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Optimization of support structures for laser powder bed fusion by Design for AM

Master's thesis in Product Development

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Cover:
[A pen tip is released from the Non-Contact-Support while the torque is measure with the help of a torque wrench, page 17]

[Chalmers digital printing]
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Abstract

This master thesis has been carried out in the framework of the CAM² (Centre for Additive Manufacture - Metal), at the department of Industrial and Materials Science, Chalmers University of Technology, Gothenburg, Sweden, as the final degree project in Master of Science in Product development.

Additive manufacturing is a manufacturing method creating geometry from a defined CAD model, building the component geometry layer upon layer. One of several Additive manufacturing methods is Laser Powder Bed Fusion. A recoater dispenses a thin layer of metal powder on top of a build platform, and thereafter, a laser energy source melts the metal powder layer according to the corresponding cross-section from the CAD model.

To produce parts with Laser Powder Bed Fusion, support structures are needed. Namely, extra material supporting the part during the print, dissipating heat away from the melt zone. In other words, supports are material that later will be removed during the post-processing.

Support structures can impact an additively manufactured part in several different ways. For example, these affect the heat dissipation during printing, the achieved surface finish, and the time it takes to remove the support structures from the part.

Therefore a method to design novel Non-Contacting-Supports appears necessary to improve the process and was developed in the present work.
A Design of Experiment was set up to find out the most influential design parameters of such Non-Contacting-Support. It could be applied to any material and hardware.

A Proof-of-Concept showing the possibilities of AM and the use of a Non-Contact-Support was designed. This was done with the help of product development methods and considering Design for AM guidelines. Then, the Proof-of-Concept was printed in polymer using Laser Powder Bed Fusion to evaluate the design and make sure the design was robust and in a later stage ready for printing in metal.

Keyword: Design for Additive Manufacturing, LPBF**,** support structures, Non-contact-support, Product development, Design guidelines, Proof-of-Concept

Nomenclature

AM – Additive Manufacturing
Non-Contact-Support – A support structure for AM with no metal contact between part and support.
LPBF – Laser powder bed fusion
DfAM - Design for Additive Manufacturing
PLM – Product Lifecycle Management
EOS – EOS GmbH (Electro-Optical Systems): A 3D printing equipment provider

Contents

1 Introduction

This master thesis was conducted at the Department of Industrial and Materials Science at Chalmers University of Technology in the framework of the competence centre, *Centre for additive manufacturing – metal (CAM²)*. CAM² is located at Chalmers in Gothenburg, where research collaboration between universities, research institutes and industrial actors are conducted to strengthen the Swedish industry's competitiveness [1]. It is a Vinnova, Sweden's innovation agency, sponsored activity, and one of their main expertise areas is powder bed fusion, especially laser powder bed fusion, LPBF.

1.1 Background

The first type of powder-based additive manufacturing technique saw daylight already in 1971, when Ciraud came up with a process with similarities to today's powder bed fusion. It was only in 1979 that Housholder developed the first powder-based selective laser sintering process that could be considered as a powder bed fusion process [2]. In the 1990s, the metal AM was born through a series of different projects resulting in various processes [3].

In the last couple of years, LPBF has caught the interest of various kinds of high-end industries like aerospace, automotive, and the medical industry. Either for the potential to lower weight by using only the needed amount of material and/or for the design freedom and possibility to create complex structures that could not be feasible with conventional methods.

Still, the technology has some challenges before reaching greater adoption, such as assuring its robustness and being competitive compared to conventional manufacturing methods like machining and casting.

Indeed, the design freedom doesn't come totally for free since complex designs typically require extensive support structures.

Support structures are needed to transfer heat from the deposited material down to the base plate and attach the printed material to the baseplate to withstand residual stresses and related distortions and hence ensure a proper print.

The downside of the support structures is connected to the fact that the build time increases since more material needs to be printed. In addition, the support structures need to be removed after print, often manually, which increases the lead time and decreases the material utilisation rate. It also increases the part cost and potentially degrades the component´s surfaces.

1.2 Aim

This master thesis aims to *develop a method to optimize and thereby minimise the number of needed support structures for a complex part produced by LPBF* in favour of reduced lead time, better surface finish, less material utilisation and lower component cost.

1.3 Delimitations

Delimitations for this project are listed below and are crucial to limiting the scope of the presented work.

- This project only focuses on laser powder bed fusion (LPBF), a powder bed metal additive manufacturing process.

- This project mainly focuses on optimizing support structures based on the identification of design limitations determined by the material properties for specific materials and the LPBF processing conditions.
- In the proposed method developed in this master thesis, only standard printing parameters are considered for the part and the Non-Contact-Support.

1.4 Research questions

Since the aim presented in section 1.2 is to *develop a method in order to optimize and thereby minimise the number of needed support structures for a complex part*, the following research questions are stated:

- How to define a methodology to derive guidelines to design Non-Contact-Support for metal AM?
- How to implement the design guidelines into a support-free component optimized for AM?

2 Theoretical background

This *Theoretical background* chapter illustrates the basics of Additive Manufacturing, in particular of the laser powder bed fusion process, supports, post-processing, and summarizes state-of-the-art research in the investigated area.

2.1 Introduction to Laser Powder Bed Fusion

Powder bed fusion is one out of seven AM technologies according to the ASTM-52900 standard [4]. It includes two processes dependent energy sources, Laser Powder Bed Fusion (LPBF) or Electron beam melting (EBM), see Figure 1.

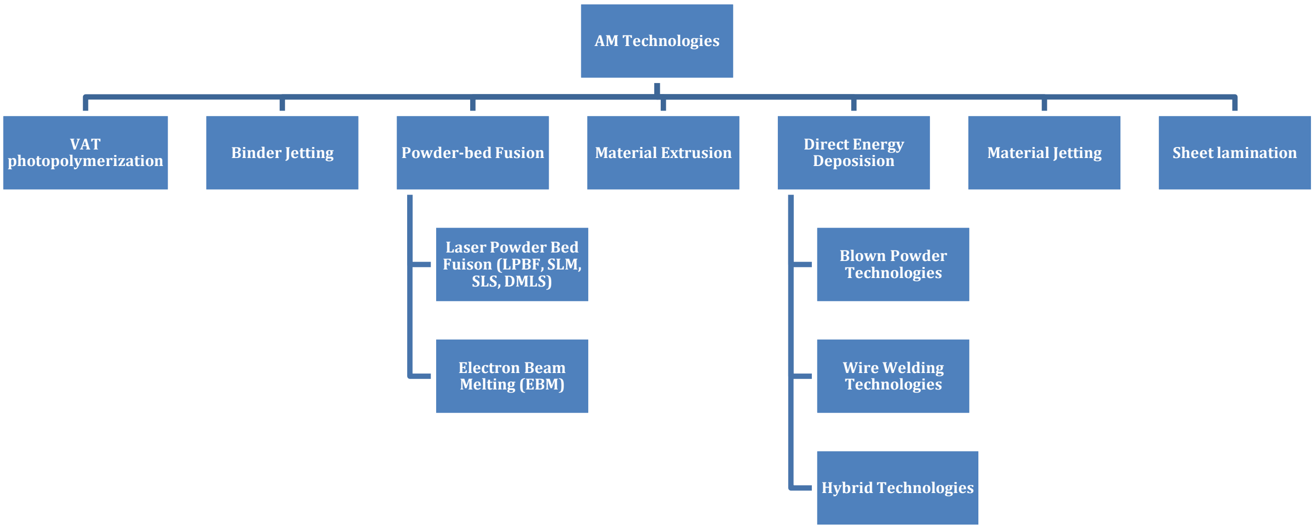


Figure 1 AM processes families, created with inspiration from [2].

LPBF is a layer-by-layer process where a recoater dispenses a thin layer of metal powder on top of the build platform in an inert-gas flushed build chamber to minimise the risk of oxidation. Then the laser energy source only melts the metal powder layer according to the corresponding cross-section from the loaded CAD model. The process is repeated by lowering the building platform and applying a new thin layer of powder, see Figure 2.

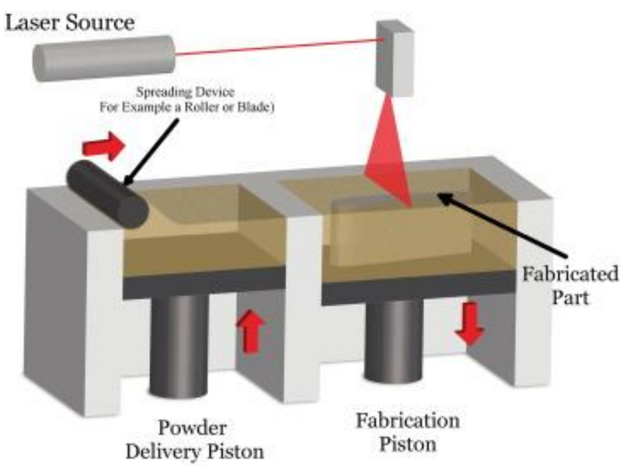


Figure 2 Showing a general overview of the Laser powder bed fusion process. Courtesy of [5] under Creative Common CC-BY license.

Because of the layer-by-layer approach, LPBF parts will be affected by a “staircase effect” and slightly differ from the CAD model since the shape of the CAD model is approximated into a stepped part depending on, for example, the layer thickness [6], see Figure 3.

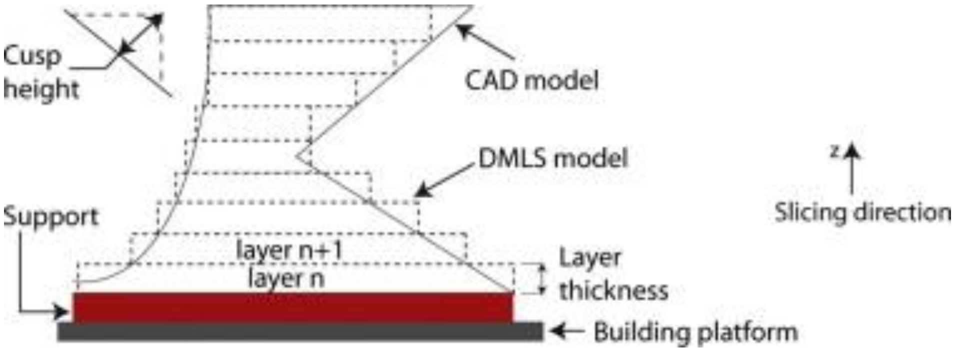


Figure 3 Describes the differences between the CAD model and the actual printed part thanks to the staircase effect. Courtesy of [6].

2.1.1 Metal Powder

Laser powder bed fusion is one of the Metal AM processes which currently offers the widest material portfolio with around 30 different alloys available [7], meaning granting the greatest possibility to print parts in various materials.

Metal powders for AM are most often produced by gas atomisation, during which metal is molten and flows through a nozzle where an inert gas jet atomises the stream into small metal droplets that solidify into metal powder upon cooling [8], see Figure 4.

The chemical composition of the metal powders affects physical properties like melting temperature [8]. The flowability of the powder depends, among other factors, greatly on the particle shape, and a spherical shape is most desirable [8]. A powder particle size distribution makes the powder bed denser because smaller particles can fill the spaces in between larger particles [2]. Appropriate particle sizes in powder for LPBF typically varies between 10 and 50 µm, but it is also material dependent.

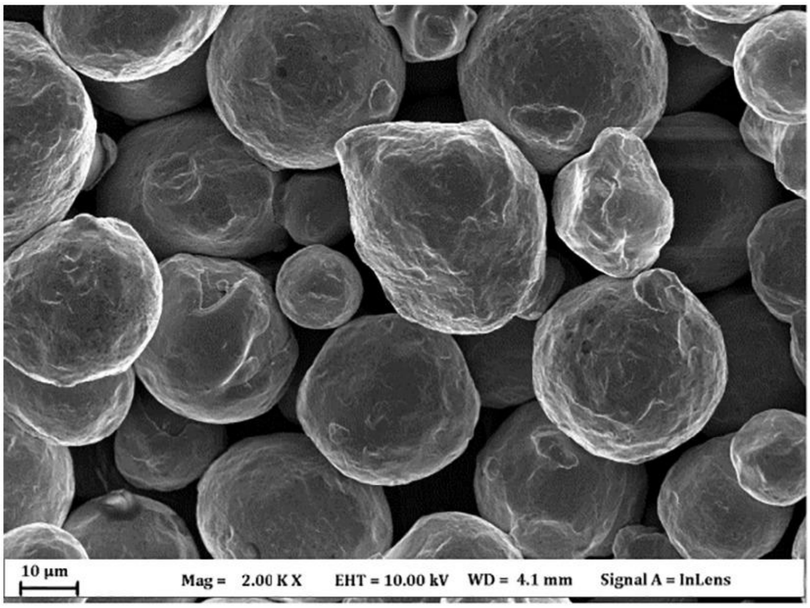


Figure 4 Showing virgin 316L metal powder particles with typically spherical shapes. Courtesy of [9] under CC-BY license.

