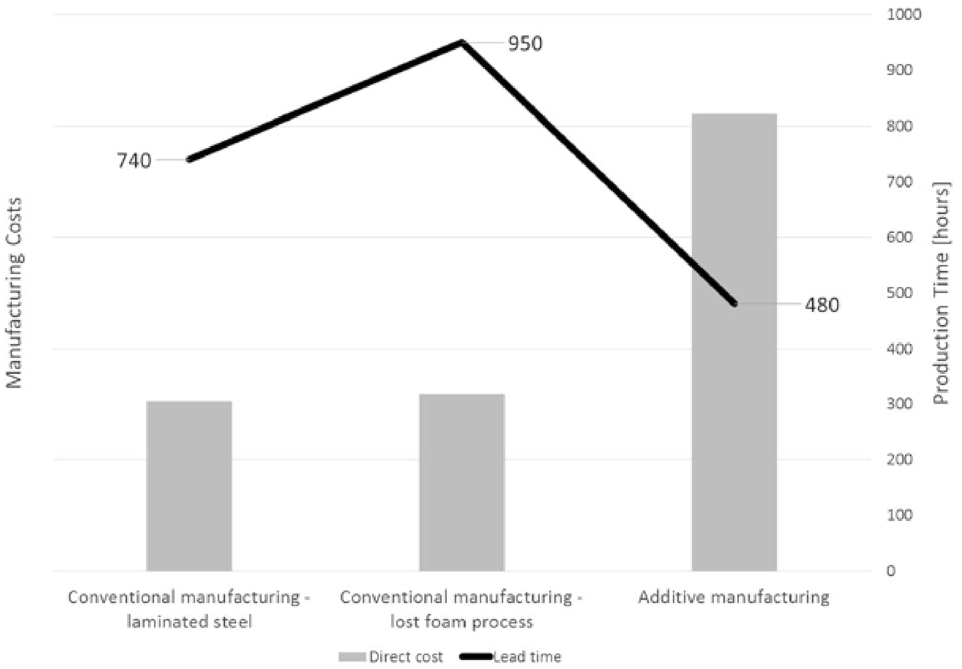


Figure 2.10: Comparison in production costs and time for different manufacturing techniques [43].

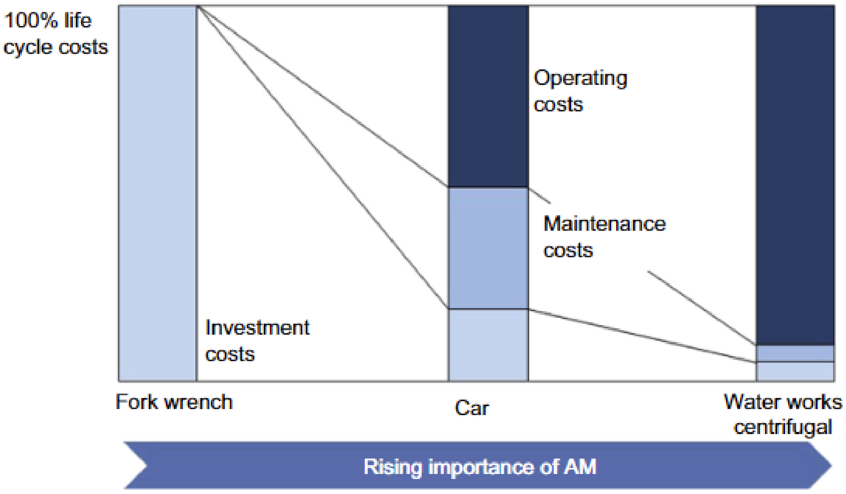


Figure 2.11: Costing structures of different product types (left) and costing types at the user/producer level [37].

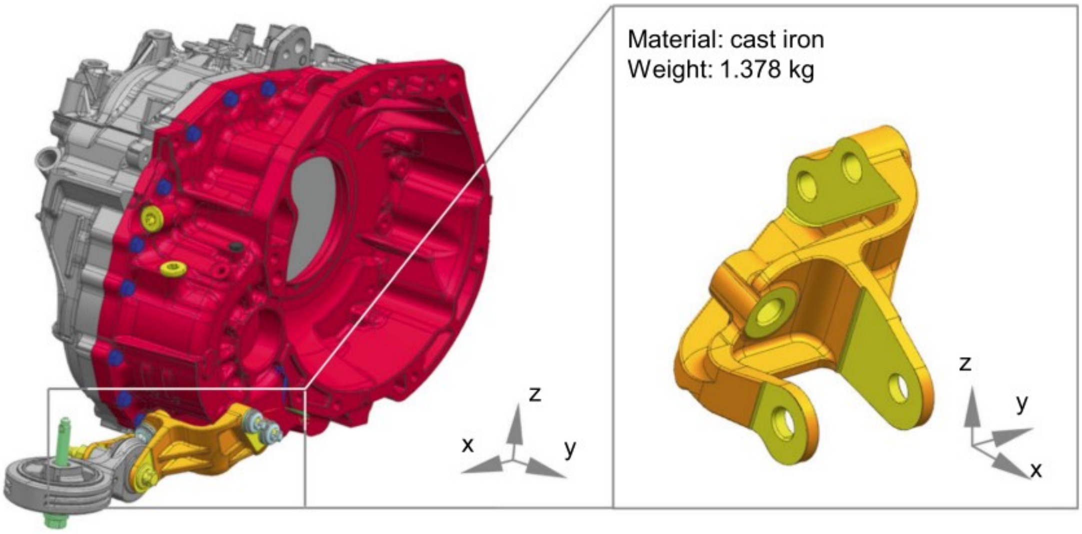


Figure 2.12: Differential mounting bracket assumed as a case study by Prairone et al. [44]

2.4.1 Life-cycle effects of additive manufacturing in automotive industry

In order to gain further insight into these environmental benefits, Prairone et al. [44] conducted a research called "Additive manufacturing for the automotive industry: on the lifecycle environmental implications of material substitution and lightweighting through redesign". In the study, two manufacturing routes for an automotive part are compared through a comparative Life Cycle Assessment (LCA). The paper investigates the case of the light-weighting of an automotive component to quantify the effects of re-design and material substitution. The original bracket is made of cast iron and the optimised bracket for MAM is made of AlSi10Mg and produced by means of LPBF. It results in 69% weight savings, the optimised bracket is shown in Figure 2.12.

In the article by Prairone et al. [44], a mass reduction factor k is defined. It quantifies the ratio between the mass of the part produced with MAM (m_p^{MAM}) and that of the part produced through traditional manufacturing (m_p^{TM}) according to Equation 2.1. This factor k is shown in Figure 2.13, showing an isocurve for different values of k. Each isocurve represents a scenario in which $CO_{2\ \mathsf{mat}}{}^{MAM} = CO_{2\ \mathsf{mat}}{}^{TM}$, where TM stands for traditionally manufactured. In the area above an isocurve the CO_2 emissions for the MAM feedstock are higher than those for traditional manufacturing. The opposite holds for the area below the curve.

$$k = \frac{m_{\mathrm{p}}^{\mathrm{MAM}}}{m_{\mathrm{p}}^{\mathrm{TM}}} \tag{2.1}$$

The ratio shown as the x-axis label is the overall yield factor, which is the ratio between the mass of the input raw material (m_{raw}^i) and that of the finished product (m_p^i). This factor means the same thing as the buy-to-fly ratio mentioned above. The overall yield factor y^i can be calculated according to Equation 2.2, for either $i = MAM$ or TM.

$$y^i = \frac{m_{\mathrm{raw}}^i}{m_{\mathrm{p}}^i} \tag{2.2}$$

The y-axis label is Equation 2.3. It quantifies the ratio of CO_2 emissions between MAM and traditional manufacturing parts.

$$\frac{\mathrm{CO}_{2\ \mathsf{mat}}^{\mathrm{MAM}}}{\mathrm{CO}_{2\ \mathsf{mat}}^{\mathrm{TM}}} = \frac{m_{\mathsf{raw}}^{\mathrm{MAM}} \cdot \mathrm{CO}_{2\mathrm{feed}}^{\mathrm{MAM}}}{m_{\mathsf{raw}}^{\mathrm{TM}} \cdot \mathrm{CO}_{2\ \mathsf{feed}}^{\mathrm{TM}}} = \frac{y^{\mathrm{MAM}} \cdot m_{\mathrm{p}}^{\mathrm{MAM}} \cdot \mathrm{CO}_{2\mathrm{fecd}}^{\mathrm{MAM}}}{y^{\mathrm{TM}} \cdot m_{\mathrm{p}}^{\mathrm{TM}} \cdot \mathrm{CO}_{2\ \mathsf{feed}}^{\mathrm{TM}}} = k \cdot \frac{y^{\mathrm{MAM}}}{y^{\mathrm{TM}}} \cdot \frac{\mathrm{CO}_{2\mathrm{feed}}^{\mathrm{MAM}}}{\mathrm{CO}_{2\ \mathsf{feed}}^{\mathrm{TM}}} \tag{2.3}$$

Where:

- $\mathrm{CO}_{2\ \mathsf{mat}}{}^i\,(\mathrm{kgCO}_2)$: Carbon dioxide emissions for feedstock material production, for either $i = \mathrm{MAM}$ or TM;
- $m_{\mathsf{raw}}{}^i(\ \mathrm{kg})$: Mass of the required raw material, for either $i = \mathrm{MAM}$ or TM;
- CO_2 feed ${}^i\,(\mathrm{kgCO}_2/\mathrm{kg})$: Carbon dioxide emissions per unit mass of feedstock material, for either $i = \mathrm{MAM}$ or TM, which can be obtained by adding the specific CO_2 emissions of the pre-manufacturing process (e.g., powder atomisation) to the carbon footprint of the raw material;
- $m_{\mathrm{p}}{}^i(\ \mathrm{kg})$: Mass of the component produced by means of either $i = \mathrm{MAM}$ or TM;
- $y^i(-)$: Overall yield factor (that is, the $m_{\mathsf{raw}}{}^i/m_{\mathrm{p}}{}^i$ ratio), for either $i = \mathrm{MAM}$ or TM;
- $k(-)$: Mass reduction factor due to re-designing and material substitution (i.e., the $m_{\mathrm{p}}{}^{\mathrm{MAM}}/m_{\mathrm{p}}^{\mathrm{TM}}$ ratio).

The study by Kellens et al. [45] shows that the specific energy consumption of MAM processes may be one or even two orders of magnitude higher than that of traditional manufacturing methods. However, comparing only the energy efficiency of the different processes has proven to be an insufficient criterion on which to base the choice of manufacturing process. All steps that are part of a manufacturing process should be included (e.g. part cleaning and thermal treatment). CO_2 emissions are also dependent on the local electric energy mix that is used, therefore, a geographically dependent variability must be considered.

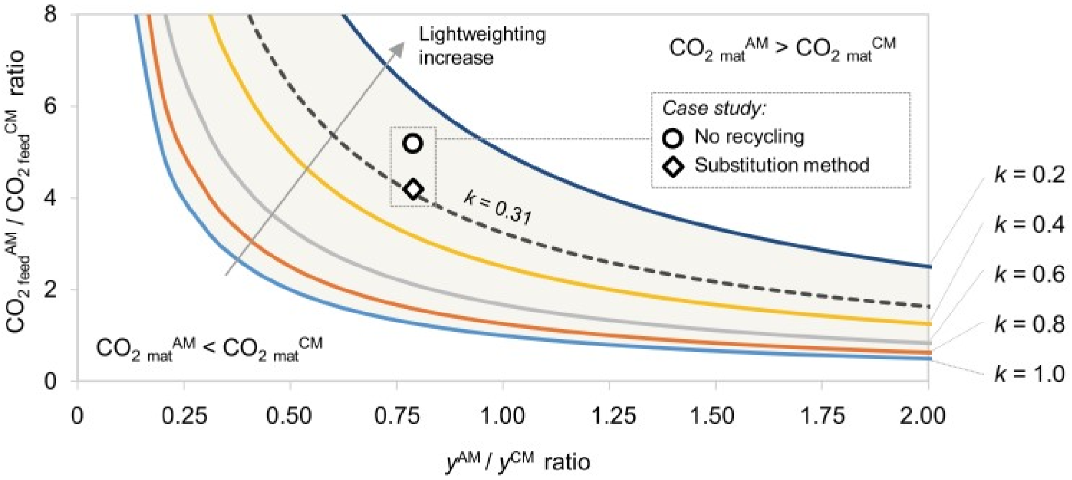


Figure 2.13: Iso-CO_2 emission curves related to feedstock material production [44]

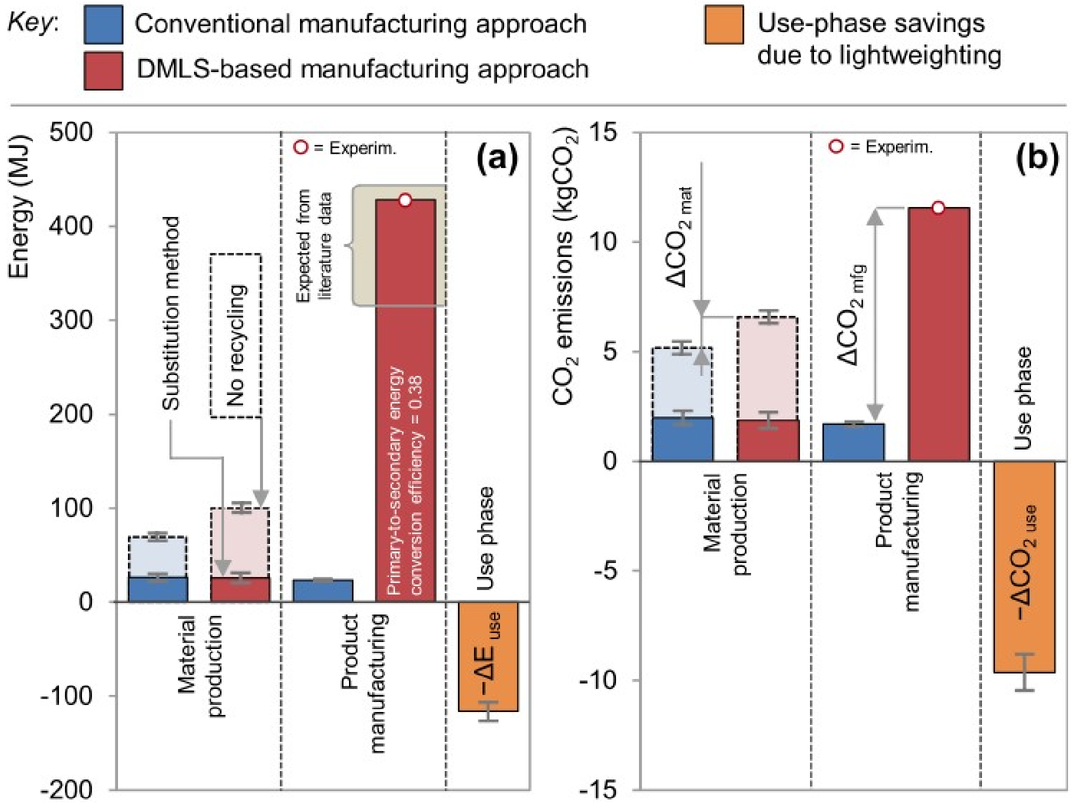


Figure 2.14: Comparative results of the life cycle primary energy (a) and CO_2 emissions (b) [44]

Figure 2.14 shows the results of the cradle-to-grave analysis of the comparison between the two production processes. The worst-case scenario is represented by the dashed lines. For example, there is no recycling of scrap material. When looking at CO_2 emissions, it shows that the carbon footprint of LPBF is 4-5 times as high. However, the impact is reduced or even nullified when end-of-life recyclability is taken into account. This is the result of the weight reduction applied and the lower ratio y^{MAM}/y^{TM}. The research states that for the case study considered here and the above detailed life cycle inventory assumptions, when material recycling is included according to state-of-the-art industrial practise, the difference in total life cycle CO_2 emissions between the DMLS-based manufacturing approach and the conventional one varies between 1.2 kg CO_2 (that is, for the best case for MAM and the worst case for TM) and + 2.0 kg CO_2 (that is, for the worst case for MAM and the best case for TM). Therefore, additional impacts from cradle to gate can be compensated for by the savings achieved during the use phase (CO_2 use), even though no definitive conclusions can be drawn due to the variability of the input data. The environmental impact savings due to the lightweighting were addressed using the fuel reduction value, which ranges from 0.16 to 0.19 l/(100 km $\cdot$ 100 kg) for a C-class turbocharged gasoline vehicle equipped with the redesigned bracket manufactured by LPBF. This study shows that the use of MAM for the production of an optimised bracket can have environmental benefits, and it quantifies the fuel savings for the optimised part of this study. However, there are limitations due to the scope of the study. It does not evaluate the influence of manufacturing techniques on, e.g. material depletion. A study by Jung et al. [46] states that when the buy-to-fly ratio is greater than 7, LPBF has lower environmental impacts than Computer Numerical Control (CNC) milling for each of the following ten impact categories: abiotic depletion, acidification, global warming, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, nonrenewable fossil consumption, nonrenewable nuclear consumption, renewable potential, and renewable water. Higher relative environmental impacts and production costs of MAM at large production volumes can be offset by one or more of the following factors:

- The parts are small and have geometries with high material waste in traditional manufacturing.
- MAM offers performance advantages that reduce life-cycle environmental impacts and costs.
- Portions of the supply chain can be eliminated, reducing the environmental impacts and costs associated with transportation and facility operations.

Future advances in metal powder production, topology optimisation, self-supporting structures, and MAM process improvements that speed up printing time while mitigating defects could potentially tip the scales, so that MAM has lower environmental and economic impacts than traditional manufacturing in a wider set of contexts.

2.5 Conclusion of literature review

This review of the literature provides an overview of MAM techniques, specifically focused on MAM using LPBF. It highlights the advantages of MAM, such as high accuracy, near-net-shaped production, and the ability to produce complex geometries. It also discusses the challenges and limitations of MAM, including surface roughness, porosity, residual stress, and the need for post-processing and support structures. The review also introduces the concept of DfAM, which involves optimising product design for MAM processes. This includes techniques such as TO and the use of lattice structures to improve product performance and reduce material usage. Furthermore, the review presents different paths for implementing MAM in businesses, ranging from incremental improvements in existing products and supply chains to the development of new products and business models. It emphasises the need to understand the process-structure-property relationships and optimise the MAM process for specific applications. In light of the advantages, challenges, and considerations discussed, the development of cost models for MAM has emerged as a crucial factor in determining its viability and economic competitiveness.

The development of cost models in the field of MAM has played a crucial role in determining its viability compared to traditional manufacturing techniques. Cost estimation for MAM is complex, and current studies have certain limitations. These studies often focus on single parts rather than assemblies and may not consider the impact on the supply chain, such as reduced inventory and transportation costs. The main cost drivers for MAM are material costs and the cost of MAM systems. However, with increasing adoption of MAM and economies of scale, raw material costs for MAM have been reduced. Additionally, the average price of MAM systems has dropped significantly over the years, making MAM more accessible. Although the cost per unit of MAM-produced products may sometimes be higher compared to traditional manufacturing, MAM offers other advantages.

It provides greater flexibility in design iterations without the need for expensive moulds, which can lead to cost savings if design modifications are required. Furthermore, MAM enables the production of products with new capabilities, such as extended useful life or reduced resource consumption, which can have positive environmental and cost-saving impacts. For example, lightweighting of aircraft parts can lead to substantial savings in carbon emissions and fuel costs.

Over time, research on MAM cost estimation has evolved, taking into account factors such as energy consumption, post-processing costs, and sustainability effects. Early cost models, such as those by Hopkinson and Dickens [28] and Ruffo et al. [29], used different cost estimation techniques and yielded conflicting results, since they had different outcomes for the cost per part when plotted in a graph, as can be seen in Figure 2.6. Subsequent models incorporated energy consumption and post-processing costs, leading to a better understanding of the overall costs involved in MAM. Different classification techniques have been employed in MAM cost estimation, including method-based, task-based, and level-based approaches. These techniques consider various perspectives, such as finance and accounting, manufacturing, and management. Each technique has its advantages and disadvantages, depending on the specific cost estimation requirements. Notable contributions to MAM cost models include the work of Baumers et al. [30] on energy consumption, Lindemann et al. [31] on post-processing costs, and Yim and Rosen [32] on design-orientated cost models. Other studies have compared the cost effectiveness of MAM with traditional manufacturing methods for specific applications, such as high-pressure die-casting for metal parts production.

MAM also has implications for the supply chain. Factors such as demand and material costs influence the adoption of MAM in supply chains. MAM enables production in smaller batches based on demand, reducing inventory levels and allowing for customisation. The flexibility of MAM machines allows further optimising resource utilisation. Tooling and moulding costs are reduced in MAM, and the ability to produce on-demand and customise products changes the relationship between manufacturers and retailers. In the automotive industry, MAM has shown promise for prototyping, tooling production, and high-performance cars. Case studies have demonstrated significant cost reductions and lead time improvements in tooling production for automotive assembly processes. MAM allows flexible production without compromising costs and lead time, meeting the demands of a fast-changing market.

One of the key challenges in evaluating the cost-effectiveness of AM is quantifying indirect cost benefits, such as the reduction in inventory and transportation costs. These benefits are often mentioned in current research but are rarely quantified in terms of production cost for different manufacturing methods. This research is a valuable contribution to the field because it addresses this gap by explicitly including inventory and transportation costs in cost models. Although these costs may not have a significant influence on the total production cost per part, incorporating them is crucial for a more comprehensive understanding of AM manufacturing expenses. For example, AM can reduce inventory costs by enabling manufacturers to produce parts on demand, rather than having to hold large inventories of finished goods. This is because AM can be used to produce small batches of parts quickly and economically. AM can also reduce transportation costs by enabling manufacturers to produce parts locally rather than having to ship them from distant factories. This is because AM machines require relatively little manual labour and can be used to produce parts from a variety of materials. By explicitly including inventory and transportation costs in the cost models, this research provides a more complete picture of the manufacturing expenses of AM. This information can be used by manufacturers to make more informed decisions about whether or not to adopt AM for different applications. It also provides insight related to the importance of including these cost factors in the manufacturing cost estimation.

