SAMULI KINNARI
AN APPROACH TO REDESIGN OF STAINLESS STEEL HANDLE FOR 3D METAL PRINTING

Bachelor of Science Thesis

Examiner: Jorma Vihinen
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ABSTRACT

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The goal of this thesis, was to approach the redesign of a stainless-steel handle and to explore its most potential redesign targets, for manufacturing with the method of selective laser melting. Additionally, it was to be documented what challenges were met, what potential was found, what knowledge is needed, and what design guidelines could be followed to be able to find the potential and utilize the design freedom provided by SLM effectively.

The thesis was carried out by performing literature review on the topic of DFAM and the SLM manufacturing method. The required knowledge and the challenge of the change of mindset was discussed. Compilations of the SLM design value network, SLM design recommendations, and things to consider in design for SLM were presented. A methodology to help identify feasible part candidates and evaluate their potential for AM production, and a methodology that defines steps to optimize mechanical systems with AM capabilities, were introduced. Additionally, practical design work was performed with the help of the compiled knowledge, the methodologies, and the suggested DFAM tools, to analyze and identify the potential redesign targets of the stainless-steel handle and derive the redesign examples of them.

As a result, high amount of design potential for the stainless-steel handle was found. In total, 12 potentials of additional value that the SLM method could provide were identified, 7 redesign targets that could be achieved with full or a partial redesign were derived, and 5 redesign examples for the optimization of the current design were made.

The thesis demonstrated that on an existing design, some parts can surely benefit from the design freedom provided by SLM as optimization, but the benefits on design are realized much more effectively with completely new designs started from a blank canvas.

It was concluded, that not all parts can benefit from a design for SLM, and that recognizing part potential is essential, and that comprehensive methodological guidance on executing the utilization of design opportunities is lacking. It was recommended, that general design theory should be used and enriched with DFAM tools in the meantime. Additionally, recommendations for the utilization of the introduced methodologies were given.
# TABLE OF CONTENTS

1. INTRODUCTION ............................................................................................................. 1

2. CASE PRODUCT AND MANUFACTURING METHOD .............................................. 2
   2.1 Low voltage switch handle ......................................................................................... 2
   2.2 Selective laser melting ............................................................................................... 3

3. APPROACH TO REDESIGN ......................................................................................... 4
   3.1 Change of mindset .................................................................................................... 4
   3.2 Dependency on the SLM method ................................................................................. 5
      3.2.1 Division of capabilities for AM ............................................................................. 5
      3.2.2 Design rules and considerations ............................................................................ 7
   3.3 Dependency on the part ............................................................................................ 9
      3.3.1 Part potential ......................................................................................................... 9
      3.3.2 Tools and methodologies ...................................................................................... 11
      3.3.3 Analysis of the handle .......................................................................................... 14
   3.4 Derived redesign targets ......................................................................................... 18

4. REDESIGN EXAMPLES ............................................................................................... 19
   4.1 Weight reduction and optimized geometry ............................................................. 19
      4.1.1 Implementation of hollow cavities ................................................................. 19
      4.1.2 Minimizing dirt collecting geometries ............................................................. 21
   4.2 Parts consolidation ..................................................................................................... 22
      4.2.1 Directly fabricated padlock mechanism .......................................................... 22
      4.2.2 Integrated snap-pin mechanism ......................................................................... 23
   4.3 Additional benefits ..................................................................................................... 25
      4.3.1 Removing the need for a separate laser marking process ............................... 25

5. CONCLUSIONS ............................................................................................................ 26

6. BIBLIOGRAPHY .......................................................................................................... 28
# LIST OF ABBREVIATIONS AND SYMBOLS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM</td>
<td>Additive Manufacturing</td>
</tr>
<tr>
<td>SLM</td>
<td>Selective Laser Melting</td>
</tr>
<tr>
<td>DFAM</td>
<td>Design for Additive Manufacturing</td>
</tr>
<tr>
<td>PBF</td>
<td>Powder Bed Fusion</td>
</tr>
<tr>
<td>DFMA</td>
<td>Design for Manufacture and Assembly</td>
</tr>
</tbody>
</table>
1. INTRODUCTION

In his master’s thesis, J. Lehtimäki explored the potential of using additive manufacturing (AM) and particularly selective laser melting (SLM) in ABB Oy product development processes. His results deemed the manufacturing method as suitable but designing components for SLM was named as an area where studies would need to continue. [1] The manufacturing method raised further interest in ABB Oy, and as a next step a full redesign and manufacturing of a potential part candidate was decided to be carried out to validate the possibilities and maturity of manufacturing with SLM.

However due to the complexity of the subject, the full redesign was not carried out immediately, instead a preceding goal for this thesis was set. The goal was to approach the redesign and to explore the most potential redesign targets at least on idea level. Additionally, it was to be documented what challenges were met, what potential was found, what design guidelines could be followed to be able to find the potential and utilize the design freedoms provided by SLM effectively. Eventually this thesis could then be used as a basis to help perform the full redesign later.