2.1.2 Recoating system

The recoating system in an LPBF machine is the system that distributes a uniform thin layer of new powder on top of the powder bed and previously solidified parts. This is a crucial process that, together with the quality of the powder, could affect the printing. Therefore, the powder must uniformly be spread out over the whole build area with the help of the recoater system. The layer thickness needs to be constant, and the entire process of powder deposition process must be both quick and reliable [10]. Furthermore, the recoater itself also could affect the print. For example, suppose that the printed part gets in contact with the recoater. In that case, it could cause pieces from the solidified part to fall loose in the powder bed, alter its quality, collide with the recoater and interrupt the build or strongly compromise the powder bed quality [11].
Furthermore, contact between the recoater and solidified material also affect the wear of the recoater, which affect the smoothness of the powder bed and, in turn, the print quality [12]. Usually, solutions of recoaters are divided into hard and soft recoaters. Hard recoaters are often manufactured from HS steels or ceramics, while soft recoaters often are made from silicon or carbon fibre as a brush [13]. The hard recoater often gives better layer height control but is less tolerant to deposited part top surface roughness and could cause premature process failure. On the other hand, the soft recoater is more susceptible to geometrical issues but could cause problems due to recoater wearing [12].

2.1.3 Supports

Support structures are extra material added underneath or nearby the part to ensure its good printability. From a thermal perspective, supports are crucial for dissipating heat away from the melt pool. From a mechanical point, these also ensure clamping of the part to the build platform [14]. After finished print, supports are removed from the part either by hand or by machining, which are both time consuming and costly. Therefore, if it is possible to reduce the need for support, this will significantly impact the cost of the part [15].

In *"A Practical Guide to Design for Additive Manufacturing", Diegel, Nordin and Motte* published a list with the main functions of the support structures [2]:

- *Support the part in case of overhangs.*
- *Strengthen and fix the part to the build platform.*
- *Conduct excess heat away.*
- *Prevent warping or complete build failure.*
- *Prevent the melt-pool from sinking into lose powder.*
- *Resist the mechanical force of the spreading mechanism on the part.*

2.1.4 Post-processing

Post-processing is needed in most cases when it comes to AM manufactured parts. For LPBF, it starts with powder removal and cleaning up the build chamber to be able to remove the build platform from the chamber. Thereafter, several different post-processes could be chosen depending on the performance requirements of the parts, including support structures removal. However, the post-processing step could be very time-consuming and costly if the part is not correctly designed, especially considering the difficulty of support removal and selecting proper post-processing. Examples of different possible post-processing steps for LPBF are listed below [2] [16]:

- **Removal from build chamber and cleaning of loose powder –** The parts are built into the powder, which needs to be removed. This could be done by vacuum cleaning, compressed air, shaking and vibration. Also, the baseplate needs to be removed from the machine by unscrewing it from the lifting platform.

- **Thermal stress relief –** This is also a step sometimes applied since internal stresses are built into the part through several thermal load cycles because of the layer by layer printing. If thermal stress relief is neglected, it could cause warping or cracking of the part.
- **Part removal from the baseplate –** After print, the part is bonded to the baseplate and therefore has to be removed, preferably with a wire EDM or a bandsaw.
- **Support removal –** All support structures need to be removed by hand or using tools and machining.
- **Heat treatment –** Depending on the processed material, the mechanical properties could be improved by heat treatment processes such as ageing, annealing, etc. This means heating the part under controlled circumstances and environment in a furnace.
- **Hot Isostatic Pressing (HIP) –** Instead of the heat treatment mentioned above or in combination with it, Hot Isostatic pressing could improve the properties of the part. High pressure in combination with elevated temperature permits to reduce porosities and surface micro-cracks in order to improve, for example, fatigue life.
- **Machining –** Features of the part requiring specific tolerances to be met needs machining.
- **Surface treatment –** If requirements on surface roughness are set, surface treatments like shot penning, tumbling and electro-polishing etc., could be necessary to reduce surface roughness and improve aesthetics and fatigue life [17].
- **Inspection –** The last step is to ensure that the part lives up to the specifications set and therefore needs to be measured and tested according to the standard of the concerned industry.

2.2 Cost calculation for metal LPBF

One may consider that the total cost of a part produced by LPBF depends on machine, material and part dependent parameters. Such as the volume of the part, the height of the part, the recoating time of the machine, the selected layer thickness, the machine's build rate, which is material dependent, the machine operating cost, and of course, the cost of the metal powder.

Timothy W. Simpson presented a model to calculate the *Total AM part cost* based on the equations 1-3 below [18]. The *Pre/Post-Postprocessing* cost is based on Wohlers report survey from 2019, which proposed that the Pre/Post-Postprocessing is around 40% of the part's total cost [18]. The Pre-processing could cover fees, such as machine preparation cost, while Post-processing covers the cost of support removal and other treatments mentioned in Chapter 2.1.4.

$$Material\ cost(SEK) = (Part\ Volume) * (Material\ Density) * (Powder\ Cost)\ [1]$$

$$Build\ Time\ (h) = \frac{\frac{(Part\ Volume)}{(Buid\ Rate*80\%)} + \frac{(Max\ Part\ Height)}{(Layer\ Height)} * (Recoater\ Time)}{3600} \qquad [2]$$

$$Total\ AM\ Part\ Cost(SEK) = \frac{(Build\ Time)*(Machine\ Operating\ Cost) + Material\ cost}{(1-(Pre/Post\text{-}Processing\ Cost\ \%))} \qquad [3]$$

The *Build Rate* variable from the equations above is the volume the machine can produce per second and is dependent on the material selection. The *Recoater Time* is the travelling time of the recoater back and forth while dispatching the powder. Finally, the *Machine Operating Cost* covers the investment into the machine, overhead costs, salaries, power consumption etc., divided per hour.

2.3 Benefits with Additive Manufacturing

Additive manufacturing offers the designer great freedom since it is possible to print complex parts, for example, complex curvature and shapes, internal channels and lattice structures. Moreover, it does not cost anything extra to add complexity to a part compared to conventional manufacturing. Therefore it does not cost any extra to customize a part for a customer. This is also because, for example, moulds don't need to be produced before the production can start.
Also, parts can be made on demand, which minimises the need for warehouses. Another benefit is that moving parts could be assembled during the production process and therefore be produced as one part with a moving functionality. This could, for example, minimise the assembly cost and time.

Since Additive Manufacturing can be a costly production method, some of the above stated properties need to be considered as value added to the product to make this production method a preferred choice [2].

2.3.1 Design for Additive Manufacturing

To take advantage of the benefits of Additive Manufacturing but also for making it as competitive as possible, in terms of maximising performance, reducing development time and cost, for example, Design for Additive Manufacturing (DfAM) - guidelines exists to guide the designer to make a suitable product.

2.4 Identification of limiting features

Diegel, Nordin and Motte highlight in *"A Practical Guide to Design for Additive Manufacturing"* that there are, in general, three different categories of features requiring support structures over a specific limit to get a sufficient print. These are angles, overhangs and bridges [2]. Other specific limiting features that could require support for a sufficient print could be holes depending on the orientation, thin walls, and the parts length to height ratio. See Table 1 for a summary of limiting values from the literature. If the angle of the feature is less than 45 degrees from the horizontal, the surface finish will become rougher, which could cause build error or recoater crashes. For all angles, overhangs and bridges, the quality of the down-facing surface is the most critical. If no supports are used, the laser heats loose powder from the powder bed, and if the produced heat can't escape sufficiently, the melt pool will increase and, thanks to gravity and capillary forces, sink into the bed, causing more particles to melt, resulting in a poor surface [15]. A way of controlling the surface quality of a downfacing surface is to add supports that will help drive the heat away from the melt pool.

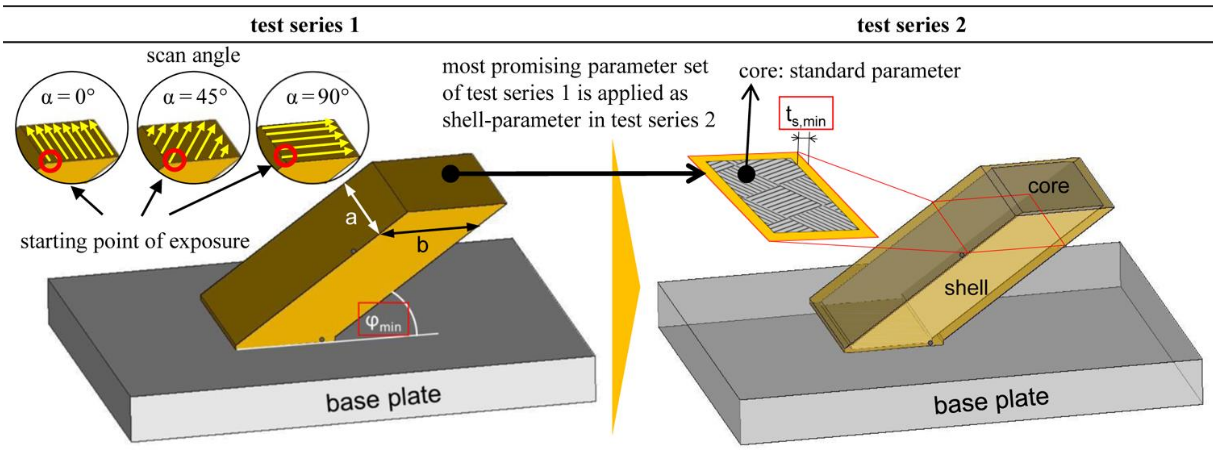
Table 1 Limiting values for critical features of parts for LPBF.

	Limiting value
Angles	<45° will require support (<60° for some materials) [2]
Overhangs	>0,5 mm require support [2]
Bridges	>2 mm require support [2]
Horizontal circular holes	>10 mm require support [8]
Thin walls	Minimum 0,3 mm thick but recommended 1 mm for avoiding support [2]
Length to height ratio	8:1 [8]

2.5 New strategies/approaches for optimized support

As mentioned above, AM comes with great design freedom and the possibility to produce complex shapes. Still, some restrictions limit the design freedom radically. According to *Pullin & Offen* [19], the most limiting factor for geometry is the use of support structures. The literature otherwise agrees that support structures are necessary or even crucial for metal AM processes such as LPBF to work [2], [20], [14].

One of the identified limitations from chapter 2.4 were overhang and angles less than 45°. These features require support to get sufficient down-facing surface and avoid print interruption. The problem arises when the laser spot points directly on loose powder instead of a support structures or to the already solidified metal of the printed part [2]. The metal powder has poor thermal conductivity [15], making it hard for the heat from the melt pool to dispatch.
Michael Cloots et al. proposed in *"Approaches to minimise overhang angles of SLM parts"* a method to minimise the need for supports for overhangs by dividing the print into a core and a shell with different printing parameters. The purpose is to lower the heat near the surface boundary to get a better surface quality and lower the overhang angle [15]. A schematics of the research can be seen in Figure 5. Parameters of most significance are scan angle and scan speed [15] [21].



φ min	35°	30°	25°	20°
a [mm]	15	15	15	15
b [mm]	9	10	12	15

Figure 5 Shows the concept of Michael Cloots et al. research where the overhanging part is divided into a core and a shell with different parameters in order to lower the overhang angle and still get a sufficient down-facing surface. Courtesy of [15].

In some places, supports structures are inevitable. For example, when heat dispassion is not sufficient, to maintain the position of the parts during the print and to print longer horizontal bridges. In the case where support is needed, several studies have been focusing on minimising the effect of the support structure on the surface, simplifying the post-processing and minimising powder waste. Material waste in LPBF is highly connected to support structures. In the report *"A Support Structure Design Strategy for Laser Powder bed Fused Parts", Filippo Ceccanti et al.* mentioned three types of waste in connection to support structures that could be minimised [12]:

- Waste that depends on the support design (e.g. melted powder building the support that later will be removed).
- Waste concerning the LPBF system (e.g. powder that has gotten caught in filters thanks to the inert gas recirculation system).
- Waste connected to the support shape (e.g. unmelted powder enclosed in printed support and therefore not accessible and reusable).

For avoiding powder getting trapped inside support and thereby avoiding waste, open-shaped supports are preferable. However, it could be challenging to create this kind of slender structure with hard recoaters because of the failure risk during the build, thanks to the low tolerance of defects from the recoater [12]. On the other hand, slender structures are less preferable from a thermal perspective since they could lead to heat accumulation [12].

