Strategic use of Additive Manufacturing

Ebba Nystedt

DIVISION OF PRODUCT DEVELOPMENT | DEPARTMENT OF DESIGN SCIENCES
FACULTY OF ENGINEERING LTH | LUND UNIVERSITY
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Strategic use of Additive Manufacturing

A case study at Atlas Copco Construction Tools

Author: Ebba Nystedt

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Abstract

As additive manufacturing is developing at an exponential rate and is stepping towards industrialization, it is difficult to keep track of what is possible to achieve today and also what can be expected tomorrow. The starting point of this thesis work is a global picture valid today of what is possible to achieve with additive manufacturing and also inspiration of its use in the manufacturing industry. Additive manufacturing provides increased degrees of design freedom in product realization. Using additive manufacturing strategically can decrease the development time for some components by allowing manufacturing of prototypes not possible before and drastic reduction of lead times. When prototyping, there are needs to be met from several functions within the organization including design engineers, purchasers, test-lab, material specialists and production development. Introducing additive manufacturing, certain needs are not possible to fulfil and trade-offs are needed to be done. In order to understand these trade-offs, a decision-making process has been developed to be used as a foundation to decision-making during the product development process, including the project preparatory phase, design phase, prototype and test-phase and production preparatory phase.

Keywords: Additive Manufacturing, Rapid Prototyping, Atlas Copco, Design Thinking,

Sammanfattning

Då additiv tillverkning utvecklas i en exponentiell takt och är på väg mot industrialisering är det svårt att hålla reda på vad som är möjligt att uppnå idag och vad som kan förväntas imorgon. Utgångspunkten för detta examensarbete är en återspegling av en global bild giltig idag för vad som är möjligt att uppnå med additiv tillverkning och inspiration av dess användning inom tillverkningsindustrin. Additiv tillverkning tillåter ökad grad av designfrihet vid produktrealisering. Strategisk användning av additiv tillverkning kan minska utvecklingstid för vissa komponenter då prototypframtagning som ej varit möjlig tidigare tillåts och ledtider minskas drastiskt. Vid prototypframtagning behöver behov från flera funktioner i organisationen mötas inklusive designingenjörer, inköpare, testlabb, materialspecialister och produktionsutveckling. När additiv tillverkning introduceras, är vissa behov inte möjliga att uppfylla och kompromisser är nödvändiga att göras. För att förstå dessa avvägningar har en beslutsprocess utvecklats som ska användas som grund för beslutsfattandet under produktutvecklingsprocessen, inklusive projektets förberedande fas, design-fas, prototyp och test-fas och produktionsförberedande fas.

Nyckelord: Additiv tillverkning, Rapid Prototyping, Atlas Copco, Design Thinking

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Lund, June 2017

Ebba Nystedt

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List of acronyms

ACCT	Atlas Copco Construction Tools
AHP	Analytical Hierarchy Process
AM	Additive Manufacturing
CNC	Computer Numerical Control
DFAM	Design for Additive Manufacturing
DFM	Design for Manufacturing
DMLS	Direct Metal Laser Sintering
EBM	Electron Beam Melting
EDM	Electron Discharge Machining
LS	Laser Sintering
MS	Master Specification
NPV	Net Present Value
PA	Polyamid
PBF	Powder Bed Fusion
PDC	Product Development Council
PK	Product Cost
R&D	Research & Development
SHS	Selective Heat Sintering
SLM	Selective Laser Melting
SLS	Selective Laser Sintering

1 Introduction

In this chapter, an introduction to the thesis project is presented.

1.1 Company description

Atlas Copco Construction Tools (ACCT), is a division within Atlas Copco's Construction Technique business area. It develops, manufactures and markets hydraulic, pneumatic, and petrol driven equipment for demolition, compaction, rock drilling and concrete applications. Products are distributed through a worldwide sales and service organization under the brands Atlas Copco, Chicago Pneumatic, Dynapac and Shenyang.

In Kalmar, ACCT are working hard towards becoming the division's leading factory with focus on sustainable production, efficiency and competence. ACCT's initiatives and engagement is to support everyone in actively contributing to our future and vision as well as meeting Atlas Copco's vision of becoming First in Mind – First in Choice.

1.2 Background

During the product development process the components are designed to meet pledged requirements. The design is also adapted to a chosen method of production. Additive manufacturing (AM) provides increased degrees of freedom in product realization. How this increase can be utilized is of interest to understand and take advantage of at ACCT.

1.3 Goal with thesis

The goal with this thesis project is:

- To reflect a global picture valid today in terms of AM and its use in the manufacturing industry.
- Describe the benefits gained through the use of AM as the production method for prototyping.
- Development of a decision model that describes and guides between traditional manufacturing and AM for prototyping.

1.4 Scope and delimitations

The thesis project's focus is to examine when and if it is strategic to use AM to cover the gap between prototyping and serial production. The established scope is to consider the product development process at ACCT. To clarify later analyzes, prototypes also means products that reach ACCT's customers during the product development process.

Delimitations have been drawn so that the parts that are considered should later be manufactured with conventional methods. Also, the major focus of the thesis is around one of the seven AM processes, powder bed fusion (PBF) later described in part 3.1.1 Powder bed fusion. Using AM in the product development process is analyzed as outsourced production but considerations of choosing suppliers has not been taken into account. The analyzes about AM components material's micro-structures and mechanical properties are limited in the literature review and thesis project.

2 Method

In this chapter, the research method used for this thesis project is described.

2.1 Research method

The research method chosen for this thesis project has been inspired by Tim Brown's innovation process Design thinking [1]. The research process has been focused around employer needs and iterations of the development of the decision model has been performed with the three process steps described in design thinking as:

1. Inspiration
2. Ideation
3. Implementation

Where inspiration was gathered from literature reviews and ideation from case studies upon which have been implemented in the decision-making model. An overall description of the research method is illustrated below in figure 2.1.

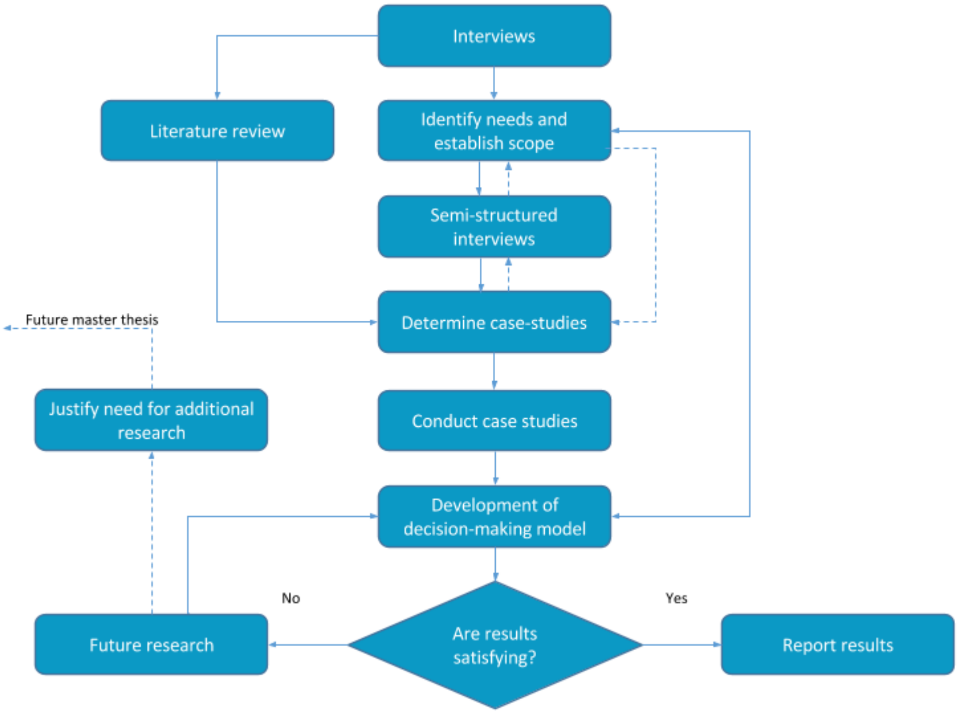

Figure 2.1 Research Process

2.2 Literature review

To a major extent, the Wohler's report [2] has been studied in this thesis project. It was chosen as source of information since most papers about AM are referring to the report, therefore the source is considered as reliable and valid today.

2.3 Interviews

During the first days of the thesis project, interviews approximately one hour long was performed with employees at ACCT. The aim was to gain a picture of ACCT today, to discover what challenges the development team are facing during the product development process and what needs do employees have when making decisions on prototyping. Later during the middle stages of the project, additional interviews were conducted. See interview guide in Appendix B for more information.

2.4 Semi-structured interviews

During the thesis work, semi-structured interviews have been performed with employees to gather information by phone-calls, meetings and by e-mail contact.

2.5 Case studies

During meetings and interviews, different components have been presented as proposals for case studies from ACCT. During the early stages of the thesis project, the challenge was to identify case studies where the application area was suited for prototyping in specific and not final-part production. The selected case-studies are strategic areas of application for ACCT where AM can be applied.

2.6 Corporate documents

As source of information, some corporate documents from ACCT have also been studied where information about the product development process and data from projects have been gathered from.

3 Additive Manufacturing

This chapter is intended to give the reader an understanding of the possibilities with AM for further recommendations on how to apply it in a product development process.

3.1 Seven AM Processes

Since January 2012, the ASTM International Committee has specified a standard definition and categorization for the different processes. Referred to as “Standard Terminology for Additive Manufacturing Technologies” it can be subdivided into seven categories [2, p. 33]:

- Powder bed fusion
- Material extrusion
- Material jetting
- Binder jetting
- Sheet lamination
- Vat photo polymerization
- Directed energy deposition

3.1.1 **Powder Bed Fusion**

The basic principles of PBF is that material in powder-form are fused together using thermal energy where the energy source is often a laser-beam or an electron-beam. The build material is the powder that is, for each layer, relocated from a powder stock with a powder roller while the build platform is moving down. There are several methods used in the AM industry that are categorized as PBF; laser sintering (LS), selective laser sintering (SLS), selective laser melting (SLM), selective heat sintering (SHS), direct metal laser sintering (DMLS), and electron beam melting (EBM). PBF enables AM in both plastics, metals and composites and hybrid materials where some of the methods has the same principles but developed for different materials. For example, DMLS and SLS are based on the same principles for sintering the material together but DMLS is for metals and SLS is for plastics. For SLS polymers, the unfused powder surrounding a part serves as a fixturing system, so no additional supports are usually necessary.

SLM and EBM are based on the same principles but the differences are that for SLM it is Laser and for EBM it is an electron beam that is fusing the material together. SLM is more suitable for geometries that are more complex while EBM is suitable for Titan- and nickel-alloys. EBM also has some unique advantages since the process is under a high temperature that decreases thermal stress distribution compared to other processes. This means that large and bulky parts can be manufactured without risk of distortion and that for example titanium parts does not need to be heat-treated after the process. EBM has been ruled out by GKN Sinter metals for small components with high complexity. There are examples of EBM manufactured Titanium-alloy parts where the test-results show similar results as the conventionally manufactured parts after performing tensile- and hardness-tests. Also, DMLS cobalt-chrome parts that shows similar results. SLM produced parts often reach a density that is above 99 percent but the technology is not sufficient enough to produce parts consistently with a density of the metal above 99.5 percent. To avoid irregularities the development of future AM machines needs system requirements that can detect and prevent these. See schematic illustration below in figure 3.1. [2, pp. 41-42, p. 48; 3 pp. 56-58]

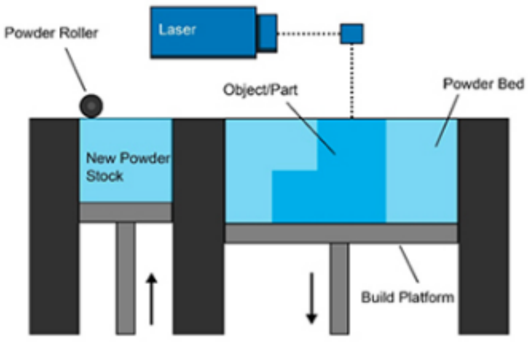

Figure 3.1 Powder Bed Fusion [4]

3.1.2 **Material Extrusion**

The common name for material extrusion with thermoplastics is fused deposition modelling, FDM, and is trademarked by 3D-printing manufacturer Stratasys. The basic principles of material extrusion are that material is melted and selectively dispensed through a nozzle or orifice. For each layer, the material is being fused together in melted condition and after each layer, either the material extruder is moving up or the build platform is moving down. See schematic illustration below in figure 3.2.
[2, p. 48; 4]

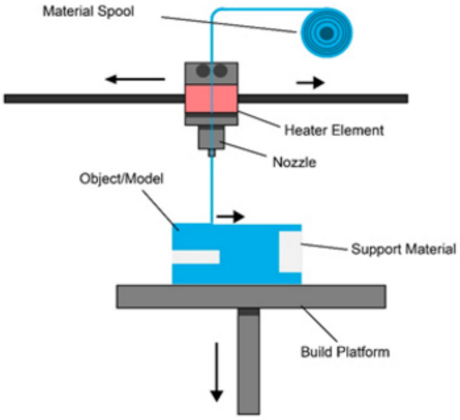

Figure 3.2 Material Extrusion [4]

3.1.3 **Material Jetting**

Material is jetted onto a build platform using either a continuous or drop on demand approach. Since material layers are cured by UV-light, the method is limited to plastics and wax as the material is deposited in drops. The process is very similar to two-dimensional ink jet printing technique. See schematic illustration below in figure 3.3.
[2, p. 35; 4]

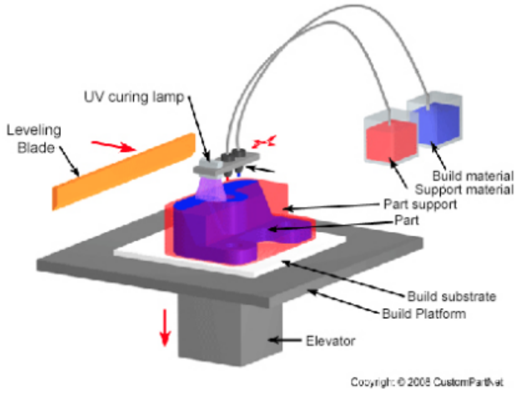

Figure 3.3 Material Jetting [4]

3.1.4 **Binder Jetting**

The binder jetting process is an AM process that is based on the principles for adhesive technologies. An inkjet print head is selectively depositing a liquid binder through a nozzle onto a powder bed. The build material is the powder that is, for each layer, relocated from a powder stock with a powder roller while the build platform is moving down. See schematic illustration below in figure 3.4. [2, p. 37; 4]

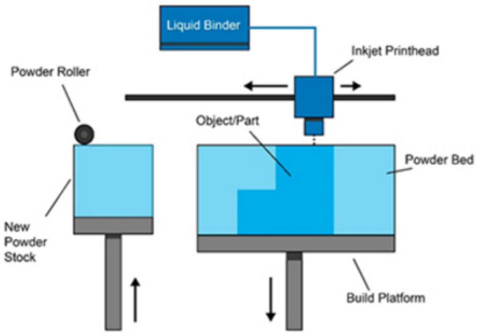

Figure 3.4 Binder Jetting [4]

3.1.5 **Sheet Lamination**

The basic principles for sheet lamination is that sheets of the material are bounded to form the object. The ultrasonic additive manufacturing uses sheets of metal that is welded together by ultrasonic welding. The laser from the ultrasonic weld is directed towards motorized mirrors that reflects the cross-section of the model. See schematic illustration below in figure 3.5. [2, p. 38; 4]

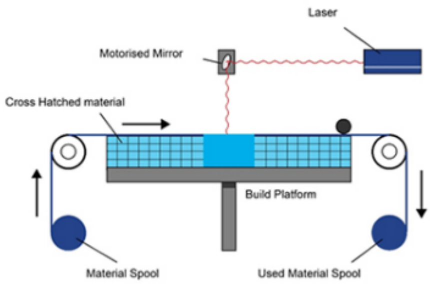

Figure 3.5 Sheet Lamination [4]

3.1.6 **Vat Photo Polymerization**

The most common method for the process of vat photo polymerization is referred to as Stereolithography, SLA or SL. The basic principles are that a liquid photopolymer is selectively cured by a light ultraviolet laser. One or two mirrors are used to reflect the laser beam and scan the cross-section of the top surface of the liquid. The laser hardens each layer and the build platform moves down. See schematic illustration below in figure 3.6.
[2, p. 39; 4]

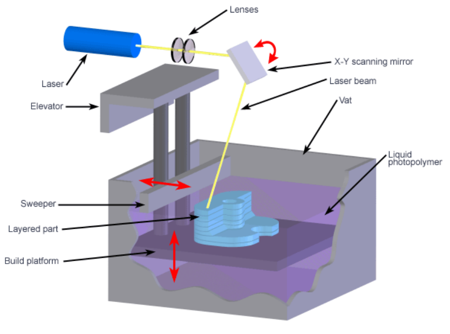

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Figure 3.6 Vat Photo Polymerization [5]

3.1.7 **Directed Energy Deposition**

The directed energy deposition process is in general used to repair or add additional material to existing components. This process is also called blown powder AM and laser cladding. The most common material is metal powder. The process' basic principle is that focused thermal energy melts and fuses material together. The nozzle is most often mounted on a 4 or 5-axis motion system or robotic arm. See schematic illustration below in figure 3.7. [2, p. 43; 4]

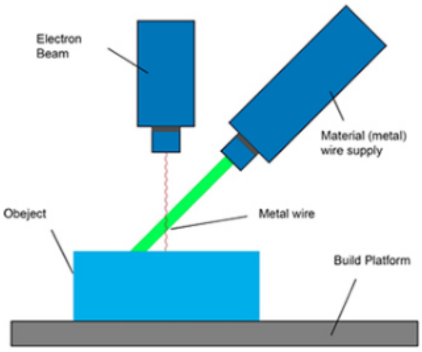


Figure 3.7 Direct Energy Deposition [4]

3.1.8 **Seven categories matrix**

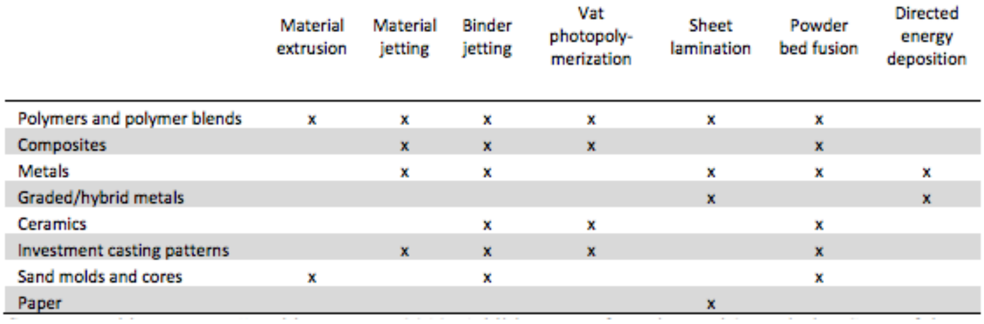
In order to get an overview of the different methods, what post-processing is necessary and what materials are available, the information has been compiled in table 3.1. Additional information about post-processing will be described in part 3.3 Post-processing. [2, 3, 4]

Table 3.1 Seven AM Categories Matrix

	Necessary post-processing	*Materials available*
Powder Bed Fusion	Depending on the machine and the geometry, it might be necessary to let the part cool down after removing from the machine. Removal of powder after print is necessary. For metals, the build platform needs to be removed after printing.	**Plastics:** Most common is Polyamid (PA), available in PA6, PA11, and PA12. Also, PP, PEEK and thermoplastic elastomers. **Metals:** Aluminium, Stainless steel, Tool steels, Maraging steels, Inconel, Titanium, Nickel, Cobalt, Chromium, Copper, Gold, Silver, Platinum, Palladium, Tantalum. Any powder material can be used.
Material extrusion	Depending on the machine and the geometry, it might be necessary to let the part cool down after removing from the machine.	**Thermoplastics exclusively:** ABS, PC, NPA, PLA, high-impact PS, PET, PVA. **Soft rubber-like materials:** TPU, soft PLA, and "Ninja flex".
Material Jetting	Depending on the machine and the geometry, it might be necessary to let the part cool down after removing from the machine. Removal of build platform is necessary and occasionally cleaning of the part.	**Plastics:** PP, HDPE, PS, and also PMMA, PC, ABS, HIPS, EDP. Wax is also available
Binder Jetting	Depending on the machine and the geometry, it might be necessary to let the part cool down after removing from the machine.	**Plastics:** ABS, PA, PC. **Metals:** stainless steel. **Ceramics**: Glass. Also available in printing in sand for sand casting
Sheet Lamination	Extraction of part from surrounding sheet material.	Any sheet material available being rolled. Plastics, paper and metals
Vat Photo Polymerization	Parts must be removed from the resin and any excess resin fully drained from the vat. Parts can be dried naturally or by using an air hose, UV light can be used as well.	**Plastics exclusively**, UV-cure Photopolymer resins.
Directed Energy Deposition	Depending on material, post-processing might be necessary to achieve desired finishes and effects.	Material in either wire- or powder form. **Metals:** Chrome-cobalt alloys and Titanium alloys.