The research paper by Prairone et al. [44] compares two manufacturing routes for an automotive part using a LCA. It focusses on lightweighting and material substitution. The study shows a weight reduction of 69% in an optimised bracket made of AlSi10Mg by MAM. The paper introduces the mass reduction factor (k) and analyses carbon dioxide emissions using iso-curves. The research also considers energy consumption and emphasises the need to include all manufacturing steps. The results show a higher carbon footprint for LPBF, but highlight the potential compensating effects during the use phase. This research is a unique study that combines the advantages that come with the use of AM with the environmental effects applied to an automotive part. Using the factor k insights can be gained about the CO_2 emissions of the AM material feedstock related to the CO_2 emissions of the material used with traditional manufacturing methods.

In conclusion, MAM offers advantages in terms of cost reduction, resource consumption, supply chain optimisation, and flexibility in the automotive industry. However, comprehensive cost models that consider the full life cycle and benefits of MAM are needed to accurately evaluate its economic impact and allow well-supported trade-offs when the choice for a production process is made.

Chapter 3

Methodology

The methodology used in this research involves a case study design to investigate the application of MAM in the automotive industry, specifically focussing on its advantages, cost competitiveness, and environmental implications. This study aims to evaluate the viability and economic advantages of using MAM within the automotive sector for the production of functional components on a large scale. Specific objectives include examining the latest advances in MAM and its implementation in the automotive industry, analysing the life cycle of parts manufactured through additive processes, and constructing a comprehensive cost estimation model to compare the overall costs of additive-manufactured parts with traditionally manufactured counterparts throughout their entire life cycle.The primary data collection method for this study is the relevant literature on MAM and specifically its application in the automotive industry.

Part of this research is a case study. The case study will focus on making a comparison between an automotive part produced with traditional manufacturing methods and the same part optimised for MAM. The goal of this case study is to give an insight into how MAM can be used for the production of high-volume automotive parts. In this case, high volume is around 10.000 parts produced per year. This relates to the goal of Lightyear to produce that many cars per year. This comparison will be mainly focused on the cost aspect and not on performance aspects or other mechanically related properties.

The information needed for this case study will be obtained from the literature study. These insights will be used for the development of a cost model. In the context of this research on MAM, it is focused on determining the cost per part produced using MAM techniques. This cost model takes into account various factors that contribute to the overall cost. The following is a list of important factors that will be included in the cost model. The model will be used to estimate the cost per part for MAM and traditional manufacturing methods. The traditional manufacturing methods compared in this research are CNC machining and High Pressure Die Casting (HPDC). These manufacturing methods are chosen because they are most commonly used in the automotive industry for the production of parts when production with sheet metal is not an option. This can be due to certain demands on mechanical properties. There is also limited literature available that compares MAM with sheet metal forming processes.

- Material Costs: Cost of raw materials used in the MAM process, such as metal powders or filaments.
- Labour Costs: The expenses associated with the personnel involved in operating the MAM equipment, post-processing, quality control, and other related tasks.
- Equipment Costs: Capital costs of acquiring and maintaining MAM equipment, including purchase or lease price, depreciation, and maintenance expenses.
- Energy Consumption: The energy required to power MAM equipment, including electricity, gas, or other energy sources.

- Post-Processing Costs: Costs involved in finishing, cleaning, and treating MAM parts after they are printed to achieve the desired quality and surface finish.
- Support Material Costs: If applicable, the costs associated with using support structures or materials during the MAM process to enable the printing of complex geometries.
- Overhead Costs: Additional indirect costs, such as facility costs, administrative expenses, and other operational overheads.
- Tooling Costs: Mostly relevant for traditional manufacturing methods. Cost for mould production and for the tools required.
- Inventory Costs: Cost related to keeping parts in inventory.
- Transportation Costs.

When considering these cost components and how they relate to each other, the cost model helps to estimate the total cost per part manufactured using different manufacturing techniques. This enables designers early in the design phase of a part to understand the cost implications of MAM use, compare it with traditional manufacturing methods, identify cost optimisation opportunities, and evaluate the financial viability of MAM adoption in different production scenarios.

In order to gain insight into the cost related to keeping inventory, a program called Arena developed by Rockwell Automation (Milwaukee, Wisconsin, United States) will be used. With this program a model will be developed to estimate inventory related cost. In Arena, graphical objects called modules are placed on a blueprint to characterise real system parameters, such as operators, machines, and material handling devices. These built-in modules are provided as part of a template. They can be customised and programmed to feature different types of application such as queueing, processing, inspection, and resource allocation. In addition to these features, Arena provides modules that represent certain aspects of manufacturing, such as machine downtime and production planning and scheduling [47]. The simulation model building process will follow the flow diagram shown in Figure 3.1. First, the objectives of the case study and the data collection plan are decided based on the formulated problem. The objective of using Arena is to gain insight into the influence of inventory cost on the trade-off between MAM and traditional manufacturing methods. The data are then collected and the desired model is conceptualised accordingly. This is done by making a flow chart of the MAM production process and traditional manufacturing methods. A simulation model is then constructed on the basis of the final conceptualised model. After the simulation model is built, verification is conducted to ensure that the model behaves as intended and is free from errors or bugs. The way this verification is performed is explained below. This step aims to validate the correctness of the model implementation. Once the model is verified, validation is performed to ensure that the simulated system behaves similarly to the real system. If the model is successfully verified and validated, new experiments or scenarios can be designed and conducted using the simulation model. These experiments are intended to investigate various conditions, variables, or scenarios to gain understanding and assess the system's behaviour. It can be with regard to the optimal inventory level and reorder point to minimise inventory related costs. Finally, the results obtained from the simulation study are documented and reported. This includes summarising the results, analysing the data, and drawing conclusions based on the simulation results.

The developed models will also be used for parametric analysis. In the context of cost modelling for MAM, parametric analysis plays a crucial role in understanding how different input parameters impact the cost estimation of MAM processes. When developing a cost model for MAM, various input parameters are considered, such as material costs, etc., as explained previously. These parameters directly influence the overall cost estimate of manufacturing a part using MAM. Parametric analysis allows to systematically vary these input parameters and observe their effects on the calculated costs. By increasing or decreasing the input parameters by a specific percentage, for example 20%, the sensitivity of the cost model is assessed to changes in these parameter changes. When a parametric analysis is conducted on each input parameter, insights into which factors have the most significant influence on the overall cost of MAM production is gained. When cost drivers that are highly sensitive to parameter variations are identified, well-informed decision-making and cost-optimisation strategies can be applied. Furthermore, parametric analysis helps to understand the relationships and trade-offs between different input parameters. In general, parametric analysis in the context of cost modelling for MAM provides a deeper understanding of the cost drivers and sensitivities within the additive manufacturing process. It helps identify critical factors, optimise cost estimates, and make informed decisions about material selection, process parameters, and overall cost effectiveness of MAM technologies. The Arena Process Analyser is the tool that assists in the parametric analysis of the constructed Arena models. This tool allows the user to create different scenarios to examine the effect of changing certain input parameters on prescribed performance measures.

Generally, simulation models of inventory-related systems cover four uncontrollable parameters [48]:

- Demand
- Order cost
- Holding cost
- Stockout cost

After Lightyear filed for bankruptcy in January 2023, the initial hope was that the company could secure new funding and potentially restart. However, as time passed, it became evident that Lightyear would not continue its operations in the same manner as before the bankruptcy. This situation had repercussions for the ongoing graduation project, which had started just a month before the bankruptcy. In the week after the bankruptcy, the supervisor offered the option to continue and complete the research project at the University of Twente, without the support of Lightyear. Given the circumstances, it was decided, in collaboration with the supervisor, to proceed with the project independently. However, this change in circumstances had a significant impact on the research plan, particularly with respect to the case study. Originally, the plan involved taking a part from the Lightyear two car, which is currently in development, and optimising it using design for additive manufacturing principles. The optimised part would then be compared to the original part produced using traditional manufacturing methods. With the unavailability of Lightyear's resources, an alternative approach was adopted, relying on parts covered in the literature. However, this shift introduced certain limitations and drawbacks to the research. The primary challenge arose from the limited availability of data for parts discussed in the literature. Due to various reasons, parts described in the literature often lack comprehensive data, which may hinder a thorough analysis, and hence missing data will be estimated to the best of my capabilities. Consequently, there is a possibility that the selected part is not optimal to compare different manufacturing methods. Despite these challenges, the decision was made to adapt the research plan and make the best use of the available resources to complete the study at the University of Twente. The further consequences of this decision and how it has affected this research will be covered in Section 4.4, the discussion of this research.

3.1 Cost model

The MAM cost model incorporates multiple process steps and is specifically designed as a cost model based on time-driven activity. This calculation method focusses on estimating costs based on the duration of various activities involved in the manufacturing process. The cost model developed in Excel incorporates several key cost drivers to accurately estimate the total cost per part. These cost drivers include the following factors that are taken into account during the cost estimation process. Further information on how these parameters are estimated is given in this chapter.

- Material cost
- Post processing cost
- Tooling cost
- Labour cost

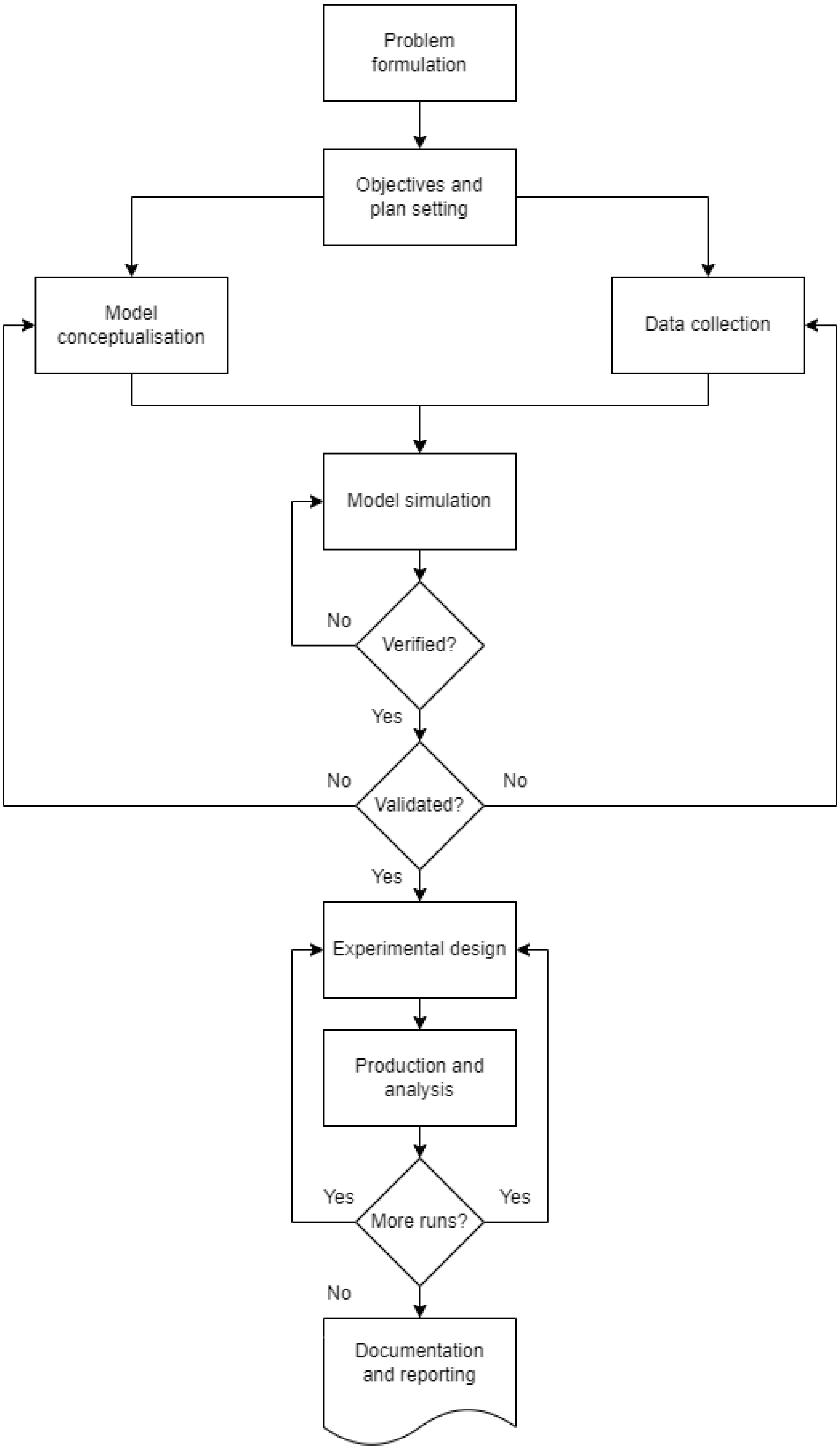


Figure 3.1: Flowchart of a simulation building process in Arena, used in this research. Adapted from [49]

- Energy cost
- Machine cost
- Rental cost
- Inventory cost

The relationship between these parameters is shown in Figure 3.2. It shows how the build cost is composed of direct and indirect costs.

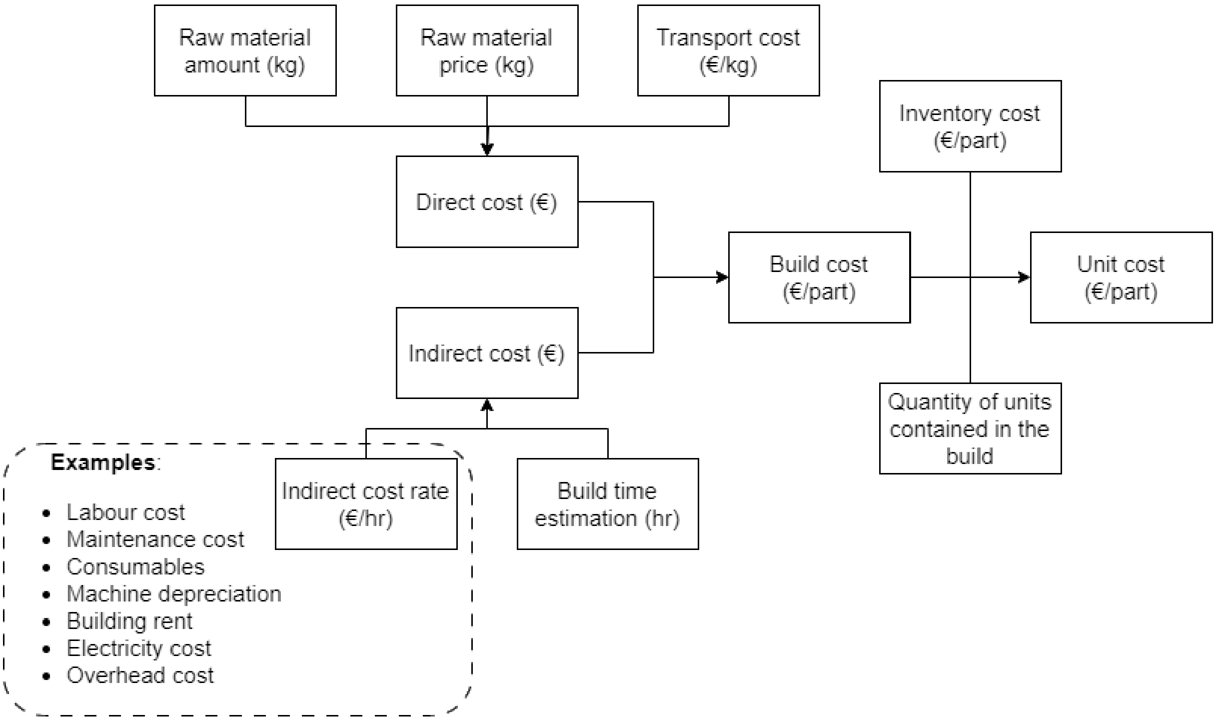


Figure 3.2: Summary of an MAM activity based cost model, adapted from [50]

3.1.1 Direct cost

Direct costs are costs that are directly related to the build of a part. An example of direct cost that is used in this model is the cost for the amount of metal powder used. This is directly related to the volume of the part that is printed. Often, these costs are easier to allocate and quantify. In the sections below is described what direct cost are included and how they are estimated.

Material cost additive manufacturing

Material cost are all the costs that can be directly related to the production of a product or, in this case, a build job. The amount of material and the type can vary per build. The cost associated with the use of argon gas is also covered in this section. The material cost (C_{mat}) are calculated according to Formula 3.1. It considers the material cost per kg (MP), the density of the material (ρ_{mat} in kg/m^3), and the volume of the part (V_{part} in m^3) that should include the material needed for the support structures if needed. In the cost model, there is the option to select multiple materials for the analysed part for both MAM and traditional manufacturing methods. The material used in the case study depends on the material used for the production of the chosen part.

$$C_{mat} = MP \times \rho_{\text{mat}} \times V_{\text{part}} \tag{3.1}$$

The materials added to the MAM cost model are shown in Table 3.1. To obtain a good estimate of the price of the different materials, an average is taken from multiple sources.

Name	Description	Price (€/kg)	Source
316L	Stainless steel, not magnetic and better corrosion resistance compared to 17-4PH	102,00	[51], [52], [31], [53]
17-4PH	Stainless steel, magnetic and less corrosion resistant compared to 316L	104,50	[54], [55]
16MnCr5	Alloyed, hardened steel for shafts, axles, gear and other machine-building components	48,00	[56]
AlSi10M	Aluminium	92,00	[57]
Ti64	Titanium	175,00	[58]
GP1-PH	Stainless steel, extremely corrosion resistant	121,50	[31]

Table 3.1: Overview of material in the Excel cost model, price is average of price from sources

When estimating the material cost for MAM, it is important to take into account the cost of support structures. These support structures are made of the same material from which the part is made. These support structures are waste; however, they can be recycled. An estimate is needed for the required amount of support material. Furthermore, there may be the occurrence of powder loss during the printing process. During the printing process, the build chamber is filed layer by layer to a maximum of the highest layer needed to produce the part. Not all of this powder is needed to produce the desired parts. However, the quality of the unused powder will degrade as a result of the heat applied during the printing process. Some of this unused powder cannot be used for another print job and will be filtered out by the machine. This will result in powder loss. To account for this powder loss, the factor α is included. This factor should be $0 \geq \alpha \leq 1$. For example, if $\alpha = 0.95$, it implies that 95% of the material is that is used to fill the build chamber is reused. The default setting for α in the cost model is 1.05. Therefore, Equation 3.1 is rewritten as Equation 3.2 when material costs are estimated for MAM.

$$C_{mat} = MP \times \rho_{\text{mat}} \times V_{\text{part}} + \alpha \times (BC_{\text{width}} \times BC_{\text{length}} \times Part_{\text{height}} - V_{\text{part}}) \tag{3.2}$$

Where:
- BC_{width}, denotes the width of the buidchamber in meters.
- BC_{length}, denotes the length of the buidchamber in meters.
- $Part_{\text{height}}$, denotes the highest height of the part(s) printed in metres.
- α, denote the material waste factor.

Material cost high pressure die casting and CNC machining

To estimate the cost of material needed for production with high-pressure die casting, Equation 3.1 is used. The amount of material needed for production with CNC machining is not dependent on the volume of the part but on the outer dimensions of the part, since the material is removed from a billet. This leads to the following Equation 3.3 to calculate the cost of the material. An overview of the different materials that are added to the cost model and their price is shown in Table 3.2 for HPDC and CNC machining.

$$C_{matTM} = MP \times \rho_{\text{mat}} \times L \times W \times H \tag{3.3}$$

Where:
- C_{matTM}, denotes the material cost for one part in €.
- L, denotes the length of the part in millimetres.
- W, denotes the width of the part in millimetres.
- H, denotes the height of the part in millimetres.
- ρ_{mat}, denotes the density of the material in kg/mm^3.
- MP, denotes the price of the material in $€/kg$.

	HPDC	CNC machining
Cast iron (€ $/kg$)	7.20 [59]	7.20 [59]
Aluminium (€ $/kg$)	16.00 [60]	16.00 [60]
Stainless steel (€ $/kg$)	9.56 [59]	9.56 [59]

Table 3.2: Price of material per kg for HPDC and CNC machining

3.1.2 Indirect cost

Indirect cost are related to the time used for a build. This requires the calculation of the cost for elements and activities that are attributed to overall costs through the build time as the cost incurred per unit of operating time (€/h). Many elements that attribute to the total indirect cost are obtained on an annual basis. These costs are broken down to an hourly rate by dividing the annual cost by the number of operating hours per year [50].

Post processing cost additive Manufacturing
In Table 2.3, which is part of the literature research, an overview of the estimates for post-processing operations is given. In the input section, there is the option to add or remove a certain post-processing operation. The following describes how post-processing is implemented for the different production methods. Within the cost model, it is possible to select, at the input area, what costs are included and what not. The user has the option to select which post-processing costs are included and what not. In the case study chapter is explained what post processing cost are included in the analysis that is performed.

Based on Table 2.3 and other sources, the following assumptions are made for post-processing costs for MAM.

- Stress relieve costs according to the paper of Vaneker et al. [11] €500 - €600 per build plate and according to Kamps et al. [56] the costs are €0,50/kg of processed material. In this research, the value of Kamps et al. is used, since this research is about production of parts in high volume and larger batch sizes can drastically reduce costs.
- The cost of wire EDM according to Vaneker et al. [11] is €200 - €300 per build plate.
- Bandsaw are the costs related to removing the parts off the build plate. In the article by Kamps et al. [56] the costs are estimated at €0,11 $/mm$. This would result in €44 for a 440 mm wide build plate. In the article by Vaneker et al. [11]. The cost is estimated as "low cost". This leaves room for interpretation of the definition of low cost. Hence the estimate by Kamps et al. is used.
- Heat treatment costs are assumed at €500 per build according Vaneker et al.
- Reduce porosity with hot isostatic pressing cost are assumed at €500 per build according to table of Vaneker et al. [11].