Michael Cloots et al. proposed a specially developed support structure with minimum support for overhangs of 0°, easy to remove and without any losses of surface quality or impairment of part geometry. Except for the particular support structure in form of a lattice, the overhanging part is divided into a connection layer and a standard layer with different process parameters [21], similar to the one described above for overhanging angles.

According to *Filippo Ceccanti et al.,* it is beneficial to create the support structures directly in the CAD software, which will increase the design freedom of supports compared to any other support generation software but will require feasibility rules for a proper built [12]. Other benefits of generating supports in the CAD system include having fewer files to handle wish is also beneficial for the Product Lifecycle Management (PLM) system [12].

F. Calignano has, through experimental investigation, shown that it is possible to find an optimal "tooth-like" connection between support and part for easy removal and reduction of deformation for most geometries [6]. Design parameters of influence can be found in Figure 6 and specific values in [6].

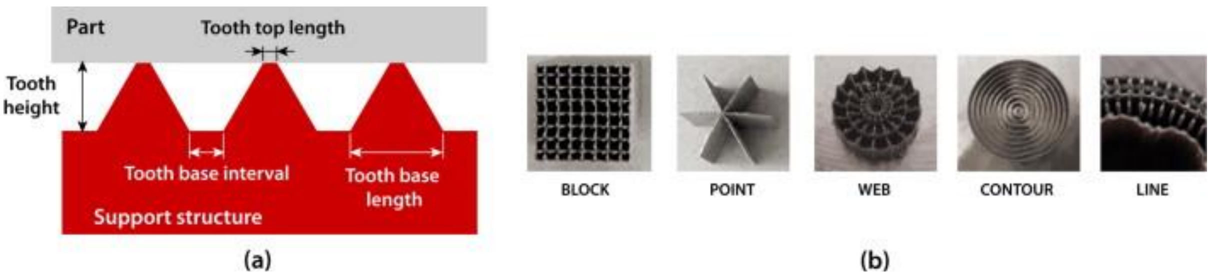


Figure 6 (a) Shows the design parameters for an optimal tooth-like connection between support and part. (b) Shows different types of standard supports possible to add a tooth connection to. Courtesy of [6].

Another interesting finding from *Kenneth Cooper et al.* is the possibility to use thermal heat support. These will minimise the effect of support structures to the surface since there is no connection or at least very little between the heat support and the part. The idea is to place the heat support as close as possible to the part, for example, to minimise overhang distortions but still with a thin amount of metal powder in between so the heat support can capture heat from the printing part through the thin powder layer [22]. The downside is that still, additional materials need to be printed. The concept can be seen in Figure 7.

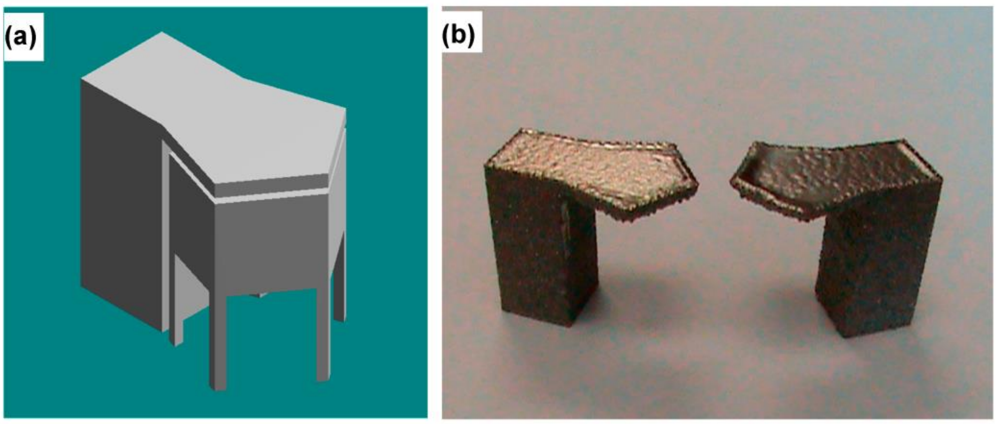


Figure 7 (a) Shows the concept of a contact-free-support inform of a CAD model. (b) Shows to the left a part printed with a "contact-free-support" under the overhang and without to the left. Courtesy of [22] under Creative Common CC-BY license.

Orientation of parts for LPBF is a research topic of its own, since it influences many other parameters such as the part quality, surface quality, support structure, build time, manufacturing cost and mechanical properties [23]. Changing design one factor may have several influences on the others. Therefore, the orientation of parts becomes a complex multi-objective optimization problem. For example, from a support structure perspective, the support volume highly influences the build time and the part's total cost. Minimising the amount of support will greatly influence the surface quality of overhangs, which is closely related [23]. The optimal orientation could be found either via solving the multi-objective optimization problem [24] by, for instance, a software or by identifying the surface type and then finding the possible optimal orientation via a flow chart [6].

Complex parts, for example belonging to the aerospace industry, could require extensive support structures, making the part impossible to either use or remove support structures, limiting the adoption of the process. On the other hand, as presented in the chapters above, it is possible to reduce both the required amount and influence of support by orientation, printing parameters, type of support etc.

By putting all these puzzle pieces together, the company Velo 3D has developed a product including specially developed hardware and software, making it possible to print within general less support than conventional solutions [25], [26].
One difference in hardware compared to conventional machines is a “non-contact recoater”, as Velo 3D refers to it. A non-contact recoater will lower the impact of shear forces introduced by, for example, a hard recoater. It also lowers the risk that the recoater breaks parts loose and thereby damage the print. In addition, less flowable powder could be used with a “non-contact-recoater” [27] compared to ordinary recoaters. Powder with smaller particle sizes, 10-20µm, is less flowable and should therefore normally be avoided [8]. The possibility to use smaller particle sizes than normally can potentially also increase the surface finish. Thinner layers are possible, which reduce the staircase effect.

One difference compared to conventional LPBF solutions is the preparation software Velo3D offers. Normally the work with the print preparation will be executed in several different softwares that often doesn’t communicate very well in between. These different tools have been integrated into one software with the benefit that analysis such as simulations, predictions and compensations for build deformation can be instantly evaluated when changing a process parameter, support placement etc. Also, the flexibility to identify features requiring specific process parameters and address a unique recipe from a process library [28] is advantageous for minimising required support structures.
Through that, the company has been able to manufacture even more complex parts with internal channels, such as shrouded impellers, heat exchangers, and manifolds [28].

3 Methodology

The Methodology chapter describes the methods and approaches used in this master thesis project under each subtask.

3.1 Literature study

Topics of interest for the project are studied through books, articles, websites, data sheets etc., in order to gather relevant information and summarise the state-of-the-art in fields of design limitations, the role of support and their impact, but also design strategies for producing complex LPBF objects. Chapter 2 is devoted to the presentation of the most relevant findings from the literature review.

3.2 Development of Non-Contact-Support

This chapter describes the methods used to identify influencing parameters and the development of a Non-Contact-Support.

3.2.1 Design of Experiment

To use Non-Contact-Support, which is not a conventional support method, the influence of design parameters on the bonding of the part to the baseplate needs to be examined. A structured way to find the relation between the design parameters and the bonding is to use Design of Experiments (DoE) [29]. Design parameters of the Non-Contact-Support are defined as factors and the bonding as the response of the DoE. A fractional factorial design will be used to find the essential factors and effects which require fewer runs [30] (in our case, printed parts is equal to the number of runs). The different designs (runs) in the DoE will be created with the help of the statistical software JMP.

3.2.2 Parametric modelling

To be able to implement the different design parameters in an efficient way created with the help of JMP in the DoE as described above, it is necessary to have a Parametric CAD model. Therefore, with the help of a parametric CAD model, the design parameters could efficiently be transferred into the CAD model without failure as the model is automatically updated. In the parametric model, parts could be generated. One part is required for each run in the DoE. Figure 8 shows how a specific parameter could affect a parametric model.

Figure 8 An example of a parametric model where the whole model is updated to fit this parameter without failure depending on parameter X. In this example, X correlates to the number of tips.

3.3 Proof-of-Concept design

In the Proof-of-Concept design chapter, the product development methods used to develop a Proof-of-Concept part, in the form of a pen that shows the possibilities of using a Non-Contact-Support, is described. The pen was chosen beforehand since it is a relatively small object that could be used in everyday life.

3.3.1 Customer needs and target specification

Identifying customer needs is the first step to making sure the product/design gratifies the customer. The customer needs constitute the base for the later target specification and could justify the product specification [31]. The methods used in this project to identify customer needs and set target specifications are simplified versions of *Ulrich, Eppinger & Yang* proposed methods in "*Product Design and Development*" [31]. Simplified versions are used because of the less complex Proof-of-Concept giveaways. The method is applied in *Customer needs and Part specification,* Chapter 5.1.

3.3.2 Concept Generation

For generating the concept and design, a five-steps method for concept generation derived from *Ulrich, Eppinger & Yangs "Product Design and Development"* [31] is used as a baseline to explore the design systematically. The following steps were applied, and further information could be found in *Concept Generation*, Chapter 5.2:

Clarifying the problem

The first step in the five-step method is to better understand the task with help from customer needs and target specifications from Chapter 3.3.1 [31]. In the case of this project, the identified limiting features described in Chapter 2.4 are of great value since they will be implemented in the developed Proof-of-Concept part.

Search Externally

The external search step aims to find existing solutions available on the market [31]. For example, in our case of a giveaway pen showing the possibilities of AM, different retracting mechanisms of existing pens are of interest. Therefore a patent search could be valuable to the concept generation process.

Search Internally

The internal search is a creative step with the purpose to generate as many ideas and solutions as possible from already captured knowledge [31]. For example, in the case of the giveaway pen, Moodboards were used to gain inspiration together with the creative method of brainstorming to develop ideas of how to integrate identified limiting features from Chapter 2.4 into an LPBF produced pen.

Explore systematically

The generated ideas and solutions from the internal and external searches are then collected and categorised with the help of the identified limiting features into a Morphological matrix. First, the identified limiting features and essential features are listed as functions. Then, the generated ideas from previous steps are listed as solutions to each function. The last step is to create overall concepts out of the solutions from each function [32].

Reflect on the Solution and the Process

The last step in *Ulrich, Eppinger & Yangs* five-step method is to reflect on solutions and processes to ensure that the whole design space has been explored [31].

4 Development of Non-Contact-Support

A Non-Contact-Support protects the part during print and clamps the part to the baseplate with the help of friction between the part and a shell. The curvature of the part and the shell share the same shape but with metal power in between. Depending on the space between the part and the shell but also the metal powder, it could probably also similarly conduct some heat as described by Kenneth Cooper et al. research "*Contact-Free Support Structures for Part Overhangs in Powder-Bed Metal Additive Manufacturing".* The authors used heat supports with no contact but a very fine clearance to the part in order to be able to print overhangs with no deformation [22].
For Non-Contact Support, parameters that could be influencing were identified based on the literature review and were used to set up the DoE. The possible influencing parameters could be seen in Figure 9, showing a red cone with a protecting shell in blue.

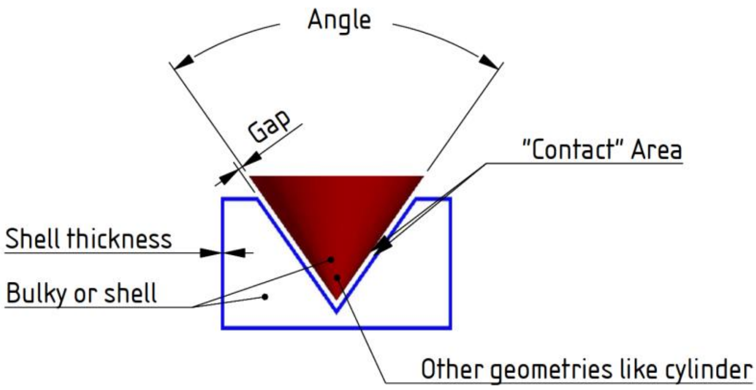


Figure 9 A sematic view of a Non-Contact-Support, showing possible influencing parameters. The part is represented in red, while the protecting shell is visualised in blue.

The selected influencing factors for the DoE are shown in Table 2, where a fractional factorial design was selected, requiring 12 different test pieces to find the essential factors. The fractional factorial design was generated with the help of the statistical software JMP. The height parameters in Table 2 is the height of the supporting area of the part. Shell thickness determines how thick the shell should be. The gap is the distance between the part and the shell where loose metal powder is filled between the two melted surfaces, and perforation determines if the shell should be solid or not.
To determine the bonding of the part, the torque needed for removing the part is measured when realising the part from the baseplate and becomes the response value to the DoE.

Table 2 The generated fractional factorial design from JMP, requiring 12 runs.