3.2 Materials

AM allows manufacturing in materials as plastics, composites and hybrid materials, metals, paper, sand and in glass. See picture 3.8 below to get an overview of the material groups and how they are implemented for each AM process.



	Material extrusion	Material jetting	Binder jetting	Vat photopoly-merization	Sheet lamination	Powder bed fusion	Directed energy deposition
Polymers and polymer blends	x	x	x	x	x	x	
Composites		x	x	x		x	
Metals		x	x		x	x	x
Graded/hybrid metals					x		x
Ceramics			x	x		x	
Investment casting patterns		x	x	x		x	
Sand molds and cores	x		x			x	
Paper					x		

Figure 3.8 Materials and Processes [2]

As metal AM continues to develop and application areas are expanding, the need for standards among material properties are growing. Since metal AM today is reaching a status where it is stepping towards industrialization, standard institute ISO Technical Committee 261 are researching and establishing standards within the field of AM. The research today is a collaboration together with ASTM international committee F42 (Formerly American Society for Testing Materials) and the research areas are within terminology, process chains, test procedures, quality parameters and supply agreements. [3, p. 45]

Today pioneer companies have developed their own standards for testing within Metal AM and with the growing research within standards, the acceptance of the new technology can increase as design knowledge increases and standards help create a trust for AM. To be able to establish standards within metal AM materials there are some challenges in the progress to be considered. There are strong links between manufacturing parameters and material properties for conventional metal manufacturing and it is very different when comparing AM components manufactured in the same material. There are many complex parameters to consider when finding links between manufacturing parameters for AM materials. According to Simon Höges at GKN sinter metals [3, p. 45], the development and qualification of cost-effective ferrous metal powder for AM is of importance for future AM processes. [3, p. 57]

3.3 Post-processing

In general, combinations of all post-processing techniques can meet all requirements on the final component. When planning for AM it is necessary to keep the number of post-processing steps required in mind since the benefits of using AM decreases as number of post-processing steps increases. The number of post-processing steps for the AM component should be compared with how many post-processing steps there is for the conventionally manufactured part in order to analyze the benefits by using AM. [2, p. 45]

3.3.1 **Support material removal**

The most common post-processing method required for AM parts is removal of support material. Regarding metal PBF, the removal of support material is always required since the part is anchored to the build platform. Due to the high thermal stresses that occur during printing in laser-based systems, as SLM and DMLS, removing the support material is extra critical. For metals, it is common that removal of support material is done after the stress relief. It is common that after printing polymer PBF parts, allow the part to go through a cooling-down stage before removing the powder that is in the container. The cool-down time is dependent on the build material and part size. Once the part has cooled down there are several methods how to remove the leftover powder. This is a critical part of post-processing since the powder still can react with the part and some areas as cavities and internal channels can be hard to reach. Common methods are brushing, compressed air and light bead blasting by using woodworking tools or dental cleaning tools. [6, p. 330] is common to use wire electric discharge machining (EDM) to remove build platform after PBF. When planning for AM one strategy is to make sure the surfaces that requires the finest surfaces roughness's are facing the build platform since this surface requires post-processing either way if a build-platform is required. [2, p. 45]

3.3.2 **Surface texture improvements**

The surface finish is often too rough for some AM parts and applications. Using the technology correctly, the need of time-consuming and costly surface finishing can be minimized. Some technologies yield better surface results than others and the technology is constantly developing. The ProX DMP 320 released in January 2016 produced by 3D-systems is said to be able to produce surfaces between 4-8 Ra in different metal materials as titanium, nickel and stainless steel. The surface roughness is depending on the surface orientation and the parts' geometry. [7] General laser-based PBF processes usually produces parts that has a surface roughness around 7.6-15.2 Ra [2, p. 48], where some studies show that SLM produces better surface roughness's than DMLS [8]. In general, the post-process treatments used on parts made by conventional manufacturing processes are also used on parts manufactured by AM processes. [2, p. 46] Computer numerical control (CNC)-machining, multi-axis turning and milling, EDM, grinding and polishing. Using shot peening the surface finishes can be improved and stress concentrations can be reduced on metal parts. Parts that consists of internal channels or cavities can be challenging to post-process. One example of how to post-process internal channels is with abrasive flow machining.

Micro-machining process combines a chemical reaction at the surface of the material with a removal process driven by fluid flow. Mirror-like surface quality is possible. Used for high-value metal AM parts. Generally, the grinding and polishing performed on conventionally made parts are also made on AM parts if needed. [2, p. 48]

3.3.3 **Accuracy**

In general, PBF's accuracy is around 0.1 mm and if tolerances below this are required it is recommended to use post-processing to achieve required results regarding for example hole tolerances or fittings. According to a case study on internal cooling channels made with SLM and DMLS the conclusion came to that DMLS can perform a higher dimensional accuracy rather than SLM. [8]

3.3.4 **Improve material properties**

Removal of thermal stresses and improvement of material properties is commonly made by three steps within metal AM: [2, p. 49]

- Stress relief
- Hot isostatic pressure to cure micro-cracks and heal internal cracks and porosity
- Precipitation and solution hardening to achieve desired material properties.

3.3.5 **Colour**

The same procedures performed on conventionally manufactured parts are performed on AM parts as well. Powder coating is very common on AM parts. [2, p. 48]

3.4 Design guidelines

The design guidelines written in this thesis work are customized for the use of PBF. Analyzing the model and see where extra support material are needed and where the critical surface finishes and tolerances are needed are key to successful results. The expected results can differ from AM processes and the same support strategy does not necessarily work for different materials. The orientation of the part and the space efficiency are parameters to consider when planning for AM. When planning for AM, an optimal and strategic part orientation helps achieve best results. By strategically planning the part orientation of the component and the build direction of the process helps achieving:

- The shortest build time, i.e. minimizing the number of layers and part height
- The minimal amount of supports
- An easy access to supports so that they can be easily removed
- The best possible surface roughness and minimal staircase effect (when layers from the build process can be detected in connection with the components surfaces).
- The minimum level of residual stresses which can lead to part distortion

The best surfaces of the final part is going to be the surface that is facing the build platform for metal AM, since it is going to be removed with either CNC-milling or wired EDM. Critical surfaces are those related to the overhangs of the part and the envelope surfaces of internal channels and holes perpendicular to the building direction. [9]

3.4.1 **Holes and internal channels**

There are some design limitations for internal channels and holes, the maximum holes that can be obtained with SLM without the need for support material are diameters below 10 mm when the hole is perpendicular to the building direction, see figure 3.9. The minimum hole diameter possible to manufacture with SLM in metal is said to be 0.4 mm. The need for support material can be avoided if the design of holes or internal channels can be redesigned. For example, holes or channels can be redesigned to have an elliptic shape. If perfect round holes are required, their envelope surface should be in line with the build direction. If the envelope surface is perpendicular to the build direction the hole tolerances are harder to achieve and the shape of the hole sometimes become oval. Hole accuracy is depending on the wall thickness and the accuracy is normally around +- 0.1 mm for SLM when the hole centrum axis is in line with the build direction. [9; 10]

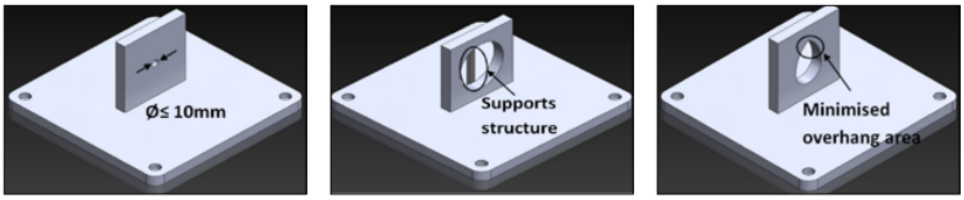


Figure 3.9 Holes and internal channels [9]

Threaded holes are possible to print but the accuracy is depending on the size of the hole. Small threads' surfaces are not usually satisfying for its application. Threads below M8 is usually considered as too small but any thread above that is possible to achieve satisfying results and the best results is achieved by using the same strategy as for regular holes. [11]

3.4.2 **Overhang areas**

The overhang area that is possible to design without the need for support material is depending on what material that is going to be used. For Titanium and steels, it is possible to design overhang areas with an angle around 60 degrees. [11]Regarding other materials, it is generally around 45 degrees. These are very rough rules and the values of the angles are depending on the length of the overhang. See below picture 3.10.

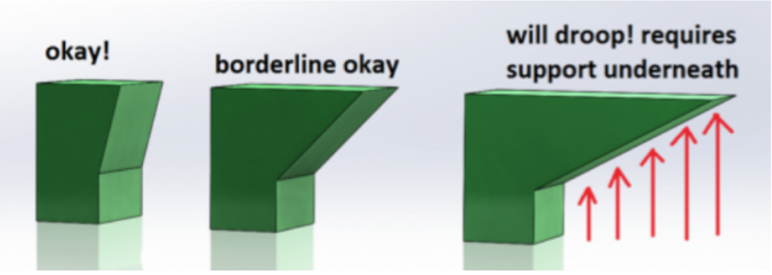


Figure 3.10 Overhang areas [9]

3.4.3 **Wall thickness**

Generally, the minimum wall thickness possible to manufacture with AM is 0.2 mm but it is recommended not to design wall thicknesses that are below 1 mm since the required accuracy is hard to obtain with wall thicknesses below that. [10]

3.4.4 **Supports**

Thickness of support and lattice structures has similar thickness requirements as regular parts and the minimum strut diameter recommended is around 0.15 mm for lattices. Supports can also be designed as “tree-supports” and wall-supports. See lattice structures in picture 3.11. [9]

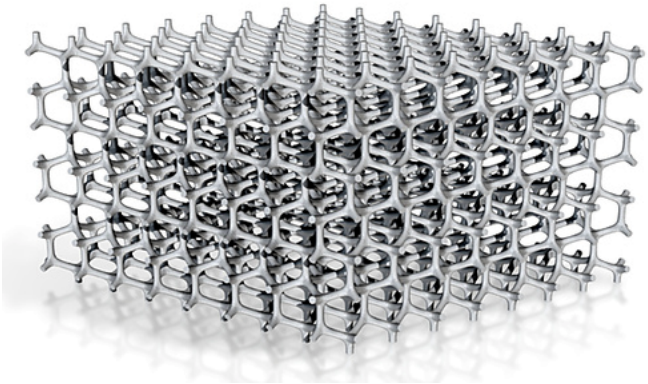


Figure 3.11 Lattice structure [12]

3.4.5 **Design guidelines matrix**

Table 3.2 Design guidelines matrix [9]

	Maximum diameter of holes and internal channels [mm]	***Minimum diameter of holes or channels [mm]***	***Minimum wall thickness [mm]***	***Maximum length-to-height ratio***	***Minimum strut diameter [mm]***	***Overhangs [Degrees]***
PBF	10	0.4	0.2	8	0.15	45

3.5 Cost structure

There are many different cost models that take different kinds of parameters into account. In general, the main direct costs of a final part are the machining cost, labor costs and the material cost. Material prices today are approximately 70€/Kg for both nylon, stainless steel and tool steel powders. [11]. The final part cost can be categorized in two parts; well-structured costs and ill-structured costs: [13]

3.5.1 **Well-structured costs**

- Materials costs
- Machine running, overhead & depreciation costs
- Labour, Machine operation & Post-processing

When pricing the final unit, the depreciation cost of the AM machine is split out over the parts manufactured and is depending on the company's determined economic-life length and the capacity of the machine. For every hour the machine is running, the part needs to cool down one hour and this time is taken into account in some pricing models. As described in part

3.1.1 Powder bed fusion this cooling time is usually longer for metal AM parts relative to plastic AM parts. If post-processing operations are necessary, these are often calculated in the final price. The time it takes to clear the machine from leftover powders after printing takes about 1 hour [11] for SLS and is taken into account for some models.

The distribution of the final part costs can be seen in the figure below for some different AM methods. For LS, the greatest direct cost is material costs, which represents almost 70 percent of the final part cost. Almost 30 percent of the unit's costs is due to machine costs. See picture 3.12.

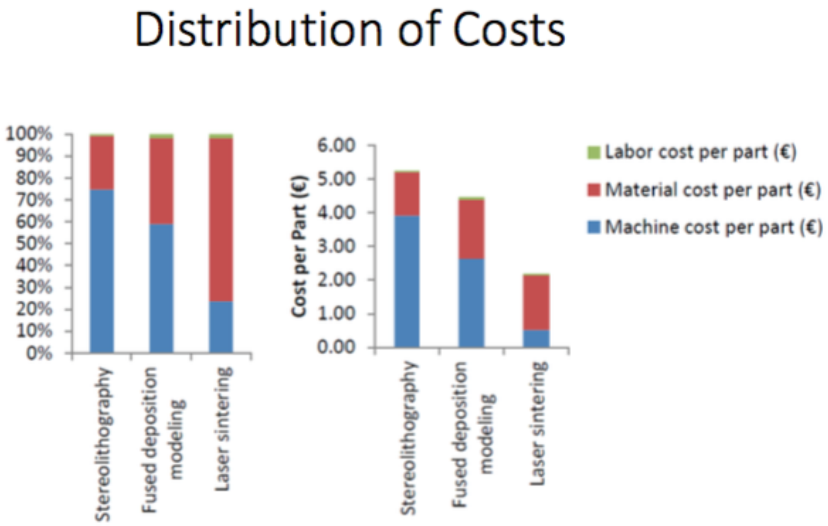


Figure 3.12 Cost distribution [13]

3.5.2 **Ill-structured costs**

- Inventory and Transportation
- Supply chain
- Vulnerability to supply disruption

When prizing units for final part production the supply, inventory and transportation costs are important to consider in a comparison between conventionally manufactured parts and AM parts. The vulnerability to supply disruption for parts that are critical for example production can also be taken into account when comparing unit prices. [13] For this thesis work, these benefits with AM has not been considered since it is of more importance for final part production rather than prototyping.

3.5.3 **Costs sourced components**

The following section is information gathered from suppliers and calculations made by the author. The cost structure is the foundation for assumptions and calculations.

3.5.3.1 Plastics

The final part price has been analyzed in order to understand ACCT's suppliers cost models. Quotation requests has been sent out to some of ACCT's present suppliers and to some new ones. For the analysis, the component volume is approximately 210 cm^3 and AM method is SLS in Nylon and no post-processing operations are required. The number of components ordered are 1, 5 and 30. It is assumed that the cost distribution is according to figure 3.12, that for laser sintering, the material cost represents 70 percent of the final part cost and the machine cost is the remaining 30 percent of the cost. The material cost for the unit is 144 SEK and the machine cost is 61 SEK. For calculations, see Appendix D Calculations.