- To improve surface finish and feature resolution with machining, Kamps et al. [56] estimate the hourly rate of machining at €35/kg based on 7 year depreciation, included tool costs, and concurrent machine supervision of a technician, so operator costs are included in this number. This value is used in the model as a value of post-processing cost when it is selected that a MAM produced part requires improvement of surface finish and feature resolution.
- Validation and certification are estimated at 10 - 20% of the total cost per part by Vaneker et al. [11].

Post processing cost high pressure die casting

The post-processing cost for HPDC depends on the number of parts required to make the assembly. Equation 3.4 is used to calculate post-processing costs for HPDC.

$$Post_{cost} = Post_{time} \times Parts \times (Operator_{cost} + Machine_{cost}) \tag{3.4}$$

Where:
- $Post_{cost}$, denotes the cost in € to post-process all parts required to make the assembly with HPDC.
- $Parts$, denotes the number of parts that make up the assembly.
- $Post_{time}$, denotes the time in hours required for the post-processing of one part required to make the assembly.
- $Operator_{cost}$, denotes the hourly rate of the operator needed to operate the post-processing machine in €.
- $Machine_{cost}$, denotes the hourly rate of the machine used for post-processing in €.

The operator cost per hour is assumed to be €34.10. The source of this number is given below in the section about labour cost. The machine cost is the value used, calculated in the section about the machine cost and the hourly rate for machines used in this model.

Post processing cost CNC machining

The post-processing cost for traditional manufacturing is assumed to be zero when quality control is not included. This assumption is made since CNC machining has a high level of dimensional accuracy and thus does not require further post-processing when the dimensional accuracy is already according to specifications. In the cost model, there is the option to select whether quality control should be included in calculating the cost per part. According to Vaneker et al. [11] validation and certification costs 10 - 20% of the cost per part. The user of the cost model can select whether the quality check cost should be included in the cost per part.

Tooling cost

Tooling costs significantly impact the cost per part in HPDC. Each unique part produced using HPDC necessitates the use of a specific mould, which can be expensive. Consequently, HPDC becomes a feasible production process primarily for high-volume part manufacturing. The cost of the mould can be distributed among all parts produced using that mould, making it economically viable. For HPDC, the cost per mould, including the cost of design and manufacture, is estimated at €20,000 per mould [61]. For CNC manufacturing, the tooling cost is related to the cost of the cutting tools and cooling fluid. These cutting bits are high wear parts of the machine and need to be replaced on a regular basis. The costs are based on the expected life time of the cutting tool and the cost per tool. The values for the CNC machining tooling cost are based on a expected life time of 10 hours per tooling bit, and the cost per tooling bit of €50.00 [62]. According to [63], the cost of the cooling fluid can be 2-3 times as much as the tooling cost. This results in an estimate of the total tooling cost per hour of €12.50.

Labour cost

Labour cost are costs related to the operator of a machine or the designer needed to prepare a part for manufacturing. Below are the cost listed that are taken into account for the different production methods. For MAM, the following process steps are included in the labour cost.

- Machine preparation - Before a part can be printed with an MAM machine, some checks need to be performed. An example is checking the recoater. The recoater may not have any damage leading to an uneven print bed.
- Build plan - This involves the preparation of a G-file needed for the production with MAM. A G-file contains the instructions for the MAM machine. This stage may include selecting the orientation of the components on the build plate, adding support structures, and nesting parts on the build plate. This build plan needs to be developed once per part. Therefore, the related development cost can be divided by the amount of parts produced.
- Build plate preparation - The preparation of the build plate is required before the production of parts can start with MAM. An empty build plate needs to be loaded into the machine.
- Powder removal - Remove the build plate from the machine after the parts are produced with MAM. When the printing process is finished, the parts need to be removed from the machine for further post-processing. This requires the operator to remove the build plate from the MAM machine after removing the last residual powder from the part and the substrate prior to further processing.

In the cost model, Equation 3.5 is used to calculate the labour cost for the three production methods.

$$C_{TO} = \frac{T_{design}}{Demand} \times C_{designer} + C_{operator} \times (T_{setup} + T_{unloading}) \tag{3.5}$$

Where:
- C_{TO}, denotes the total labour cost in €.
- T_{design}, denotes the time in hours a designer needs the part such that it can be manufactured with HPDC.
- $C_{designer}$, denotes the hourly rate for a designer in €.
- $C_{operator}$, denotes the hourly rate for a operator in €.
- T_{setup}, denotes the time in hours an operator needs to prepare the machine for production€.
- $T_{unloading}$, denotes the time in hours an operator needs to unload the machine.

According to Rickenbacher et al. [64] $C_{designer}$ is €59.20 per hour and $C_{operator}$ is €34.10 [65].

Electricity cost

Electricity costs are calculated as follows. The electricity price per kWh (€/kWh) used is €0,1128/kWh for industrial users [66]. The electrical cost is calculated with Equation 3.6 and Equation 3.7.

$$E_{total} = E_{setup} \times T_{setup} + E_{production} \times T_{production} \tag{3.6}$$

$$C_{energy} = E_{total} \times P_{energy} \tag{3.7}$$

Where:
- E_{total}, denotes the total amount of energy used during a production run in kWh.
- E_{setup}, denotes the energy consumption per hour of the production machine during setup in kWh/h.
- T_{setup}, denotes the time required in hours for the setup of the production machine.
- $E_{production}$, denotes the energy consumption per hour of the production machine during production in kWh/h.
- $T_{production}$, denotes the time required in hours for production.
- P_{energy}, denotes the price for electricity in $€/kWh$.

Machine cost additive manufacturing

The machine cost of a product is based on the machine cost per hour. The cost per hour of the machine is influenced by multiple factors. The first one is the purchase value of the machine. The cost of the machine per hour is calculated according to Equation 3.8. This formula includes the remaining value of the machine after the depreciation period as a percentage of the purchase value. It also includes the maintenance cost per year as a percentage of the purchase value.

$$C_{machine} = (\frac{P_{machine} - Per_{rest} \times P_{machine}}{D} + Per_{maintenance} \times P_{machine}) \times \frac{1}{h_{up}} \tag{3.8}$$

Where:
- $C_{machine}$, denotes the cost of the machine in $€/h$.
- $P_{machine}$, denotes the purchase price of the machine in €.
- Per_{rest}, denotes the percentage of machine value remaining after the depreciation period.
- D, denotes the depreciation period in years.
- $Per_{maintenance}$, denotes the percentage of machine value for the annual maintenance cost.
- h_{up}, denotes the machine uptime in $(h/year)$.

In the model, there is the option to choose from a list of multiple MAM machines, the user can select the best-suited printer for the part. This choice can be based on the size of the part to be printed. The differences between printers are in the volume of the build space, the purchase value, and the scan speed. The assumption is made that the different printers are devalued in 7 years according to straight-line depreciation with a rest value of 10% [56]. The annual maintenance cost is estimated at 5% percent of the purchase value of the printer [67]. Annual uptime, the time the machine is available for printing and not in maintenance, is estimated at 90% [65]. The cost of argon gas is €1.63 $/m^3$ [57]. Argon gas is essential to create a controlled atmosphere within the MAM machine, providing the necessary protective environment for the printing process. In order to include the cost of argon in the model, Equation 3.8 is updated to Equation 3.9 to include the cost of argon gas for MAM, where $Argon_{usage}$ is the usage of argon gas in m^3/h and C_{argon} is the estimated argon cost in € per m^3. Different MAM machines have different usages of argon gas per hour due to the difference in size of the build chamber. Table 3.4 shows an overview of all the different MAM machines in the model.

$$C_{machine} = (\frac{P_{machine} - Per_{rest} \times P_{machine}}{D} + Per_{maintenance} \times P_{machine}) \times \frac{1}{h_{up}} + Argon_{usage} \times C_{argon} \tag{3.9}$$

The total cost of the machine per additively manufactured part is determined by multiplying the cost of the machine per hour $C_{machine}$ by the estimated build time per job T_{build} in hours. This build time includes the time required to prepare the machine for production. The setup and unloading time per build job is estimated at 1.6 hours [33].

Build rate cm^3/h	EOS M290	EOS M400-4
316L	13.3	42.6
AlSi10Mg	26.6	85.1

Table 3.3: Build rate depending on the material and used machine [68].

According to Yi et al. [68] the build rate depends on the type of material used and the machine that is used. The parameters used are shown in Table 3.30.

	EOS M290	EOS M300-4	EOS M400-4
Purchase value	€480,000	€700,000	€1,420,000
Beam power (W)	400	4 x 400	4 x 400
Max build rate (cm^3/h)	37.5	100	100
Nominal build volume (X×Y×Z (mm))	250 ×250× 215	300 × 300 × 400	400 x 400 x 400
Energy consumption rate during setup (kWh)	2,4	26	22
Energy consumption rate during building (kWh)	8,5	36	45
Recommended installation space (m^2)	7	22	39
Argon gas usage (m^3/h)	0,6	1	1,2

Table 3.4: Overview of MAM machines in the cost model that can be used for the production of parts [68, 69, 70, 71, 57].

Machine cost high pressure die casting and CNC machining

In the model, neither HPDC nor CNC machining includes a specific machine. Instead, a representative purchase value for the necessary machinery is chosen. The reason for this choice is that the model relies on formulas that do not necessitate specific data from the individual machines. Only the purchase value and depreciation period are considered in the model, making it more adaptable and applicable to various manufacturing setups without being tied to particular machine configurations. The purchase value for the HPDC machine is €750.000 [61] and €400.00 [72] for the CNC machine. To calculate the time required to produce the part with CNC machining, the material removal rates shown in Table 3.5 are assumed in the model. The assumption is made that 5% additional material is needed to clamp the material in the CNC machine. The excess material in the form of chips was removed 80% when roughing and 20% under the finishing process conditions [73].

Milling operation	Aluminium	Steel	Titanium
Roughing	$18.7-26.3$	$9.4-13.2$	$1.6-2.2$
Finishing	$0.9-1.3$	$1.3-1.9$	$0.1-0.2$

Table 3.5: Material removal rate for CNC machining in kg/h [73].

Rental cost

Rental costs cover the cost of rental of factory space. These rental costs are costs incurred during the manufacturing process that cannot be attributed to a specific product job. These production overhead costs are necessary for the manufacturing process to run, but are not directly related to the cost of individual products or jobs. The annual rental costs per m^2 used in this model are €95.40.

This value is the average of the following sources [53, 65, 56, 67]. In the cost model, the assumption is made that 20 m^2 is needed for administrative purposes. The space needed for either of the production machines is added to these 20 m^2. Table 3.4 shows what the required amount of space is per machine that is in the model.

Transport cost

An important consideration for Lightyear was the inclusion of transport costs in the analysis, particularly due to the proximity of MAM part production to the assembly location of the vehicle, which often results in reduced labour requirements, as described in the literature review. To incorporate transport costs into the analysis, certain assumptions were made. Parts produced using MAM are assumed to be manufactured in Europe, whereas those produced using other methods are assumed to be manufactured in Asia. The assembly location is also located in Europe. Consequently, parts manufactured in Europe will be transported by truck, while those from Asia will be transported by overseas boat. Average transport distances and costs per km per kilogramme were used to estimate the transport costs for MAM-produced parts in Europe and parts produced in Asia, respectively. The cost model offers the flexibility to produce parts in Europe or in low-wage countries such as India or China. According to statistics from the European Union, the average cross-trade distance within the EU is approximately 746.5 km [74]. Cross-trade, defined as international road transport between two different countries, is carried out by a road motor vehicle registered in a third country. The average rate for road freight transport in Europe is €0.09/km to transport one tonne [75]. In comparison, the average rate for transporting one tonne from Asia to Europe is €3000.00 [75]. Due to the low cost of transport by truck compared to other cost factors. Transport is not included in the cost estimate for MAM due to insignificance. This cost factor does not include the costs related to packaging.

3.2 Inventory cost using Arena

As mentioned above, Arena will be used to estimate the cost of keeping inventory for the different production processes. First, the assumptions made are explained. Then the model is described for HPDC, and CNC machining at the end of the section, and the models that are developed are verified and validated. Arena models for CNC machining and HPDC will be used to estimate holding costs. These storage costs are mainly dependent on the space required to store the parts. As mentioned in the literature section, lead times for CNC machining and HPDC can be much longer due to the production taking place further from the location where the cars are assembled. For MAM, an estimate is made that production can be to demand. Meaning that the inventory levels will be at a much lower level since lead times for MAM are shorter compared to other manufacturing methods due to the shorter lead times. Hence, the assumption is made that inventory levels for MAM parts is at a low level, leading to negligible holding costs for these parts. Hence, it is not included in the model.

3.2.1 Assumptions

Multiple assumptions are made to simplify the model that is built.

1. Simplification of working areas. In this case, we have a production department and a demand management department.
2. First come first serve is applied
3. All the manufacturing machines are of the same type. For HPDC, only one type of mould can be used at a time.
4. Failure of machines in parts of the manufacturing process is not taken into account.
5. The initial inventory level is set at the target level, so the production process is at first idle.

Entity no.	Order quantity	Inter-arrival period (hours)	Entity no.	Order quantity	Inter-arrival period (hours)
1	81	164	27	78	170
2	78	154	28	83	174
3	89	170	29	85	207
4	73	178	30	78	183
5	80	178	31	78	153
6	84	144	32	83	203
7	81	149	33	76	194
8	86	170	34	79	164
9	84	178	35	77	153
10	77	183	36	89	180
11	80	179	37	75	137
12	83	177	38	82	180
13	79	148	39	83	171
14	88	198	40	77	195
15	81	179	41	81	146
16	82	151	42	86	170
17	82	128	43	79	174
18	80	173	44	77	145
19	82	158	45	82	200
20	80	177	46	79	162
21	77	171	47	79	131
22	80	166	48	76	144
23	88	160	49	80	178
24	79	174	50	72	202
25	82	165	51	79	128
26	75	191	52	84	141
27	78	170	53	77	158

Table 3.6: Order quantity and inter-arrival period data used for the Arena model

The model is simulated for the duration of one year. To ensure that the input for the model is the same every time the model is simulated. An Excel file is used for generating the input demand and inter-arrival time of the orders. In this way, a comparison can be made between the different models of HPDC, and CNC machining. The demand used in the Arena model is based on the following assumption. Lightyear has to goal to produce 10,000 cars annually of their more affordable car. Based on this, the assumption is made that the weekly demand is normally distributed with $\mu = 80$ $(10,000/52 \simeq 80)$ and $\sigma^2 = 5$. The time between orders, called waiting time, is also normally distributed by $\mu = 7 \times 24 = 168$ and $\sigma^2 = 20$. An overview is given in Table 3.6.

3.2.2 High pressure die casting Arena model

The flow chart of the HPDC model is shown in Figure 3.3 and in Figure 3.4 shows how the model is shown in Arena. In Appendix A the graphical interfaces of the different modules are shown. Each model in the figure is marked by a number corresponding to the numbers in the Appendix. The simulation model is divided into two main functions. The first section is the lower part in Figure 3.4, which characterises the demand management procedures of the company that produces the parts.

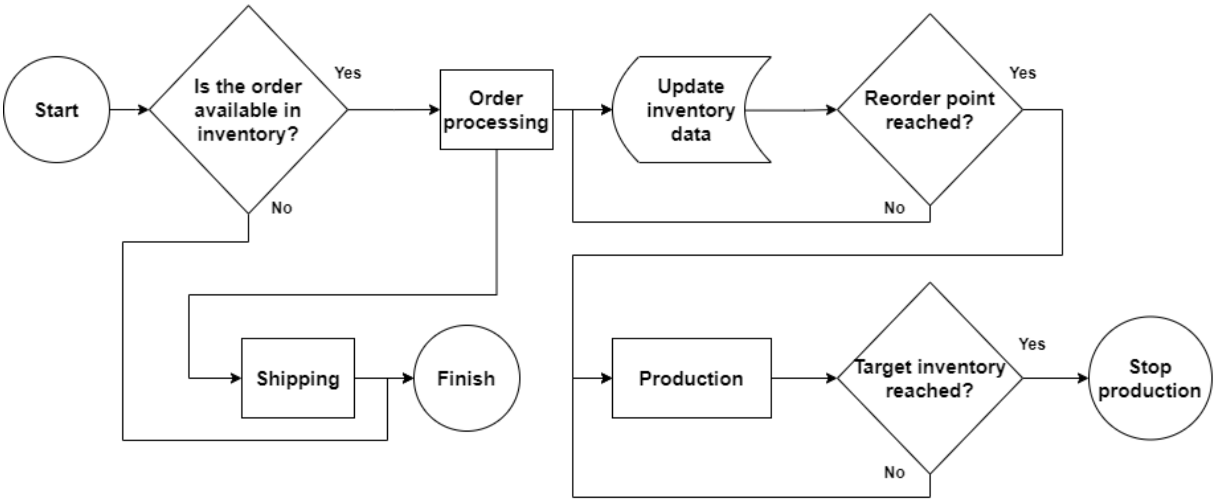


Figure 3.3: Flowchart of the HPDC production process, adapted from: [76]

In this section, customer orders are received, processed, and fulfilled. In the second section, shown in the top section of Figure 3.4, the production management process of the company is represented. In this section, production is initiated, and by monitoring the inventory level, stops when the target stock level is reached.

The first section of the model simulates the arrival of entities. Module number 11 in Figure 3.4 called "Customer Arrive" creates an entity at time = 0 hours, the start of the simulation. This entity is assigned an order number in the next module (12). The next module (13) assigns to the entity a waiting time that is read from the Excel file. The next module (14) is a hold module that holds the entity for the assigned waiting time. When the simulation has progressed for the given waiting time, the entity is released and passes through a module (15) that duplicates it. The original entity continues through the model. The duplicate entity passes through a decide module (19) that checks if it is the last value of the Excel file. If not, this duplicate entity loops back to module (12) that assigns the order number and waiting time as given by the Excel file. This entity is then held by the hold module (14) for the given waiting time, until the waiting time and the loop repeats. Meanwhile, the original entity as previously described continues with a couple of modules (16,17) that assign a demand value to the entity. This value for the demand is also read from the Excel file as explained above.

After assigning the demand value to the entity, it goes through a module (18) that counts the number of customers and a module that writes the demand value of the entities to an Excel file. This is done to validate the values used in the model. Module number 19 checks the inventory level.

When the inventory level is higher than the demand amount of products; the inventory level is updated (22). The amount of demand products is subtracted from the inventory level. Then in the next module, number 23, the decision is made if production needs to restart. Production is restarted if the inventory level is lower than the reorder point. When the reorder point is reached. The production status in module 24 is updated by changing the status from 0 to 1 and the production starts. The next step is to dispatch orders, which is done using a dispatch module (25) in Arena. This removes entities from the system.

The production management section of the model is activated when the production value is set to 1 by module 15. The section starts with a create module (1) that is labelled "Raw Materials". This module generates entities that denote the incoming materials. These entities are held by the next module (2), which holds the entities until production starts. Once production starts, the entities go to

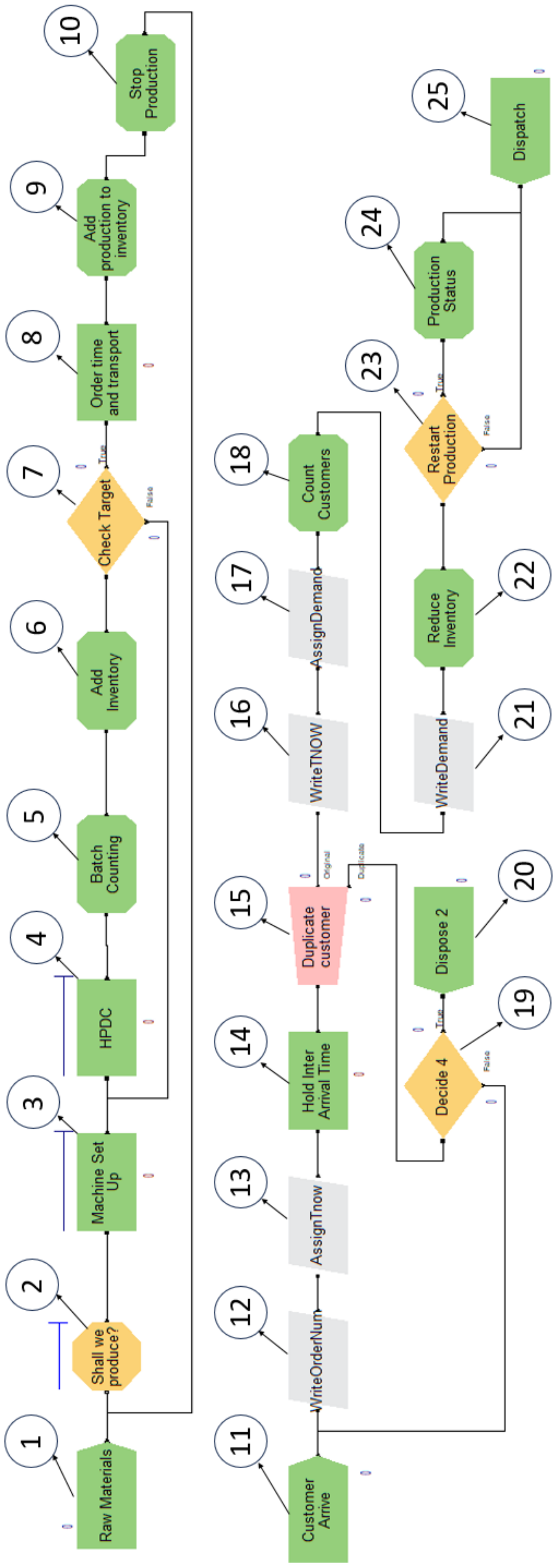


Figure 3.4: Arena interface of HPDC model

the next module. This model takes into account the machine setup time with a Seize-Delay-Release module (3). This holds the entity for a prespecified period of time. In this case, the time it takes to prepare the machine for production. This setup time is set in hours and is specified in the next section. Next is the casting process (4), which is modelled according to the same principle as the set-up of the machine. The two modules (5,6) that follow then count the number of products produced and add them to the inventory. The decision module (7) then checks whether the updated amount of parts produced has reached the target stock variable. If this target stock variable is reached. Production is stopped by setting the production variable to 0 (10). If the target stock level has not been reached, the production process continues until the inventory level is reached. In module 9 the number of parts produced is on hold for the duration of the assumed transport time. This transport time is a random variable according to the triangle. The minimum, maximum, and most likely transport time are set. This approach is used instead of, for example, an normal distribution since the chance that transport takes longer than expected is larger than the chance that it is shorter than expected.