	Height [mm]	Shell Thickness [mm]	Gap [mm]	Perforation
1	20	2	0,2	Yes
2	20	1	0,3	No
3	10	2	0,3	Yes
4	10	1	0,1	No
5	30	2	0,4	No
6	20	0,5	0,1	Yes
7	10	1	0,4	Yes
8	30	1	0,2	Yes
9	30	2	0,1	No
10	20	0,5	0,4	No
11	10	0,5	0,2	No
12	30	0,5	0,3	Yes

A part was developed as a parametric CAD model to interpret the values from the DoE, making it possible to generate several different output parts with different parameters from the same CAD model. A pen tip inspired the design of the test parts since it was considered a suitable shape and supported the next stage in this Master Thesis, described in *Proof-of-Concept design,* Chapter 5*.* A cross-section of one of the test parts (Number 1 in Table 2) can be seen in Figure 10, together with the specified values of the factor retrieved from the DoE. The upper section of the part contains an hexagonal bolt (M8) to make it possible to measure the required torque for releasing the pen tip. In order to make the shell perforated, a Gyroid lattice structure was selected, resulting in reduced density together with less material utilisation. In the case of part number 1, the weight was decreased by 13% thanks to the lattice with the chosen parameters.

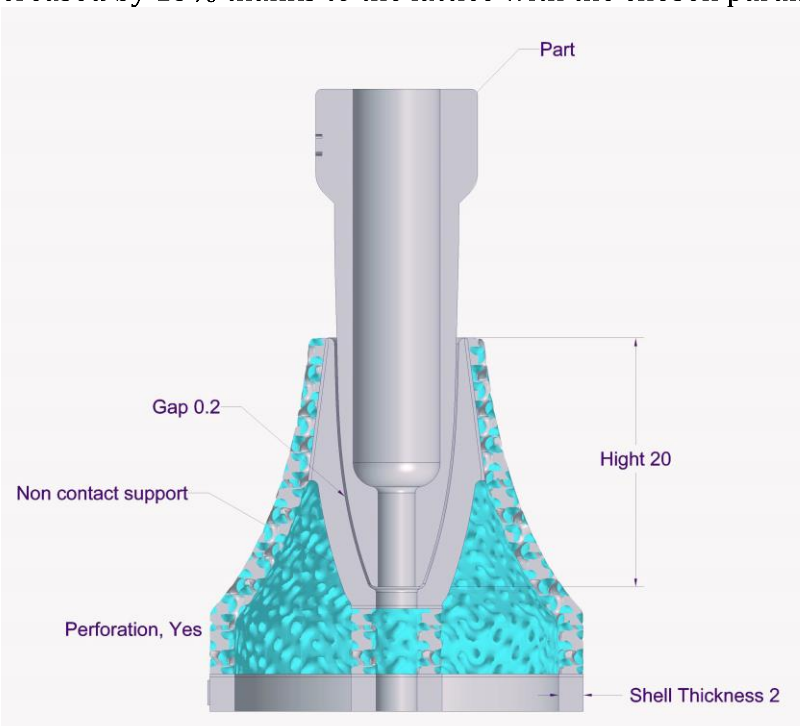


Figure 10 Cross-section of test part number 1 with design parameters retrieved from the DoE. Specified values are in mm.

All the generated test part files coming from the CAD software were then imported into the built preparation software Materialize Magics, with the purpose to clean up the STL files and virtually position all the parts into the build volume of the EOS M290 machine. No supports were added in the preparation software since the file from the CAD software already included it, in terms of the lower section in Figure 10. The assignment of specific process parameters for the parts was done in EOSPRINT, and the standard parameter 316L_040_FlexM291 was selected at this early stage. The build volume containing three sets of the DOE (36 parts) can be seen in Figure 11 & Figure 12.

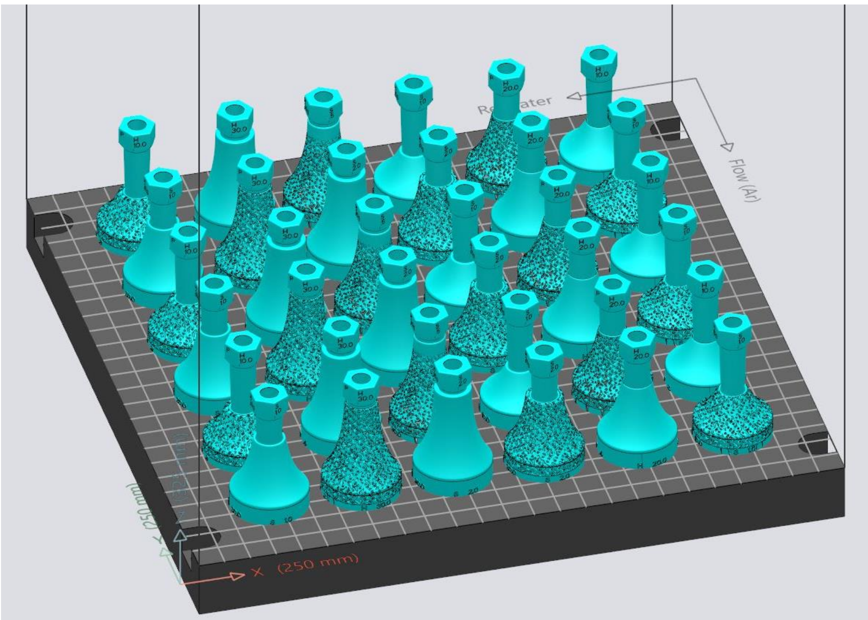


Figure 11 A 3-dimensional view of the build volume, showing both the recoater and airflow direction.

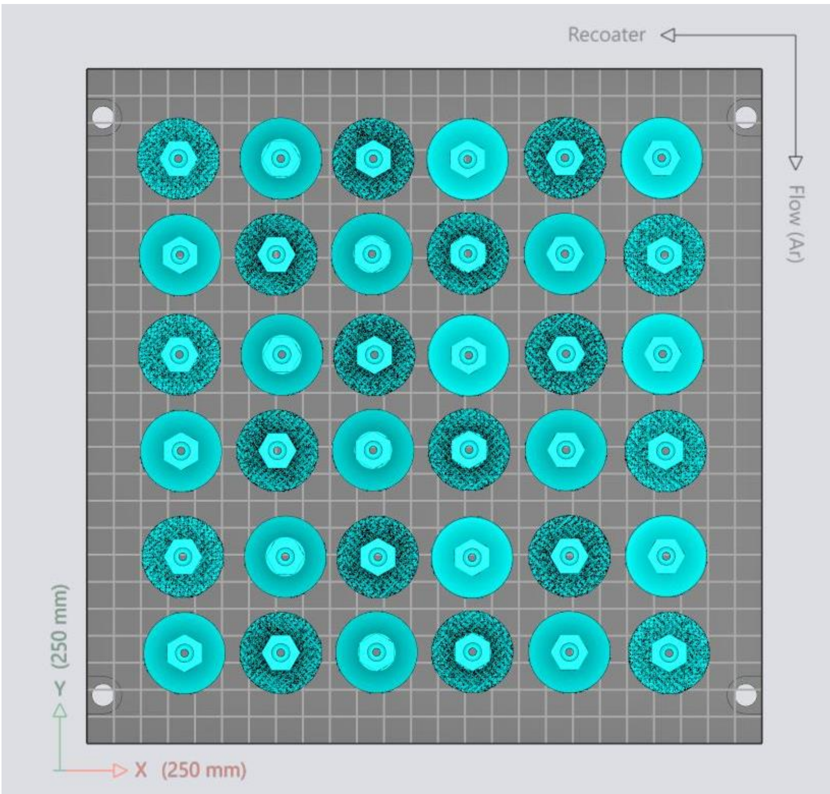


Figure 12 A top view of the build volume shows three identical part sets where group one contains rows one and two from the bottom etc.

The total build time of the parts in Figure 11 & Figure 12 is expected to be around 24h, of which 87% is assigned for the exposing process and 13% for the recoating.

The next step in the method after the parts in Figure 11 & Figure 12 are successfully printed is to examine the bonding by measuring the torque needed to release the tip from the shell, Figure 13. The idea is to have a minimum bonding of the part to ensure an easy release but still a good enough bonding to ensure a sufficient print and surface quality. The torque results of the different runs are then interpreted into the statistical software JMP to find out the most influencing and promising design parameters of the used material for the Non-contact-support.

Figure 13 Shows an illustrative view of using a torque wrench to realise the shell from the part and measure the required torque. Note that a torque wrench that allows measuring torque needs to be used. The one in the picture above is only to illustrate the purpose.

4.1 Test Print

Two sets of the DoEs were printed at EOS, Electro Optical Systems Finland Oy. Unfortunately, a build error arose at part nr 6 from the DoE, which stopped printing after 10,5mm, see Figure 14.

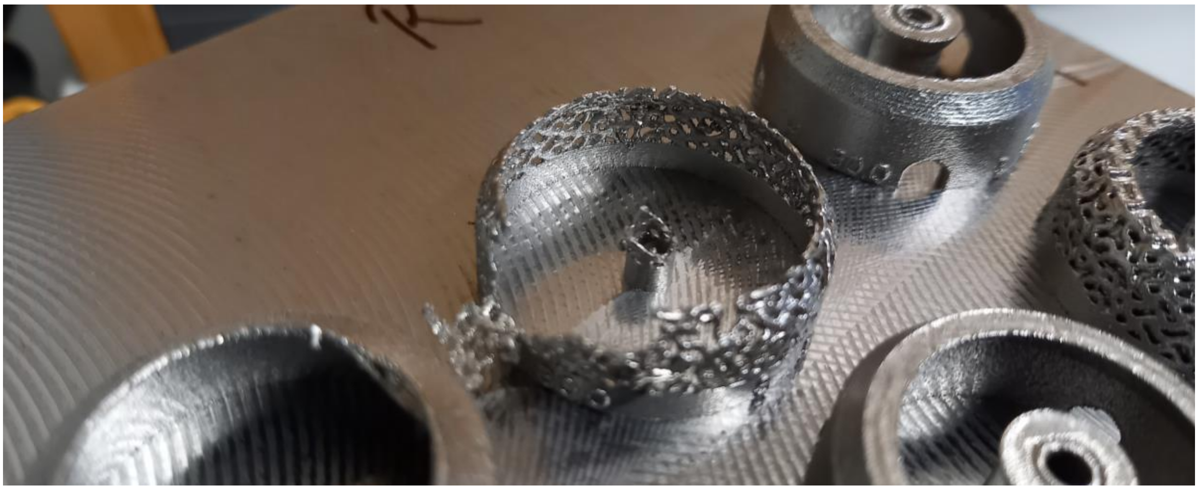


Figure 14 The part nr 6 from the DoE was damaged during the test print and therefore stopped the whole printing process. Photo: Shaafi Shaikh, EOS Finland Oy.

Since the other parts looked good, see Figure 15-18, this shows that the combination of DoE parameters and other process variables for part number 6 was not optimal for this material, and to complete the DoE, some more prints are required.

Figure 15 All the other parts were sufficiently printed until the build error of part nr6 stopped the whole printing process. Photo: Shaafi Shaikh, EOS Finland Oy.

Figure 16 Shows two sets of the DoE parts still attached to the build plate after the interrupted build, thanks to a build error accruing at part nr 6 of the upper DoE in the picture. Part nr6 could be found in the second location from the right in the first row from the top . Photo: Shaafi Shaikh, EOS Finland Oy.

The parts in Figure 14-18 were printed in IN718 with the standard printing parameter IN718_PerformanceM291_2.11 of 40µm layer height. A possible solution to solve the error occurring for part nr 6 could be to decrease the layer height to 20 µm, but that will prolong the print time and also increase the cost. Another aspect could be to skip the contour parameters to limit the heat input in the thin features. Also, when printing such thin and complex features, the obvious choice is to use a soft recoater to avoid such printing error, which is not standard procedure. A soft recoater may be more prone to wear but will not cause a collision that leads to interruption of the print.

5 Proof-of-Concept design

This chapter describes the development process of a Proof-of-Concept part which is the next step after finding out suitable design parameters for the Non-Contact-Support as described in Chapter 4 that would be used in this method. The aim is to show the possibilities of AM manufacturing and the use of Non-Contact-Support.

5.1 Customer needs and Part specification

Together with the stakeholders of this master thesis, it is specified that the customer need for this project is a Proof-of-Concept part showing the possibility to print critical features with minimum support. The Proof-of-Concept part should be a giveaway feature in the case of a pen.

From the customer needs, critical features should be included in the Proof-of-Concept part. These features are identified in Chapter 2.4 and, together with the above described needs, is the basis for the target specification hierarchy shown in Table 3.

Table 3 Part specification hierarchy sorted showing most important first.