When ordering parts from suppliers when the order quantity is one, the extra amount of money the suppliers charge differs between factors 4-15, see figure 3.13. The component cost for the different suppliers is presented in figure 3.14. [14][16]

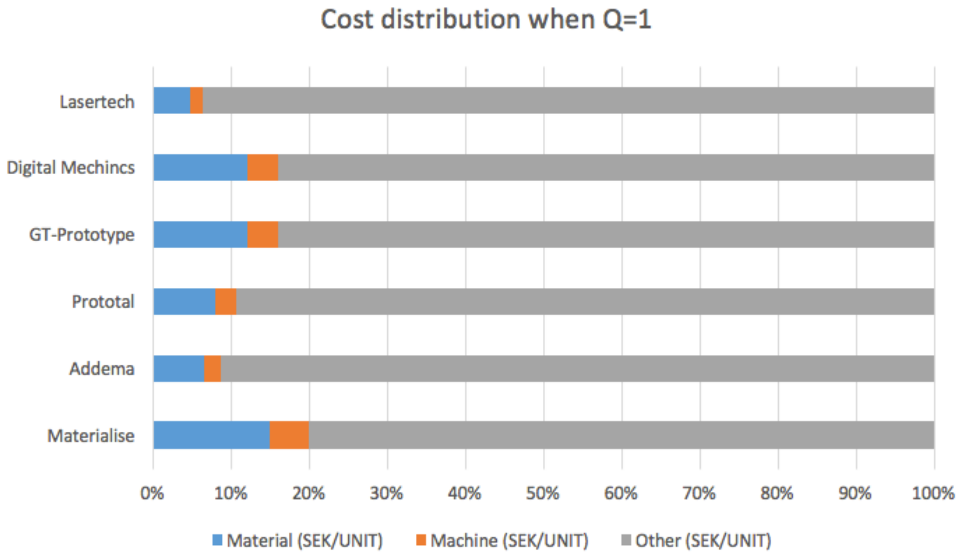


Figure 3.13 Cost sourced components Q=1 [14; 16]

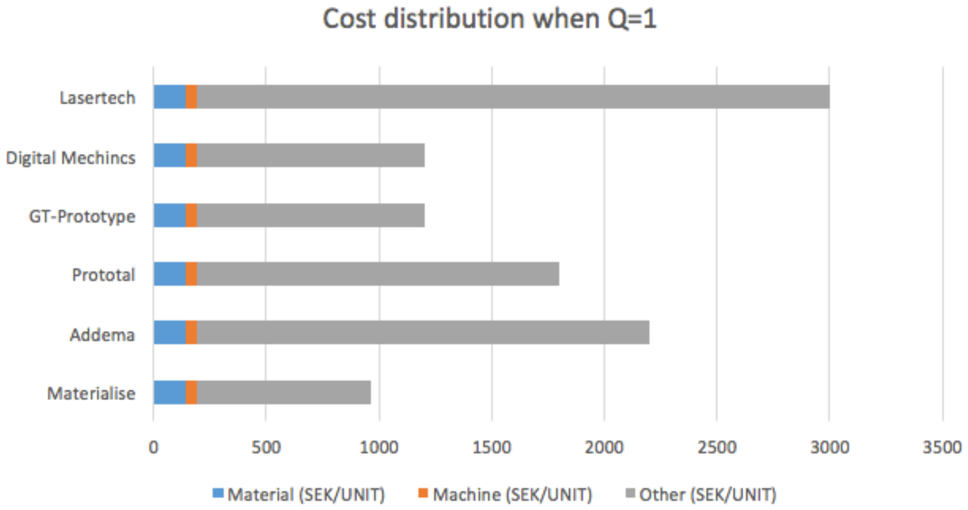


Figure 3.14 Cost sourced components Q=1 [14; 16]

When ordering parts from suppliers when the order quantity is five, the extra amount of money the suppliers charge differs between factors 2-8, see figure 3.15. The component cost for the different suppliers is presented in figure 3.16. [14; 16]

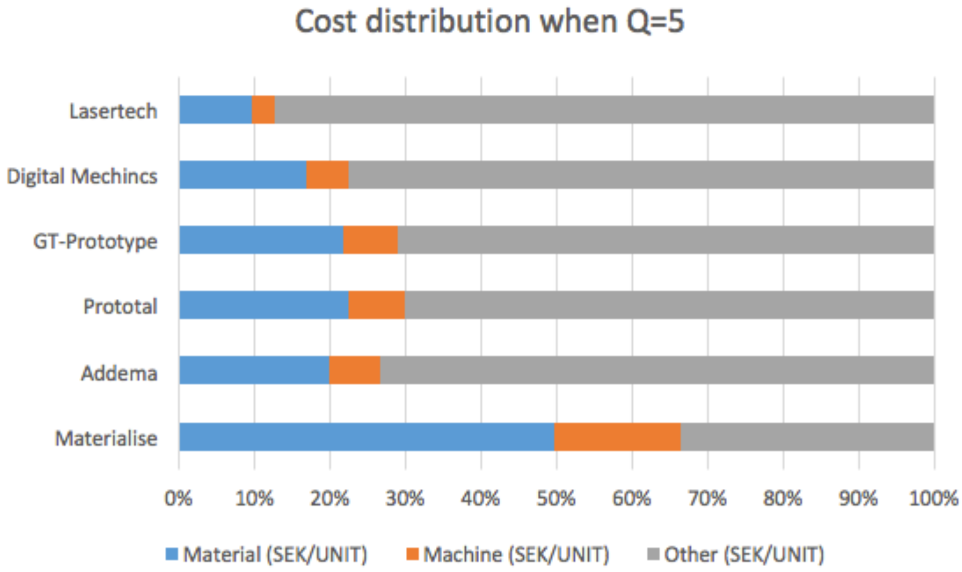


Figure 3.15 Cost sourced components Q=5 [14; 16]

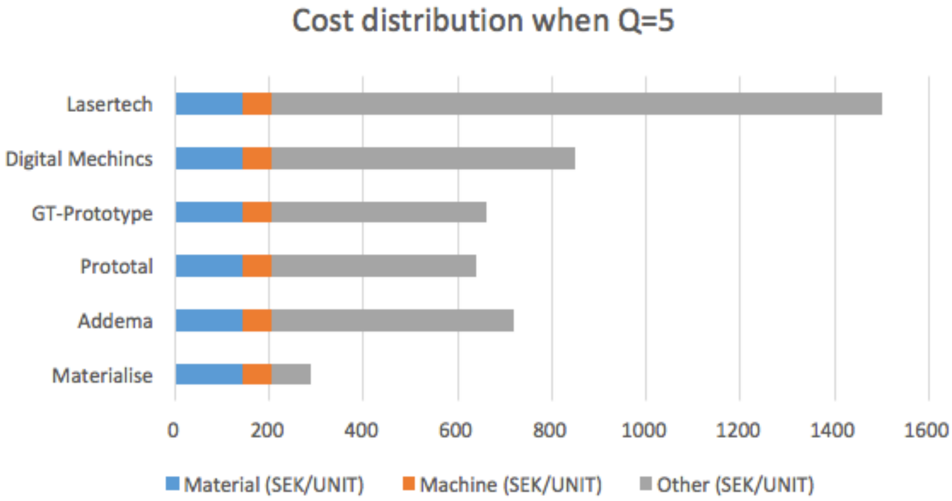


Figure 3.16 Cost sourced components Q=5 [14; 16]

When ordering parts from suppliers when the order quantity is thirty, the extra amount of money the supplier charge differs between factors 2-5, see figure 3.17. The component cost for the different suppliers is presented in figure 3.18. [14; 16]

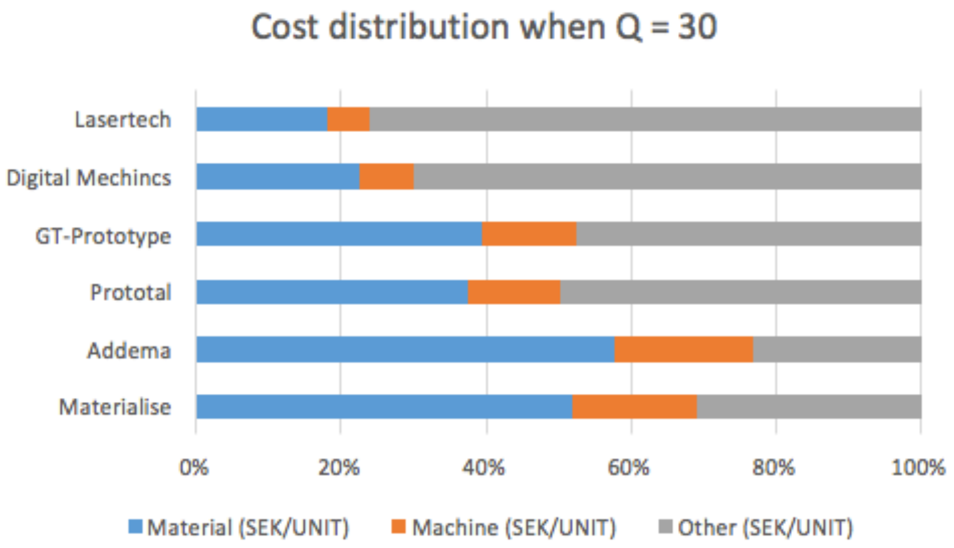


Figure 3.17 Cost sourced components Q=30 [14; 16]

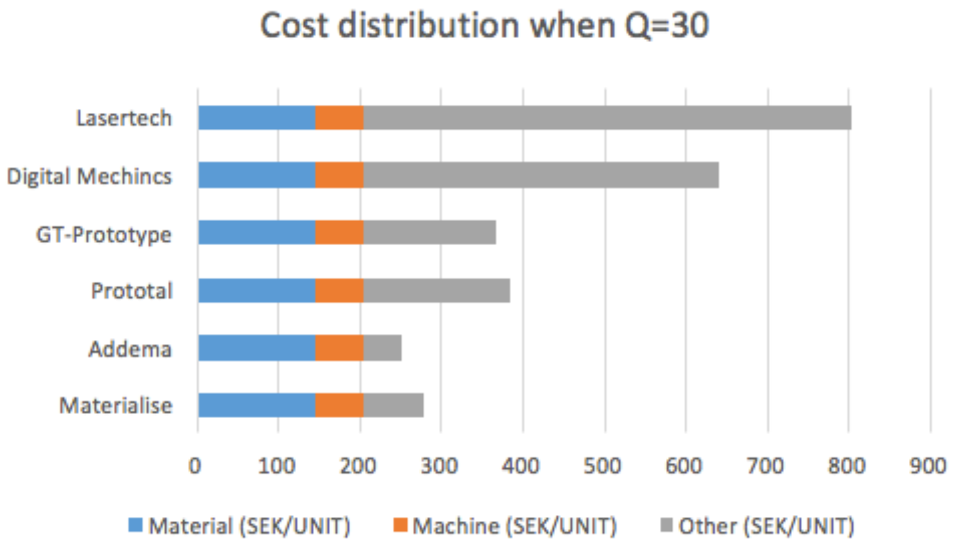


Figure 3.18 Cost sourced components Q=30 [14; 16]

3.5.3.2 Metals

There are two suppliers that ACCT has used so far for metal AM, Lasertech and 3D-met print. Requests has been sent out to receive prices for some components. Also, a new supplier, materialise, has been considered. [15][16]

Table 3.3 Cost sourced metal components [15;16]

Supplier	*Part Volume [cm^3]*	*Material*	*Number of components*	*Price [SEK]*
Lasertech	21	Maraging steel	1	8 200
Lasertech	21	Maraging steel	33	3 500
3D-met print	21	Maraging steel	1	12 000
3D-met print	21	Maraging steel	5	4 400
Materialise	21	AlSi10Mg	1	1 800
Materialise	21	AlSi10Mg	30	1 500
Lasertech	1 600	Aluminum	1	26 800
Lasertech	1 600	Maraging steel	1	40 000
3D-met print	1 656	Maraging steel	2	35 000

3.6 Tooling applications of AM

There are a number of prototype manufacturers that are using AM technologies to develop low volume molds in plastic and silicone materials in order to test the manufacturing process, end-component materials and the design of the component in its final design.

3.6.1 **Injection molding**

Injection molding is a process to use when the number of components are high (>1000), this because of the cycle times are short, 3-4 seconds, in best cases. [17 p. 78] The manufacturing of tooling for injection molding is a key business since its long lead times and high costs which have an impact on the product development process. In some cases, the tooling process has an impact of 15 percent [3, p. 78] of the final plastic part price.

When looking into AM there is a possibility to minimize lead times during the product development process when using AM. Since the most of the parts of the mold are standard components, there is no reason to look into using AM for these parts when prototyping an injection mold. With conventional manufacturing techniques, the lead times are long since there is a high level of complexity of the design of the molds. In order to analyze the costs of an injection mold, the different components in the final part should be analyzed as single elements. It is important to identify the components that can be ordered from a catalogue which have standardized geometries and functions. The injection mold costs breakdown could be as below: [18, p. 64]

1. Part analysis
To be able to estimate the total cost of an injection mold an initial analysis of the part's geometry and complexity is required.
2. Structure of the mold
The parts that hold the mold in place as bases, rails and support pillars are preferably ordered from sub-supplier catalogue were standards.
3. Ejection system
The parts that helps removing the plastic part from the mold as lifters and sliders are included in the ejection system and are depending on the mold's shape and complexity.
4. Injection system
The parts that helps transporting the melted plastic from the injection machine through the mold as runners, gates and sprue bushing are included in the ejection system. The design of these parts is very important.
5. Cavity and core
The cavity and core constitutes together the shape of the final plastic part. These are traditionally manufactured in steel by the toolmaker and the complexity of the parts is depending on the final part.

See below in picture 3.19 an injection mold where the cavity and core represents the complex parts where AM is useful.

Figure 3.19 Cavity and core injection mold [19]

3.6.2 **Injection molding vs AM**

It is common to compare injection molding with AM and find a break-even point where the relative high unit price of AM components is the same as injection molded parts, where the depreciation cost of the tooling is considered. In the analysis below in figure 3.20 the component is calculated to be approximately 7x7x7 mm which is the size of a sugar lump. See Appendix D for calculations.

For this size of component and with this cost model the break-even is approximately by 100 000 units. As can be seen in figure 3.20, the assembly and operator costs are almost negligible for both the AM part and the injection molded part. Also, the material and machine costs are negligible for the injection molded part which means that the comparison in costs for the components where volumes are as high as 100 000 units, the comparison is between the tooling for injection molding vs material and machine cost for the AM part. [20]

	IM@20K	AM	IM@100K
Assembly	€ 0.035 (1.2%)	€ 0.012 (1.0%)	€ 0.035 (3.0%)
Operator	€ 0.009 (0.3%)	€ 0.117 (9.9%)	€ 0.004 (0.3%)
Material	€ 0.011 (0.4%)	€ 0.360 (30.4%)	€ 0.011 (1.0%)
Machine	€ 0.042 (1.4%)	€ 0.694 (58.7%)	€ 0.024 (2.1%)
Tooling	€ 2.900 (96.8%)	€ - (0.0%)	€ 1.075 (93.6%)
Total	€ 2.997	€ 1.183	€ 1.149

Figure 3.20 Injection molding vs AM [20]

3.7 Successful Additive Manufacturing Applications

Three successful application areas have been chosen as inspiration for the application areas in the industry.

3.7.1 **Manufacturing of injection mold**

Danish circular-pump manufacturer Grundfors explored the opportunities with AM molds for injection molding. Some parts of their pumps require injection molding details where the construction material usually is rugged thermoplastics as glass-reinforced PA, PC, PPS and POM. To be able to qualify the prototype in a product development process it is desired that the material and design is equal to the part that is manufactured. Two parts, one simple geometry and one more complex geometry were chosen for the tests. The first trial of prototyping was for the simple part, as the results were satisfying, Grundfors explored the opportunities for a more complex detail. The outer and inner side of the complex detail can be seen in figure 3.21 below.

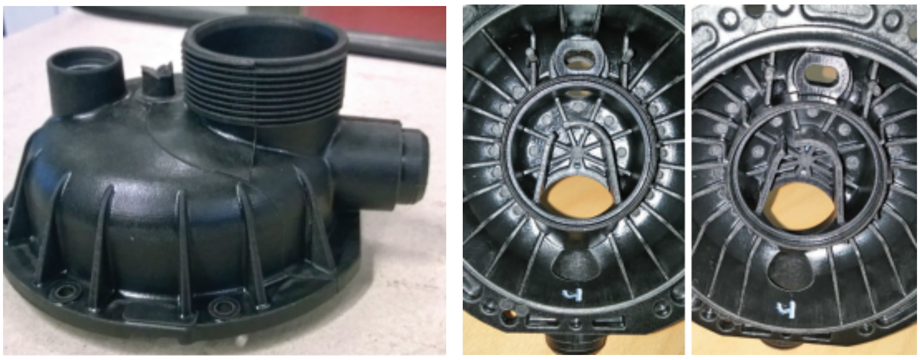


Figure 3.21 prototype injection molding [21]

After this case study, Grundfors estimates that they can save 50 percent of the costs and 70 percent of the lead times during the product development process by choosing AM instead of conventionally manufacturing techniques for producing the prototype injection mold. This nine-part geometry with both threads and many ribs would take up to five weeks to obtain but after using Stratasys printers they had a functioning prototype mold where they could test the same material as would go to serial-manufacturing in just 10 days from first sketch. [21]

3.7.2 **Precision parts for engines and transmission in automotive industry**

GKN Sinter Metals AB is a world-leader within the area of Powder Metallurgy, PM and is producing around 11 Million PM parts per day. About 80 percent of these parts are going into the automotive industry where companies have realized the value of noise-reduced and weight-reduced AM parts in final part production. The design below in figure 3.22 is a re-developed pulley with a honeycomb structure between the hub and the outer gear ring and cavities inside the hub and gear. These features not only reduce the mass of the component but, more importantly, offer a significant noise reduction which in automotive industry is worth putting extra efforts in AM compared to conventionally manufactured parts. [3, p. 55]

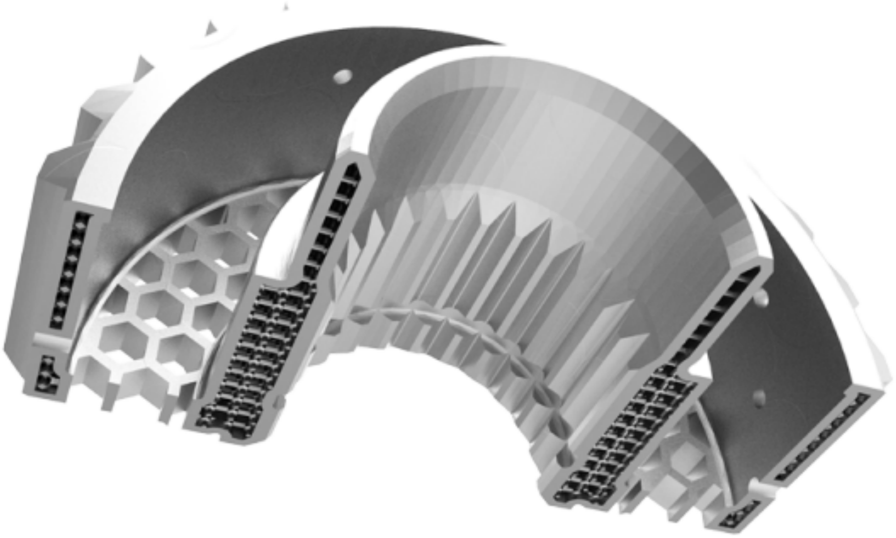


Figure 3.22 Design for AM pulley [3, p. 60]

3.7.3 **Additive manufactured gas-turbine blades**

In February 2017 gas-turbine manufacturer Siemens performed a technological breakthrough where they for the first time manufactured and full-load tested AM gas turbines. The company managed to save 90 percent of the lead time during their prototyping process. The gas turbines must withstand extreme conditions in terms of high corrosion, pressure, forces and temperatures. At full power, gas turbine blades must carry loads off 11 tons, which is approximately the weight of a fully loaded London double-decker bus. The surrounding temperature is around 1,250°C when the turbine is in full operation and the rotation speed is 1,600 km/h at full power. Within just 18 months, the team behind the project succeeded in developing the entire process chain, from the design of individual components, to the development of materials, all the way to new methods of quality control and the simulation of component service life. In addition, Siemens tested a new additively manufactured blade design with a fully revised and improved internal cooling geometry as can be seen below in figure 3.23. [22]