3.2.3 CNC machining Arena model

This model is based on the same flowchart as HPDC shown in Figure 3.3, the same input data is also used, shown in Table 3.6. The difference from the HPDC Arena model is the process time required to produce one part. Depending on the number of parts demanded annually, the number of machines can be adjusted. The number of machines used in the model will be selected in the case study. The difference from the HPDC model in Arena is module number 23 in Figure 3.4. In Appendix B is the module shown, adapted for CNC machining.

3.2.4 Model verification and validation

In this section the focus is on how the model is verified and validated. This is done in order to validate that the model gives results that can be expected and that are in line with the behaviour of such a system in the real world. The model is first verified and then validated. Verification is the process that ensures that the predictions of the model are the correct outcome based on the input variables of the model. The purpose is to confirm that the model is doing what it modeler thinks in should do. Validation is the process that is focused on ensuring that the model represents the real world as much as possible. It gives insight into if the model is build correct. The process also depends on the quality of the input data that are used.

3.2.4.1 Simulation model verification

Verification is a critical aspect that ensures that the simulation model, its inputs, processes, and outputs are accurate, consistent, and free of bugs or errors. This validation is achieved through measurable facts and reproducible test data. In this project, multiple approaches were used to verify the simulation model, including system debugging, visual scrutiny, model-logic evaluation, and output evaluation. Each of these verification methods plays a significant role in ensuring the reliability and validity of the simulation model. The following sections discuss the use and effectiveness of these verification techniques in the context of this study.

Arena provides valuable user assistance in debugging the model, which proved crucial during the model's development. Various bugs were detected and promptly resolved using Arena's debugging features. Moreover, the simulation speed can be adjusted to a lower rate, allowing entities to be visually tracked within the model. This visual inspection ensures that the different decision models function as intended. Additionally, the input data read from the Excel file is cross-verified through this process to ensure accurate and error-free reading from the file. These functionalities offered by Arena contribute significantly to the model's reliability and accuracy during its development and testing phases.

Verification of the simulation model included a crucial step that involved comparing the total entities exiting the system with the processed orders. Initially, entities entered the simulation model as customers but were subsequently transformed into order quantities through the Assign module. Consequently, these orders exited the simulation model in the form of multiple entities, representing the individual order quantities. To ensure the accuracy and reliability of the simulation models, this verification step was performed repeatedly throughout the development process. In all simulation models, the results consistently confirmed the precision of the simulation results. This comparison between processed orders and entities leaving the system enhanced the validity and reliability of the simulation model's performance.

3.2.4.2 Simulation model validation

Validation is the method of confirming that the simulation model is accurate enough to represent the real-world system [77]. In the literature, numerous techniques have been mentioned that can be used to validate a simulation model [77, 49, 78]. The following are the techniques that were used in this research.

- Conceptual validation - The aim of this validation technique is to determine if the scope and level of detail in the simulation model meet the required objectives. This involved evaluating whether the simulation models constructed successfully achieved the intended goals set for this thesis project. Specifically, the generation of sales orders, the processing of each order through various modules, and the results related to average inventory levels were found to align with the scope of this research project, fulfilling its core objective.
- White-box validation - This is a microlevel approach aimed at validating the accuracy of essential components within the model by comparing them to their real-world counterparts. In this study, the performance of the Process module in simulation models for HPDC and CNC machining was evaluated against its actual performance. Each process module was linked to a corresponding machine, recorded as a resource in the Arena simulation, and the processing time closely matched the real-world performance based on data found in the literature.

Chapter 4

Results & Discussion

In this case study, the cost model that is developed will be applied for the cost estimation of producing an automotive part with MAM compared to traditional manufacturing methods. Therefore, it requires the selection of an automotive part. There are multiple criteria for the selection of this part. As mentioned above, the objective of this case study is to provide information on whether MAM is a suitable, cost-effective production technique for the selected part and to gain insight into the influence of relevant parameters.

4.1 Part selection

The part selection for this case study involves the consideration of multiple criteria, which are listed below. These criteria serve as input for a design matrix analysis, enabling the identification of the most suitable part for the study. A total of eight parts have been selected for the design matrix analysis, and further details of these parts are provided below. The design matrix operates by assigning different weights to each selection criterion. In addition, every option is ranked by assigning a score ranging from 0 (poor) to 5 (very good). By multiplying the score of a part for a specific criterion by the weight assigned to that criterion and summing them, a final score is calculated for each option. This approach helps to effectively evaluate and compare the various parts, facilitating the identification of the optimal part for the case study.

4.1.1 Selection criteria

The selection criteria for the part are described as follows, with the objective of identifying the most suitable component for the case study. The selection process will be based on the specified criteria and relevant data will be considered. Initially, the plan was to choose a part of the car that was in the development phase during that period before Lightyear's bankruptcy. Subsequently, this chosen part would undergo optimisation through DfAM using topology optimisation techniques. Due to Lightyear's bankruptcy, multiple parts that can be used for this case study are found in the relevant literature. No literature on selected parts provides information on the annual demand for parts or data on the costs of producing the parts.

- **Volume**
The volume and size of the part are very important for the degree of fit of a part for high volume production with MAM. The cost model has shown what the influence is of the size of a part on the cost per part. The difference between volume and size is that for a part the volume is expressed in cm^3 while for a part the size is the width, length and height of the part. A part that has a low volume compared to the size is better suited for MAM production. This is also referred to as the buy-to-fly

ratio. The buy-to-fly ratio is simply the ratio of the mass of the starting rod of material to the mass of the final finished part [79]. A buy-to-fly ratio is commonly used in the aerospace industry, hence the name. A ratio of ten to one means that only 10% of the original material that is acquired remains in the final part. Thus, a higher ratio means that more material needs to be removed. Therefore, it requires more energy and time when subtractive manufacturing methods are used. Parts with a high ratio tend to be more cost-effective when produced with MAM.

- **Outer dimensions**

The outer dimensions of a part are important because they influence how many parts can be made in a single build. If more parts fit into a single build, it results in more cost-effective production of the part. More parts can be made at the same time when their outer dimensions are smaller.

- **Weight reduction**

A part that exhibits a significant weight reduction compared to its traditionally manufactured counterpart is better suited for MAM production. This weight reduction results in substantial environmental savings throughout the useful life of the automotive part. When evaluating the suitability of a part for MAM production, both the relative amount of kilograms saved and the absolute amount of weight reduction are important factors to consider.

- **Part consolidation**

When a part consolidates multiple components into a single piece that can be manufactured using MAM, it becomes an advantageous option for MAM production. This consolidation significantly reduces assembly costs, as it eliminates the need to assemble multiple individual parts. Additionally, when original components were previously produced at different locations, producing the consolidated part with MAM can also lead to cost savings in transportation, as the need to transport separate parts to the assembly location is reduced or eliminated. Therefore, opting for this consolidated part offers notable benefits in terms of both assembly efficiency and potential reductions in transportation costs.

- **Build volume utilization**

Achieving cost-effective production necessitates maximising the utilisation of the available build space. The impact of the use of the build plate is further demonstrated in this case study. If a part can be printed by stacking, as illustrated in Figure 4.1, it becomes more suitable for inclusion in this case study. Stacking allows optimal use of the build space, resulting in improved cost efficiency during the additive manufacturing process.

- **Material**

Material selection for a part is important because certain metal powders can be more expensive compared to solid materials. This consideration becomes crucial when determining the economic viability of producing the part using MAM. The decision-making process must account for these material costs to ensure the overall economic feasibility of using MAM to manufacture the specific part.

- **Post processing**

The suitability of selecting a part for the case study is influenced by the necessary post-processing procedures. The availability of different post-processing options within the cost model introduces cost variations, specific to each production technique. For instance, certain post-processing steps may be more economical for one production method compared to another. An example is the requirement for heat treatment in MAM-produced components, which might be unnecessary for parts manufactured with the other manufacturing techniques. This consideration underlines the importance of evaluating post-processing requirements for the parts that may be used in the case study.

Figure 4.1: Example of motor-cross footrests printed stacked on top of each other developed in a collaboration by EOS and Pankl [80].

4.2 Optional parts for case study

Below are the parts listed that were found in the relevant literature and selected as options to use in this case study. For each of the optional parts, an overview of relevant characteristics is given. From these options, the part that is used in the case study will be selected.

Option 1: Bracket electric motor
In Figure 4.2 an automotive bracket to hold an electric motor is shown. In the figure, the geometry of the original part is shown on the left. The part is topologically optimised using DfAM, and the finished workpiece after post-processing is shown on the right in the figure.

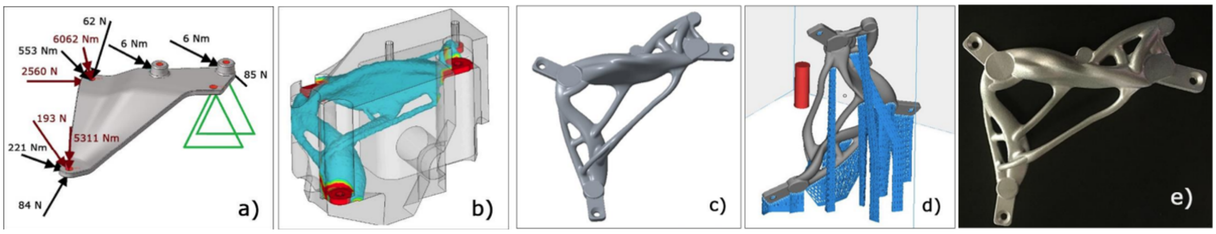


Figure 4.2: Option 1 case study: Bracket electric motor [81]

Criteria	**Value**
Dimensions (LxWxH)	135 x 80 x 65 mm
Weight before optimisation	0,088 kg
Weight after optimisation	0,085 kg
Weight reduction	3.4 %
Material	AlSi10Mg
Part consolidation applied?	No
Total weight reduction per vehicle	0,003 kg
Post processing steps	Thermal treatment, support removal, machining

Table 4.1: Option 1 case study: Overview of selection criteria [81]

Option 2: Brake caliper

The brake calipers shown in Figure 4.3 are a front and a rear caliper, intended for a student race car. In the paper, there is no mention of the weight of the student race car.

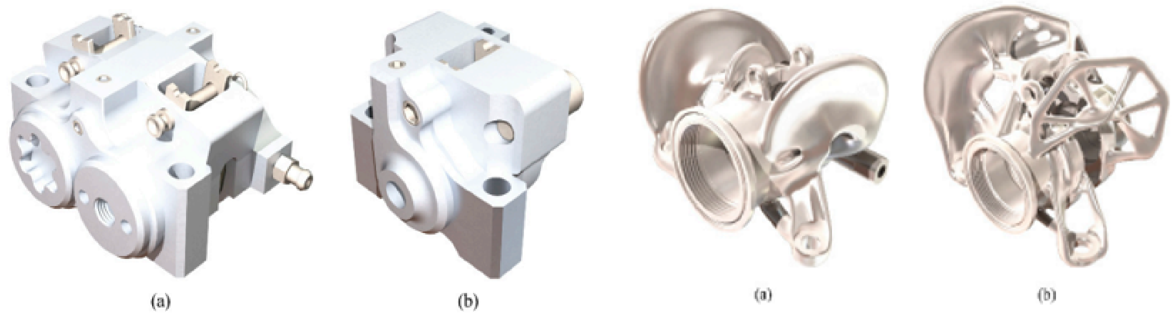


Figure 4.3: Option 2 case study: Brake caliper [82].

Criteria	Value
Dimensions (LxWxH)	90 x 45 x 80 mm
Weight before optimisation	0, 320 kg - 0, 210 kg (front rear caliper)
Weight after optimisation	0,230 kg - 0,119kg (front rear caliper)
Weight reduction	36,9 % - 48,5 % (front rear caliper)
Material	Ti6Al4V
Part consolidation applied?	No
Total weight reduction per vehicle	0,668 kg
Post processing steps	Thermal treatment, support removal, machining

Table 4.2: Option 2 case study: Overview of selection criteria [82].

Option 3: Steering columns

The steering column shown in Figures 4.4 and 4.5 is part of the front substructure of a two-passenger rear mid-engine coupe. On the left of the figure is the original geometry and on the right the optimised structure.

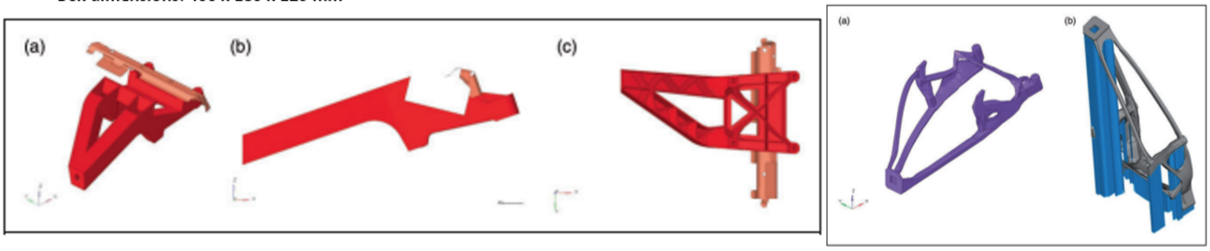


Figure 4.4: Option 3 case study: Steering column [83].

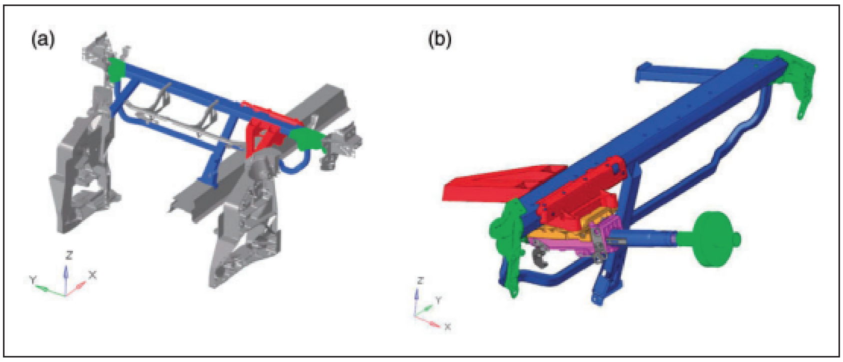


Figure 4.5: (a) Global view of the front area and (b) detailed view of the model in including section of the steering assembly [83].

Criteria	**Value**
Dimensions (LxWxH)	400 x 185 x 125 mm
Weight before optimisation	1,537 kg
Weight after optimisation	0,721 kg
Weight reduction	53,1 % -
Material	Ti6Al4V
Part consolidation applied?	No
Total weight reduction per vehicle	0,721 kg
Post processing steps	-

Table 4.3: Option 3 case study: Overview of selection criteria [83].

Option 4: Seatbelt bracket

GM partnered with the software company Autodesk to use generative design and additive manufacturing for lightweighting a bracket for the seatbelt is cars. In a proof-of-concept project, they employed generative design resulted in a 40% lighter and 20% stronger design than the original as shown in Figure 4.6.

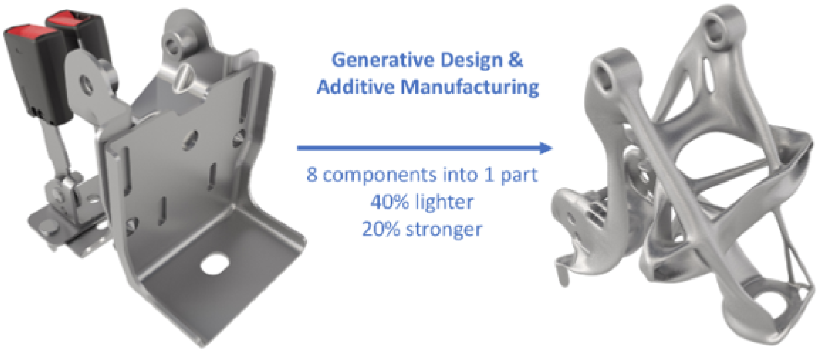


Figure 4.6: Option 4 case study: Seatbelt bracket [84]

Criteria	Value
Dimensions (LxWxH)	400 x 185 x 125 mm
Weight before optimisation	-
Weight after optimisation	-
Weight reduction	40,0 % -
Material	-
Part consolidation applied?	Yes, 8 parts to 1
Total weight reduction per vehicle	-
Post processing steps	-

Table 4.4: Option 4 case study: Overview of selection criteria [84].

Option 5: Brake pedal

Figure 4.7 shows the brake pedal of a five-door hatchback car. On the left of the figure is the original geometry shown and on the right is the optimised geometry. The arm brake pedal generally consists of four child parts, which are boss (1), arm (2), pad (3), and stopper (4) as numbered in the figure. The boss is made of cold-drawn steel and acts as a connection between the arm brake pedal and its mounting. The arm is the main body of the arm brake pedal, made of hot-rolled steel, which holds and transfers the braking force accordingly. The pad, made of hot rolled steel, is where the driver rests his/her foot to transfer the braking force during the braking event [85].

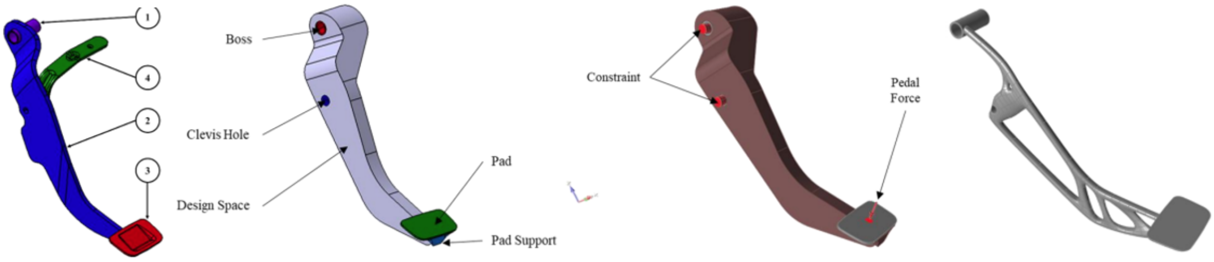


Figure 4.7: Option 5 case study: Brake pedal [85].

Criteria	Value
Dimensions (LxWxH)	-
Weight before optimisation	1,000 kg
Weight after optimisation	0,460 kg
Weight reduction	54,0 % -
Material	316L
Part consolidation applied?	Yes, 3 parts to 1
Total weight reduction per vehicle	-
Post processing steps	-

Table 4.5: Option 5 case study: Overview of selection criteria [85].

Option 6: Differential mounting bracket

In Figure 4.8 the differential mounting bracket of a car is shown. The component is made of cast iron and is conventionally manufactured using a casting process followed by finish milling and painting [44]. In Figure 4.9 shows how the differential mounting bracket is optimised for MAM through topology optimisation.

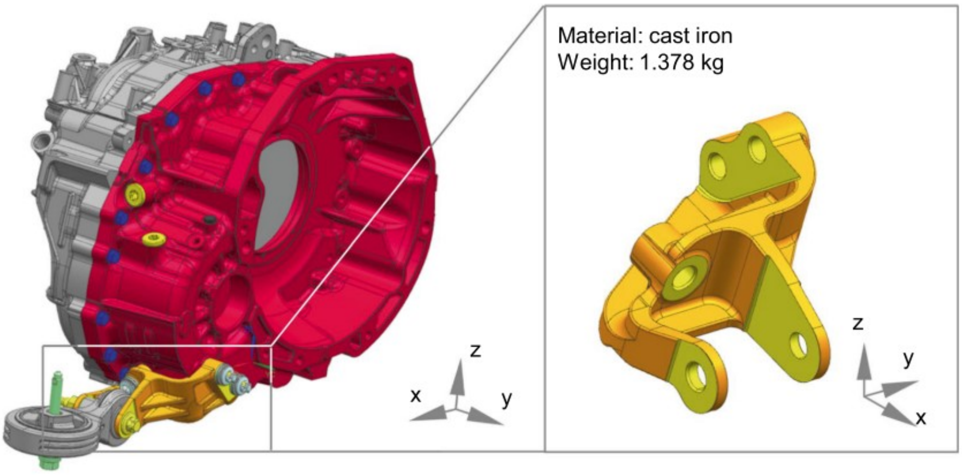


Figure 4.8: Option 6 case study: Deferential mounting bracket [44].

Criteria	**Value**
Dimensions (LxWxH)	95 x 74 x 120 mm
Weight before optimisation	1,378 kg
Weight after optimisation	0,427 kg
Weight reduction	69,0 % -
Material	AlSi10Mg
Part consolidation applied?	No
Total weight reduction per vehicle	0,951 kg
Post processing steps	Support removal, shot peening

Table 4.6: Option 6 case study: Overview of selection criteria [44].