No.	Metric	Unit	Value
1	Designed for metal LPBF	Binary	Pass
2	Attach to baseplate with Non-Contact-Support	Binary	Pass
3	Include overhang angles of a minimum of 25^0 without support	degrees	25^0
4	Include horizontal overhangs of minimum 0,5 mm without support	mm	0.5 mm
5	Maximum surface roughness	Ra (µm)	20 µm
6	Designed for ball pen refills	Binary	Pass

5.2 Concept Generation

This chapter outlines the different steps in the Concept Generation process derived from Ulrich, Eppinger & Yangs five-step method [28] described in Chapter 3.3.2.

5.2.1 Clarifying the problem

The concept generation problem formulation was defined as: design a giveaway feature in the form of a pen, including demanding features for LPBF manufacturing with a minimum of support. In most pen designs, a mechanism for retraction is necessary. In addition, the pen should be nice holding in hand and should have a sufficient grip. Demanding and limiting features for LPBF can be found in Chapter 2.4. These aspects mentioned above are divided into subfunctions/problems and will be the focus to solve and include during the further development and design processes. These are listed below:

- **Angles** – Below 45^0, angles could be challenging to print by LPBF but possible with exceptional handling. Therefore the pen should include an overhang angle specified by the part specification in Chapter 5.1, *Customer needs and Part specification,* showing the possibilities.

- **Overhangs & Bridges** – Horizontal overhangs and bridges are challenging even for tiny distances. In addition, different parameters and procedures could prolong this; therefore, the part should include an overhang of the specified value in Chapter 5.1 *Customer needs and Part specification.*
- **Pen Mechanism** – To minimise the risk of getting ink in the wrong places, most pens use some protection or retraction of the ink. Again, this is something that should be included or solved.
- **Grip** – To make the pen comfortable to write with, it should also include some gripping surface there to put the fingers.

5.2.2 Search externally

As described in *Concept Generation* 3.3.2, a patent search was conducted at this stage. It resulted in several solutions for pen mechanism, for example, retraction, twisting fountain, etc. However, it also showed that the patents for most common pen mechanisms such as [33] [34] were expired and didn't necessarily need to be avoided. A dissection of common pen mechanisms can be seen in Figure 17, where most likely the mechanism described in inventor *D. Parker* [33] and *H. Schultz* [34] patents above could be seen as the first from top respectively second and third in the figure.

Figure 17 A dissection of common pen mechanisms, where the first from the top most commonly is based on the D.Parker patent [33] while the second and third probably is based on the H. Schultz patent [34] and the fifth shows a twisting pen mechanism.

5.2.3 Search internally

To get a feeling and essence of different patterns and surfaces, several mood boards were composed. One general mood board inspired by architecture and everyday life together with one organic mood board showing solutions and patterns from nature was set up. The mood boards were used as a communication tool with stakeholders but also as an inspiration for the brainstorming of design ideas. The mood boards can be seen in Figure 18 and Figure 19.

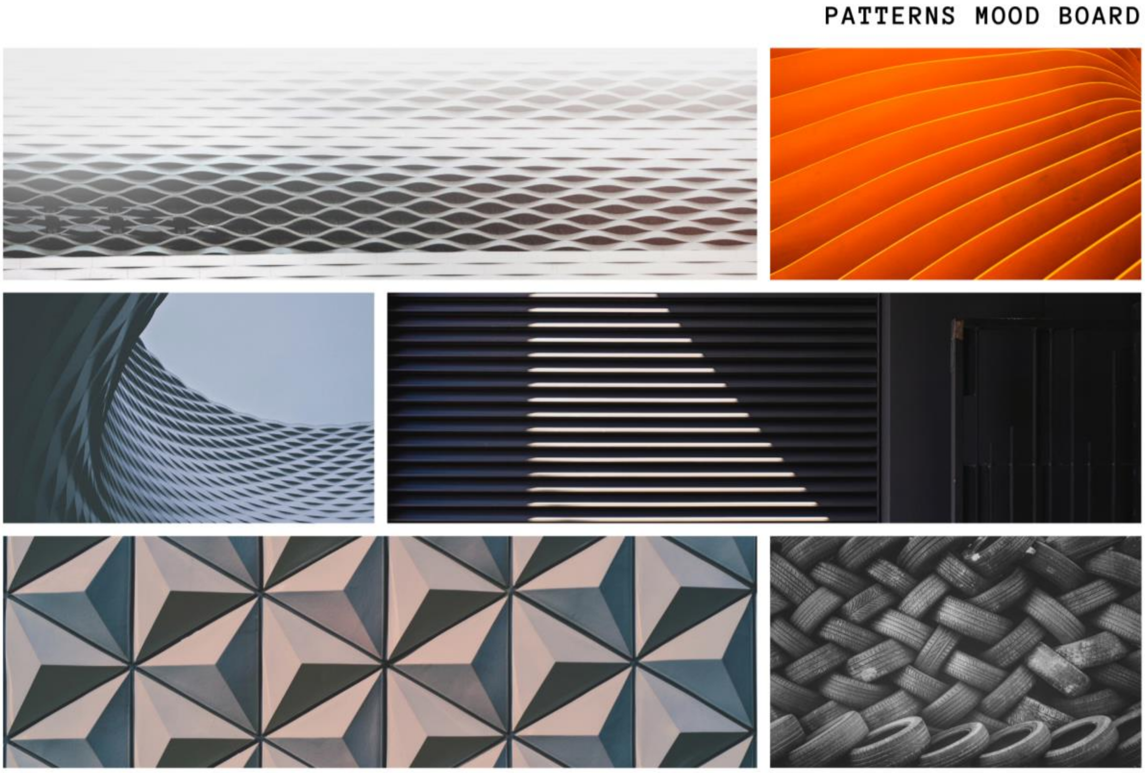


Figure 18 Patterns mood board with inspiration from architecture and everyday life. Pictures retrieved from [35].

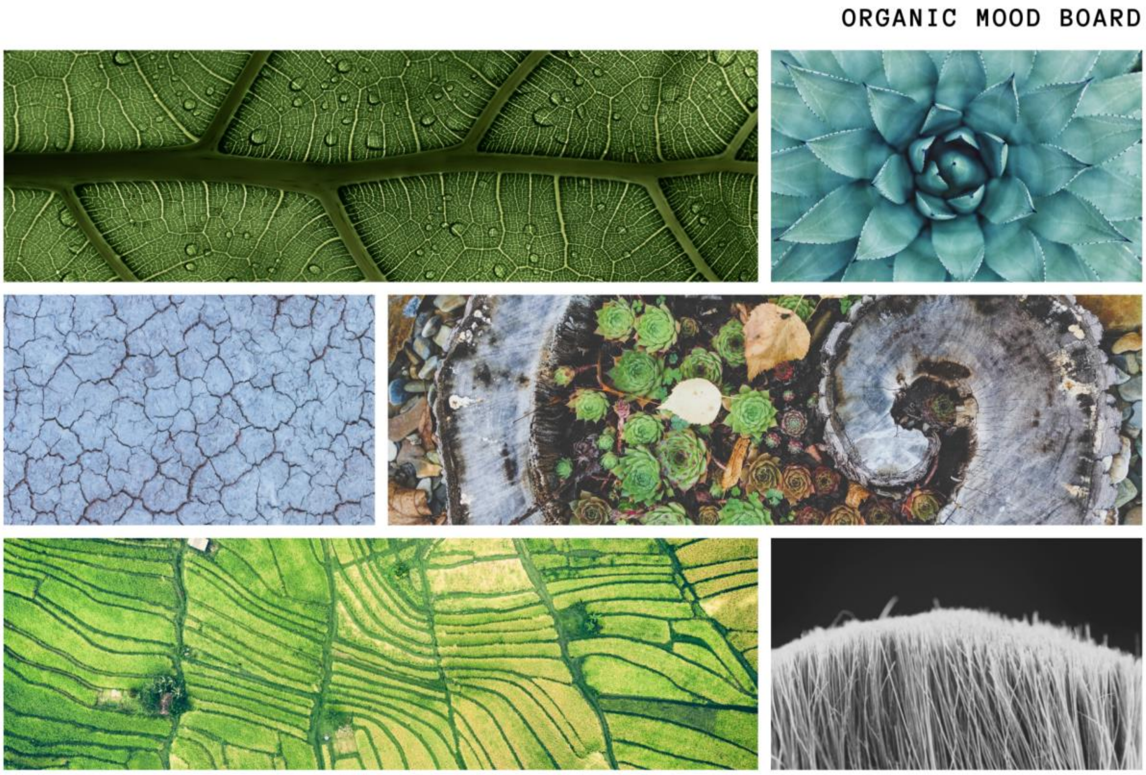


Figure 19 Organic mood board showing solutions and inspiration from nature. Pictures retrieved from [36].

To generate solutions to the subfunctions in Chapter 5.2.1 *Clarifying the problem,* a brainstorming session was performed with the insights from 5.1 *Customer needs and Part specification* and 5.2.2 *Search externally* as input. The design idea output from the brainstorming session was summarised and arranged into a morphological matrix (Table 4) that could be found in 5.2.4 *Explore systematically.*

Also, in conjunction with the brainstorming, a thin and thick pen comparison was conducted (see Figure 20). The slender pen expressed more elegance while the thicker one experienced a bit clumsy, which also was confirmed by the stakeholders.

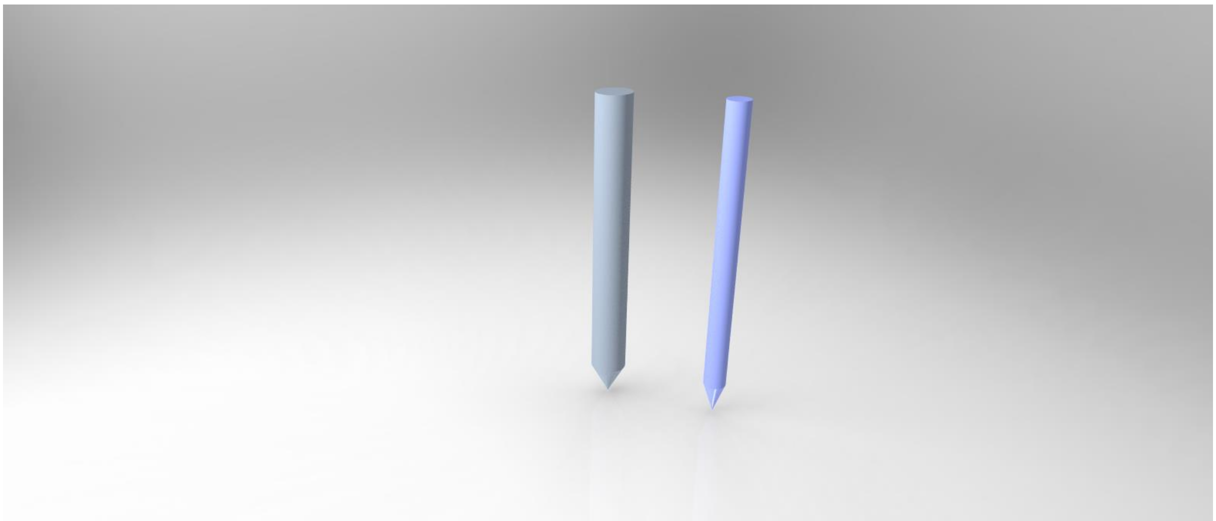


Figure 20 Shows a comparison of a thick (grey) and thin (blue) pen to understand what to seek in this design project.

5.2.4 Explore systematically

Solutions to the subproblems from Chapter 5.2.1 are arranged into a morphological matrix showing the different design possibilities (see Table 4). The morphological matrix generated various concepts that included one solution for each subproblem, visually showing how different design solutions could look together. Drawings on the different developed concepts are illustrated in 5.2.6 *Generated concepts.*

Table 4 A Morphological matrix of the solutions to the subproblem

Angles	Triangle 	Tire 	Grill 	Organic patterns Voronoi 	Spiral/helical sweep 
Overhangs (& Bridges if possible)	The clipp 	Horizontal pattern 			
Mechanism	Click 	Twisting 	Cap pen 	Fontain pen 	
Grip	Knurling 30x30 or lattice pattern 	Honeycomb 	Arcitecture pattern 	Triangle pattern 	

5.2.5 Reflection

The last step in the five-step method is reflection. The generated solutions to the subtasks in Chapter 5.2.4 shows a wide range of solutions in the design space for such application. Also, a meeting with stakeholders was held to present both the generated solutions from Chapter 5.2.4 and the concepts in Chapter 5.2.6. The conclusion was that the stakeholders seem to be satisfied with the result so far.

5.2.6 Generated concepts

The first iteration of the generated concepts from the morphological matrix in Chapter 5.2.4 *Explore systematically* are visualised by simple drawings in Figure 21.