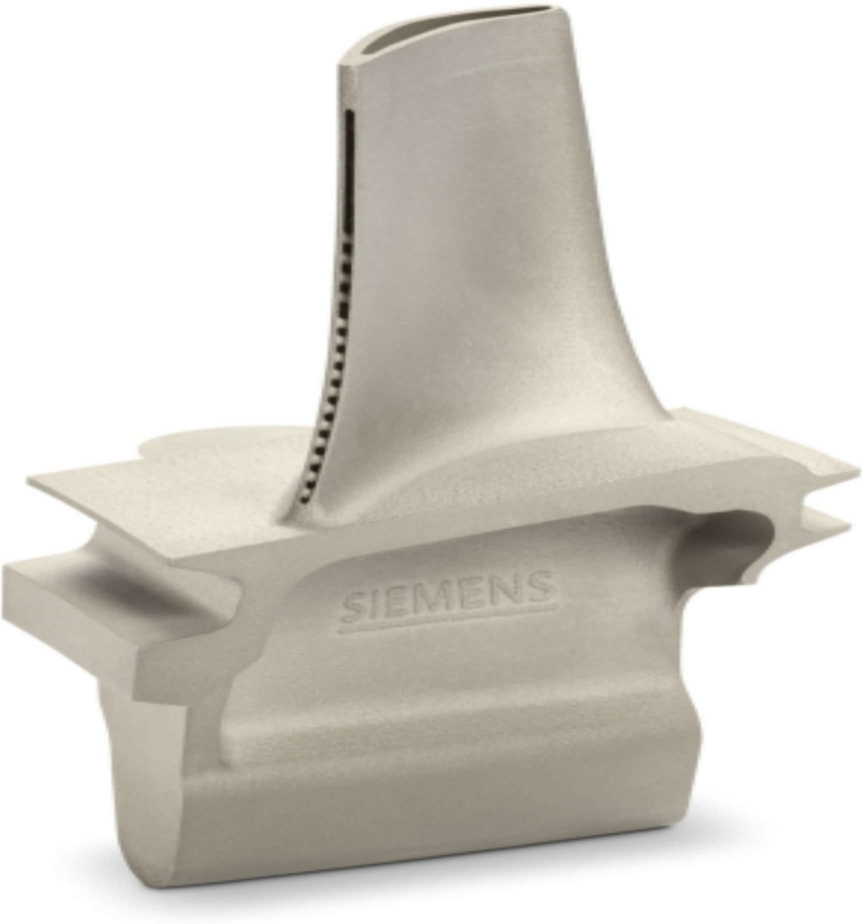


Figure 3.23 AM gas turbine-blade [22]

4 Theory of decision-making

This chapter is intended to give the reader an understanding of theories applied within the decision model developed in this thesis work.

4.1 Analytical Hierarchy Process

Analytical hierarchy process (AHP) is a decision-making tool that can help describe the general decision operation by decomposing a complex problem into a multi-level hierarchical structure of objectives, criteria, sub-criteria and alternatives. Applications of AHP have been reported in numerous fields as budget allocation, project selection and within manufacturing. More and more researchers are realizing that AHP is an important generic method and are applying it to various manufacturing areas. AHP's hierarchic structure reflect the natural tendency of human mind to sort elements of a system into different levels and to group like elements in each level. From a human factor point of view, AHP can be a very effective tool to assist human decision-making. The analytical hierarchy process can be divided into seven steps as below: [23]

Step 1: Decompose problem
Step 2: Define criteria for manufacturing selection
Step 3: Design Hierarchy
    Level 1 Overall objective
    Level 2 Criteria
    Level 3 Sub-criteria
    Level 4 Decision alternatives
Step 4: Perform pairwise comparison and prioritization
    Level 2 Criteria comparison
    Level 3 Sub-criteria comparison
Step 5: Rate the alternatives
Step 6: Compare the alternatives with respect to the sub-criteria Level 3. Pick one alternative as reference.

Step 7: Compute the overall score of each alternative synthesis
By integrating the assigned weights of criteria and supplier's rating, the final score of each alternative is determined in order to develop an overall evaluation process

4.2 Sensitivity Analysis

In a sensitivity analysis, the financial model is used to answer "what-if" questions by calculating the change in net present value (NPV) that corresponds to a change in the factors in the model. Both internal and external factors affect project value. Internal factors are such as the development team has a major impact on, as product development costs and production costs. External factors are those the team cannot change arbitrarily, including the competitive situation, sales volume over a longer period, and product price. Product development teams cannot directly control external factors, but they are often affected by internal factors. This is a tool often used in the automotive industry. [24, p. 457]

4.2.1 **Sensitivity analysis to understand trade-offs**

According to Ulrich & Eppinger [24, p. 461], the development team tries to handle six potential interactions between the internally driven factors. These potential interactions are shown schematically in figure 4.1. Potential interactions between two optional internal factors depend on characteristics in the specific product context. In many cases, the interactions consist of trade-offs. For example, reduced development time can lead to reduced product performance. Increased product performance may require additional product costs. However, some of these interactions are more complex than simple trade-offs. For example, shortened development time may require increased development costs, but prolongation of development may even lead to increased costs if the extension is due to a lead in implementing an important task instead of a planned extension of the schedule. [24, p. 457]

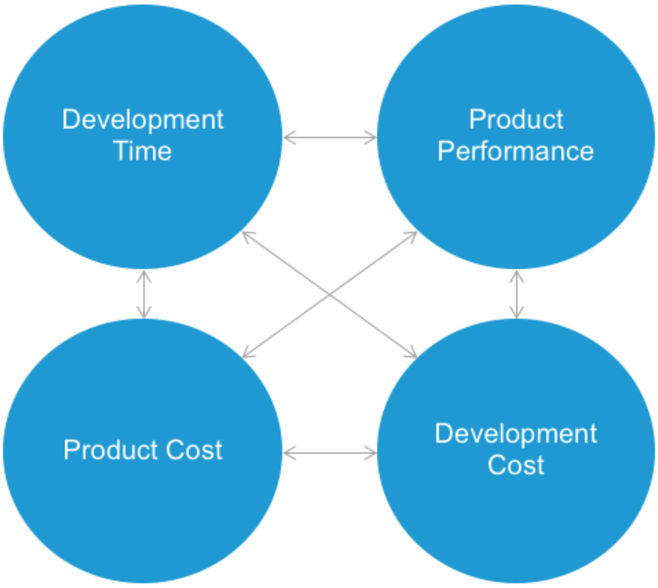


Figure 4.1 Six interaction

Usually these interactions are important because of the interrelationship between internal and external factors. For example, increased development costs or increased development time can strengthen product performance, thereby increasing sales volumes or allowing higher prices. With a shortened development time, the product can be placed on the market earlier and thus increase sales volume. [24, p. 461]

5 Atlas Copco Construction Tools

This following chapter represents the empirical data for this thesis work. The chapter contains compiled data from interviews performed with employees as design engineers, strategic buyers, material specialists, the Research & development (R&D) manager, the production development manager and the test-lab manager. Also, data has been gathered through corporate documents.

5.1 Product development process

In order for the reader to easier understand the product development process at ACCT, the stages are described in this chapter. The process is illustrated below in picture 5.1.

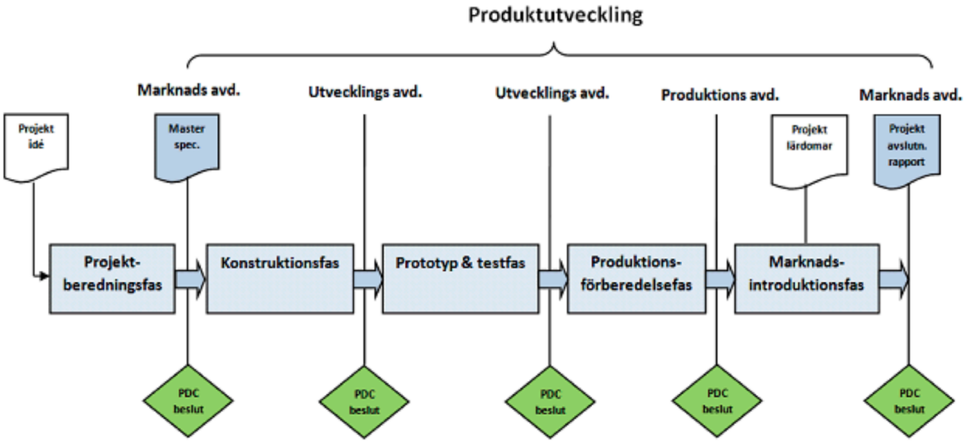


Figure 5.1 Product development process

5.1.1 **Project preparatory**

During the project preparation phase a preliminary design is presented. The construction shall be verified against the requirements by simulations or prototype testing. The responsibility is shared between the Product

Development and Marketing Department, depending on orientation. Responsibility for establishing the resulting specification, Master Specification (MS), is the marketing department which is also responsible of project preparation phase will be presented and pass the Product Development Council (PDC) meeting before the project can start.

5.1.2 **Design phase**

During the project preparation phase, bases for the final design is developed so that prototype or pre-series can be ordered. The final construct is based on the requirements of the MS and verified by calculations, simulations and prototype testing and documented as procedures for documentation of technical documentation. Responsibility for this and the results presented at the PDC meeting has the Technology Manager (Konstruktionschef), alt. the project manager.

5.1.3 **Prototype- and test-phase**

During prototype and test phase parts are ordered, assembly of prototypes or pre-series are performed as well as testing and verification of the product. The goal is that by tests and verifications ensure that the product meets the requirements of the MS. If the test results show that the design needs to be improved corrected and verified deficiencies. The changes documented as procedures for documentation of technical documentation. The responsibility for this and the results are presented on the PDC meeting has the Technology Manager (Alt. The project manager).

5.1.4 **Production preparatory phase**

During the production preparation phase, mainly all planning and preparation work are carried out to start serial production (SOP), where quality assurance processes and components are important elements. Since most of this work is related to the Product Company, the responsibility also passes from project management to the product company during this phase. Project management responsibilities is transferred to the product company after a formal project handover meeting conducted. Main Activities for the design department and Lab department during this phase is the release of drawings and to conduct the final verification of performance required for the customer documentation to be completed. Although project-related activities and Marketing Service division are essential elements in this phase. Responsibility for preparing the phase transition and the results are presented on the product council meeting by the project manager.

5.1.5 **Market introduction**

During the market introduction phase serial production (SOP) is started so that stock building in the distribution center is ensured. The marketing department prepares and carries out the necessary activities required in order to introduce the product to the market. Service division is responsible for the monitoring and reporting of identified quality defects from the field after that sales of the product started. Upon delivery of the first unit from the Product Company the project is financially closed by inactivating the project account.

5.1.6 **Project closure**

12 months after the market launch, the project is closed. Responsible for ensuring that the project will be formally terminated is the marketing department, which also includes the establishment of the Project Completion Report.

5.1.7 **Decision gates and deliverables**

Between the above phases and the project closure, the results are presented for the PDC. PDC has the authority to approve or deny entry into the next phase of the project and to decide when project can be closed. Results and decisions are documented in the PDC portal.

A minimum requirement for a PDC approval for the phase transition in a product development project is that all deliverables have been produced and are ticked off before the PDC meeting. What deliverables each department are responsible for the development and the phase transition, these will be already specified in the PDC portal. The project manager (Alt. Engineering Manager) is responsible for the status of deliverables compiled and presented at the PDC.

5.2 Decision-making

There are guidelines at ACCT saying that decision-making should be done based on facts and numbers. There is no present method for how to make decisions during the product development process; neither for prototyping or for making decisions and reflect what consequence or risk they have. When deciding on prototype manufacturing, decisions are usually made in an interplay between the design engineer, strategic buyer and project manager. Depending on the situation and during what stage in the process the decision is made, the presence of the different people from the different functions vary.

5.2.1 **R&D**

The R&D department's organization structure is according to a divisional structure where areas of responsibility and areas of knowledge are divided on the basis of ACCT's products. The R&D department is divided into three groups where the responsibility is divided between the product families. Each group has one technical manager and the groups are targeting different markets. The project manager is most often an employee from the product category area where the project belongs to. The design engineering functions at the R&D department is divided into the groups:

- Hydraulics (HYD)
- Compactors (LCC)
- Motor-driven breakers (HH)

5.2.2 **Purchasing**

The organization structure at purchasing differs from the structure at the R&D department where areas of knowledge and responsibilities between the different purchasers are not based on the products but the manufacturing technology associated to ACCT's suppliers. Each strategic buyer handles different suppliers categorized in the areas:

- Plastic components, packing, fasteners, indirect materials
- Machining, metal sheet, tubes & pipes, steel raw mat, forgings
- Castings and welding
- Aluminum, rubber, hydraulics, electronic, electricals, transports etc.
- Magnesium, springs

5.3 Prototyping

"We want to test prototypes that are as close to the final result as possible. That is, what is going to be produced in serial-manufacturing" – Pontus Andersson, Lab Manager, interviewee 8[1]. This quotation is very expressive for the demands put on the prototypes produced at ACCT today. In general, there are two types of prototypes at ACCT; proof of concept prototypes and physical prototypes. Today, all prototypes used in ACCT's product development process are sourced from suppliers.

5.3.1 **Proof of concept prototypes**

The proof of concept prototypes is typical to use as foundation to decision-making during the early stages of the product development process as the project preparatory phase described in part 5.1 Product development process. Also, before the product development process during the idea-stage as foundation for production technical discussions. Proof of concept prototypes or not necessary physical prototypes but can be CAD-models or sketches.

5.3.2 **Physical prototypes**

The physical prototypes are typical to use as a foundation to decision-making on whether a design meet the criteria set in advance, which the design should be able to achieve for its field of application. These criteria are specified in the MS as described in part 5.1.1 Project preparatory. When testing components, only hardware tests are performed with a data sheet as support. At ACCT, typical tests that are performed on the final product is:

- Vibration tests
- Audio tests
- Energy measurements
- Lifetime tests
- Component tests

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[1] See Appendix B Interview Guide

Tests are usually performed during the prototype- and test-phase at ACCT but physical prototypes are sometimes required earlier in the process if there are uncertainties and the design needs to be verified.

5.3.3 **Prototyping criteria**

Based on the results from the different interviews with employees; prototyping criteria and sub-criteria has been determined. Various prototyping scenarios has been described, upon which have been interpreted into needs in order to set criteria to each scenario. The results from the interviews are illustrated below in table 5.1 and are intended to set the foundation to the AHP described in part 4.1 Analytical hierarchy process.

Table 5.1 Prototyping criteria

Prototyping scenario	***Description***	***Criteria***	***Sub-criteria***
When prototyping, there is a need to test the material that is intended to go into serial manufacturing.	The ability to receive desired material properties	Quality	Material Properties
Some designs have specific surface requirements that needs to be obtained in order to test design functions, for example bearings.	The ability to receive the general surface requirements	Quality	Surfaces
If a design has a fitting character that is critical for testing the function of the design, required tolerances needs to be obtained.	The ability to obtain the general tolerances required	Quality	Tolerances
Designs that are required to meet specific end-user needs should be prototyped so that they reflect the end-product in the best way. For example, buttons and colour on final product.	The ability to visualize the final component	Quality	Visual aspects

When future product demands are uncertain, there is a need to keep the flexibility open and not freeze designs to production technologies that does not lock the production to high or low volumes.	How flexible is the alternative in terms of production volumes high/low	Flexibility	Volume flexibility
There is a need for testing multiple designs when concepts are uncertain and different prototyping methodologies have different possibilities in multiple design flexibility.	The ability to test multiple designs	Flexibility	Multiple design flexibility
The need for being flexible in terms of design changes is important and the more uncertain the design suggestion is, the more important is design flexibility.	How flexible is the alternative in terms of design changes	Flexibility	Redesign flexibility
There is a need to obtain material flexibility and have the possibility to easily change material if that is needed during the product development process and be able to test the new material.	How flexible is the alternative in terms of material changes	Flexibility	Material flexibility
When prototyping requires investments in tooling in order to receive the prototype, it is of great value to avoid in a product development process.	Requirements of investments in tooling	Cost	Tool cost
The cost of the prototype is not of the greatest importance but the price cannot be too high.	General cost of the prototype	Cost	Prototype cost
During the product development process, there is a need to be able to quickly make design changes after feedback from testing the prototype.	Required time if design changes are needed	Time	Redesign time
When planning for prototyping it is necessary to keep lead times low in order to test prototypes fast and correct mistakes if necessary.	Lead time from order to delivery	Time	Lead time

5.4 Projects

"Product development projects at ACCT, where the product development process involves developing new and working with new technology, tend to run over time by 50 percent." - R&D manager Erik Sigfridsson, interviewee 10[2]. This quotation is very expressive for the project outcomes at ACCT and is laying the foundation for the interest in AM.

For this thesis, two product development projects have been studied; Rock Drill 100 and Cobra Electro. The Rock Drill 100 is a product that belongs to the product family Hydraulics and the Cobra Electro is within the motor-driven breakers family.

5.4.1 **Rock Drill 100**

One of the final products studied in this thesis is an electric hydraulic rock drill which is illustrated in the picture below. The product is developed to target the mining industries in South Africa and was developed during 2013, see picture 5.2 below.

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[2] See Appendix B Interview Guide

Figure 5.2 Rock Drill 100

According to market research, there is a customer demand for a solution with better penetration rate rather than present pneumatic solutions on the market. Since South African mining industries represent 80 percent of the country's total energy consumption, there is a demand to decrease the consumption by 10 percent or heavy fines will be introduced. New noise level regulations are planned to take an effect during the year and it is predicted that the present pneumatic solutions will have difficulties in lowering noise levels.

The plan is to positioning the market as a premium Atlas Copco product with:

- Increased energy efficiency
- Better penetration rate
- Better ergonomics
- Low noise level

During the product development process, there were a total of 30 units planned to be produced, including units for first trial, testing in mines and the pre-series.

5.4.2 **Cobra Electro**

One of the projects studied in this thesis work is the project when developing the Cobra Electro, a hand-held electric breaker developed to target world-wide developed markets with a need for lower vibration levels, lower weight and better energy efficiency. The product was developed during 2015 and can be seen below in figure 5.3.

Figure 5.3 Cobra Electro

Since 1990's, the market demands for a hand-held tool that could not be limited in application due to necessity of the power source as compressor or a power pack. Market studies showed that in urban areas where the amount of job is rather small and requires less time for the execution the work place very often has a limited access and availability of the electrical power on site. Special attention for the closed environment such as basements or spaces inside the buildings that can hardly be reached by the air hose from compressor or cannot be polluted by the exhaust from the power pack.