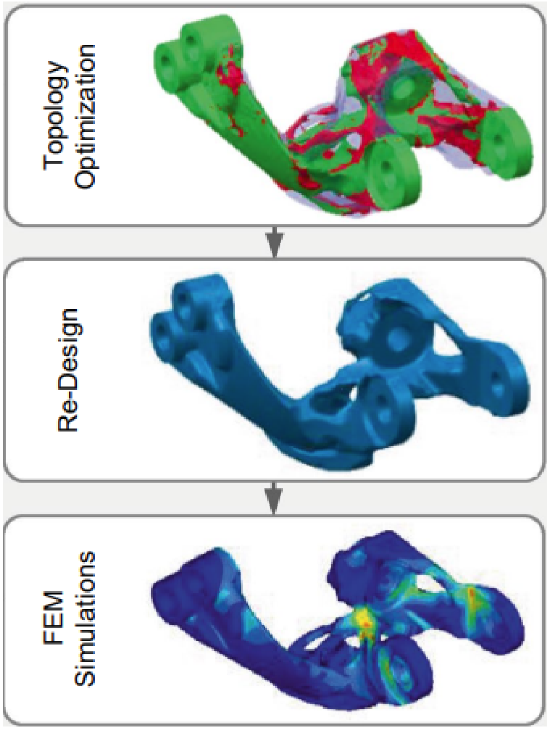
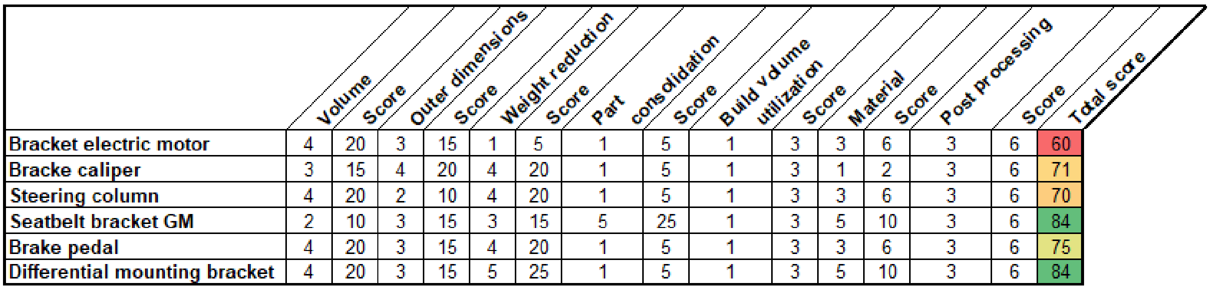


Figure 4.9: Option 6 case study: Redesign for AM of the differential mounting bracket [44].

4.2.1 Selected part

The part selected for the case study is option six presented in the research by Prairone et al. [44] and is also covered in Section 2.4.1 of the review of the literature. The choice for this part is based on the design matrix shown in Figure 4.10. In this figure, can be seen that the total score for the seatbelt bracket and the differential mounting bracket is the same. The decision was made to use the differential mounting bracket in this case study since in the paper, a lot of data related to energy usage during production is given. Compared to the seatbelt bracket as shown in Figure 4.6 and Table 4.4, there is also more known about the selection criteria as can be seen in the related tables.



	Volume	Score	Outer dimensions	Score	Weight reduction	Score	Part consolidation	Score	Build volume utilization	Score	Material	Score	Post processing	Score	Total score
Bracket electric motor	4	20	3	15	1	5	1	5	1	3	3	6	3	6	60
Bracke caliper	3	15	4	20	4	20	1	5	1	3	1	2	3	6	71
Steering column	4	20	2	10	4	20	1	5	1	3	3	6	3	6	70
Seatbelt bracket GM	2	10	3	15	3	15	5	25	1	3	5	10	3	6	84
Brake pedal	4	20	3	15	4	20	1	5	1	3	3	6	3	6	75
Differential mounting bracket	4	20	3	15	5	25	1	5	1	3	5	10	3	6	84

Figure 4.10: Design matrix analysis with the scores of the optional parts for the case study.

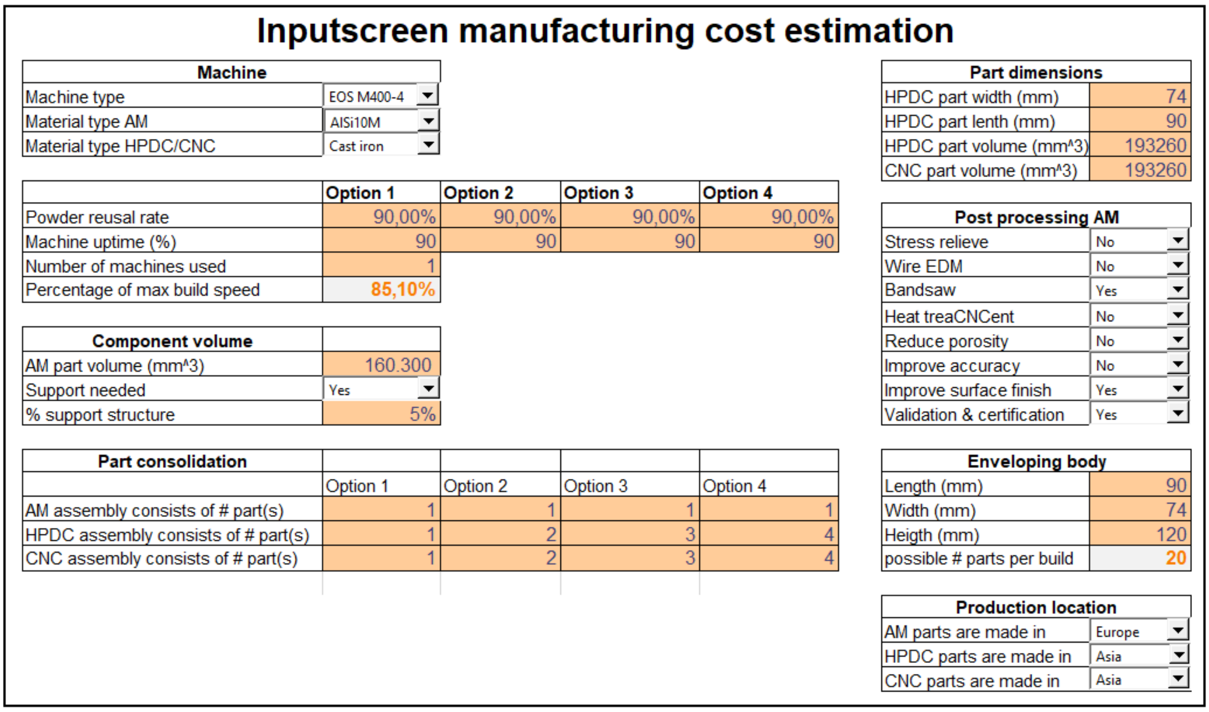
4.2.2 Cost model parameters

Based on the part selected for the case study, the input parameters are calculated to estimate the manufacturing costs. These input parameters are inserted into the input screen of the cost model. This input screen is shown in Figure 4.11. In the various drop-down lists, the user can, for example, select the material that is used for the production of the part. There is also the option to compare the influence of part consolidation, powder reusal rate, and machine uptime on MAM cost. This is further elaborated in Section 4.3.2. The cell with orange text indicates that the value is calculated/determined on the basis of the inserted values.

4.3 Results of cost estimation for production cost

With the input parameters listed in the section above, multiple analyses will be performed. This will be done to formulate an answer to the main research question. With the cost model that is developed during this research, a case study is performed. Multiple analyses will be performed with the developed models, as discussed above in the methodology section. The results section contains multiple sections. The first section deals with the comparison of the different production techniques based on the input parameters of the selected part for the case study, resulting in estimates for the manufacturing cost. This will be combined with the Arena model to calculate the total cost of the supply chain. Then, a parametric analysis is performed. This further details the influence of the various input parameters in the case study.

The manufacturing cost estimate of the selected part gives the following results. In Figure 4.12 the cost estimate part is shown, depending on the number of parts produced. For the selected part, the cost per part is the same when comparing MAM and HPDC at 92 parts. The cost per part are equal at 234 parts produced when comparing HPDC and CNC.



Inputscreen manufacturing cost estimation

Machine	
Machine type	EOS M400-4
Material type AM	AlSi10M
Material type HPDC/CNC	Cast iron

	Option 1	Option 2	Option 3	Option 4
Powder reusal rate	90,00%	90,00%	90,00%	90,00%
Machine uptime (%)	90	90	90	90
Number of machines used	1			
Percentage of max build speed	85,10%			

Component volume	
AM part volume (mm^3)	160.300
Support needed	Yes
% support structure	5%

Part consolidation				
	Option 1	Option 2	Option 3	Option 4
AM assembly consists of # part(s)	1	1	1	1
HPDC assembly consists of # part(s)	1	2	3	4
CNC assembly consists of # part(s)	1	2	3	4

Part dimensions	
HPDC part width (mm)	74
HPDC part lenth (mm)	90
HPDC part volume (mm^3)	193260
CNC part volume (mm^3)	193260

Post processing AM	
Stress relieve	No
Wire EDM	No
Bandsaw	Yes
Heat treaCNCent	No
Reduce porosity	No
Improve accuracy	No
Improve surface finish	Yes
Validation & certification	Yes

Enveloping body	
Length (mm)	90
Width (mm)	74
Heigth (mm)	120
possible # parts per build	20

Production location	
AM parts are made in	Europe
HPDC parts are made in	Asia
CNC parts are made in	Asia

Figure 4.11: Input screen for the model that estimates the production cost for the different manufacturing methods.

For MAM and CNC, the cost divers, except for the labour cost, are not dependent on the number of parts produced annually. For HPDC, the tooling costs per part depend on the number of parts produced. In the following Figures 4.13 through 4.17 show the influence of the different cost drivers on the total cost per part. A comparative analysis is conducted for the various production methods, focussing on the cost per part for production volumes of 250 and 2500 parts annually.

In Figure 4.13, the distinct contributions of the cost drivers to the total cost of MAM are shown for the production of 250 and 2500 differential mounting brackets. The most significant percentage shift lies in the impact of the Total operator cost, registering at 2,85% which is a small change. In particular, the cost of the MAM machine and the cost of materials exert the most substantial influence on the manufacturing cost per part, accounting for more than 72% of the total influence. The cost per additively manufactured differential mounting bracket is €176.48 when producing 250 and €171.37 when producing 2500 parts annually. It also shows that the number of parts produced has a low influence on the cost per part. Therefore, economies of scale have a low influence on MAM compared to other manufacturing methods. The cost per part is reduced by 2. 9% when comparing the cost per part for 250 and 2500 parts produced.

Figures 4.14 and 4.15 show the contribution of cost drivers to the HPDC production cost. In the figures, it can be seen that tooling costs are a large part of the total production cost. Especially at lower production volumes of 250 parts. This is due to the high cost for the design and production of a mould. The influence of these cost factors is reduced by more than 50% when comparing the manufacturing cost of 250 and 2500 parts on an annual basis.

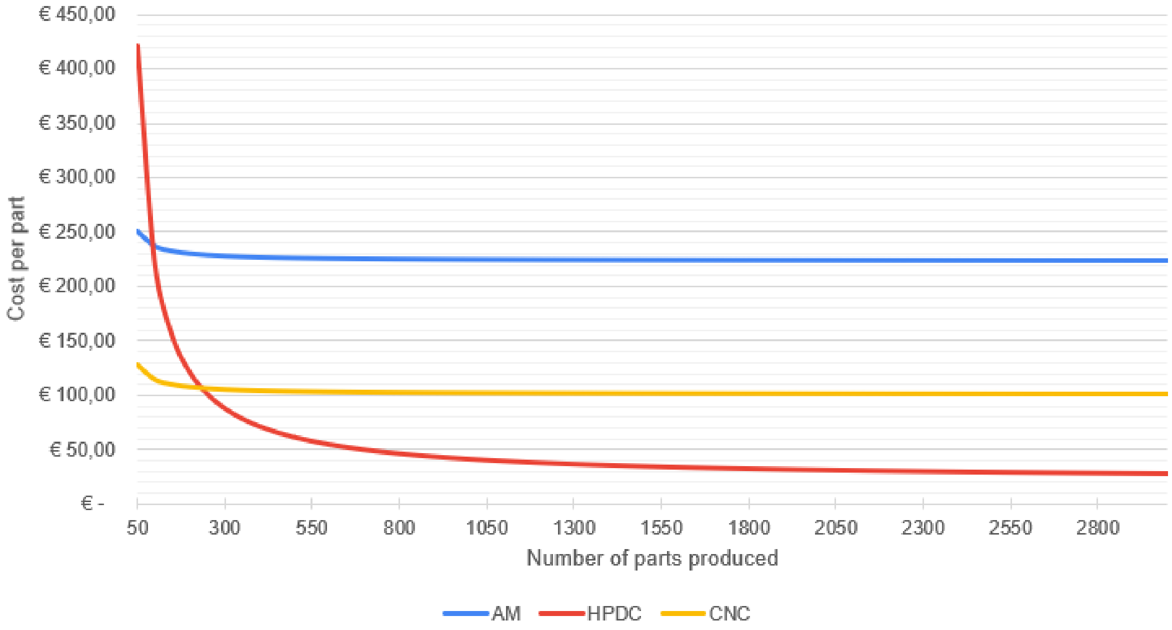
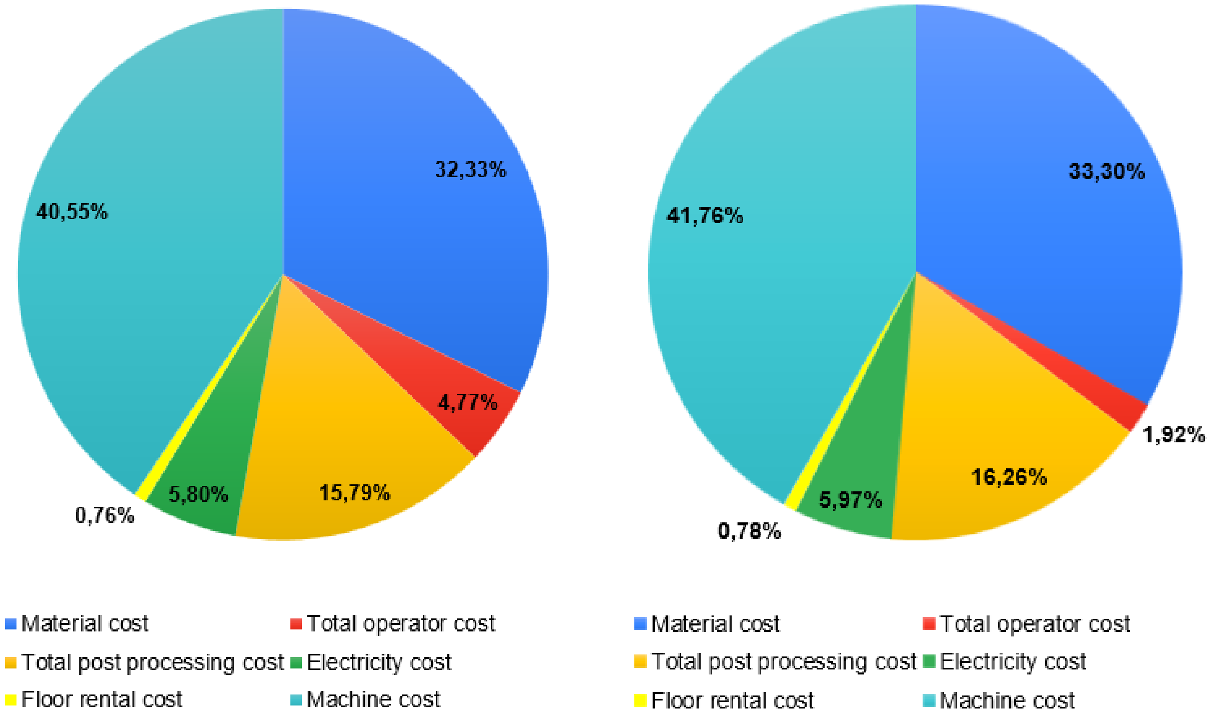


Figure 4.12: Cost comparison of the production cost per part between the different production methods depending on the number of parts produced for the selected part in the case study.



(a) Cost drivers for the production cost of 250 differential mounting brackets

(b) Cost drivers for the production cost of 2500 differential mounting brackets

Figure 4.13: Comparison of cost drivers for the production cost with MAM

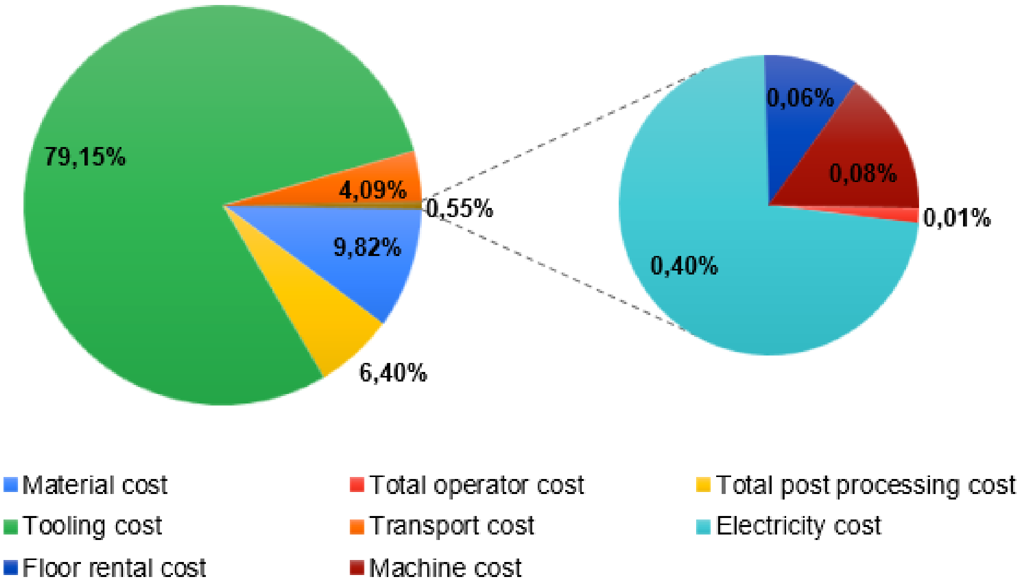


Figure 4.14: Cost drivers for the production cost of 250 differential mounting brackets with HPDC

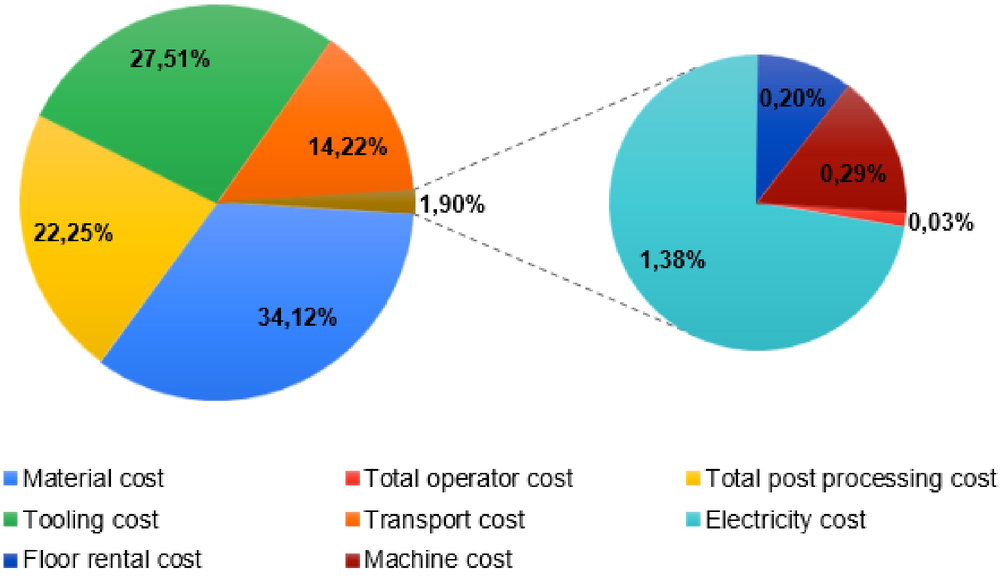


Figure 4.15: Cost drivers for the production cost of 2500 differential mounting brackets with HPDC

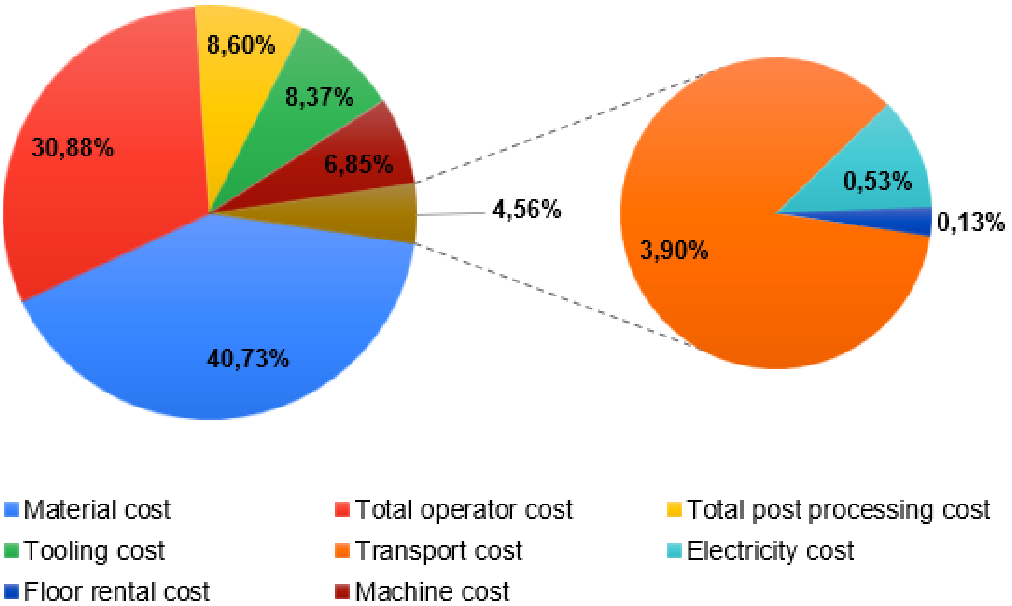


Figure 4.16: Cost drivers for the production cost of 250 differential mounting brackets with CNC manufacturing

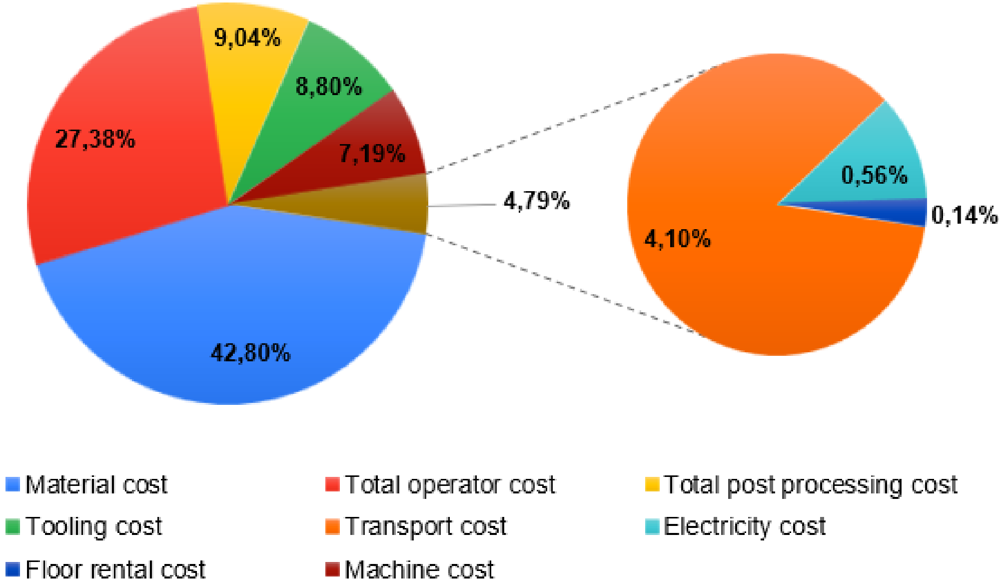


Figure 4.17: Cost drivers for the production cost of 2500 differential mounting brackets with CNC manufacturing

Figures 4.16 and 4.17 provide an overview of the impact of cost drivers on CNC manufacturing expenses. These figures highlight the notable role of material and operator costs in overall manufacturing costs per part. These factors contribute more than 70% of the total manufacturing cost. Of the material used to produce this part, 76% is removed during CNC operation. Possible cost savings due to material recycling of removed material are not taken into account. In Figure 4.18 is shown how the different manufacturing methods compare with each other for different demand values. These graphs show the influence on the total production cost for different demand values.