For the mechanism subfunction, all solutions could fit since they are well proved and existing. The question is how suitable the different solutions are for LPBF production. For example, the Cap pen and Fountain pen do not contain any moving parts and would probably be relatively easy to produce. In contrast, the Click and Twisting retractable pen mechanisms will be more challenging, but, on the other hand, they will add value by showing the possibility of producing moving parts in metal LPBF.

- **Concept 1 –** Combines Knurrling for grip-ability and writing comfort and a wave formed Grill pattern for the over part of the pen. The Knurling is something that most commonly is achieved through turning. The Grill pattern has a horizontal bridge-like feature included in the pattern, but the concept also includes a clip, and for the pen mechanism, it uses the retractable click function.

- **Concept 2 –** Combines a complex architectural pattern for grip-ability, which might maybe also be possible to create with CNC machining. Together with an organic Voroinoi pattern for the upper part of the pen. The Voronoi pattern would be possible to cut out on sheet metal, but if the shape is more complex, it will certainly not be possible to produce with conventional manufacturing machines. The concept also contains a clip and click mechanism.

- **Concept 3 –** Has a triangular pattern for grip-ability. Probably very difficult to produce a small pattern like this on conventional manufacturing machines. The upper part of the pen has a hollow helical swipe as a structure, which is probably also very difficult to produce on conventional machines. The concept also contains a clip and click mechanism.

- **Concept 4 –** Uses a Honeycomb pattern to create a good grip for the writer. Such a pattern can probably be crated also with conventional CNC machines. For the upper part of the pen, the concept uses the same triangular pattern as concept 3. The concept also contains a clip and click mechanism.

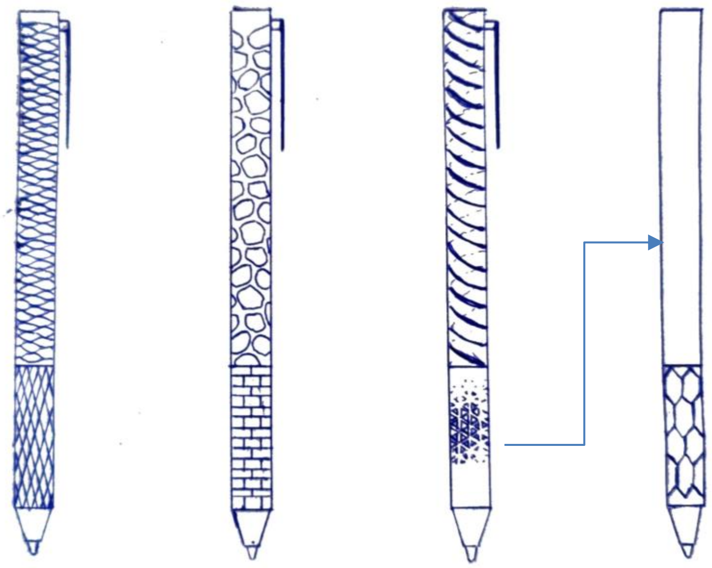


Figure 21 Design concepts generated from the morphological matric (Table 4). Number 1 to the left and number 4 to the right.

The drawings in Figure 21 illustrate how different design solutions could fit together visualised on a simplified pen shape. The figure was used as discussion material with the stakeholders. The discussion resulted in that the stakeholders founding the organic form from concept 2 together with the triangular pattern from concepts 3 and 4 of most interest. Therefore, an additional concept combining these concepts into one was created, see Figure 22.

Figure 22 A visualisation drawing showing the stakeholders input on how an organic shape and a triangular pattern could look together.

5.3 Part Design

Stakeholder input led to a new concept being combined from the previous concept as described in Chapter 5.2.6. The combined concept was iterated once again. This time with even more organic shape and inspiration from nature in mind to fortify the organic appearance, which was an input from the stakeholders. The main inspiration for the second iteration comes from a leaf also found in the mood board, Figure 19. Together with the leaf cells, the leaf veins create the main structure of the pen to produce an organic feeling, see Figure 23. A 3D model was created in CAD for visualising the concept, designing the mechanical parts and also to be able to export STL files that later will be sent to the printer. For rendered images of the concept, see Figure 24-Figure 28.

Figure 23 A comparison of a leaf (Photo: Clay Banks [37]), and the crated design shape, trying to interpret the Vains and cells of the leaf.

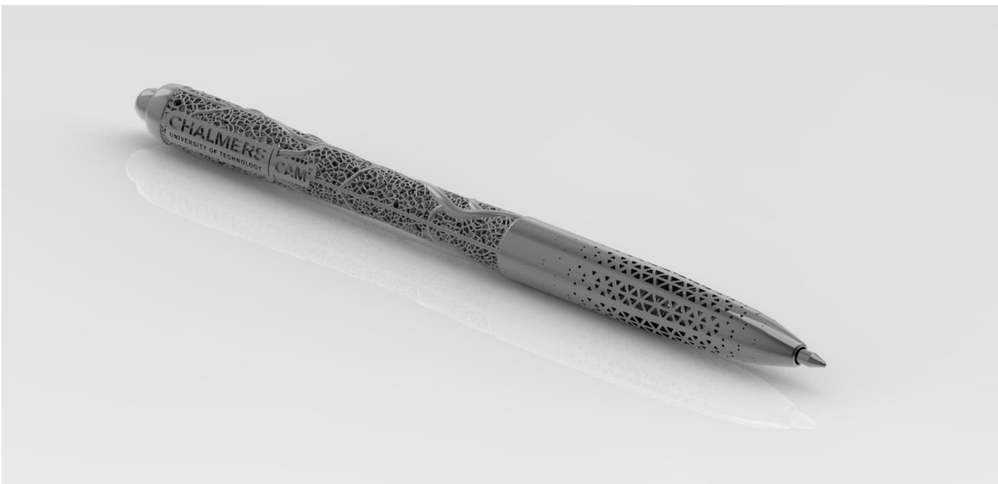


Figure 24 Rendered image of the selected concept, including the leaf veins and the leaf cells, informs of a lattice Voronoi pattern to make the "cell shapes" stochastic.

Figure 25 Rendered image of the selected concept, including only the leaf veins.

Figure 26 Rendered image of the opposite side as Figure 24, including the leaf veins and the leaf cells, informs of a lattice Voronoi pattern to make the "cell shapes" stochastic.

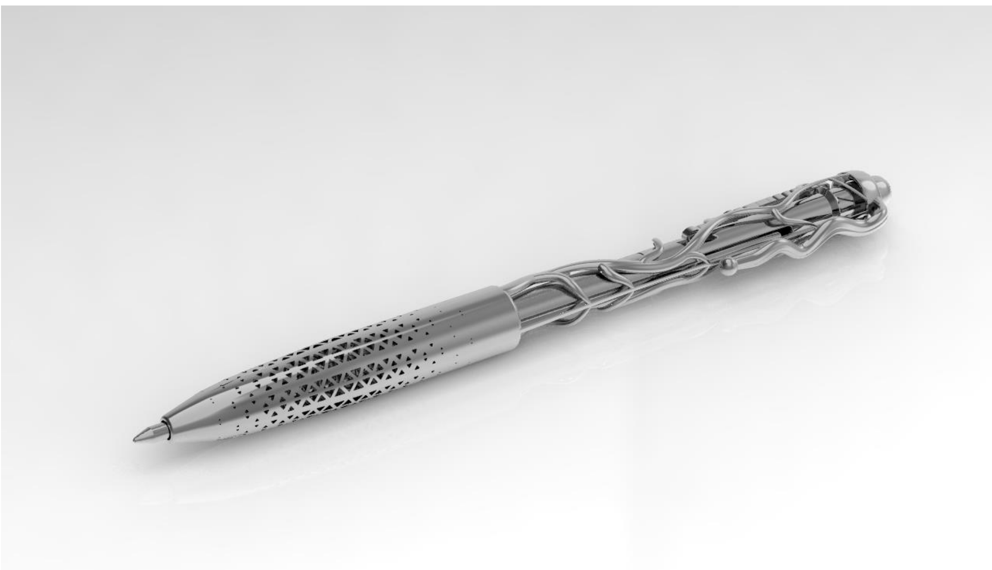


Figure 27 Rendered image of the opposite side as Figure 25, including only leaf veins.

Figure 28 Rendered image of the Proof-of-Concept pen and the Non-Contact-Support that is shelling the pen's tip.

6 Result & Discussion

This chapter focuses on presenting the results and discussing the work of this master thesis concerning both, Non-Contact-Support and the Proof-of-Concept.

As mentioned in Chapter 3, the overall method for this project is tailor-made to fit and be as efficient as possible and consists of several different minor methods suitable for solving the tasks of each subarea to the project. In general, the ordinary DfAM guidelines was something that has been trying to permeate the whole project, which is necessary to develop a suitable design for AM.

6.1 Non-Contact-Support

The Research concerning Non-Contact-Support resulted in the method presented in Chapter 4, which is a way to find out the design parameters suitable for a Non-Contact-Support, which could also be used to find design parameters for different materials.

6.1.1 Cost example

To compare the financial aspects of using a Non-Contact-Support versus a standard support created in Materialise Magics for the same pen tip, a cost calculation is necessary and based on the model presented in Chapter 2.2, *Cost calculation for metal LPBF*. The compared parts and their supports are shown in Figure 29. The selected values and the result of the cost calculation in terms of a *Total AM part cost* is presented in Table 5. A discussion of the chosen values and results for the analysis is presented in Chapter 6.1.2, *Discussion concerning Non-Contact-Support.*

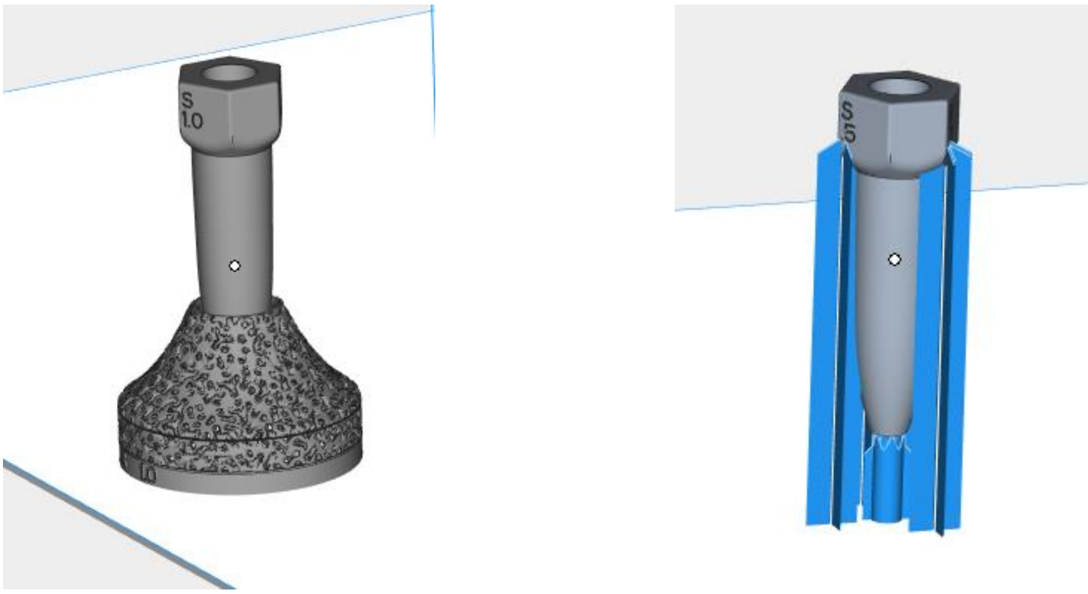


Figure 29 The two pen tips that are compared in the cost example. To the left, the pen tip is supported with Non-Contact-Support (DoE nr 7) and to the right with standard support in blue created with Materialise Magics.

Table 5 Cost example comparison between Non-Contact-support and standard support created with Materialise Magics for the same part. The Build rate and Density were specified in the material datasheet by EOS machine manufacturer for EOS M290.