The plan was to target the market with:

- Significantly lower vibration levels
- Better energy efficiency
- Unique state-of-the-art technology in line with AC brand position
- Possibly lighter than competitor breakers with the same impact energy

5.4.3 **Innovation strategies**

The innovation strategies applied within ACCT is influenced by the Technology Push model and the Demand-Pull model. The Cobra Electro is one example of a technology push project where ACCT are working with and developing new technology where they are entering a market as the only alternative of the technology used for the application. At the time of writing, there is another project at ACCT under development where the product aims to enter the market with new technology with the same principles as the Cobra Electro.

5.4.4 **Planning process**

As the starting point for the planning process before project-start, the development team has a pre-determined road map for the project which is specified in the MS. The road map is a plan for how the project's profitability is intended to break-even during its economic life-length, which is three years. Therefore, only sales volumes for the three first years are specified. In the road map, there is also a specified product cost (PK), which the final product is optimized around. Example of road map data:

- Development costs
- Production costs
- Marketing costs
- Sales volume year 1
- Sales volume year 2
- Sales volumes year 3
- Production cost/unit
- Product price/unit

5.5 Analysis

Since many of ACCT's final components and prototypes are sourced from suppliers there is a high degree of design flexibility in the product development process, there is no need to design for in-house technologies in production. For these kind of components, it is beneficial to have several design options early in the project, as described by Ulrich & Eppinger [24, p. 334]. Design options are possible both in terms of different Design for Manufacturing (DFM) suggestions but also different designs for each DFM suggestion. When projects are insecure, it is of high value to be able to sequentially analyze two or more design options and test these. By introducing AM, feedback from the testing process can be received fast. With the high degree of design freedom in product realization that comes with AM, testing multiple designs is possible for components not possible before with conventional technologies. It is universally known that using AM in product development processes decreases development times. When introducing AM in prototyping, especially for metal components, it is important to reflect on where demand levels can be lowered. Thus, avoiding the requirement that only test the components that are intended to go to serial-manufacturing. According to interviewee 10, ACCT's high-technology (Technology push) projects run a big risk of running over time. Using AM to prototype in the product development process is one way to minimize risks for projects that are insecure since testing can be done relatively fast.

Decision-making on prototyping has an impact on the development time, development costs and product quality [24, p. 355]. As can be explained by ACCT's processes and outcomes, it is difficult to develop high quality products in a short time period. Based on the interviews, it is found that there is a need at ACCT to be able to understand the trade-offs that are needed to be done, when making decisions on prototyping, in a structured and analytical way. The need for a decision-making model for these kinds of trade-offs are primarily for the physical prototypes since there are more criteria to meet and the decision is more complicated to make. Even though the need is lower for a decision-making model for proof of concept prototypes, it is still beneficial to use AM for these kinds of prototypes.

Since design engineers are planning for high volume production during the early stages of a product development process, there are risks of not reaching the market on time because of the long lead times that are associated with the tooling required of high volume production. With the innovation strategies that ACCT are using today, it has shown that penetrating the market has been harder than expected according to road maps from MS. Therefore, the development team is planning for production volumes early in the product development process, which are not reached until years later. It is uncertain what sales volumes the project team should plan for in the early stages of the development process, therefore, the development team ensures there is a high-volume production method chosen in order to maintain a certain level in production to meet future predicted demands. Since there are great uncertainties in the planning, it is also uncertain to know if these selected methods will yield the economies of scale they are planned to do. AM is today a method that is suited for low volume production which is strategic to apply on components during the product development process. Today at ACCT, investments are made in expensive tools before sales volumes to achieve economies of scale are hedged. The introduction of AM allows production of prototypes and also some of the first-selling units as an option not possible before in order to invest in tooling when sales volumes are secured and the product has penetrated the market.

The differences in the divisional organization structure applied within purchasing department and R&D department can have an effect on decision-making, the knowledge and experience are not integrated from a successful or failed projects to the next [25, p. 236]. For example, if the team is in the process of making a decision to manufacture a mold for a hydraulic machine it is not certain that the knowledge from this project is integrated to decision-making for mold manufacturing for the compressors. The same purchaser will be involved, but not the same design engineer or project manager. What ACCT needs to figure out is how to apply a matrix organizational structure where knowledge can be shared between the divisions within R&D [25, p. 236], in an interplay with the respectively purchaser. If not doing this, ACCT will continue to repeat the same mistakes and not learn about failures or success. This is also important when introducing AM as there will be unsuccessful attempts to apply the technology before understanding how to use it in the best possible way.

6 Introducing AM in a product development process

The model and tools suggested for ACCT to apply in their product development process are developed in order to introduce AM as an alternative in the prototyping process. The aim is to simplify the decision-making process in order to understand the trade-offs that are needed to be done during the prototyping process by the decision-maker when introducing AM. Also, three areas of application are presented.

6.1 Planning process

It is during the early stages in a product development process at ACCT where AM is most useful as the project preparatory phase and the design-phase. What is important during these stages is to reflect over what is critical to test or not depending on what type of component is tested. If a component is critical for the function of the end-product, testing is important to minimize risks. Generally, there are high demands put on the components at ACCT. By reflecting on the predetermined requirements as tolerances, surface requirements and material properties it can be easier to understand how important they are for the purpose of prototyping and what requirements that can be eased on. For example, verify the design by tests in the early stages and not consider the choice of material but use available materials for AM. By doing this, the desire of only testing what is going into serial-manufacturing is ignored in order to test a design in the early stages of the process.

6.1.1 **Prototyping objective**

By setting up the purpose of the prototyping process, it can be easier to understand the trade-offs of what is needed to be tested during the product development process and during the present stage. The prototype plan can be applied on both proof of concept prototypes and physical prototypes. An example of a structure to follow for a prototype plan is illustrated below in table 6.1 and is recommended by Ulrich & Eppinger [24, p. 387] to apply in a product development process. The prototype plan is also recommended to use at ACCT during the product development process. In table 6.1 an example of a prototype plan for an ACCT product, Rock Drill 100, is exemplified.

Table 6.1 prototype plan

	Geometry for Rock Drill 100
Purpose	Choose definite geometry based on characteristics for energy efficiency, penetration rate, ergonomics and noise levels.
Approximation level	Correct geometry
Study Plan	Build xx test models. Assemble components on test fixture. Perform necessary tests.
Timetable	Date xx - Choose geometry proposals Date xx - Complete design for test fixture Date xx - Test models and test fixture built Date xx - Assembly completed Date xx - Tests completed Date xx - Analysis of test results completed

In table 6.1 an example of a purpose with prototyping is to choose the definite geometry for the Rock Drill 100. If the purpose is to choose the definite geometry, hardware tests are needed to be performed, which means that a physical prototype is necessary for the prototyping process. When planning for the study plan it is recommended to have as many design options as possible, especially during the early stages in the project. The xx in the study plan and the timetable are parameters that are depending on project and design options.

Take advantage of the design freedom that comes with having many sourced components. Introducing AM allows testing multiple designs easier!

6.2 Areas of application

For this thesis, three areas of application have been chosen to be studied in more detail, injection molded components, machined components and cast components, see part 7 case studies for a more detailed study on some of ACCT's components. When considering components for prototyping with AM, there are some differences between the idea behind choosing components for the application areas.

6.2.1 **Injection molded components**

Since prototypes for injection molding components require tooling, the degree of design complexity for a component is not laying the same foundation to decision-making as for components who do not require tooling. The benefit with introducing AM is that it allows a tool-free production and the possibility to produce prototypes not possible before. Many materials available for injection molding are also available for AM which means that direct AM can be applied on components. Also, it allows manufacturing of prototype molds.

The recommendation for ACCT is to always consider using AM as an alternative when prototyping for injection molded components. And most important of all, to start produce prototypes for these components.

6.2.2 **Machined components**

When considering AM for prototyping of machined components, the design complexity is relevant for choosing components to the decision model. Three levels of design complexity are chosen to illustrate the differences. **Think about the complexity and if the geometry is considered simple, the relative benefits with AM compared with machining can be very small.**

6.2.2.1 Simple geometry

Geometries in picture 6.1 are relatively simple and the turning, milling and grinding processes are considered easy and not so time consuming. The benefits with using AM for these components are relatively small if time consuming post-processing operations are required on the AM component.

Figur 6.1 Simple geometries [26]

6.2.2.2 Intermediate complex geometry

The geometries in picture 6.2 have an intermediate complexity for machining. The benefits with AM are increasing as there is a higher degree of design complexity but the benefits are depending on what requirements are put on the prototype. The relative benefits with AM are depending on required post-processing operations.

Figure 6.2 Intermediate complexity [27]

6.2.2.3 Complex geometry

The geometry in picture 6.3 is considered complex and is very difficult to produce with conventional machining. The injection mold cavity and core in picture 3.19 are also considered as complex geometries and the benefits with AM are ideal. Same thing here is that the relative benefits are depending on the necessary post-processing operations.

Figure 6.3 Complex geometry [28]

6.2.3 **Cast components**

Since cast components require tooling as injection molding, the same principles apply here that it is not the complexity of the component that is laying the foundation to decision-making but the tool-free production that AM allows. Unlike injection molding, the materials available for direct AM part production of cast components are limited. As sand is available for AM, it is possible to produce sand molds for sand casting and this is a very interesting area of application for ACCT.

Always consider using AM as a prototyping alternative for sand-mold manufacturing for prototyping.

6.3 Evaluate the relative benefits and limitations

Since the purpose of the decision model is to introduce AM as an alternative it is recommended to analyze a component's suitability for AM and determine the alternatives possible for prototyping. The alternatives are the production methods associated to realization of the prototype and for some components CNC-machining to receive geometries that normally requires tooling as for example casting.

It is important to understand that AM is not suitable for all components, it is costly for large components and most often it will require post-processing operations to achieve the desired requirements.

6.3.1 **Planning for AM**

When considering using AM for a component, the initial step is to analyze the part for AM. Important in this stage is to understand the part orientation's impact on results, the need of support material and the accuracy of the process. The user should keep in mind that there is no right or wrong answer in this stage as the results from AM is depending on the geometry, material, machine and AM-process. Important things to consider before using AM are:

- Tolerances below 0.1 mm are generally not possible to achieve
- If perfect round holes are desired they should be in line with the print direction
- The best surfaces for metal AM parts will be the one facing the build platform
- The critical surfaces are the surfaces related to the overhang areas
- Surfaces below 8 Ra are generally not possible to achieve
- Combinations of all post-processing techniques can meet all requirements

6.3.2 **Compare post-processing operations**

By comparing the number of post-processing steps for the AM alternatives with the conventional manufactured alternatives, the relative benefits with AM produced parts can be considered. The limit for the number of post-processing steps is relative to the hours associated to the different processing steps as labor and machine costs at suppliers most often is calculated into the post-processing price. If planning for using AM on tooling as for example injection molding, have in mind that the necessary post-processing operations on the final component produced with an AM mold are necessary on the component produced with the conventionally manufactured mold. The same principles apply to cast components where the manufacturing processes are the exact same.

6.4 Decision model

The decision model that has been developed for ACCT's prototyping process is a hybrid quantitative and qualitative model. The quantitative part is intended to consider facts and give support to decision-makers to consider the alternatives from an objective point of view. The qualitative part considers the prototyping criteria and the different prototyping alternatives are analyzed relative each other in order to determine how well they meet the criteria. The general idea is that the user(s) should perform quantitative component and risk-analysis and qualitative trade-offs. The process is based on the sensitivity analysis and analytical hierarchy process described in part 4.1 and 4.2. The unit price analysis has inspiration from part 3.5.3 cost sourced components.

The process of making the decision can be studied below in picture 6.4 where the orange parts represents the quantitative fact-based part and the blue represents the qualitative part. It is illustrated as a linear process but it is recommended to perform activities in parallel with each other.

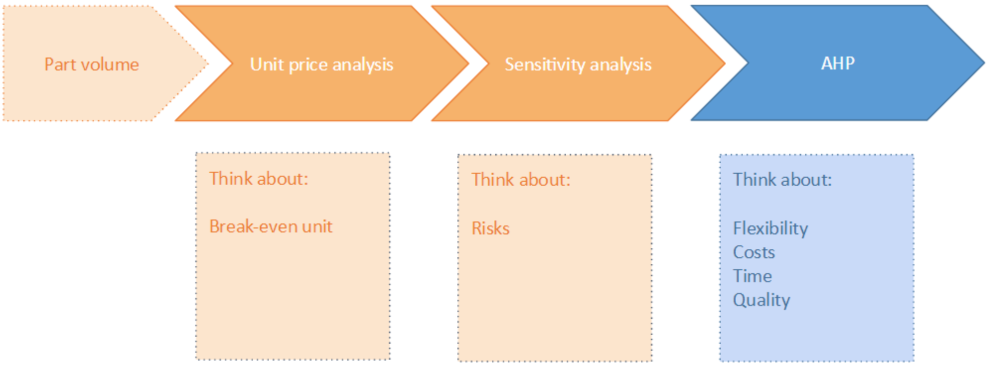


Figure 6.4 Decision process

6.4.1 **Unit Price analysis**

Before starting the unit price analysis, the user needs to be aware of the part volume of the component. As unit-prices for AM components are rapidly increasing when part volume increases, it is good to have this in mind when planning for using AM in a product development process. It is difficult to estimate the final price of sourced AM components as described in part 3.5 cost structure.

For SLS-printed components, it is possible to estimate the unit price by calculating the material cost for the part and assume that this represents 70 percent of the cost. The part volume is calculated as the mean value of the absolute volume and the actual part volume of the component as not all powder is possible to recycle after the print to the next. [11] This cost is then multiplied whit a factor (x) between two and ten, this yields a range where the price probably will be within when having the component sourced. To calculate this, use formula 6.1.

$$Unit\,\mathrm{Pr}\,ice = \frac{PartVolume \cdot MaterialCost \cdot x}{0.7} \tag{6.1}$$

When analyzing components for metal AM it is recommended to send quotation requests to suppliers as Lasertech, 3D-met print and Materialise to compare prices as it is difficult to estimate these.

6.4.1.1 Break-even for tooling

When planning for AM for a component whose final-part production method requires investments in tooling it is interesting to have the break-even point in mind. As described in part 3.6.2 injection molding vs AM, the break-even unit can be estimated just by comparing the tooling cost split over the number of units produced and the material and machine cost for AM parts. See section 7.1 injection molding when this is applied on a component at ACCT.

6.4.2 **Project management tool**

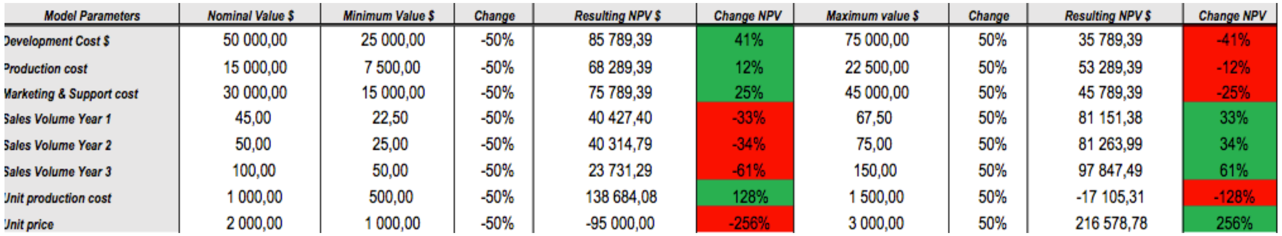
As a foundation to decision-making at for example PDC-meetings during the product development process, an Excel-tool is developed so that decision-makers can understand risks and consequences of prototyping decisions by looking at scenarios like "What if". The decision made by the team can have an effect on internal factors but external factors are not possible to affect during the product development process.

The aim with the tool is to create an awareness around the risks when making decisions on prototyping and estimate their effect on costs like development costs, production costs, development time (effect on sales profits). The aim is also to create an understanding for how to analyze costs during the project since it is easy to limit one's mindset that the costs that already have been allocated in the project are very high. The tool shall make it easier for decision-makers to think about what really matters in the presence of the project and that is how to best use resources in the coming stages of the project. With the MS as source for information, the input to the project management tool is the development cost, production cost, marketing cost, sales volumes year 1-3, production cost/unit and product price/unit.

6.4.2.1 Sensitivity analysis

When performing a sensitivity analysis, the NPV for the project is calculated with the input variables. The sensitivity of the project is calculated by changing the input variables from minimum value to maximum value and the change of the NPV can be calculated while holding all other variables constant. See NPV calculations in Appendix D Calculations. The effect from different scenarios can therefore be analyzed as missing sales volumes the first year, increased development cost and increased production cost/unit.

An example of a sensitivity analysis is presented in figure 6.5. The effect on NPV when development costs are increased with 50 percent can be compared with having decreased sales profits during the first year by 50 percent. If the project is delayed by 50 percent in time, it would be the same as missing out 50 percent in sales profits during the first year as the scheduled time for the project is approximately one year for ACCT's projects. In figure 6.5, the difference from these two scenarios can be compared and having increased development costs by 50 percent has a negative effect on the project with -41 percent while having decreased sales profits has a negative effect with -33 percent. As using AM will be costly, especially for metal AM, the extra cost can be added to the project and the sensitivity can be analyzed and compared with the sensitivity from decreased sales profits. An example of a scenario where a sensitivity analysis can be of great value for ACCT is when deciding not to produce a prototype for an injection molded component before investing in tooling, this kind of scenario is described in part 7.1 Case studies.



Model Parameters	Nominal Value $	Minimum Value $	Change	Resulting NPV $	Change NPV	Maximum value $	Change	Resulting NPV $	Change NPV
Development Cost $	50 000,00	25 000,00	-50%	85 789,39	41%	75 000,00	50%	35 789,39	-41%
Production cost	15 000,00	7 500,00	-50%	68 289,39	12%	22 500,00	50%	53 289,39	-12%
Marketing & Support cost	30 000,00	15 000,00	-50%	75 789,39	25%	45 000,00	50%	45 789,39	-25%
Sales Volume Year 1	45,00	22,50	-50%	40 427,40	-33%	67,50	50%	81 151,38	33%
Sales Volume Year 2	50,00	25,00	-50%	40 314,79	-34%	75,00	50%	81 263,99	34%
Sales Volume Year 3	100,00	50,00	-50%	23 731,29	-61%	150,00	50%	97 847,49	61%
Unit production cost	1 000,00	500,00	-50%	138 684,08	128%	1 500,00	50%	-17 105,31	-128%
Unit price	2 000,00	1 000,00	-50%	-95 000,00	-256%	3 000,00	50%	216 578,78	256%

Figure 6.5 Sensitivity analysis from project management tool. Numbers are assumptions and have no connection to ACCT’s development projects.