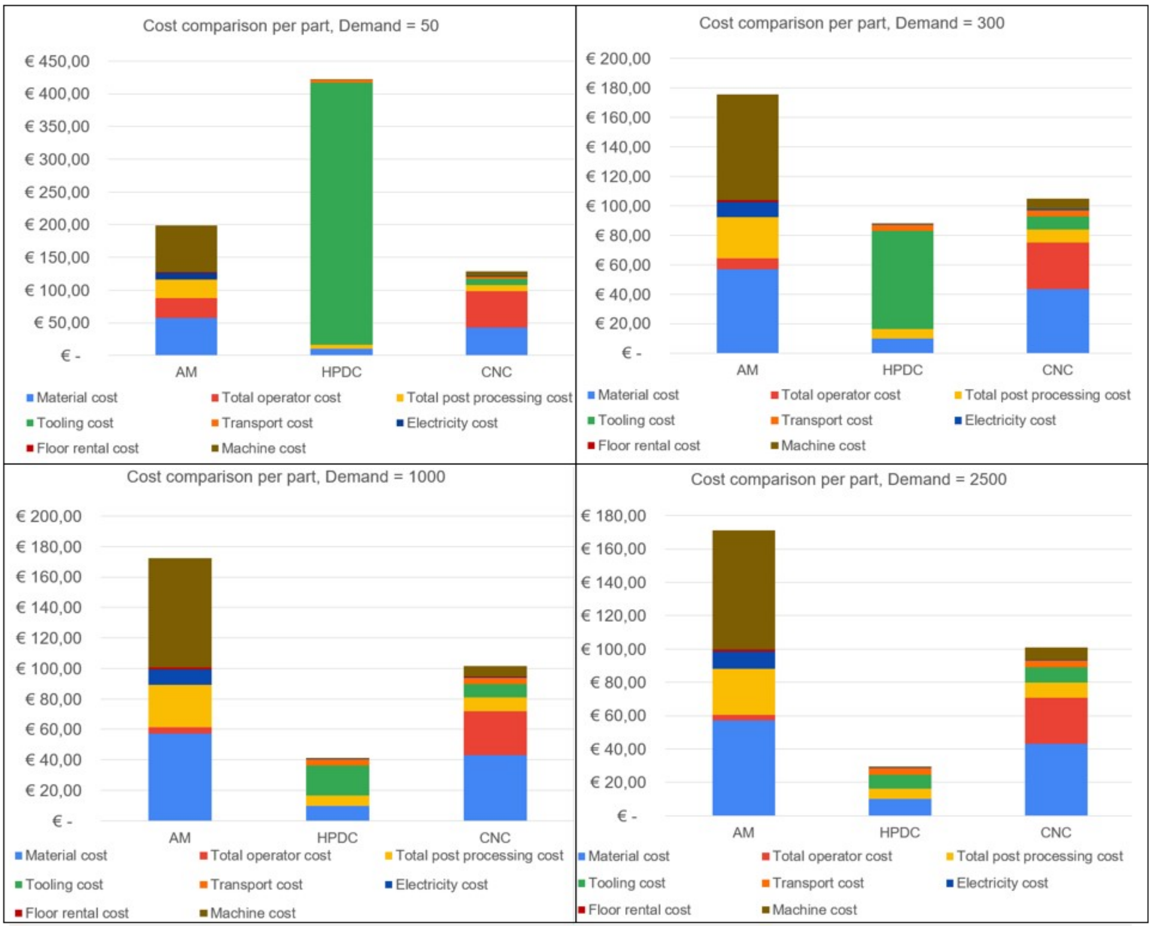


Figure 4.18: Cost drivers for the the different manufacturing methods for different demand values and influence on the total cost per part

4.3.1 Results Arena simulation

To gain insight into the associated inventory costs for various production methods, the simulation models developed in Arena are used. These models enable us to examine the maximum number of items stored within the inventory. This approach is chosen because, in practise, inventory levels fluctuate daily, necessitating varying amounts of storage space. Renting different sizes of storage spaces is not a practical solution. Therefore, we select the maximum inventory level during a specific period as the size of the shelf, as described in [86]. In an effort to minimise storage costs, it is imperative to keep the maximum storage size as small as possible. The inventory holding cost is calculated based on an annual rental cost per square metre, resulting in a holding rate of 0.00173 per m^2 per day. This cost is then multiplied by the maximum number of parts present in the inventory. The order time is determined using a triangular delay distribution in Arena. This distribution is selected over a normal distribution because the assumption is made that the likelihood of an order taking longer than expected is greater than the likelihood of it being shorter than the most likely value. First, the results given for the HPDC-related inventory cost in Figure 4.19 show the level of HPDC

Start inventory	480 units
Target stock	460 units
Reorder point	310
Safety stock factor	1.25
Most likely order time	25 days

Table 4.7: Parameter values used in the Arena model for HPDC manufacturing

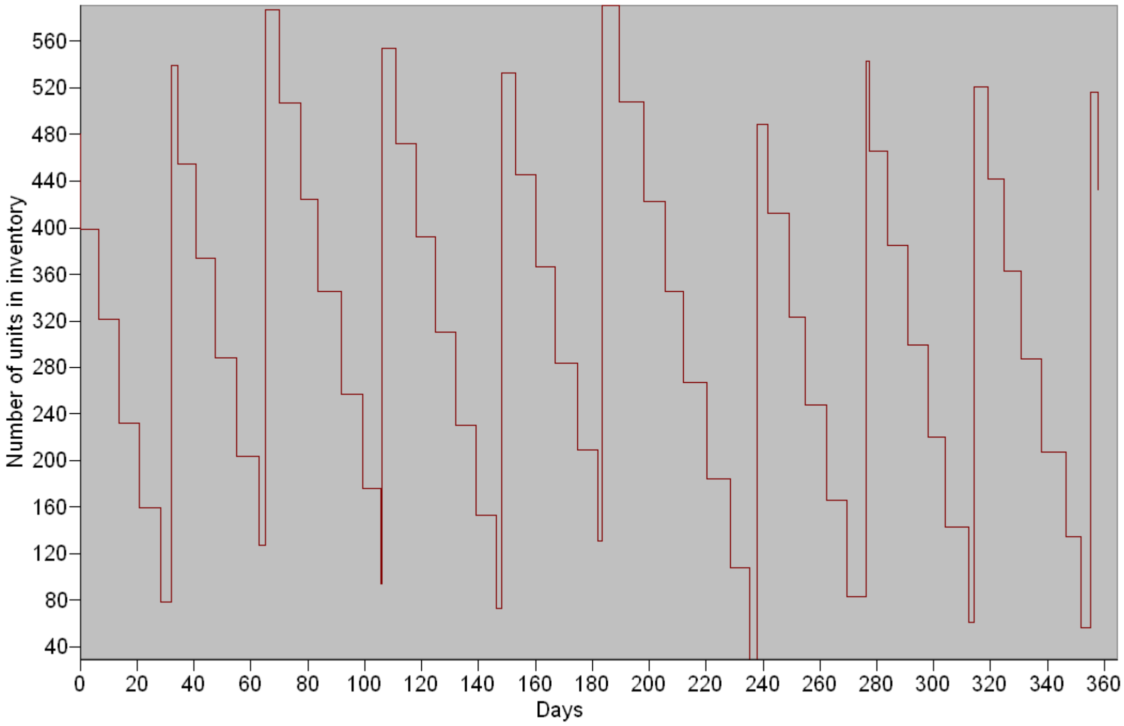


Figure 4.19: Number of units in inventory for HPDC

parts inventory. The parameters shown in Table 4.7 are used in the model. The values found are an optimum resulting in the lowest number of maximum inventory level. This optimum is found using the Arena Process Analyser. With this tool, the results of multiple scenarios can be compared. The maximum number of parts in inventory is 591 and the minimum number is 29 with these parameters and the assumptions made. The given values are taken from 50 different simulations to make the results significant.

Start inventory	480 units
Target stock	460 units
Reorder point	340
Safety stock factor	1.25
Most likely order time	25 days

Table 4.8: Parameter values used in the Arena model for CNC manufacturing

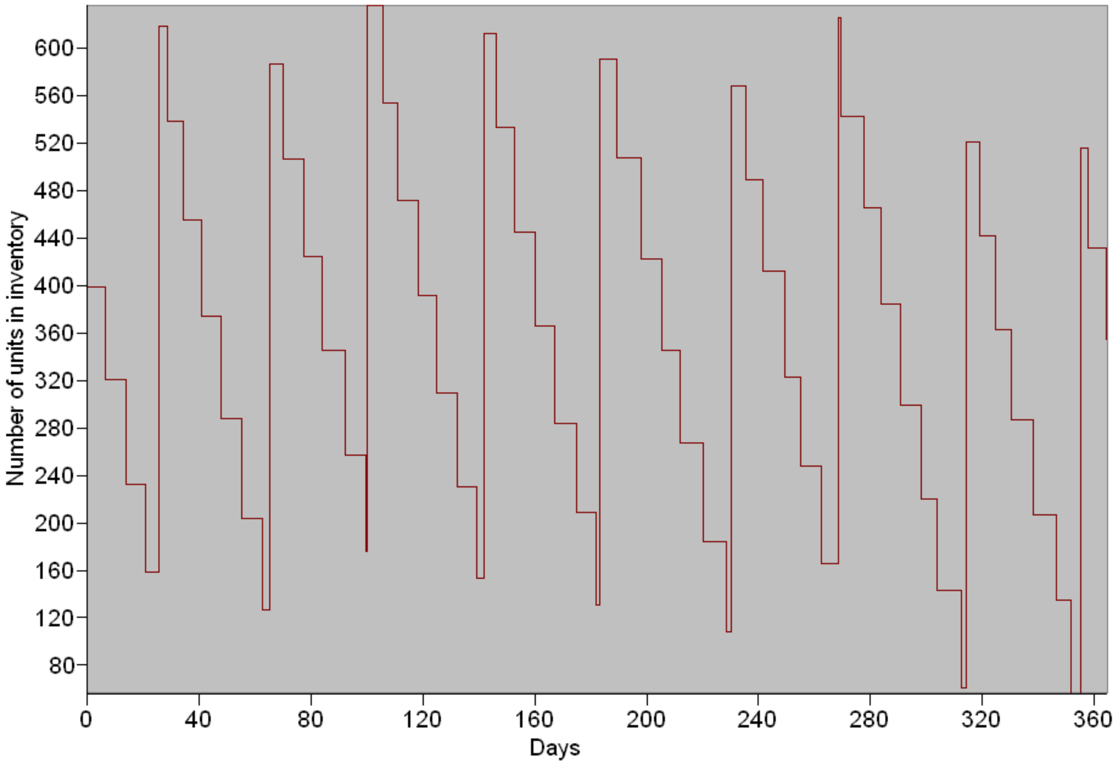


Figure 4.20: Number of units in inventory for CNC

The following are the results for the CNC related inventory cost. The input parameters used for the model are shown in Table 4.8. As can be seen, the input parameters for CNC are comparable to CNC. The maximum number of parts in storage for CNC is 636. This results in a storage cost of $636 \times €0.00173 = €1.10/day$. This is not a significant factor when comparing it to the total manufacturing cost per part of the selected part with CNC which is without inventory cost €100.82 when producing 2500 parts.

4.3.2 Parametric analysis

This section describes the influence of the different input parameters on the manufacturing cost per part. The input parameters that are used for this analysis are based on their influence on the manufacturing cost, which is shown in Section 4.3. For MAM, the most influential parameters on total manufacturing cost are material and machine cost. Together, they contribute about 70% of the total manufacturing cost. If these cost factors can be reduced, there will be a large influence on the total cost. For HPDC, the cost factors that have the most influence on the total manufacturing cost are material and tooling costs. The most influential factors in CNC manufacturing are material and operator cost with an overall contribution of more than 70%.

For MAM, the two most influential cost factors in total manufacturing costs are selected. First, the material costs are assessed. To gain insight into what parameters influence the material cost. Different parameters are varied to evaluate the sensitivity of this selected factor to the chances of this parameter. The parameters that are varied are listed below.

- Powder reusal rate: As MAM technology advances, the re-usability rate of powder materials is expected to increase. This can lead to cost savings as less material is wasted.

- Material Cost: The cost per kilogram of raw material is expected to decrease due to economies of scale in raw material production and supply. Raw material suppliers are also working to lower production costs, resulting in overall reduced material costs per part.
- % Support structure needed: Its related to further development of printing techniques that decrease the amount of support structures needed. Reduction of metal powder usage during printing and printing time as a result of the lower amount of material that needs to be printed. It does not take into account the possible reduction of post-processing time due to the lower amount of material that needs to be removed.

Secondly, the machine costs are evaluated to gain insight into what parameters have a large influence on this cost factor. The described parameters are varied to evaluate the sensitivity of the machine cost to the parameter. The varied parameters are listed below.

- Machine uptime: Refers to the amount of time an MAM machine is operational and available for production. Maximising machine uptime is essential for efficient production. Reduced downtime means that more parts can be produced in less time, potentially lowering the cost per part.
- Build Rate: Increasing the build rate of an MAM machine directly impacts productivity. Higher productivity can lead to lower cost per part, making MAM more cost-effective.
- Machine purchase value: This factor refers to the initial cost of acquiring an MAM machine. While it is an upfront investment, it is crucial to consider because it significantly affects the overall cost of using MAM for production.

	Chance of parameter	Corresponding cost per part	Percentage change of manufacturing cost
Powder reusal rate	Base value = 90.00%	€171.37	-
	2.5 % increase	€167.44	2.29%
	5% increase	€163.51	4.58%
	7.5% increase	€159.58	6.88%
Material cost	Base value = €92.00	€171.37	-
	5 % decrease	€168.52	1.66%
	10% decrease	€165.66	3.33%
	15% decrease	€162.81	4.99%
% Support structure needed	Base value = 5.00%	€171.37	-
	1 % decrease	€170.25	0.65%
	2% decrease	€169.14	1.30%
	3% decrease	€168.04	1.94%

Table 4.9: Influence of parameters related to material cost on total manufacturing cost per part when number of parts produced is 2500

In Tables 4.9 and 4.10 is shown the influence of the selected parameters related to the cost of material and the machine on the total cost of production. The cost shown per part is when the number of parts produced is 2500. This number is chosen because it relates to the goal of this research with respect to the cost effectiveness of high volume. The results show that the powder reusal rate has the largest impact on the material cost per part.

It can be concluded that, with parameters and assumptions set, it can be concluded that MAM is not a cost-effective option for this part in high volume for the automotive industry. There are advantages of MAM that are not taken into account. Such as a more flexible supply chain and the option to apply modifications to a design without the need for a new mould. However, it is unlikely that they have such a large influence on the price trade-off for the selection of the manufacturing method for this part to justify the current difference in the manufacturing cost when producing 2500 parts per year.

	Chance of parameter	Corresponding cost per part	Percentual chance of manufacturing cost
Machine uptime	Base value = 90.00%	€171.37	-
	2.5 % increase	€169.58	1.05%
	5% increase	€167.87	2.04%
	7.5% increase	€166.26	2.98%
Build rate	Base value = 85.10 cm^3/hr	€171.37	-
	2.5 % increase	€169.53	1.07%
	5% increase	€167.78	2.09%
	7.5% increase	€166.13	3.06%
Machine purchase value	Base value = €1.420.000	€171.37	-
	2.5 % decrease	€169.71	0.97%
	5% decrease	€168.05	1.94%
	7.5% decrease	€166.39	2.90%

Table 4.10: Influence of parameters related to machine cost on total manufacturing cost per part when number of parts produced is 2500

In addition to comparing manufacturing costs, there are also possible cost savings during the operating phase of an automotive vehicle or during maintenance, as described in Section 2.4 of the review of the literature. These operating costs are not taken into account in the cost model that is used. The model is developed for Lightyear, and hence operating costs are less relevant. The weight savings per part when using MAM is 0.951 kg per vehicle. During the lifetime of a vehicle, assuming it drives 200,000 km, this results in 3.5 litres of fuel saved or around €10.00 using the data referenced in Section 2.4. This is not a significant factor on its own when making the decision to buy a vehicle. However, when weight is saved by optimising multiple parts in a vehicle, significance increases.

However, this does not indicate that MAM is not viable for manufacturing parts for the automotive industry in large volumes for other parts. There are factors such as the application of part consolidation and the buy-to-fly ratio that have a large influence on the viability of MAM as a production method from a cost perspective. The mentioned factors are selected since they are parameters that can be set or estimated early in the design phase, and hence guide designers early in the production process with answering the question whether producing the part with MAM should be taken into account and is a viable option. These factors also have a great influence on the viability of using MAM as a manufacturing method.

To assess the impact of part consolidation on the cost per part, particularly when a component comprises multiple parts using HPDC and CNC manufacturing, four scenarios are analysed for each manufacturing technique. These scenarios maintain the standard parameter set, but vary the number of components in the assembly, considering the application of part consolidation. In particular, there is only one scenario considered for MAM due to its inherent design flexibility and cost-effectiveness associated with part consolidation. To gain insight into the effect of part consolidation on costs per part, several assumptions are made. The part selected for this case study initially consists of a single piece. However, the analysis considers part consolidation, where the total material volume remains constant, but the part is transformed into an assembly. Resulting in multiple loading and unloading steps during manufacturing. In Scenario 1, it consists of 1 part, in Scenario 2, it comprises 2 parts, and so on, up to Scenario 4 with 4 parts. For HPDC, the cost of producing the assembly increases as a result of the additional moulds that are required. In Figure 4.21, the solid green line labeled "AM future" represents a hypothetical scenario that combines the most favorable cost reductions from Tables 4.9 and 4.10. This scenario illustrates the potential for significant cost savings through the continued development and adoption of MAM technologies. With a remarkable 21.1% reduction in cost per part when producing 2500 parts, this scenario aligns with the anticipated advancements in

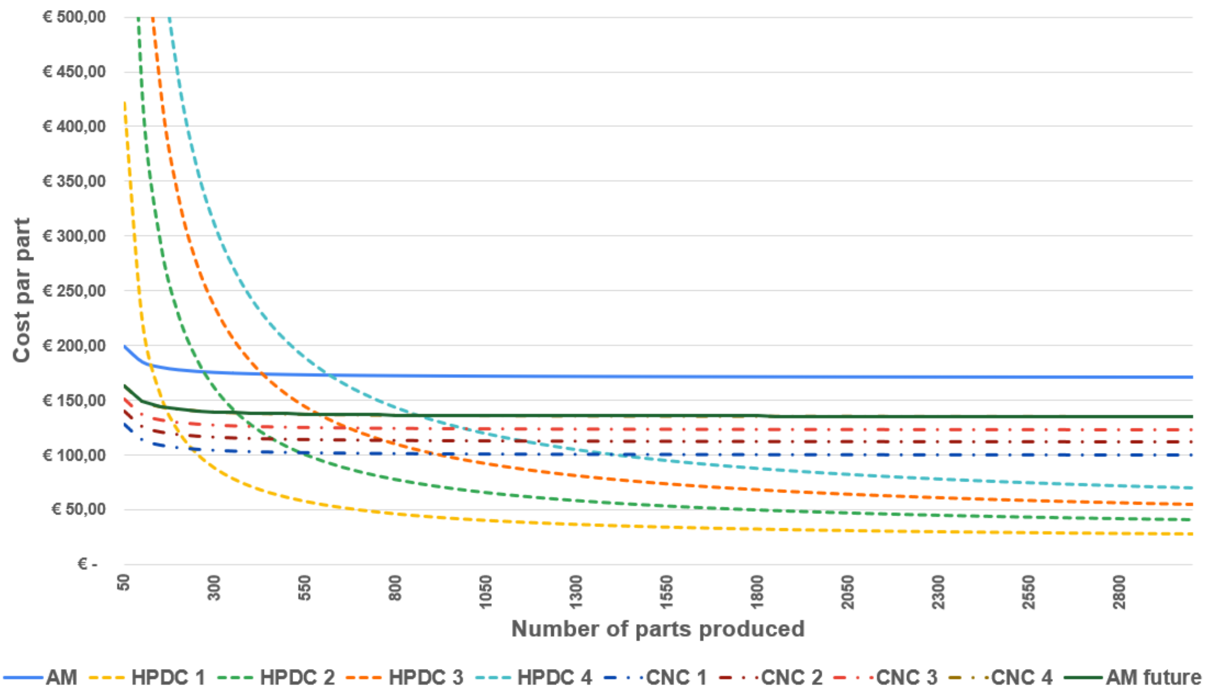


Figure 4.21: Different scenarios for applying part consolidation and the influence on cost per part depending on numbers of parts produced. The number behind the manufacturing method indicates the number of parts combined if produced with MAM

MAM capabilities. Notably, the cost per part in this scenario closely approaches that of the "CNC 4" scenario, which employs part consolidation to produce a single part instead of four separate parts. This comparison highlights the potential of MAM to rival traditional manufacturing methods in terms of cost-effectiveness.