	Non-Contact-Support (nr 7)	Standard support	Non-Contact-Support (nr 7)	Standard support	Comments
Material	SS316L	SS316L	Ti64	Ti64	
Density (kg/mm³)	7,97E-06	7,97E-06	4,41E-06	4,41E-06	* EOS datasheet
Build rate (mm³/s)	3,7	3,7	6,2	6,2	* EOS datasheet
Layer height (mm)	0,04	0,04	0,04	0,04	
Recoat Time (s)	6	6	6	6	*Estimated value
Powder Cost (sek/kg)	600	600	3000	3000	*Approximate figures
Pre-/post Processing cost + logistics	0,05	0,6	0,05	0,6	* Discussed in Chapter 6.1.2
Part Volume inclusive support (mm³)	120441	83092	120441	83092	*For 36 parts
Max part height (mm)	50,00	50,00	50,00	50,00	
Machine operating cost (SEK/h)	142,69	142,69	142,69	142,69	*Machine 5 millions, Depreciation 4 yr.
Machine operator cost/job	1600	1600	1600	1600	* 800 SEK/h
Material cost (SEK)	575,95	372,61	1593,44	1049,61	
Built time (h)	13,39	9,88	8,83	6,74	
Total AM Part Cost (SEK)	**119,48**	**234,90**	**130,21**	**250,76**	

6.1.2 Discussion concerning Non-Contact-Support

The fractional factorial DoE method is suitable for finding out the most influencing parameters in a complex system among many parameters with limited tests. To further develop the Non-Contact-Support and find out more exact behaviour of such support and to use the result as a surrogate model for design optimization, a finer screening method with even more tests or even a full factorial design could be suitable.

The DoE of the Non-Contact-Support in this project was designed for testing only one material at a time. Most certainly, a material change would have several effects on the optimal combination of DoE/design parameters. Different material powder could have

differences in powder particle size, which could affect the minimum possible gap between part and shell. Of course, different metal powders have differences in thermal and mechanical properties, which also could have significant effects on the design parameters and limitations. For example, the thermal conductivity of the powder and the solidified metal could affect the Non-Contact-Support, meaning a better or worse heat dispatch for different materials that, in the worst case with faulty design parameters, could lead to overheating of the material. In terms of mechanical properties, different materials have different mechanical strengths meaning a material with higher mechanical strength in a solidified state would require less melted material to clamp the part to the baseplate in an optimal design than a material with lower mechanical strength in the solidified state.
Of course, the developed DoE method could be applied to find out the most suitable design parameters for a Non-Contact-Support for different materials. It only requires several different runs of the whole DoE, each run of the whole DoE, corresponding to one new material.

In addition, only one layer thickness was selected for the DoE, but of course, different layer thicknesses could also affect the behaviour of the Non-Contact-Support, and this aspect needs further investigation, especially when the trend in the industry is to increase layer thickness to reach higher productivity.
Another aspect that may limit the adoption of the result from the DoE is the use of only one machine. Machines from different providers can vary in various ways. They, therefore, could produce a slightly different result, but in general, the methodology should be transferable to other machines.

In this report, it is easy to think that the Non-Contact-Support is designed for just one product, a pen tip, but the idea is that the Non-Contact-Support is transferable to a wider range of products needing support and that are produced with AM. The condition is that the product needs to have a "leg", a corner, a cone, a cylinder or similar feature that could be shelled or even other geometries. The only condition is that it needs to be possible to realise the product from the shell by adding a force or torque to the z-axis of the machine.

From the result of the DoE, when knowing what design parameters have the most influence and are most suitable for the Non-Contact-Support, design guidelines could be completed to ease the work of assigning correct design parameters, for example, depending on the material.

As mentioned above, a surrogate model for design optimization could be completed with greater data collection, including different materials and different machines. Then, the surrogate model could be implemented into a build preparation software for an automatic optimized configuration and generation of the Non-Contact-Support depending on some input values, like material, machine, etc.

The design of the Non-Contact-Support is not optimized, and therefore, efforts could be spent to find an optimal design. Thereby, identify what features are needed for the Non-Contact-Support to use the minimum amount of material for the Non-Contact-Support to work, thereby making it even more competitive by reducing the total volume. Another point that would be worth investigating is whether it would be possible to have the supporting shape consisting only of bars or organic shapes like the leaf veins of the Proof-of-Concept and still have enough heat conductivity?

The cost comparison from Chapter 6.1.1 shows that the Non-Contact-Support becomes more affordable to produce despite the slightly larger total volume of material produced and, therefore, consumes more metal powder than the part produced with standard support. The reason for the cost reduction with the novel support solution is that no or very little time is needed for post-processing. The part only needs to be separated from the shell, while with standard supports, dedicated support removal and probably machining are necessary. In addition, the Non-Contact-Supports shell could even be used as a pen stand and therefore serve a function even after print and not be wasted.

The orientation of the standard support could be argued about, but it was selected to be printed in a standing position due to the accuracy of the holes and also this orientation allows the most effective utilization of the build volume so that as many parts as possible could be printed at the same time. When optimizing the orientation in Magics, it found the solution with the bolt head at the top most suitable.

To make the comparison realistic, the Pre/Post-processing percentage was set to 5% of the total part cost for the Non-Contact-Support. In contrast, the present design for the standard supported pen tip probably requires less post-processing than the average part considered in the Wohlers Survey. On the other hand, smaller parts could cost more to machine in terms of the total part cost than larger and more expensive components. Therefore the same percentage was chosen for the Pre/Post-processing for the standard supported part as considered in Wohlers report survey from 2019, namely 40%.

To get an even more realistic cost example, a logistic factor was added to the Pre/Post-processing cost, which is a difference compared to Timothy W. Simpsons cost model. The logistical factor means taking height for the cost and time to get the part to the machine shop for support removal, which could be in a different geographical location. The logistical cost factor is set to 20% of the total part cost, which means by adding the logistical factor to the Pre/Post-processing cost, this sums up to a total of 60% of the total part cost. Of course, larger and more expensive parts will have a lower percentage.

Another parameter of the cost calculation interesting to discuss is the machine operating cost. This is derived by the assumption that the machine costs around 5 million SEK, the depreciation is set to be 4 years. The machine could run for up to 24 h/day, which gives the machine operating cost of approximate 143 SEK/h. It is important to note that this underestimates the machine operating cost since, in reality, it is impossible to have the machine running full time. For example, maintenance needs to be scheduled; it takes time to load/unload the machine for each print. Also, maintenance costs (service and maintenance contract, software, building rent, etc.) consumables (sieves, build plates, recoater blades, processing gas, electricity, etc.) are excluded. Hence, a more realistic evaluation will be between 200 to 400 SEK/hour for the equipment in question.

Another difference compared to Timothy W. Simpsons cost model is the machine operator cost which is a start cost added to the equation. The machine operator cost takes height for the time and costs to load/prepare the machine and after print unload, which takes engineering hours and is expected to take 1 hour each and with a price of 800 SEK/h this sums up to a start cost of 1600 SEK/h for each print section.

The result of the cost calculation gives that the material cost is higher for the Non-Contact-Support, because of the slightly bigger volume. The same applies to the build time. This is because a slightly larger volume takes longer to print. On the other hand, the Total part cost for the Non-Contact-Support is less than for the standard supported part, and that is thanks to less post-processing.
There is no big difference in cost per part between Stainless steel 316L and Titanium 64, even though the Titanium 64 powder is more expensive to purchase. This is due to the higher material-dependent build rate value for titanium compared to stainless steel.

By switching from a standard supported part to a Non-contact-support, the total part cost could be reduced by 49% for SS316L and 48% for Ti64, which is a significant cost reduction. Therefore a Non-Contact-Support should be considered when choosing supports for LPBF thanks to the great cost reduction.
In addition, it should be mentioned that one of the driving forces behind the design of non-contact support was to use it as a pen holder, and hence providing an additional advantage of the AM when it comes to the component integration. This allows to minimize to the minimum material waste and provide an additional advantage compared to the conventional support as in that case, pen holder should be produced as a separate part in a separate build, boosting significantly cost of the component.

6.2 Proof-of-Concept design

For the product development parts of this master thesis, a well-known method, the five-step method from *Ulrich, Eppinger & Yang* was selected. It seemed to work fine for an AM development project with no interference to the DfAM guidelines of Additive Manufacturing.

The Proof-of-Concept design from Chapter 5 was evaluated with the help of LPBF Polymer print to make sure the design was robust and that the pen was successfully built before moving on to print the pen in Metal LPBF. Unfortunately, the first polymer print was not 100% successful. A small piece in the middle of the design was missing, see Figure 30. Besides this, the print was satisfying, providing a good prototype.

The difference in height between the pen tip (DoE part) and the Proof-of-Concept pen is is worth discussing. The total height of only the pen tip in the DoE part (Non-Contact-Support excluded) is 40mm, while the total height of the whole pen in the Proof-of-Concept (Non-Contact-Support excluded) is 130mm high. The required height ratio between the Non-Contact-Support shell height and the part (pen tip), see Figure 31, is examined in the DoE (Height parameter), Chapter 4. Based on the result from the DoE, the required height ratio could be scaled up and be applied to fit other higher parts, like in the case of the Proof-of-Concept, a whole pen.

Figure 30 Showing the first polymer print of the Proof-of-Concept. One part in the middle of the pen was not successfully printed; see red arrow. Photo: Karolina Johansson, Lasertech LSH AB.

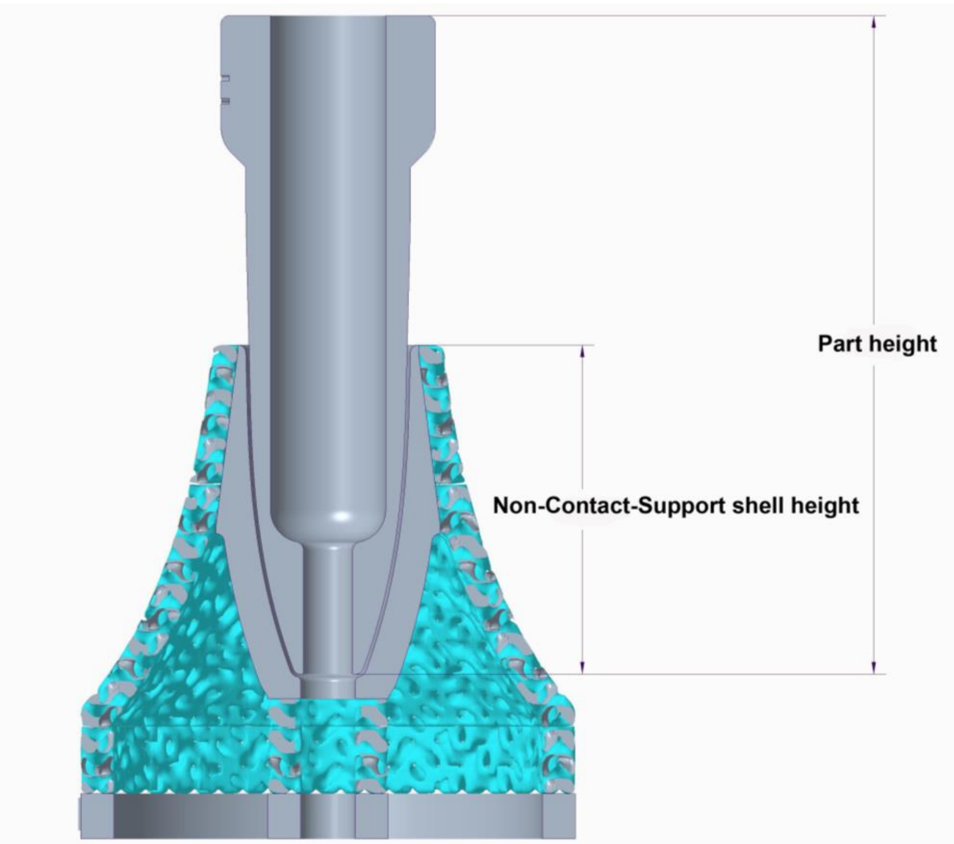


Figure 31 Visually shows the ratio between the part height and the Non-Contact-Support shell height. In the DoE, a suitable ratio is examined. This ratio could be scaled up to other parts.

7 Conclusions

This chapter focuses on answering the research questions stated in Chapter 1.4 and suggestions for further development.

7.1 Research question 1

How to define a methodology to derive guidelines to design Non-Contact-Support for metal AM?

The first step in defining a methodology to derive guidelines to design non-contact support is to identify relevant factors. In the case of this master thesis, the relevant factors were set to be Height (of shell), Thickness (of shell), Gap (between the shell and part), and the presence of perforation of the shell or not.
Secondly, based on the identified influencing factors, a DoE was set up with identified factors defined as factors in the DoE. As response value of the DoE, a quantity measuring a suitable bonding between part and shell should be selected and preferably done by measuring the required torque to realise the part from the shell. The result from the measurement is then imported into a statistical software like JMP, with the help of statics, analyse the result to find out the most influencing design parameters and suitable optimized quantities for the parameters. Finally, from the result of the DoE design guidelines could be formulated, guiding the designer to assign correct values of, for example, a suitable gap distance between part and shell for specific material. For defining guidelines for another material, the method should be applied again.

7.2 Research question 2

How to implement the design guidelines into a support free component optimized for AM?