6.4.3 **AHP – Evaluation of alternatives**

With the prototyping objective as starting point, and the alternatives for prototyping, the AHP problem definition is illustrated below in figure 6.6.

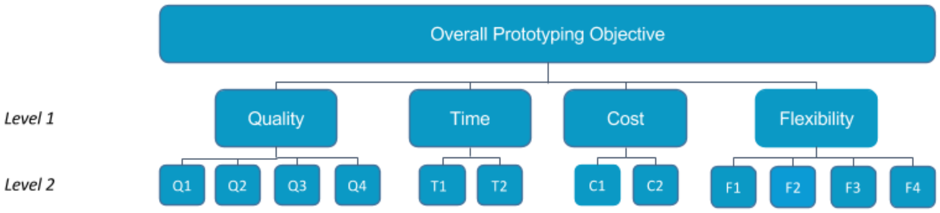


Figure 6.6 AHP problem decomposition

There is always a need to achieve the quality requirements put on the final component when prototyping. But, it is not always possible to achieve these while keeping a high degree of flexibility and low lead times which is of great importance during a product development process. By using pairwise comparison, the criteria are set towards each other and trade-offs between quality, time, cost and flexibility can be made. The Level 2 criteria are described in table 6.2 and are the same from part 5.3.3 Prototyping criteria. See Appendix C AHP Process for how to perform the pairwise comparison and hierarchical synthesis.

Tabell 6.2 Prototyping Criteria

	Sub-criteria	*Description*
Q1	Material properties	The ability to receive desired material properties
Q2	Surfaces	The ability to receive the general surface requirements
Q3	Tolerances	The ability to obtain the general tolerances required
Q4	Visual aspects	The ability to visualize the component; look and feel
F1	Volume flexibility	How flexible is the alternative in terms of production volumes high/low
F2	Multiple design flexibility	The ability to test multiple designs
F3	Redesign flexibility	How flexible is the alternative in terms of design changes
F4	Material flexibility	How flexible is the alternative in terms of material changes
C1	Tool cost	Requirements of investments in tooling with high costs
C2	Prototype cost	General cost of the prototype
T1	Redesign time	Required time if design changes are needed
T2	Lead time	Lead time from order to delivery

6.5 The value of time

For this thesis work, many attempts on quantifying the value of time and use it in a decision model has been performed. Here, some ideas that are not integrated in the model are presented. According to research from consulting firm McKinsey & Co [29], high-technology products reaching the market 50 percent over time but on budget have decreased sales profits by 33 percent during its first five years. While reaching the market 50 percent over budget but on time will yield decreased sales profits by 4 percent. With these numbers as assumptions, the differences in costs can be calculated for the Rock Drill 100 and the Cobra Electro.

Source: McKinsey & Co.

Figure 6.7 Effect on time to market [29]

Another idea for calculating the value of time for projects at ACCT is to consider how many products are planned to be sold per day during the first year and assume that every day during the product development process is equal to this profit per day. If the project is delayed, every day the product is not on the market sales profits will be lost.

These analyses are something to have in mind when making decisions on prototyping with AM as it has the possibility to reduce lead times drastically in a product development process.

6.6 Analysis

As the decision-making theories applied in the decision-making process are practiced within manufacturing and product development today, they are considered relevant for ACCT to apply in their product development process. Quantitative analysis focuses only on measurable quantities and the NPV relies solely on what is measurable [24, p. 464], it does not take intangible factors into account. Therefore, the qualitative criteria complement the numerical analysis by its integration of non-quantitative factors as flexibility. Each of the theories has their uncertainties but together in the hybrid process they provide a synergy to decision-making.

It is important that the user(s) has an understanding of the uncertainties of the results from AM as the material's micro-structure have an effect on the mechanical properties of the final part. Chapter 3 Additive Manufacturing, which is intended to give the user(s) knowledge about theories of AM is limited due to its lack of analysis of the material's micro-structures. But it can be stated that it is very hard to predict results.

Testing AM components is key to conclusions and the benefits with AM is that failure or success can be realized fast.

As all prototypes at ACCT are sourced from suppliers, there is a supplier selection process to all alternatives in the decision-model. It is uncertain whether ACCT's present AM-suppliers can perform necessary post-processing operations to meet requirements put on the prototypes. Since supplier selection is considered as out of scope for this thesis work, it is possible to continue future research here and analyse suppliers for AM at ACCT.

7 Case studies

The case studies chosen for this thesis work are determined as strategic areas of application for ACCT. The research question for the case studies is; how to produce prototypes in the best way? This chapter is also used as a basis for exemplifying the decision-making process in order to increase the understanding of the process. Data for case studies have been gathered with the same procedures as for chapter 5 Atlas Copco Construction Tools and are also representing the empirical data for this thesis work.

7.1 Injection molded component

For this study, a component has been selected that is designed for injection molding. The component is a manifold that is intended to transfer and regulate water flow in a hydraulic rock drill, Rock Drill 100. The desired construction material is plastic as PA6, PA12 or POM. The component is illustrated below in figure 7.1.

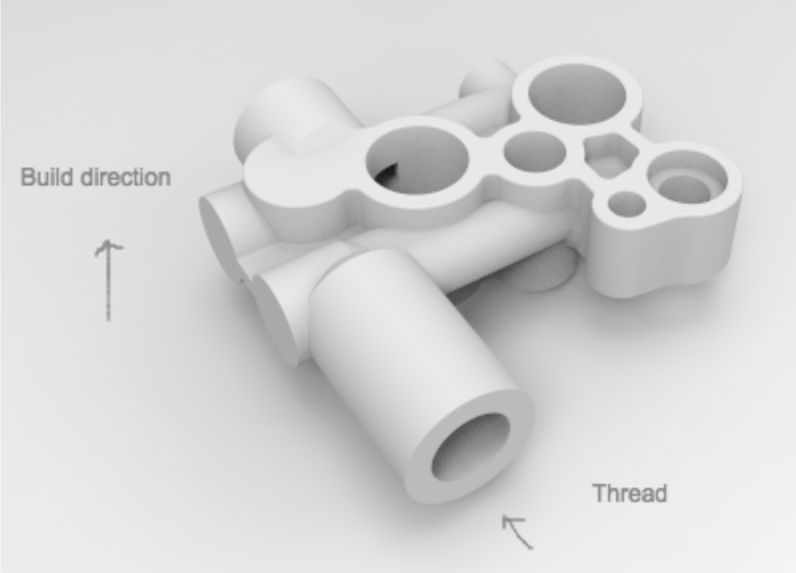


Figure 7.1 Manifold

7.1.1 **Evaluate the relative benefits**

The part consists of three holes where the surface roughness required will not be possible to obtain by using AM today. These holes need to be post-processed in order to obtain the surface requirements. The component also has one thread, which is recommended to post-process. These are relatively easy post-processing operations, so the relative benefits with AM is considered as ideal. In general, the surfaces can be quite rough for the application area. Print direction as in picture 7.1 to obtain the best surfaces regarding surface roughnes. The method chosen for this analysis is SLS using material PA2200 from EOS, which is equal to PA12.

7.1.2 **Prototyping alternatives**

In order to receive the prototype for this component, there are four alternatives determined and these are compared below in table 7.1.

Table 7.1 Prototyping alternatives

Alternative	***Tool-steel mold (A1)***	***Aluminum mold (A2)***	***AM mold (A3)***	***AM component (A4)***
Number of post-processing steps	0	0	0	3

The price for a tool-steel injection mold for these kinds of components are between 200 000 – 350 000 SEK. The supplier of tool-steel molds is located in China and the lead times are normally around 20 weeks from order to delivery. Prices for aluminum molds are around 80 000 – 100 000 SEK for these components and lead times around 10 weeks. Lead times for an AM mold is depending on the supplier and material chosen but it is assumed, for this analysis, that it is shorter than for tool-steel molds and aluminum molds. The AM mold will probably need some post-processing operations as well, but for this analysis they are considered equal to the one's needed at the tool-steel mold and aluminum mold. An AM component is possible to receive within a week from a local supplier.

7.1.3 **Decision model**

The process of using the decision model is described in this section. Input data to the sensitivity analysis are real numbers from the project Rock Drill 100.

7.1.3.1 Unit price analysis

The part volume of the unit is (60 + 210) /2 = 135 cm^3 and with the equation 6.1 described in part 6.4.1 Unit price analysis, the unit price is beforehand estimated to be approximately between 200 - 900 SEK/unit for the AM component, this is without consideration of the post-processing steps in the final price.

The mold cost for the AM mold is harder to predict and is depending on if it is manufactured in plastic or in metal. If it is planned for using AM on tool-steel molds, the price will probably be higher than the conventionally manufactured mold, but prototype molds in plastic will be less expensive.

7.1.3.2 Break-even tooling

In picture 7.2 the break-even unit is illustrated for one of ACCT's molds that were manufactured for the Cobra Electro. The mold is assumed comparable in price for the analysis of the manifold mold. The final mold cost is 330 000 SEK. When assuming that the final part price including post-processing operations will be 300 SEK, the break-even unit is at 1 100 units when only comparing these costs.

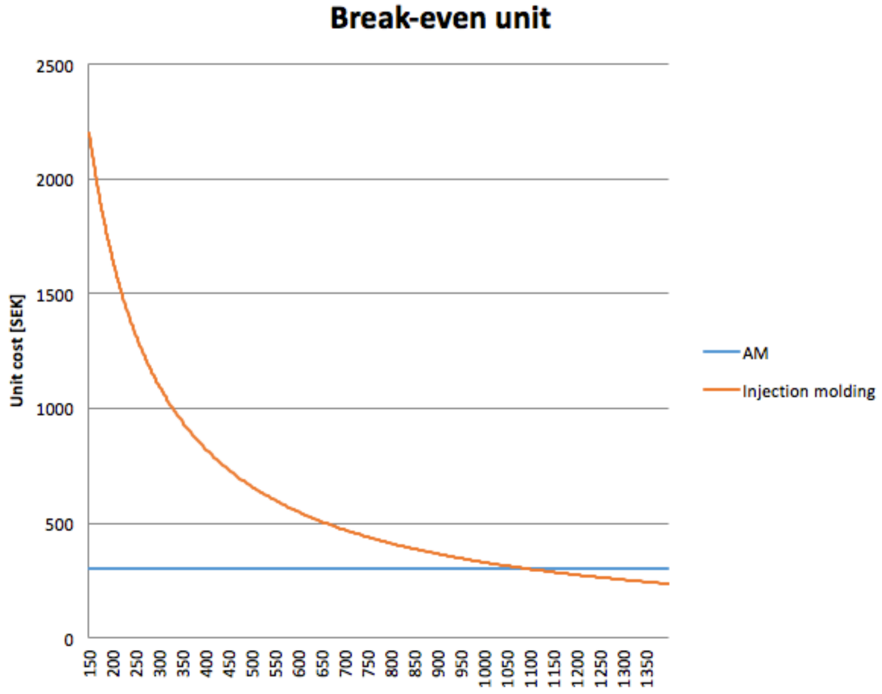


Figure 7.2 Break-even unit

7.1.3.3 Sensitivity analysis

The risk of not producing a prototype and invest in a tool-steel mold before testing the component is analyzed around the long lead times that are associated with the alternative. The risk of making these kinds of decisions is that after waiting 20 weeks for manufacturing of the tool-steel mold, it can appear that the final components do not meet the requirements of the application. Sometimes it is as bad as it is necessary to completely redesign the component, scrap the mold, and wait for another 20 weeks to receive the new tooling. These 40 weeks in total, in some cases, represents a time delay by 50 percent of the project and is direct linked to that sales profits decrease by at least 50 percent the first year since the product is not on the market.

By looking at this risk, the NPV of the project can be calculated and compared to its planned value. This change in NPV can be compared with the change in product development costs since producing a prototype mold for these kinds of components can be costly, for example producing a prototype mold in aluminum with CNC-milling or produce prototype molds with AM to cover the first units until the final mold is ready. Below in table 7.2 the numbers from the project management tools are presented.

Table 7.2 Sensitivity analysis. X is the nominal value of the product development cost that is planned for the project according to the MS. Y is the nominal value of the planned sales volumes during year 1 according to MS.

Rock Drill 100	***Nominal value***	***Minimum value***	***Change NPV***	***Maximum value***	***Change NPV***
Product development cost [SEK]	X	-	-	X*1,5	-10 %
Sales volumes year 1 [units]	Y	Y*0,5	-20 %	-	-

The comparison in table 7.2 is between the difference of the effect on NPV in the project when increasing the product development cost by 50 percent and decreasing sales profits the first year by 50 percent. Before making these sort of decisions, it is recommended to consider its risk and impact on the project and reflect upon whether it is worth risking the time to maintain the planned development cost. Increased development costs by 50 percent have a negative effect on the project with -10 percent while decreased sales profits have an effect by -20 percent.

When analyzing the AM component alternative, the risk of not reaching the market on time is compared with producing the product during the first three years with a higher product cost (PK). By assuming the unit cost of Rock drill 100 is increased by 300 SEK/unit, the change in NPV is compared with a delay by 50 percent in time which results in decreased sales profits as the previous example. The change in NPV can be seen in table 7.3 and the change of the PK will affect the project's NPV by -2 percent.

The question to be asked here is; is it worth the risk of reaching the market too late if the change in NPV is as less as -2 percent over a three-year period?

Table 7.3 Sensitivity analysis. Z is the nominal value of the unit production cost that is planned for the project according to the MS. Y is the nominal value of the planned sales volumes during year 1 according to MS.

Rock Drill 100	*Nominal value*	*Minimum value*	*Change NPV*	*Maximum value*	*Change NPV*
Unit production cost [SEK/Unit]	Z	-	-	Z + 300	-2%
Sales volumes year 1 [units]	Y	Y*0,5	-20%	-	-

7.1.3.4 AHP

The AHP is used in order to ease the qualitative decision, the alternative 1 is not considered here as it is not really comparable as a prototyping method for this analysis. See Appendix C AHP Process for the pairwise comparison of criteria for this case study.

The level 1 criteria's weight is determined in table 7.4 by pairwise comparison. The same procedure is applied for the level 2 criteria and they can be seen in table 7.5.

Table 7.4 Level 1 criteria

	Quality	*Flexibility*	*Cost*	*Time*
Weight	0.43	0.85	0.14	0.85

Table 7.5 Level 2 criteria

	Q1	*Q2*	*Q3*	*Q4*	*F1*	*F2*	*F3*	*F4*	*C1*	*C2*	*T1*	*T2*
Weight	0.26	0.26	0.26	0.26	0.78	0.78	0.78	0.78	0.26	0.26	0.78	0.78

By choosing alternative 2 as the reference and rate the other alternatives if they are better '+', equal to '0' or worse than '-' according to the criteria, the final score of the hierarchical synthesis can be calculated and used as a guideline for decision-making. Below in table 7.6, the final score of the alternatives can be seen.

Table 7.6 Rate alternatives

	Q1	*Q2*	*Q3*	*Q4*	*F1*	*F2*	*F3*	*F4*	*C1*	*C2*	*T1*	*T2*	*Score*
A2	0	0	0	0	0	0	0	0	0	0	0	0	0
A3	0	0	0	0	0	0	+	0	0	0	+	+	2.0
A4	-	0	0	0	+	+	+	+	+	+	+	+	4.0

It is assumed that the AM component is able to meet some of the quality requirements that are set for the testing, i.e. the tolerances are achieved and the component achieves the surface requirements after post-processing operations. It is assumed that the material properties from the direct AM application are not as satisfying as the components from the molds.

7.1.4 **Recommendation**

With the sensitivity analysis performed above, it is considered not worth the risk of reaching the market too late in order to decrease the unit cost with 300 SEK for this scenario. The outcome from the AHP shows that the AM component meets the criteria best of the alternatives that have been compared. The recommendation is to use AM to produce prototypes for these kinds of components. Tests can be performed on the component within a week and if the results are satisfying, it is recommended to keep the component as an AM component during the entire product development process while waiting for production of the final tool-steel mold or when the product has penetrated the market.

Below in picture 7.3, the component can be seen manufactured with AM without any post-processing operations. The thread has been modelled using Creo Parametrics and the holes that usually requires plugging has been covered. These three covered holes can be seen in the lowest picture.

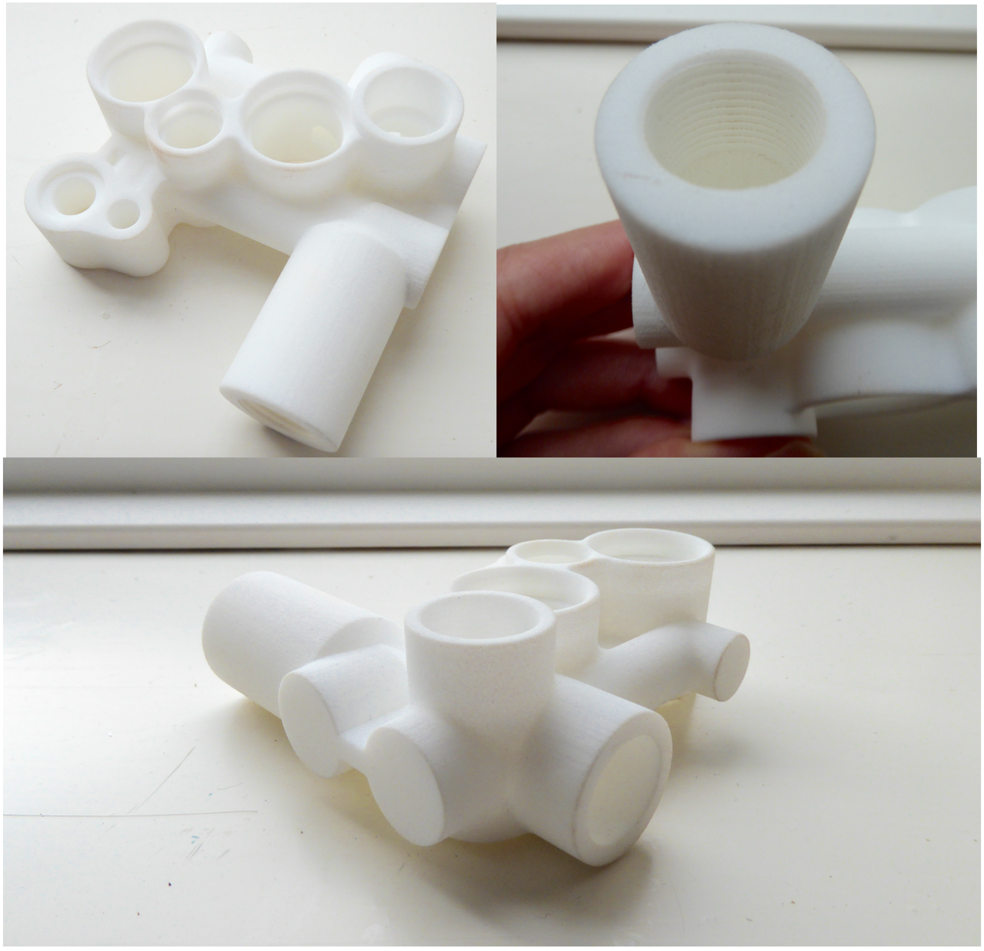


Figure 7.3 SLS printed manifold

7.2 Machined components

For this study, a component has been selected that is designed for manufacturing with machining as; turning, milling and drilling. The part is a control valve manufactured in steel. The complication with this part is that it is rather complex to manufacture since there are many operations to obtain the requirements on geometry, surfaces and tolerances. This component was a part of a product that was developed during 2005 but for this analysis it is assumed that the component is a part of the Cobra Electro. See component in picture 7.4.