The results of the application of the cost per part for the different scenarios are shown in Figure 4.21. The number in the legend is related to the different scenarios. The graph shows that part consolidation has a large influence on the cost part. The cross-over point for HPDC to become the most cost-effective option compared to the MAM changes from 124 to 437, when comparing Scenarios 1 and 4. When comparing the cross-over point of scenario 1 for HPDC and CNC machining with scenario 4 for HPDC and CNC machining, the cross-over point for cost-effectiveness increases from 234 parts to 861 parts.

The buy-to-fly ratio is a significant factor when contrasting MAM and CNC machining in terms of material usage. This ratio indicates the amount of material used in the part in comparison to the material removed. When a larger amount of material must be removed, the cost of production increases. In the literature section, a study by Jung et al. [46] is referred, stating that when the buy-to-fly ratio is greater than 7, LPBF has lower environmental impacts than CNC machining for a number of environmental impact factors. For the subject part of this case study, the buy-to-fly ration is 4.1. To gain further insight into the influence of the buy-to-fly ratio on manufacturing cost, the following assumption is made. The amount of material needed to produce the part with CNC machining remains the same. However, the buy-to-fly ratio is changed. This can, for example, be achieved by altering the wall thickness of the part. The result is shown in Figure 4.22. The results show that the buy-to-fly ratio has a large influence on the cost per part for MAM. The cost per part reduces as the buy-to-fly ratio increases compared to CNC machining and HPDC. The cost per part for CNC machining increases slightly as more material needs be be removed, increasing the time

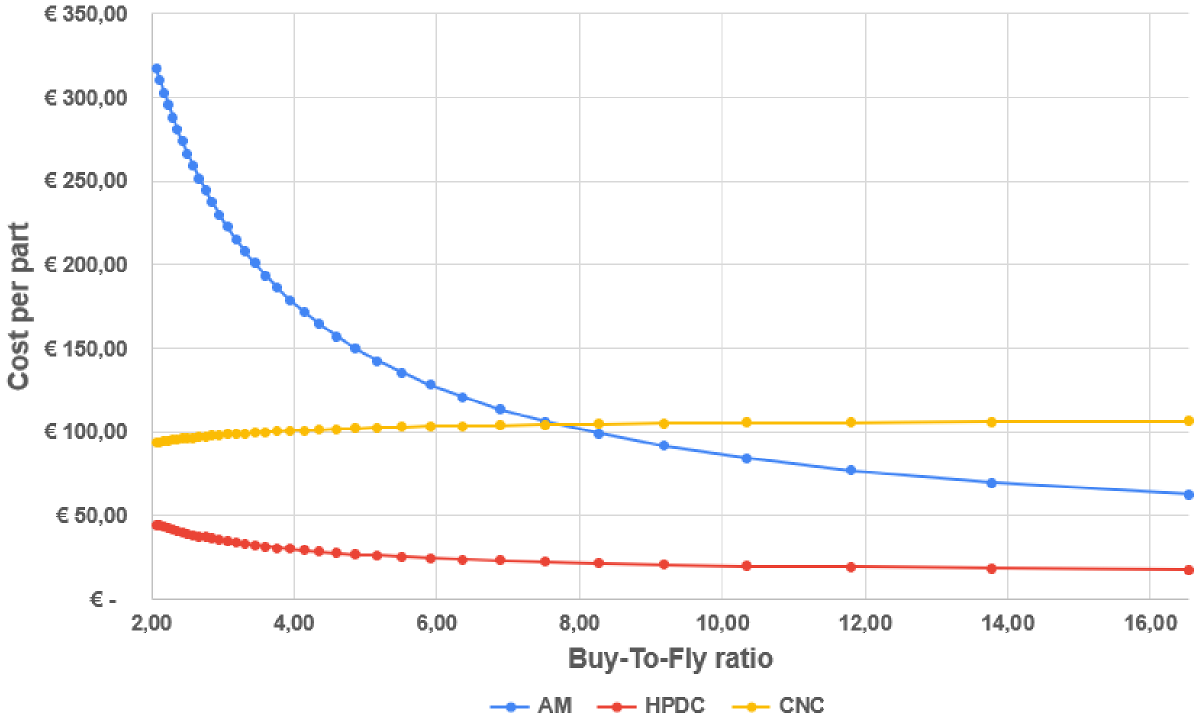


Figure 4.22: Influence of the buy-to-fly ratio on the cost per part for different manufacturing methods

required for production. The cost per part for HPDC decreases slightly since the amount of material required decreases. However, this is because of the lower material cost and shorter production time. The cost reduction for HPDC is lower compared to MAM. This graph shows the relevance of taking into account the buy-to-fly ratio when selecting the production method.

4.4 Limitations

In this chapter, the limitations of the thesis will be discussed. The discussion is focused on the following processes during the study. First, the influence of the bankruptcy of Lightyear on the study, followed with possible improvements for the estimates made by the model, and finally on the scope of the research.

The study was significantly affected by the bankruptcy of Lightyear, particularly during its early stages, when the scope of the investigation was defined and the relevant literature was being reviewed. The final research question was unclear during this period. However, once it became evident that the company would not undergo a restart, a collaborative decision was made with the University of Twente to continue the research. Consequently, the study had to rely more on data from other sources and existing research than on data directly obtained from the company. Another consequence is a shift in focus regarding the development of a tool that designers of parts can utilise to estimate production costs early in the design process, gaining more insight into relevant manufacturing methods. This is caused by the lack of the possibility of having the model examined and reviewed by Lightyear designers. They possess extensive experience in part design and can offer valuable insights into which influential parameters should be included or highlighted from a designer's perspective. In the current cost estimation model, these considerations have been addressed to the best of my ability.

The automotive industry is fiercely competitive, making it difficult to find pertinent data on the subject. Despite efforts to reach out to authors of relevant literature and posing numerous questions, no responses were received. Consequently, assumptions were made to the best of the researcher's ability. The cost model was developed in a flexible manner, allowing easy adjustment of the underlying parameters to enhance the accuracy of manufacturing cost estimates. Given the high competitiveness in the industry, precise estimations are essential as profit margins tend to be narrow.

Two key factors vital for refining the model's estimates, other than improving made parameter assumptions, are how production time is calculated and the calculations of overhead-related costs. First, in terms of the estimation of production time, it is a critical factor in improving all three types of manufacturing methods. This discussion focusses on production time estimation as it cannot be enhanced solely by finding more accurate input parameters, such as the build rate per hour. Currently, the production time for MAM is estimated by dividing the total volume of parts on a build plate by the build rate. However, research indicates that it is also significantly influenced by the height of the build. In the MAM production process, a sweeper adds a new layer of powder after the laser has melted sections of the previous layer. Research demonstrates that production time is affected by the height of the build, builds with lesser height finish faster due to a lower amount of sweeps required to lay new powder. This aspect is crucial to include for further improving the manufacturing cost estimate. This is emphasised in this discussion because enhancing this estimate necessitates additional formulas for accurate estimates that are highly dependent on the specific manufacturing machine used by the production company. Similarly, the estimation of production time for HPDC and CNC machining faces comparable challenges. In the context of CNC manufacturing, the refinement of the estimation can be achieved by considering removal rates specific to the various tools utilised in the process. Each part comes with distinct accuracy requirements that significantly influence production durations. In HPDC cost estimation, a standardised value for casting time is presently employed for casting a part, irrespective of the part's size. However, in HPDC, it is vital that a part is designed in a way that facilitates its release from the mould. Currently, considering this aspect is at the discretion of the designer, using the manufacturing cost estimation model.

Furthermore, in estimating overhead costs, these include expenses such as administrative costs or office space rentals. Presently, these overhead costs are not included in the manufacturing cost estimate. In related research on the subject of this study, it is common to incorporate these costs by adding 10-15% to the manufacturing cost. However, in the current model, only the rental cost is considered for the space required for the machine used. This omission results in an underestimate of the overhead cost for the three manufacturing methods. An approach to rectify this underestimation is to add a specific percentage of the currently estimated production cost to gauge the total manufacturing cost. However, this method is not highly accurate and can vary significantly depending on the location and size of the manufacturing company. Consequently, the decision was made to exclude the overhead costs related to administrative expenses, among others, because they do not significantly enhance the accuracy of the estimate. It is not incorporated into any of the three manufacturing methods, allowing comparisons between the manufacturing methods. A recommendation for future research would be to gain more insight into understanding overhead costs, as according to the existing literature, they constitute more than 10% of total manufacturing costs.

Regarding the scope of the study, a crucial aspect to mention is the inclusion of life cycle costs. Originally, the suggestion to include costs throughout the life cycle came from Lightyear. Their motivation stemmed from the perceived advantages of using MAM in this context. These benefits include potentially shorter lead times, reduced inventory levels, and an overall more resilient supply chain. These aspects are of significant importance given the worldwide focus on carbon emission reduction and the increasing public interest in sustainability. In particular, Lightyear, a company committed to addressing its carbon footprint, intended to incorporate insights from an LCA study into the research. In the review of the literature, reference was made to the study by Priarione et al. [44], which focusses primarily on comparing CO_2 emissions among manufacturing methods and provides limited information on material depletion, a vital environmental aspect. Unfortunately, due to time constraints, this research could not go into this aspect further. However, it remains a crucial area for future investigations given the growing environmental awareness. Furthermore, this study does not encompass the impact of MAM on part assembly into sub-assemblies. Understanding how assembly affects manufacturing costs, as well as its implications for maintainability and reliability, is significant. As part consolidation can reduce maintenance needs, it can influence overall life-cycle costs. This also merits exploration in future research.

Another aspect that increases the difficulty of including life cycle costs into a cost model about manufacturing cost for an automotive company is that even though some customers might be willing to pay a premium for parts produced in a more environmentally friendly manner. This willingness is not universal, especially when focussing on developing a car with a target price of €40,000. Particularly when in this case, profit margins are narrow and parts need to be produced in high volumes. The understanding about how to incorporate this in a cost model is limited, hence is should be subject for future studies. As highlighted in the results section, a significant portion of the life cycle cost is incurred by the vehicle's end user. Considering these costs from the perspective of the automotive manufacturer is a challenge. Therefore, all the comparisons made in this study are mainly centred on the cost of manufacturing and inventory of a part or assembly.

Chapter 5

Conclusions

This study contributes to how MAM can be implemented in the automotive industry for the production of parts in high volume ($\geq$ 2500 parts / year). This is done by developing a cost estimation model that includes the key aspects of cost estimation for MAM. The study started as research for a company called Lightyear. Lightyear is an automotive startup founded in 2016 with a mission to make electric vehicles accessible to all. Their first innovation, the Lightyear 0, emphasised aerodynamic efficiency and integrated solar panels for an extended range. Unfortunately, due to financial challenges and the high price point of Lightyear 0, the company filed for bankruptcy in January 2023, impacting the course of the research.

The research aimed to evaluate the viability and sustainability of applying MAM within the automotive industry to produce functional parts in a high volume. The scope was defined to encompass metal parts, excluding additive manufacturing of polymers. The research explored key challenges faced by the automotive industry, especially in terms of on-demand manufacturing and cost effectiveness, comparing MAM with traditional manufacturing methods. In light of Lightyear's vision to produce more affordable electric vehicles, particularly the Lightyear 2 with a targeted price of 40,000.00, the study also addressed associated challenges. Cost efficiency was a significant concern, especially with respect to the relatively high cost of MAM. Therefore, the following research question is formulated:

"Can metal additive manufacturing be applied in the automotive industry to produce functional parts in high volume when comparing costs throughout the life cycle?"

This is combined with the following sub-questions:

- What are the key advances and recent developments in metal additive manufacturing technology and how have these innovations been adopted and applied within the context of the automotive industry?
- What is the life cycle of additively fabricated metal parts in the automotive industry?
- How can the costs for the entire life cycle of additive and conventionally manufactured parts be calculated?

These questions can be answered as follows. MAM is a rapidly developing technology with the potential to revolutionise the automotive industry. MAM offers a number of advantages over traditional manufacturing methods, including greater design flexibility, reduced costs, and improved resource efficiency. Recent advances in MAM technology have made it more affordable and accessible to automotive manufacturers. As a result, MAM is being adopted and applied in a variety of ways within the automotive industry, including prototyping, tooling production, and high-performance automobile manufacturing. In the future, MAM is expected to play an even greater role in the automotive industry. MAM has the potential to enable new and innovative product designs, as well as more efficient and sustainable manufacturing processes. MAM is expected to impact the future of the automotive industry in several ways, including enabling on-demand manufacturing, mass customisation, and repair and refurbishment of automotive parts and components. MAM can also be used to produce lightweight automotive parts and components with new capabilities, such as improved performance or durability. In general, MAM is a promising technology with the potential to have a significant impact on the future of the automotive industry. By enabling the production of lightweight, high performance, and customised automotive parts and components, MAM can help automotive manufacturers reduce costs, improve fuel efficiency, and reduce emissions. The last two advantages are a major part of the life cycle of MAM parts in the automotive industry. However, these advantages mainly influence the total cost of ownership of an automotive vehicle. For a cost model that is developed to help the designer make a decision about viable production methods early in the design process, it has proven difficult to include these advantages in a life cycle cost model. This is related to the fact that a significant part of these cost savings are achieved during the operating phase of an automotive vehicle.

This research validates the viability of producing parts in high-volume using MAM, emphasising the importance of designing parts to take advantage of MAM benefits. The case study selected for this thesis was not optimal for MAM, resulting in other manufacturing methods showing lower manufacturing costs per part, even when considering inventory and transport costs, a novelty in the area of MAM cost estimation models. Although costs related to inventory and transport were considered, the study highlighted that these factors do not significantly influence the selection of manufacturing methods. The inclusion of these cost factors is a novelty of this research. These costs are often left out of the comparison due to the assumptions that need to be made, and it can be difficult to prove their relevance in a broader context. However, for the specific case of Lightyear, the request was to include these costs factors. Restrictions for the production location allowed assumptions to lead to results about the significance of these cost factors.

For MAM, the key cost drivers, which contribute more than 72% to the cost per part, are the costs related to material and machines. An increase of 7.5% in powder reusal will result in a reduction of manufacturing cost per part of 6.88% for the part selected in the case study. Given ongoing advances in MAM, future improvements are expected to lead to a lower cost per part. To make MAM a viable option for high-volume metal-part production, it is crucial to leverage its advantages in part design. Factors such as part consolidation and the buy-to-fly ratio compared to traditional manufacturing significantly influence cost effectiveness. The cost model developed allows engineers to assess early in the design stage whether MAM can be a cost-effective option, requiring only rough estimates of the part. This model supports the further integration of MAM in the production of automotive vehicles.

In general, MAM can be applied in the automotive industry to produce parts in high volume when comparing cost throughout the life cycle, with the current level of development in the area of MAM. Using its benefits is crucial from a cost perspective, as shown in the case study.

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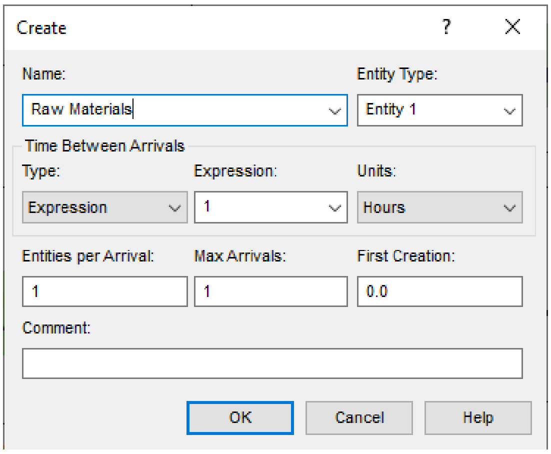
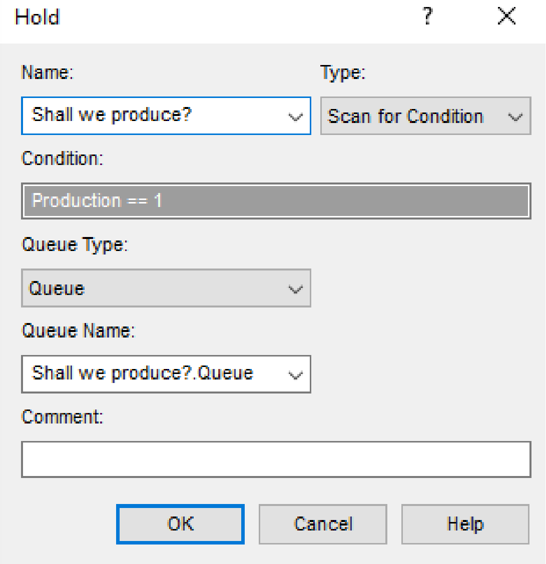
Appendices

A Arena modules HPDC


Create

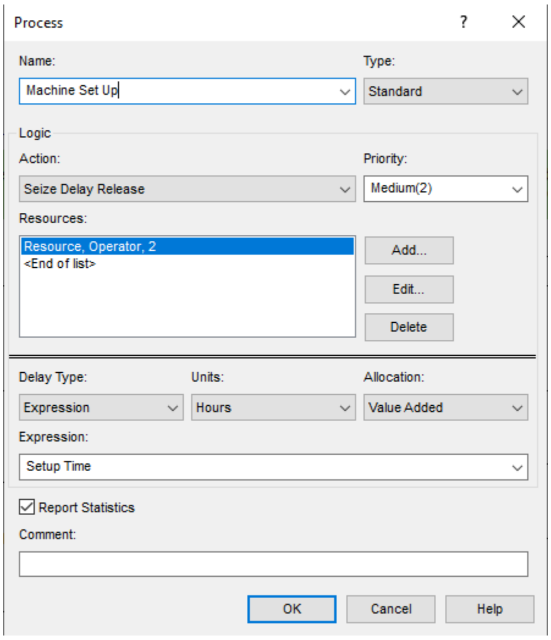
Name: Raw Materials
Entity Type: Entity 1
Time Between Arrivals
Type: Expression
Expression: 1
Units: Hours
Entities per Arrival: 1
Max Arrivals: 1
First Creation: 0.0
Comment:

Figure 6: Module number 1 in HPDC Arena model


Hold

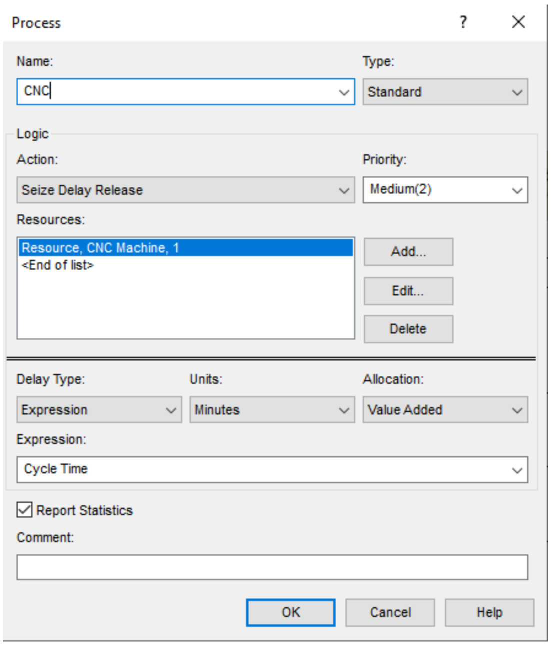
Name: Shall we produce?
Type: Scan for Condition
Condition: Production == 1
Queue Type: Queue
Queue Name: Shall we produce?.Queue
Comment:

Figure 7: Module number 2 in HPDC Arena model


Process

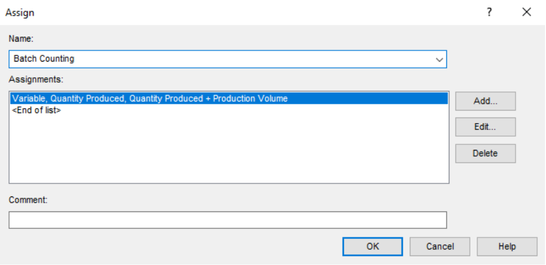
Name: Machine Set Up
Type: Standard
Logic
Action: Seize Delay Release
Priority: Medium(2)
Resources:
Resource, Operator, 2
<End of list>
Delay Type: Expression
Units: Hours
Allocation: Value Added
Expression: Setup Time
☑ Report Statistics
Comment:

Figure 8: Module number 3 in HPDC Arena model


Process

Name: CNC
Type: Standard
Logic
Action: Seize Delay Release
Priority: Medium(2)
Resources:
Resource, CNC Machine, 1
<End of list>
Delay Type: Expression
Units: Minutes
Allocation: Value Added
Expression: Cycle Time
☑ Report Statistics
Comment:

Figure 9: Module number 4 in HPDC Arena model



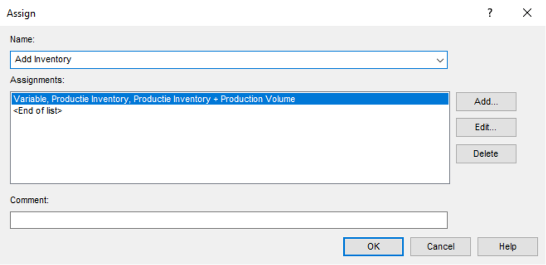
Name: Batch Counting

Assignments:

Variable, Quantity Produced, Quantity Produced + Production Volume
<End of list>

Comment:

Figure 10: Module number 5 in HPDC Arena model



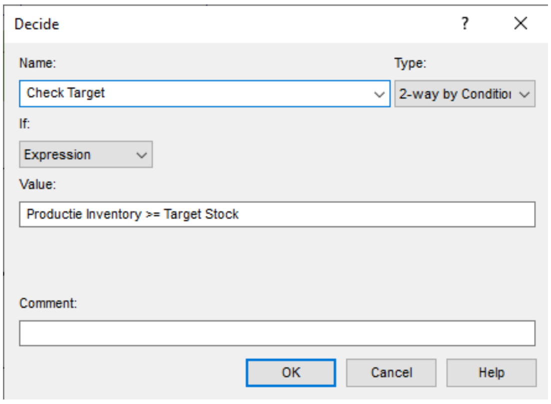
Name: Add Inventory

Assignments:

Variable, Productie Inventory, Productie Inventory + Production Volume
<End of list>

Comment:

Figure 11: Module number 6 in HPDC Arena model



Name: Check Target

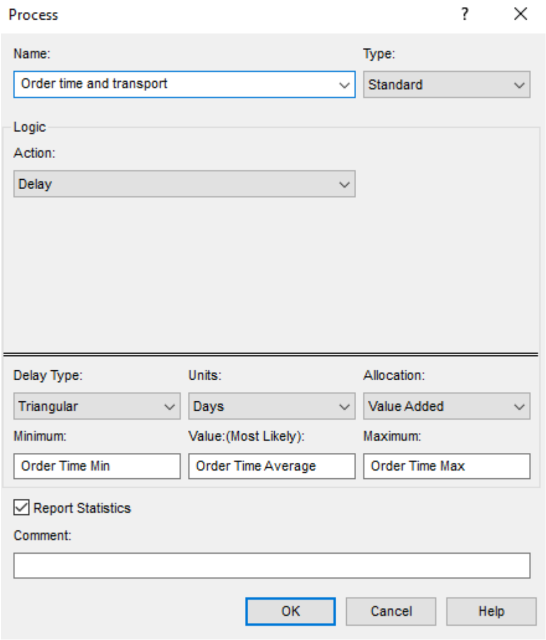
Type: 2-way by Conditio

If: Expression

Value: Productie Inventory >= Target Stock

Comment:

Figure 12: Module number 7 in HPDC Arena model



Name: Order time and transport

Type: Standard

Logic

Action: Delay

Delay Type: Triangular

Units: Days

Allocation: Value Added

Minimum: Order Time Min

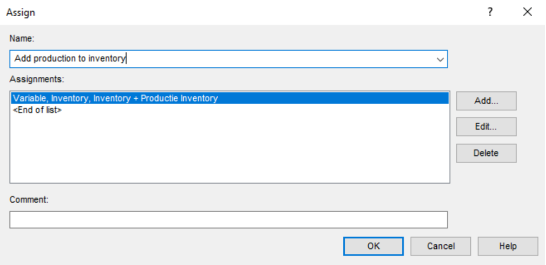
Value:(Most Likely): Order Time Average

Maximum: Order Time Max

☑ Report Statistics

Comment:

Figure 13: Module number 8 in HPDC Arena model



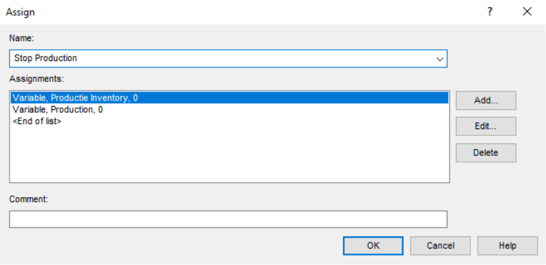
Name: Add production to inventory

Assignments:

Variable, Inventory, Inventory + Productie Inventory
<End of list>

Comment:

Figure 14: Module number 9 in HPDC Arena model



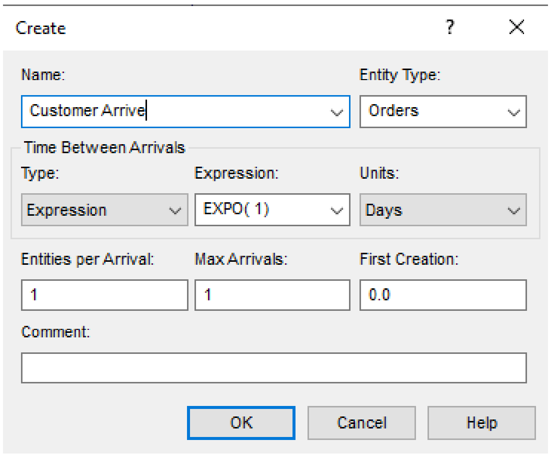
Name: Stop Production

Assignments:

Variable, Productie Inventory, 0
Variable, Production, 0
<End of list>

Comment:

Figure 15: Module number 10 in HPDC Arena model



Name: Customer Arrive

Entity Type: Orders

Time Between Arrivals

Type: Expression

Expression: EXPO(1)

Units: Days

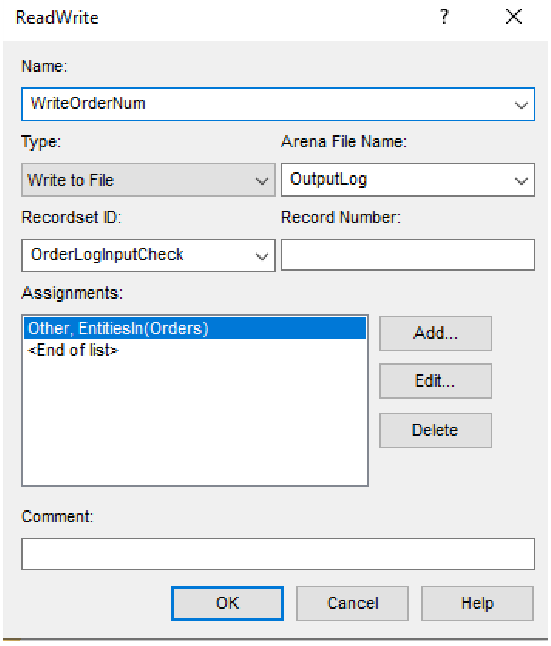
Entities per Arrival: 1

Max Arrivals: 1

First Creation: 0.0

Comment:

Figure 16: Module number 11 in HPDC Arena model



Name: WriteOrderNum

Type: Write to File

Arena File Name: OutputLog

Recordset ID: OrderLogInputCheck

Record Number:

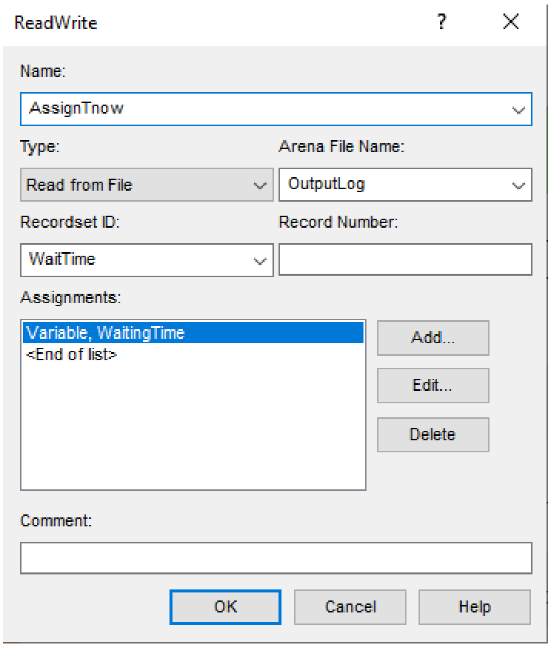
Assignments:

Other, EntitiesIn(Orders)

<End of list>

Comment:

Figure 17: Module number 12 in HPDC Arena model



Name: AssignTnow

Type: Read from File

Arena File Name: OutputLog

Recordset ID: WaitTime

Record Number:

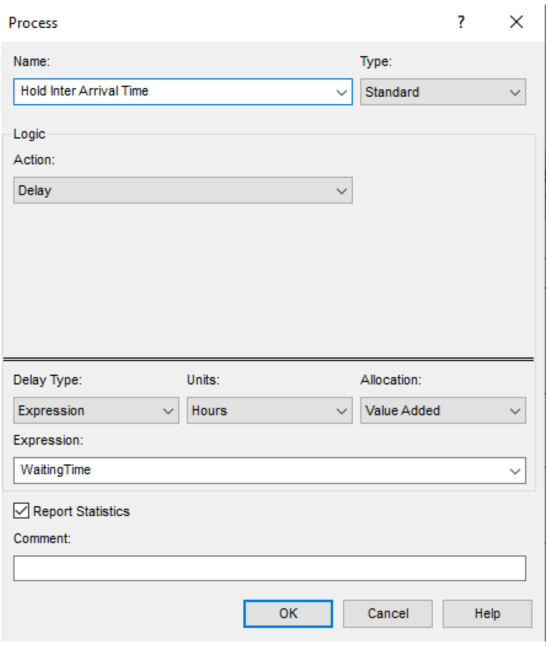
Assignments:

Variable, WaitingTime

<End of list>

Comment:

Figure 18: Module number 13 in HPDC Arena model



Name: Hold Inter Arrival Time

Type: Standard

Logic

Action: Delay

Delay Type: Expression

Units: Hours

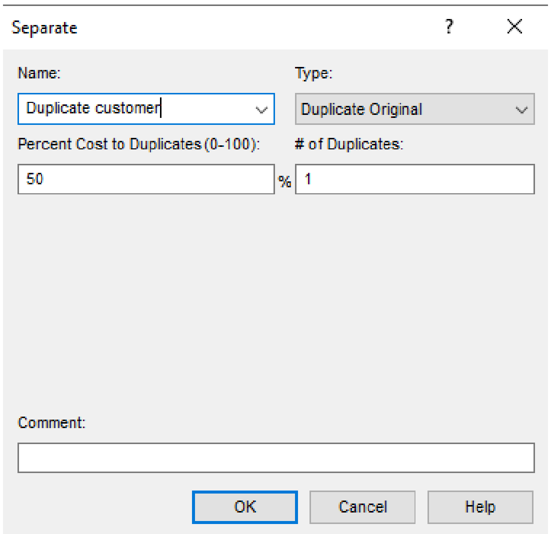
Allocation: Value Added

Expression: WaitingTime

☑ Report Statistics

Comment:

Figure 19: Module number 14 in HPDC Arena model


Separate

Name: Duplicate customer

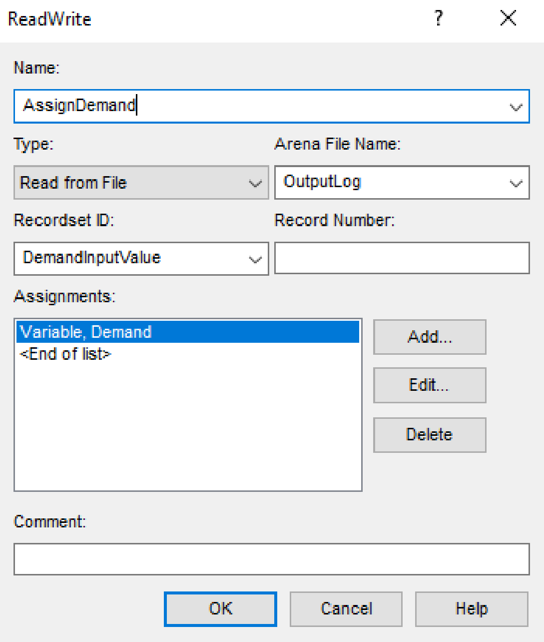
Type: Duplicate Original

Percent Cost to Duplicates (0-100): 50 %

# of Duplicates: 1

Comment:

Figure 20: Module number 15 in HPDC Arena model


ReadWrite

Name: AssignDemand

Type: Read from File

Arena File Name: OutputLog

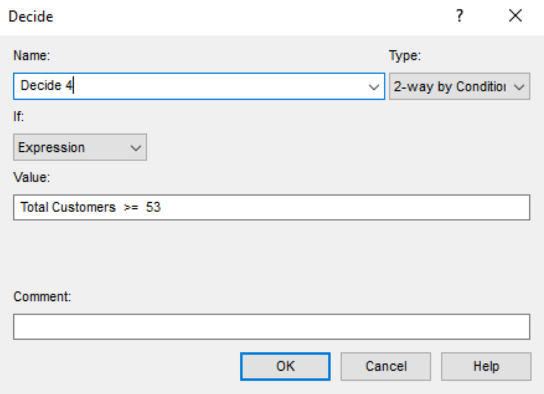
Recordset ID: DemandInputValue

Record Number:

Assignments:
Variable, Demand
<End of list>

Comment:

Figure 22: Module number 17 in HPDC Arena model


Decide

Name: Decide 4

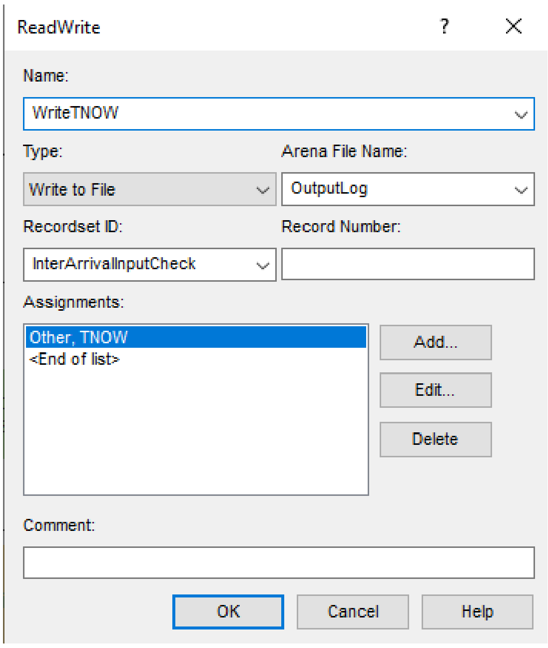
Type: 2-way by Conditio

If: Expression

Value: Total Customers >= 53

Comment:

Figure 24: Module number 19 in HPDC Arena model


ReadWrite

Name: WriteTNOW

Type: Write to File

Arena File Name: OutputLog

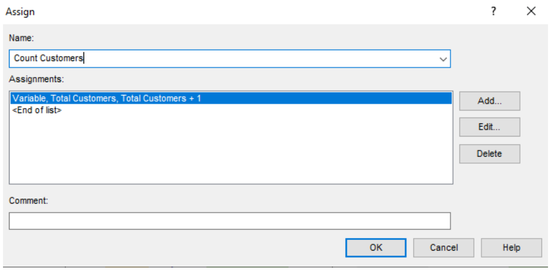
Recordset ID: InterArrivalInputCheck

Record Number:

Assignments:
Other, TNOW
<End of list>

Comment:

Figure 21: Module number 16 in HPDC Arena model

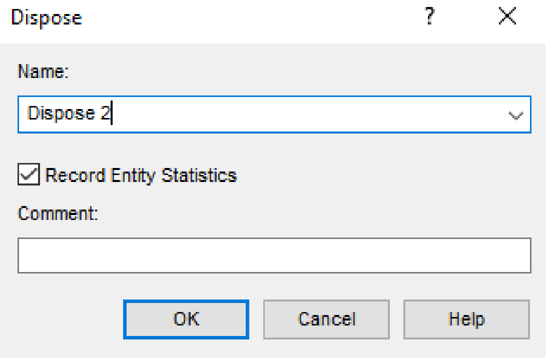

Assign

Name: Count Customers

Assignments:
Variable, Total Customers, Total Customers + 1
<End of list>

Comment:

Figure 23: Module number 18 in HPDC Arena model

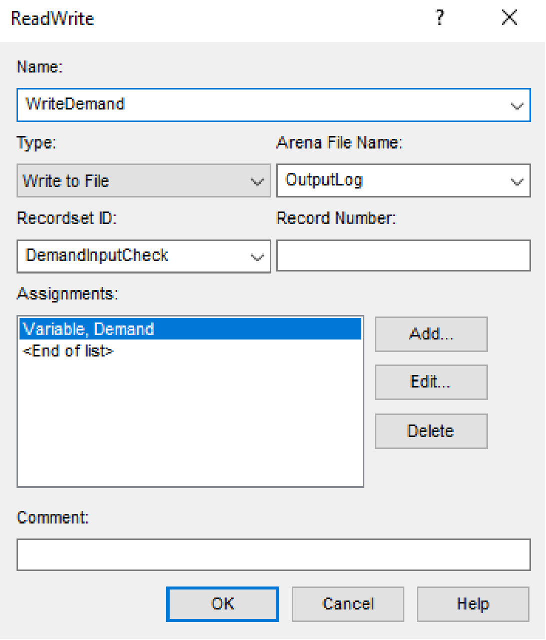

Dispose

Name: Dispose 2

☑ Record Entity Statistics

Comment:

Figure 25: Module number 20 in HPDC Arena model


ReadWrite

Name: WriteDemand

Type: Write to File

Arena File Name: OutputLog

Recordset ID: DemandInputCheck

Record Number:

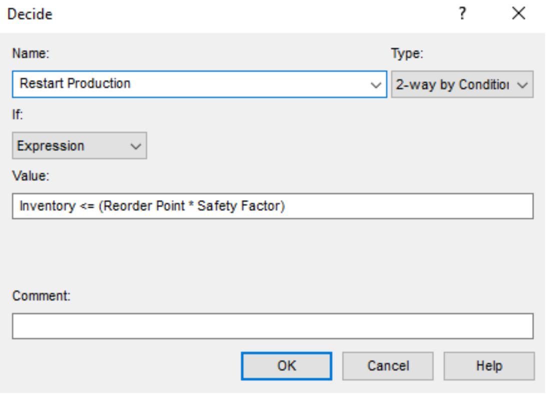
Assignments:

Variable, Demand

<End of list>

Comment:

Figure 26: Module number 21 in HPDC Arena model


Decide

Name: Restart Production

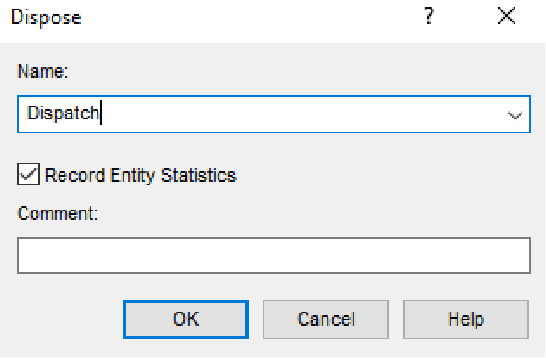
Type: 2-way by Conditio

If: Expression

Value: Inventory <= (Reorder Point * Safety Factor)

Comment:

Figure 28: Module number 23 in HPDC Arena model

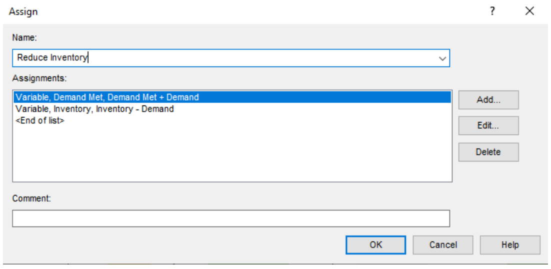

Dispose

Name: Dispatch

☑ Record Entity Statistics

Comment:

Figure 30: Module number 25 in HPDC Arena model


Assign

Name: Reduce Inventory

Assignments:

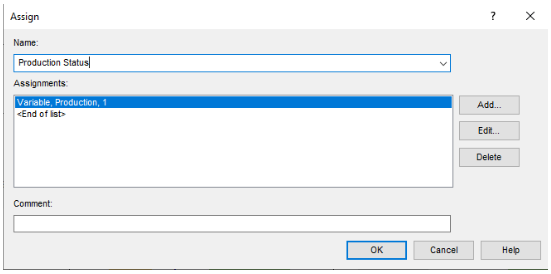
Variable, Demand Met, Demand Met + Demand

Variable, Inventory, Inventory - Demand

<End of list>

Comment:

Figure 27: Module number 22 in HPDC Arena model


Assign

Name: Production Status

Assignments:

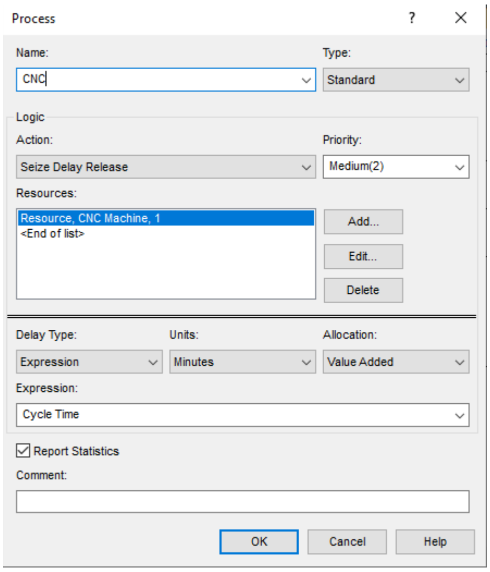
Variable, Production, 1

<End of list>

Comment:

Figure 29: Module number 24 in HPDC Arena model

B Arena modules CNC


Process

Name: CNC

Type: Standard

Logic

Action: Seize Delay Release

Priority: Medium(2)

Resources:
Resource, CNC Machine, 1
<End of list>

Delay Type: Expression

Units: Minutes

Allocation: Value Added

Expression: Cycle Time

☑ Report Statistics

Comment:

Figure 31: Arena module CNC model