There could be several different ways to implement the design guidelines into a support-free component. The first and most straightforward way that could be adopted directly after the design guidelines are established and work in the same way as the commonly DfAM guidelines. Meaning from a material-specific table, the designer finds an optimized value for the different design parameters (Height, Thickness, Gap and Perforation) that easily could be assigned to the design of the Non-Contact-Support.
Another way to implement the design guidelines into a support-free component is to have a surrogate model based on the DoE built into a build preparation software. Then you have to specify some input variables like material, placement, geometry, for example. Then, the build preparation software generates an optimized Non-Contact-Support to the component based on the result of the DoE and the design guidelines.

7.3 Further development

The next step in developing the concept, Non-Contact-Support, is to print the parts in the DoE in metal to measure the torque required to release the part from the shell and thereby find out the most influencing design parameters.

To further develop the concept of, Non-Contact-Support, additional DoEs for different materials need to be executed. Thereafter a surrogate model based on the results from the different DoEs, containing different materials and machines, for example, could be completed to make it possible to optimize the design parameters of the Non-Contact-Support. The final step of the development would be to implement the surrogate model based on the DoEs into a build preparation software, making it possible to automatically generate Non-Contact-Supports based on some input information, like material, machine type, for example.

References

[1] ”CAM2 | Centre for Additive Manufacture - Metal,” 15 11 2019. [Online]. Available: https://www.chalmers.se/en/centres/cam2/Pages/default.aspx. [Använd 01 09 2021].

[2] O. Diegel, A. Nordin och D. Motte, A Practical Guide to Design for Additive Manufacturing, Springer, 2020.

[3] METAL_AM, ”Background to Additive Manufacturing,” [Online]. Available: https://www.metal-am.com/introduction-to-metal-additive-manufacturing-and-3d-printing/background-to-additive-manufacturing/. [Använd 02 09 2021].

[4] A. International, ”Standard Terminology for Additive Manufacturing - General Principles - Terminology”. West Conshohocken, PA Patent ISO/ASTM 52900.

[5] S.Haeri, ”Optimisation of blade type spreaders for powder bed preparation in Additive Manufacturing using DEM simulations,” *Powder Technology,* vol. 321, pp. 94-104, 2017.

[6] F. Calignano, ”Design optimization of supports for overhanging structures in aluminum and titanium alloys by selective laser melting,” *Materials and Design,* 2014.

[7] E. Hryha och D. Riabov, ”Metal Powder Production for Additive Manufacturing,” *Encyclopedia of Materials: Metals and Alloys,* vol. 3, pp. 264-271, 2022.

[8] EPMA, ”Introduction to Additive Manufacturing Technology - A guide for Designers and Engineers,” European Powder Metallurgy Association, 2019.

[9] C. Pauzon, E. Hryha, P. Forêt och L. Nyborg, ”Effect of argon and nitrogen atmospheres on the properties of stainless steel 316 L parts produced by laser-powder bed fusion,” *Materials & Design,* vol. 179, nr 107873, p. October, 2019.

[10] K. Stevenson, ”All About 3D Printer Recoater Blades,” Fabbaloo, 7 07 2020. [Online]. Available: https://www.fabbaloo.com/2020/07/3d-printer-recoater-blades. [Använd 16 09 2021].

[11] O. Diegel och T. Wohlers, ”From silicone and rubber to steel and ceramic: the weird and wonderful world of wipers,” Metal AM, 2019. [Online]. Available: https://www.metal-am.com/articles/from-silicone-and-rubber-to-steel-and-ceramic-the-weird-and-wonderful-world-of-wipers/. [Använd 16 09 2021].

[12] F. Ceccanti, A. Giorgetti och P. Citti, ”A Support Structure Design Stategy for Laser Powder Bed Fused Parts,” *Procedia Structural Integrity,* vol. 24, pp. 667-679, 2019.

[13] K. V. Praet, ”Tips and Tricks for Metal 3D Printing,” Materialise, 21 06 2017. [Online]. Available: https://www.materialise.com/en/blog/metal-3D-printing-recoaters. [Använd 16 09 2021].

[14] J.-P. Järvinrn, V. Matilainen, X. Li, H. Piili, A. Salminen, I. Mäkelä och O. Nyrhilä, ”Characterization of effect of support structures in laser additive manufacturing of stainless steel,” i *Physics Procedia 56*, Elsevier, 2014, pp. 72-81.

[15] M. Cloots, L. Zumofen, A. Bernardus Spierings, A. Kirchheim och K. Wegener, ”Approaches to minimize overhang angles of SLM parts,” Rapid Prototyping Journal, 2017.

[16] T. W. Simpson, ”Postprocessing Steps and Costs for Metal 3D Printing,” Additive Manufacturing Media, 21 05 2018. [Online]. Available: https://www.additivemanufacturing.media/articles/postprocessing-steps-and-costs-for-metal-3d-printing. [Använd 10 09 2021].

[17] M. Kahlin, H. Ansell, D. Basu, A. Kerwin, L. Newton, B. Smith och J. Moverare, ”Improved fatigue strength of additively manufactured Ti6Al4V by surfacepost processing,” *International Journal of Fatigue,* vol. 134, 2020.

[18] T. W. Simpson, ”Industrializing AM: A Simple Cost Equation,” *Additive Manufacturing,* 10 08 2020.

[19] J. Pullin och A. Offen, ”Back to the Drawing Board - Addressing the design issues of RM,” News Publications Plc, Coventry, West Midlands, 2008.

[20] I. Gibson, D. Rosen, B. Stucker och M. Khorasani, Additive Manufacturing Technologies, Springer International Publishing, 2021.

[21] M. Cloots, A. Spierings och K. Wegener, ”Assessing new support minimizing strategies for additive manufacuring technology SLM,” 2013.

[22] K. Cooper, P. Steele, B. Cheng och K. Chou, ”Contact-Free Support Structures for Part Overhangs in Powder-Bed Metal Additive Manufacturing,” Inventions, 2018.

[23] L. Di Angelo, P. Di Stefano och E. Guardiani, ”Serch for the Optimal Build Direction in Additive Manufacturing Technologies: A Review,” *Journal of Manufacturing and Materials Processing,* 2020.

[24] Y. Qin, Q. Qi, P. Shi, P. J.Scott och X. Jiang, ”Automatic determination of part build orientation for laser powder bed fusion,” *Virtual and Physical Prototyping,* vol. 16:1, pp. 29-49, 2020.

[25] D. Bentley, ”Support Structures: The Need, Impact, and Elimination Strategies,” Velo 3D, 12 02 2020. [Online]. Available: https://www.velo3d.com/support-structures-the-need-impact-and-elimination-strategies/. [Använd 14 09 2021].

[26] Velo 3D, ”Frequently Asked Questions,” Velo 3D, [Online]. Available: https://www.velo3d.com/faq/. [Använd 14 09 2021].

[27] B. Neirinck och K. Eckes, ”Rethinking Doctor Blades And Counter-Rotating Rollers,” Aerosint, 30 01 2020. [Online]. Available: https://aerosint.com/rethinking-doctor-blades-and-counter-rotating-rollers/. [Använd 14 09 2021].

[28] ”Velo3D: How a ‘support-free’ Laser Powder Bed Fusion process could remove roadblocks to serial Additive Manufacturing,” Metal AM, 2019. [Online]. Available: https://www.metal-am.com/wp-content/uploads/sites/4/2019/10/Metal-AM-Autumn-2019-sp-1.pdf. [Använd 14 09 2021].

[29] JMP, ”Design of experiments,” SAS Institute Inc., [Online]. Available: https://www.jmp.com/en_au/statistics-knowledge-portal/what-is-design-of-experiments.html. [Använd 11 10 2021].

[30] JMP, ”Types of Design of Experiments,” SAS Institute Inc., [Online]. Available: https://www.jmp.com/en_au/statistics-knowledge-portal/what-is-design-of-experiments/types-of-design-of-experiments.html?utm_source=organic&utm_medium=skp&utm_campaign=doe_ap#screening-designs. [Använd 11 10 2021].

[31] Ulrich, Eppinger och Yang, Product Design and Development, New York: McGraw-Hill Education, 2020.

[32] D. Ullman, The Mechanical Design Process, New York: McGraw-Hill Education, 2016.

[33] D. Parker, ”Writing instrument”. United States Patent US2971283A, 23 05 1958.

[34] H. Schultz, ”Retractable pen”. United States Patent US3819282A, 02 11 1972.

[35] Unsplash, ”Photos: Michael Nöthiger, Ryunosuke Kikuno, Victor, The blowup,The blowup, Imthaz Ahamed.,” [Composition of Photos], [Online]. Available: https://unsplash.com/. [Använd 18 10 2021].

[36] Unsplash, ”Photos: Clay Banks, Erol Ahmed, Dave Hoefler, Pavel Neznanov, Ivan Bandura, Sam Moqadam.,” [Composition of Photos], [Online]. Available: https://unsplash.com/. [Använd 08 10 2021].

[37] C. Banks, Artist, *A Ficus Lyrata Leaf in the sunlight (2/2) (IG: @clay.banks).* [Art]. Unsplash.com, 2020.

[38] ”DMLS Materials for Additive Manufacturing of metal parts,” EOS, [Online]. Available: https://www.eos.info/en/additive-manufacturing/3d-printing-metal/dmls-metal-materials. [Använd 15 09 2021].

[39] X. Wu, D. Zhang, Y. Guo, T. Zhang och Z. Liu, ”Microstructure and mechanical evolution behavior of LPBF (laser powder bed fusion)-fabricated TA15 alloy,” *Journal of Alloys and Compounds,* vol. 873, nr 159639, 25 August 2021.

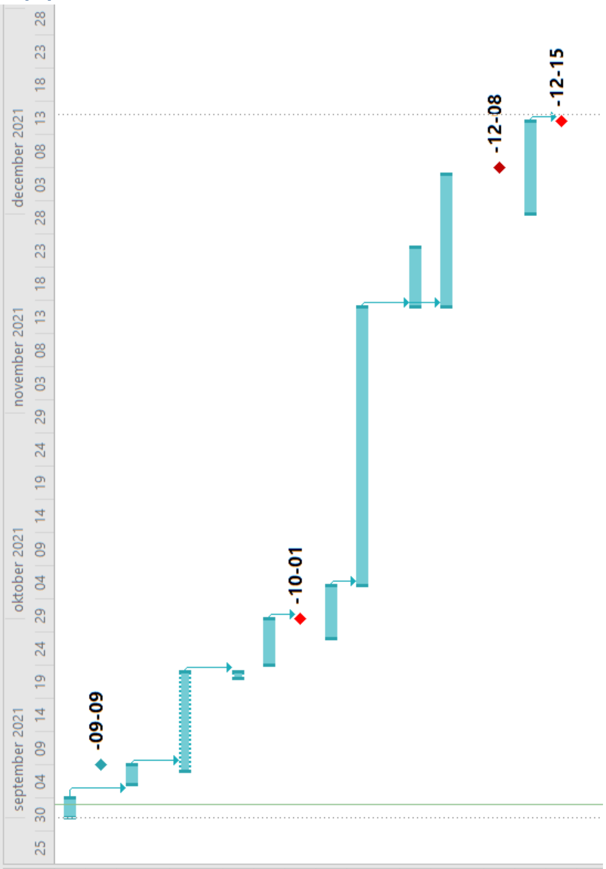
[40] EOS GmbH, ”EOS StainlessSteel 316L Material Data Sheet,” 2021.

[41] EOS GmbH, ”EOS Titanium Ti64 Material Data Sheet,” 2014.

Appendix

GANTT-SCHEMA

	Aktivite	Aktivitet	Varaktighet	Start	Slut	Föregående aktiviteter
1		Planning	3 dagar	on 21-09-01	fr 21-09-03	
2		Planning report meeting	0 dagar	to 21-09-09	to 21-09-09	
3		Identification of support structures	3 dagar	må 21-09-06	on 21-09-08	1
4		Litterature study on limitaions	11 dagar	on 21-09-08	on 21-09-22	3
5		Choice of component	1 dag	on 21-09-22	on 21-09-22	4
6		Prepare opponering	5 dagar	fr 21-09-24	to 21-09-30	
7		Opponering	0 dagar	fr 21-10-01	fr 21-10-01	6
8		Design of test	6 dagar	ti 21-09-28	ti 21-10-05	
9		Conducting tests and DfAM	30 dagar	on 21-10-06	ti 21-11-16	8
10		Final print	7 dagar	on 21-11-17	to 21-11-25	9
11		Working Final report/Prepare results	14 dagar	on 21-11-17	ti 21-12-07	9
12		Send report to opponen	0 dagar	on 21-12-08	on 21-12-08	
13		Prepare presentation	10 dagar	on 21-12-01	ti 21-12-14	
14		Final presentation	0 dagar	on 21-12-15	on 21-12-15	13



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