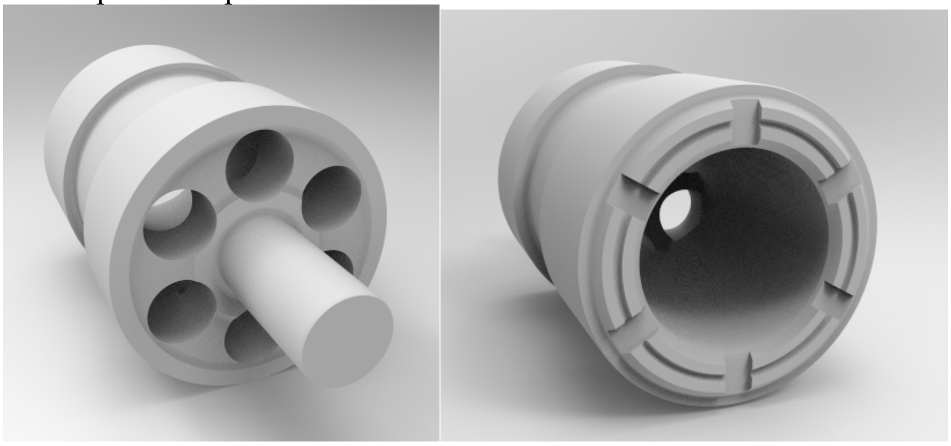


Figure 7.4 Control valve

7.2.1 **Evaluate the relative benefit**

The component's outer mantle surfaces have a general high surface requirement, which is not possible to obtain with AM. The outermost diameters of the detail have a fitting character where tolerance requirements below 0.1 mm needs to be obtained. These are not possible to achieve with AM, as the requirements on surfaces and tolerances apply to the same surfaces, it means that it is possible to achieve these requirements with the same post-processing operation on an AM part. Placing the part so that the build direction is axial of the component, the best surfaces are obtained where the surface requirements are highest. Also, the holes will obtain the best tolerances and be perfect round. The build platform will face the stub shaft's cross-section. Support material will be needed on the surfaces around the holes. See figure 7.5.

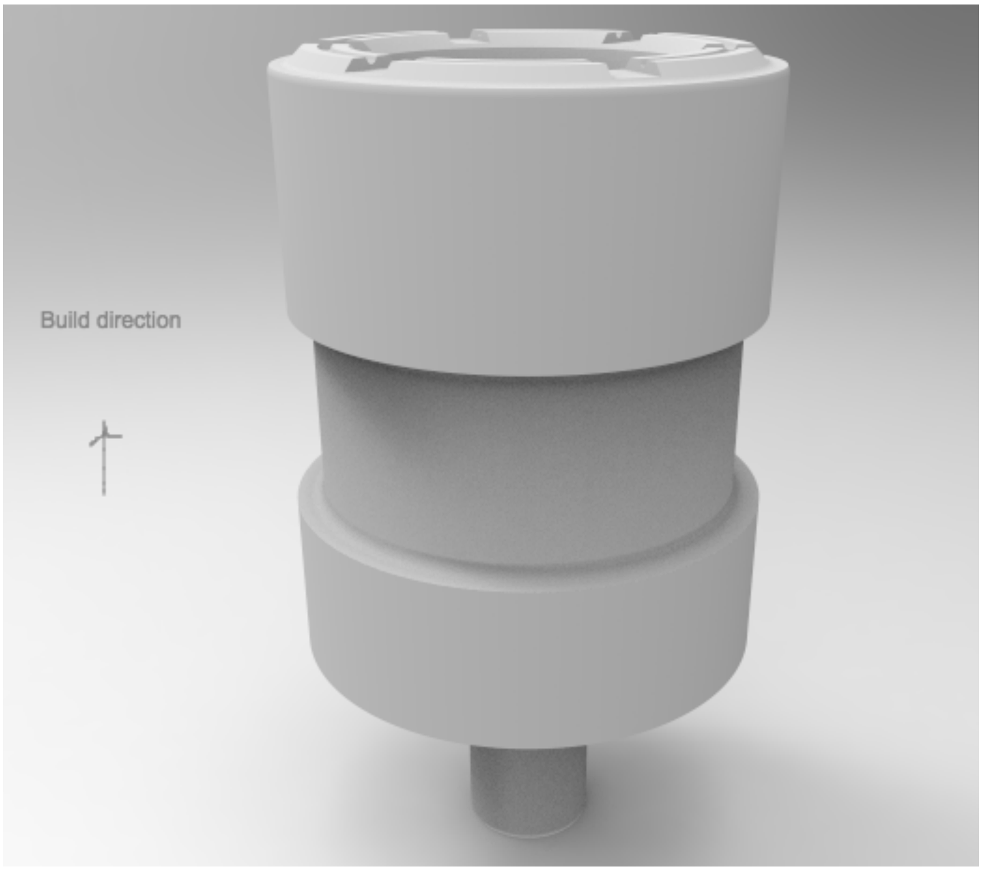


Figure 7.5 Build direction control valve

7.2.2 **Prototyping alternatives**

The alternatives for prototyping this component is to either use machining or AM with necessary post-processing operations. Without post-processing, the item is delivered with coarse surfaces. This operation is necessary either way to obtain the surface requirement required, so the same operation performed on the machined component is performed on the AM component. Because of the complexity of the detail, the machining alternative demands high set-up costs and labor costs due to time-consuming preparations. The turning operation necessary on the AM part is a relatively easy operation so the relative benefits with AM are ideal. Removal of support material is always necessary as the build platform needs to be removed for SLM which is the process ACCT's present suppliers are using. The alternatives are presented in table 7.7.

Tabell 7.7 Prototyping alternatives

Alternative	*Machining (A1)*	*AM + Machining (A2)*
Number of post-processing steps	0	2

7.2.3 **Decision model**

The process of using the decision model is described in this section. Input data to the sensitivity analysis are real numbers from the project Cobra Electro.

7.2.3.1 Unit price analysis

The volume of the component is approximately 20 cm^3. Having the AM component sourced from a local supplier costs between 3 500 – 4 400 SEK per unit in maraging steel, without the necessary post-processing operations included in the price.

7.2.3.2 Sensitivity analysis

When considering to use AM during the product development process and have the component produced with the final price 4 000 SEK per unit, the cost for the 30 units covering the process would be 120 000 SEK. When considering this as an extra production cost in the project, the sensitivity would be negligible as can be seen below in table 7.8 but the impact on having it as the final part production method the first three years would have a major impact. The sensitivity would be negligible even when considering having the 100 first units produced with AM as well. The sensitivity of reaching the market 50 percent over time is compared to the change by adding extra production costs. Because of the complexity with this component, there is a risk that production technical issues are detected late in the development process and that these issues can have an effect on the development time. For example, issues when deburring the machined holes as can be seen in figure 7.6. The assumption that the project risks reaching the market 50 percent over time is high but includes a risk-margin time if issues are discovered in the project preparatory process. The risk is that major design changes are needed to be made which can possibly lead to a 50 percent time delay since the prototype and test-phase is scheduled for six months during the Cobra Electro project.

Figure 7.6 Machined component with defects that have arisen in production when deburring the holes.

Tabell 7.8 Sensitivity analysis. X is the nominal value of the production cost that is planned for the project according to the MS. Y is the nominal value of the planned sales volumes during year 1 according to MS. Z is the planned unit production cost for the project according to the MS.

Cobra Electro	***Nominal value***	***Minimum value***	***Change NPV***	***Maximum value***	***Change NPV***
Unit production cost [SEK/Unit]	Z	-	-	Z + 4000	-43%
Production cost [SEK]	X			X + 120 000	0 %
Production cost [SEK]	X	-	-	X + 400 000	-1 %
Sales volumes year 1 [units]	Y	Y*0,5	-20%	-	-

The same trade-off should be analyzed here; is it worth the risk of reaching the market too late if the sensitivity in the project is -1 percent?

7.2.3.3 AHP

The criteria are reviewed with the same procedure as in case study for injection molding and therefore they yield the same weight for this AHP analysis. The two alternatives are rated below in table 7.9 where the machined component is chosen as reference. It is assumed that the AM component will obtain the surface requirements and tolerances after post-processing but material properties are not as satisfying as for the machined component.

Tabell 7.9 Rate the alternatives

	Q1	*Q2*	*Q3*	*Q4*	*F1*	*F2*	*F3*	*F4*	*C1*	*C2*	*T1*	*T2*	*Score*
A1 (reference)	0	0	0	0	0	0	0	0	0	0	0	0	0
A2	-	0	0	0	0	0	0	0	0	-	0	+	0.51

As machining allows a high degree of flexibility as well, it can be seen from the ratings that the alternatives are very similar how they meet the criteria. What determines that the AM component yield the higher score is the short lead times associated to AM.

7.2.4 **Recommendation**

It is difficult to draw conclusions from the decision-model but if tests can be performed on the component within a week and if the results are satisfying, it is recommended to keep the component as an AM component during the entire product development process while prototyping the final-part production component.

7.3 Cast component

The component chosen for this case study is a component that is designed to be produced with sand casting. The component cannot be published in the report due to confidential reasons. At the time of writing, the component is under development and is used as a foundation for analysis and evaluation of topology optimization.

7.3.1 **Proof of concept**

As the component is under development and the component's geometry is rather complex, there is a need for a proof of concept prototype. The purpose of prototyping for this scenario is to use as a foundation to production technical discussions where CAD-models are not sufficient. There is no need to apply the decision-making model for this scenario, but AM is strategic to use since it enables manufacturing of complex geometries fast.

It is important to know that AM has many application areas and not only for direct prototyping production.

8 Implementation plan

The implementation plan developed for this process is a three-stage approach where inspiration is from the implementation of Cooper's stage-gate product innovation process [30], where relevant fragments have been selected and adopted to suite ACCT's organization and processes.

8.1 Stage 1 - Lay the foundation

The initial stage is to lay the foundation of the decision-making process. It is important to have commitment from senior management when leading this change forward otherwise it can be a frustrating battle. [30, p. 332] The decision-making process can not only be implemented by one person; therefore, it is important to assemble a team who will introduce AM in the product development process. Since there is a community with design engineers with an interest of AM at ACCT today, it is recommended that these people will represent "The Team" and seek commitment from senior management.

When the team has studied the process, and understood the basics of it, it is the team's mission to hold workshops with others involved. One example of a workshop activity necessary for the implementation of the process is to have a "Problem Detection Session". The aim is to break out key problems with the decision model and identify solutions for these. By assessing small teams from different functions and give example scenarios to analyze, the pitfall with the process can be identified and possible solutions can be recommended. [30, p. 334]

As AM is developing at an exponential rate, it is important to understand how to improve this decision model as the technology is evolving. Therefore, the team is also responsible for mapping the next steps. As AM is stepping towards industrialization it is necessary to adapt the process for final-part production, the team should have a plan for when this is necessary to do and by who. Also, se Chapter 9 Future Research for inspiration for how to make adjustments.

8.2 Stage 2 - Design the decision-making process

As the outcomes of the decision model have an impact on other processes at ACCT, it is important to integrate the process in present processes in all functional areas. As the decision model is targeting design engineers, project management and purchasers it is important to integrate and adjust test-processes and production preparatory processes.

8.3 Stage 3 - Implementing decision-making process

In order to integrate the decision model into projects, there are several approaches. Recommended for ACCT is to use the “piloting” [30, p. 348] approach. This is a gradual approach to bring the process into projects by choosing a hand-selected project where the process is integrated. Some people can regard this approach as slow, but it gives the team time to design the process and integrate it with other functional areas.

While implementing the decision model, an important factor for the success of the decision-making process is to educate engineers in AM. As described in part 3.4 Design Guidelines, knowledge, experience and planning helps achieve the best results of AM. Also, as described in 5.5 Analysis, it is very important to integrate the knowledge between the different functions in the organisation.

9 Future research

During the thesis project, valuable input has been received that have been out of scope. This chapter introduces opportunities for future research and possible opportunities for further development of the decision model.

9.1 Explore additional areas of application

As the case studies are limited to some manufacturing technologies, it is recommended to consider using AM for prototyping for additional technologies at ACCT as there are several other technologies where tooling is required. By using the same research process as this thesis work it is possible to find additional areas of application at ACCT.

9.2 Future master thesis opportunities

As the scope of this thesis project only considers the product development process there are two loose ends of the model where future research is possible.

9.2.1 **Final part production**

If considering using AM as final-part production, it changes the entire design process and the design engineer should apply to design for additive manufacturing (DFAM) and not DFM. Below in picture 9.1 a manifold for a hydraulic machine is illustrated that is developed by Henrik Nilsson who also is a master thesis student at Atlas Copco. The design to the right is a component where DFAM has been applied and the new design has the possibility to reduce the weight by 92 percent of the component by the new design and when changing from metal to plastic. [31]

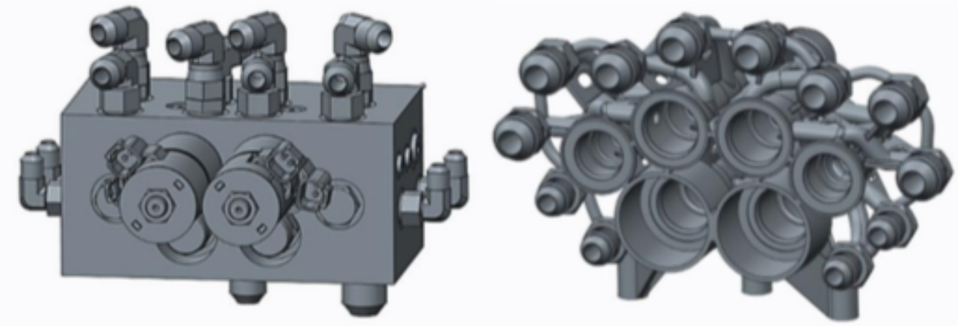


Figure 9.1 Manifold [31]

To decision-making, this adds another parameter to have in mind when trade-off analyses are performed. A scenario to analyze is; is it possible to allow a higher price for ACCT's products if the weight of the product is drastically reduced?

DFAM also have the possibility to increase function for some components as improved fluid dynamics since increased design freedom allows optimized design of cooling channels. This is applied today for final-part production of tool-steel injection molds. Studies has shown that the same results with the same material as for conventionally manufacturing can be obtained. [3, p. 85] As described in part 3.7.2 Precision part for automotive industry, DFAM also has a possibility to reduce noise levels. These are all very interesting areas for ACCT since there is always a need to reduce weight and noise levels on end-products.

9.2.2 **AM suppliers**

As AM components at ACCT are sourced from suppliers today, there is also a future thesis opportunity to analyze AM suppliers for final part production. There are many parameters to consider in these kinds of analysis as production capacity, deliver reliability, flexibility and most important of all; the true costs of AM parts compared with conventionally manufactured parts. When considering costs of AM for final part production, there are additional supply chain costs to be considered in the final price of AM parts that has not been taken into account for this thesis work. For example, at ACCT today, the supplier agreement with injection molding suppliers are that production batches of six months of demands are produced and stored at the supplier. These supply chain costs that adds to the unit cost should be taken into account when comparing injection molding with AM. In case study 7.1, these costs are not considered in the analysis and when they are considered, the break-even unit will probably be a lot higher than 1 100 for the manifold.

During this thesis work a new 3D-printer has been launched on the market, Hewlett-Packard's HP Multi Jet Fusion [32], see figure 9.2. They claim that their new Jet Fusion technology is 50 percent cheaper and ten times faster rather than competitors for in-house production. The new supplier, Materialise, that has been considered in this thesis work for prototyping has recently acquired one of these to use for outsourced production. There is a possibility and a future master thesis opportunity to analyze in-house vs outsourced production with this new technology.

Figure 9.2 HP's Multi Jet Fusion [32]

10 Conclusion

The conclusion of the thesis project.

The conclusion from the thesis project are that strategic use of additive manufacturing in a product development process at ACCT is during the early stages of the projects. Since, many components are sourced from suppliers in ACCT's products AM allows taking advantage of the design flexibility that comes with outsourced production. If testing an AM component which normally requires tooling as injection molding during the early stages of the project and the results are satisfying, it is recommended to continue using AM during the entire product development process while waiting for production of the final-part production tool.

If ACCT shall continue position themselves on the market with products as "state-of-the-art technology in line with Atlas Copco brand position" future research within AM as final-part production method has the possibility to add value to ACCT.

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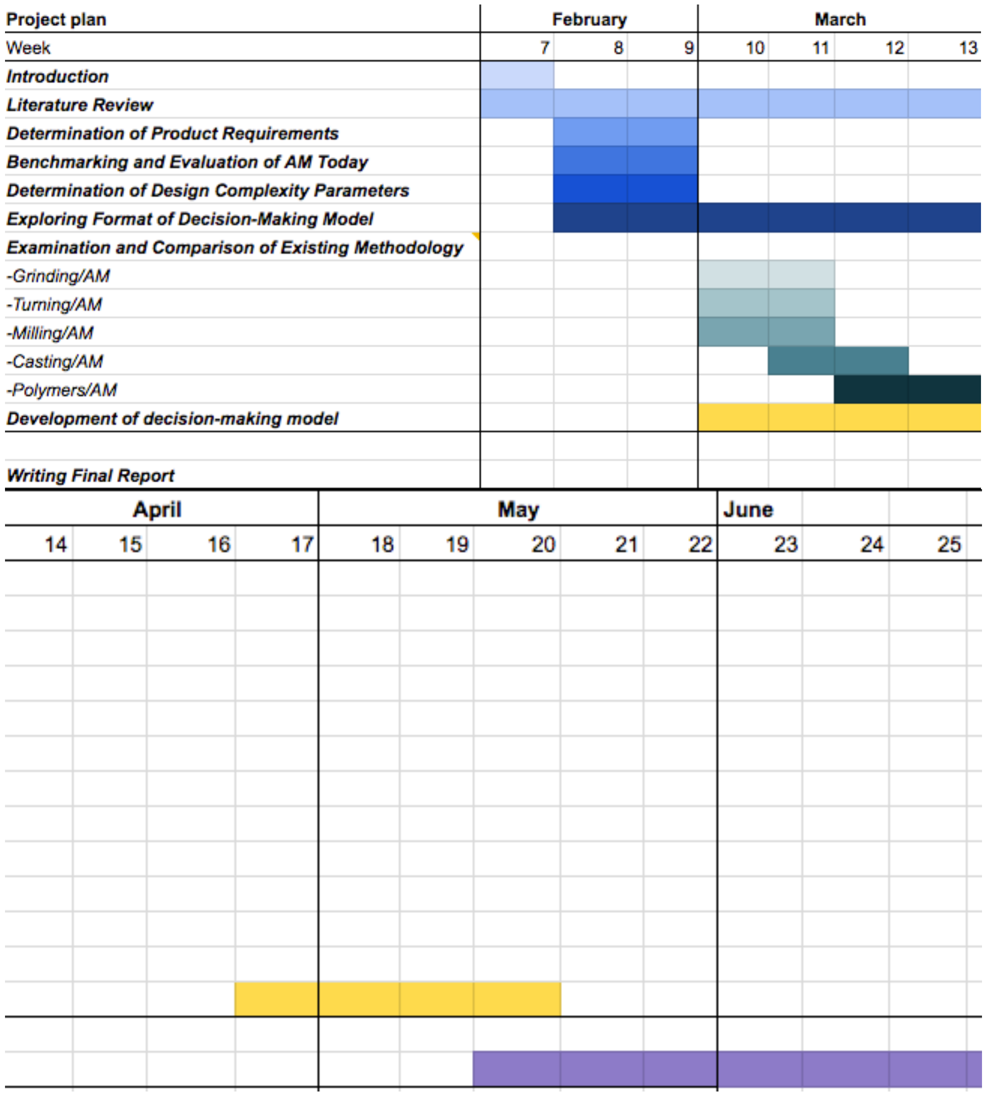
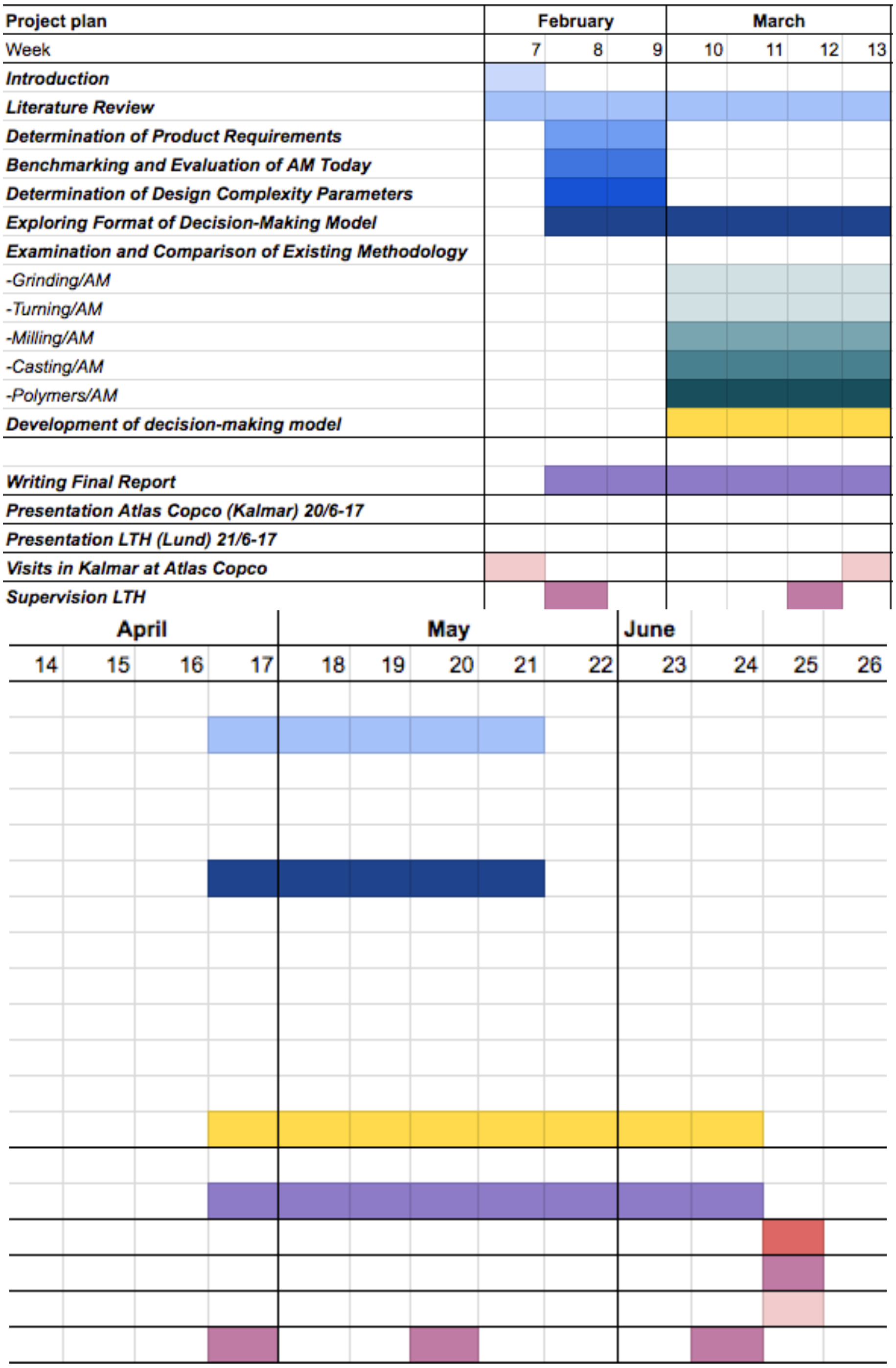
Appendix A Time plan

A.1 Project plan



Project plan	**February**			**March**				**April**				**May**					**June**		
Week	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Introduction	■																		
Literature Review	■	■	■	■	■	■	■												
Determination of Product Requirements		■	■																
Benchmarking and Evaluation of AM Today		■	■																
Determination of Design Complexity Parameters		■	■																
Exploring Format of Decision-Making Model		■	■	■	■	■	■												
Examination and Comparison of Existing Methodology																			
-Grinding/AM				■	■														
-Turning/AM				■	■														
-Milling/AM				■	■														
-Casting/AM					■	■													
-Polymers/AM						■	■												
Development of decision-making model				■	■	■	■				■	■	■	■					
Writing Final Report														■	■	■	■	■	■

A.1 Project Outcome



Project plan	February			March				April				May					June			
Week	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Introduction	■																			
Literature Review	■	■	■	■	■	■	■				■	■	■	■	■					
Determination of Product Requirements		■	■																	
Benchmarking and Evaluation of AM Today		■	■																	
Determination of Design Complexity Parameters		■	■																	
Exploring Format of Decision-Making Model		■	■	■	■	■	■				■	■	■	■	■					
Examination and Comparison of Existing Methodology																				
-Grinding/AM				■	■	■	■													
-Turning/AM				■	■	■	■													
-Milling/AM				■	■	■	■													
-Casting/AM				■	■	■	■													
-Polymers/AM				■	■	■	■													
Development of decision-making model				■	■	■	■				■	■	■	■	■	■	■	■		
Writing Final Report		■	■	■	■	■	■				■	■	■	■	■	■	■	■		
Presentation Atlas Copco (Kalmar) 20/6-17																			■	
Presentation LTH (Lund) 21/6-17																			■	
Visits in Kalmar at Atlas Copco	■						■												■	
Supervision LTH		■				■					■			■				■		

Appendix B Interview guide

This is a guide for the interviews performed with employees at ACCT.

B.1 Interviewees

The interviewees for this thesis work is listen in table 0.1.

Table 0.1 Interviewees

Name	*Interviewee*	*Title*	*Date*
Mats Åhlin (Supervisor)	1	Sr. Material Specialist	---
Ambjörn Johansson	2	Design Engineer (HYD)	15/2 - 17
Anders Lundgren	3	Design Engineer (HYD)	15/2 - 17
Per-Anders Karlsson	4	Design Engineer (MDB)	15/2 - 17
Magnus Hansson	5	Design Engineer (LCC)	15/2 - 17
Hans Frost	6	Production Development Manager	16/2 - 17
Olof Elmersson	7	Design Engineer (LCC)	16/2 - 17
Pontus Andersson	8	Lab Manager	16/2 - 17
Anette Törnqvist	9	Strategic buyer	15/3 - 17
Erik Sigfridsson	10	R&D Manager	30/3 - 17

B.2 Basic questions

All interviews started with a short introduction from the author about the goals with the thesis work and what the aim with the interview was. Also, the interview started with that the interviewee described what their role is at ACCT and what the person's function at ACCT is doing.
The basic questions asked during the sessions at 15-16 February 2017 with interviewee 2-8 were:

1. What challenges do you face?
2. How does the development process look like when developing components for your product area?
3. What production methods are usually used for conventional prototype/final part production for you?
4. What requirements are generally put on prototypes?
5. What is necessary to test?
6. What parameters do you consider when making a decision?
7. When is the decision made to produce a prototype?
8. How can design work be affected with new opportunities that comes with AM?

At the 15th of March 2017, an interview conducted with interviewee 9 where the focus was around suppliers and tooling costs basic questions asked were:

1. What are the costs of tool-steel molds and aluminum molds?
2. What are the lead times associated to these components?
3. How does supplier agreement look like?

At the 30th of March 2017, an interview conducted with interviewee 10 where the focus was around project management. Basic questions were:

1. What challenges do the project manager face?
2. How far is the responsibility of the project manager?
3. What is the main reason for being delayed in projects?
4. How do you plan for volumes during development?
5. How do the project manager perform risk analyses during the project?
6. What is the project manager's role in decision making?

Appendix C AHP – Process

The AHP-process is described in this chapter in more detail.

C.1 AHP

The AHP process can be seen in figure 0.1.

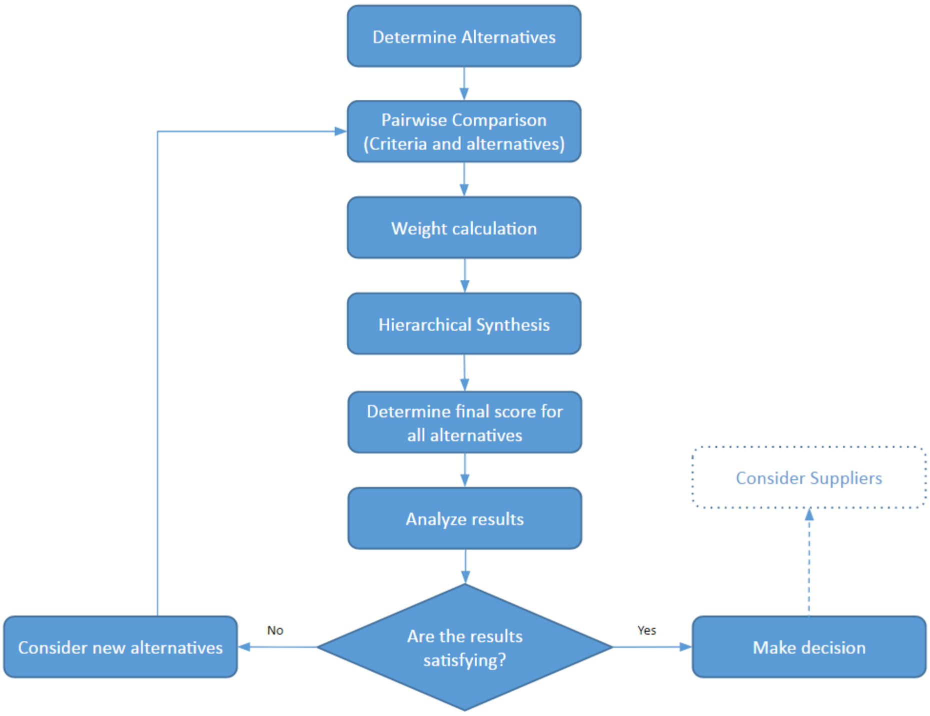


Figure 0.1 AHP process

C.1.1 Step 1: Perform pairwise comparison and prioritization

Compare each criteria relative the others by starting at the first column and pairwise rate the criteria with +1 “More important”, -1 “Less important” and 0 “Equal important”. Sum the scores for each column and calculate the normalized value for each criteria by using normalized values from table 0.2. Since there are seven outcomes, the normalized values are determined as 1/7, 2/7 etc.

Table 0.2 Level 1 criteria normalized values

Sum	*-3*	*-2*	*-1*	*0*	*+1*	*+2*	*+3*
Norm	0.14	0.28	0.42	0.57	0.71	0.86	1

In table 0.3 the structure of pairwise comparison of level 1 criteria is illustrated.

Table 0.3 Level 1 pairwise comparison

	Quality	***Flexibility***	***Cost***	***Time***	***Sum***
Quality	x				
Flexibility		x			
Cost			x		
Time				x	

With the same principles as Level 1 criteria, the level 2 sub-criteria are compared. Since there are 23 outcomes, the normalized values are determined as 1/23, 2/23 etc.

Table 0.4 Level 2 criteria normalized values

Sum	*-11*	*-10*	*-9*	*-8*	*-7*	*-6*	*-5*	*-4*	*-3*	*-2*	*-1*	*0*
Norm	0.043	0.087	0.13	0.17	0.22	0.26	0.30	0.35	0.40	0.43	0.47	0.52

Sum	***+1***	***+2***	***+3***	***+4***	***+5***	***+6***	***+7***	***+8***	***+9***	***+10***	***+11***
Norm	0.57	0.61	0.65	0.70	0.74	0.78	0.82	0.87	0.91	0.96	1

Table 0.5 Pairwise comparison level 2

Sum	***Q1***	***Q2***	***Q3***	***Q4***	***F1***	***F2***	***F3***	***F4***	***C1***	***C2***	***T1***	***T2***	***Sum***
Q1	x												
Q2		x											
Q3			x										
Q4				x									
F1					x								
F2						x							
F3							x						
F4								x					
C1									x				
C2										x			
T1											x		
T2												x	

C.1.2 Step 2: Rate the alternatives

Compare the alternatives with respect to the 12 sub-criteria. Choose one alternative as reference and compare the rest towards the reference with the same procedure as step 1. For this part rate the alternatives how well they fulfill the criteria compared to the reference chosen. Choose +1 if the alternative is “better than”, 0 if the alternative is “equal to” and -1 if the criteria is “worse than”.

Table 0.6 Rate the alternatives

	Q1	*Q2*	*Q3*	*Q4*	*F1*	*F2*	*F3*	*F4*	*C1*	*C2*	*T1*	*T2*	*Sum*
A1 (reference)	0	0	0	0	0	0	0	0	0	0	0	0	
A2													
A3													
A4													

C.1.3 Step 3: Compute the overall score of each alternative synthesis

By integrating the assigned normalized values, the final score of each supplier is determined in order to develop an overall evaluation process. If the calculated sum is less than zero for the alternatives compared to the reference, it will mean that the alternative is less appropriate for the situation rather than the reference. If the sum is above zero, the alternative is a better choice. To calculate the score, the values from Level 1 Criteria are multiplied with respectively Level 2 sub-criteria and give the score by multiplying with either +1, -1 or 0 depending on the rate given from step 6.

C.1.4 Step 4: Consider supplier alternatives (Out of scope)

In order to successfully manufacture the prototypes, the supplier alternatives need to be taken into account. This is out of scope of this thesis' work but there is a future master thesis opportunity here to analyze how to choose suppliers for AM components and compare with present suppliers at ACCT.

C.2 AHP-ratings in case studies

Ratings by the author used in case studies can be seen in table 0.7 and 0.8

Table 0.7 Level 1 weight

	Quality	***Flexibility***	***Cost***	***Time***	***Sum***	***Weight***
Quality	x	-	+	-	-1	0.42
Flexibility	+	x	+	0	+2	0.86
Cost	-	-	x	-	-3	0.14
Time	+	0	+	x	+2	0.86

Table 0.8 Level 2 weight

Sum	***Q1***	***Q2***	***Q3***	***Q4***	***F1***	***F2***	***F3***	***F4***	***C1***	***C2***	***T1***	***T2***	***Sum***	***Weight***
Q1	x	0	0	0	-	-	-	-	0	0	-	-	-6	0.26
Q2	0	x	0	0	-	-	-	-	0	0	-	-	-6	0.26
Q3	0	0	x	0	-	-	-	-	0	0	-	-	-6	0.26
Q4	0	0	0	x	-	-	-	-	0	0	-	-	-6	0.26
F1	+	+	+	+	x	0	0	0	+	+	0	0	+6	0.78
F2	+	+	+	+	0	x	0	0	+	+	0	0	+6	0.78
F3	+	+	+	+	0	0	x	0	+	+	0	0	+6	0.78
F4	+	+	+	+	0	0	0	x	+	+	0	0	+6	0.78
C1	0	0	0	0	-	-	-	-	x	0	-	-	-6	0.26
C2	0	0	0	0	-	-	-	-	0	x	-	-	-6	0.26
T1	+	+	+	+	0	0	0	0	+	+	x	0	+6	0.78
T2	+	+	+	+	0	0	0	0	+	+	0	x	+6	0.78

Appendix D - Calculations

The calculations performed in thesis are presented here.

D.1 Cost structure sourced components

70 €/Kg = 684 SEK/Kg = 0.684 SEK/g
Nylon density is approximately 1 g/cm^3.
Volume of the component is 210 cm^3.
Material price = 0.684*210*1 = 144 SEK
Machine cost = (144/0.7) - 144 = 61 SEK
[33; 34]

D.2 Injection molding vs AM

Comparing Small component, if material price is 70€/Kg and nylon powder has a density of 1g/cm^3 the part volume of the analysis is 0.360/1000 = 0.00036 m^3 which is equal to 360 mm^3. The size of the component is approximately 7x7x7 mm which is compared to a sugar lump.
[11; 34]

D.3 NPV

With MS as source of information input to NPV is:

G = Product development cost + Production cost + marketing cost
Q1 = Number of units planned to be sold year 1
Q2 = Number of units planned to be sold year 2
Q3 = Number of units planned to be sold year 3

PK=Product cost
SP= Unit sales price
r= ACCT's discount rate %
i=Time period
n=3

D.3.1 NPV equation:

$$NPV = \sum_{i=1}^{n} \frac{(SP - PK) * Q_i}{(1 + r)^i} - G$$

[35]