The thesis was carried out by performing literature review on the topic of design for additive manufacturing (DFAM) and the SLM manufacturing method. Additionally, practical design work was performed to identify the potential redesign targets of the stainless-steel handle and derive redesign examples of them.

The structure of the thesis is divided so, that in chapter 2, the case product and manufacturing method are introduced to help understand the further analysis made later.

In chapter 3, the change of mindset and knowledge required by DFAM is discussed, the approach to redesign’s dependency on the manufacturing method and on the part to be redesigned is explored, and the tools and methodologies that can help the designer are introduced. On this basis, potential redesign targets are defined.

In chapter 4, five redesign examples are made of these targets, from which they can be evolved or used as inspiration in the full redesign made in the future.

The complete thesis, will therefore provide the reader awareness of what challenges will be faced, what needs to be considered, what knowledge is needed, what tools and methodologies can help, and what kind of potential can be gained when performing the redesign of similar parts as the case part with SLM.
2. CASE PRODUCT AND MANUFACTURING METHOD

2.1 Low voltage switch handle

The subject of redesign in this thesis is a product of ABB Oy, Protection and Connection -division. A stainless-steel handle which is used to operate a switch-disconnector mechanism, that disconnects and connects electricity flow in the circuit it is installed to.

The stainless-steel handle in its current state is a copied design implementation of a plastic version, which is used in most application cases. Only minor design changes were made to allow functionality with the stainless-steel material, which is often needed in medical and food industry applications due to its anti-corrosion properties. The design is suboptimal, and suffers from production and function related issues, which result in the need for a redesign. The handle is part of a larger product family with handles of different sizes, materials and functions. While the handle would seem to be a simple product at first, it contains multiple functions and it is often used in demanding conditions, which both set requirements for its shape, structure and working principle. These requirements and the previously mentioned issues, are explored in chapter 3.3.3.

A brief description of the handles usage is made to help understand the further analysis made later. During use, the components are installed in a housing box. An axle (2.) connects the mechanism (3.) to the handle (1.), which is attached to the door of the housing. An example of the assembled components without the housing is shown in figure 1.

![Figure 1. Assembled components, including handle (1.), axle (2.), mechanism (3.). Adapted from [1, p.40]](image-url)
2.2 Selective laser melting

The discussion of approaching the redesign made in chapter 3. and the redesign examples of the handle made in chapter 4. are performed with the assumption of using SLM as the applicable manufacturing method. The following description of the SLM manufacturing method is made only on a general process level, and further knowledge of the process, available materials, and production with the method can be gained from the previously mentioned master’s thesis by J. Lehtimäki [1].

SLM is a type of powder bed fusion (PBF) -process, where the part is built one layer at a time by fusing together material which is in powder form. PBF-processes share a workflow, which is illustrated in figure 2. [1, p.8]

*Figure 2. PBF-process workflow. [1, p.8]*

First the powder is leveled on the building platform as a thin even layer by powder levelling rollers. A laser is then used to generate heat and fuse the set of powder particles together. The part is eventually formed from the fused particle layers by repeating the two steps. Additional heat is provided to the building platform and powder to make the process more efficient. Inert shielding gas is used to protect the partly molten metal from oxygen. [1, p.8]

The layer thickness exceeding melt pool, distinctive to SLM’s sintering mechanism, ensures the fusion between layers and provides well-bonded and dense structures with distinct properties of cast and wrought alloys. However, due to the increased density, supports are necessary for overhanging features and rougher post-processing methods are needed. The main challenges of SLM are stresses, distortions and the balling effect of the melt pool caused by heat concentration in the part or incorrect process parameters during buildup. The challenges can be affected by changing the geometry and orientation of the part and adjusting process parameters. [1, p.12, p.50]
3. APPROACH TO REDESIGN

In the beginning of writing this thesis and the effort to derive the redesign examples for the handle, it was quickly realized that the greatest challenge was getting into the mindset of DFAM-thinking. How to approach the redesign in a way that ensures all the possibilities provided by SLM are considered, and the potential targets for the use of them in the case part in a way that most effectively will gain additional value are found.

In the following chapters the required change of thought is discussed, the issue of how value can be achieved and what needs to be considered depending on the manufacturing method and on the part to be redesigned is explored. Tools and methodologies that can help the designer are introduced, and finally the potential redesign targets for the handle are derived after its analysis.

3.1 Change of mindset

The AM methods are unlike traditional manufacturing methods in many ways, and a large difference can be found when looking at them in the design point of view. I. Gibson et al. describe in their book [2, p.400-403] how design for manufacture and assembly (DFMA) with traditional manufacturing methods has typically encouraged designers to focus on tailoring their designs to reduce manufacturing, assembly and logistics costs and difficulties. Design has typically revolved around DFMA and finding an optimal solution by iterative design for both aspects.

By using an aircraft cooling duct redesign (shown in figure 3) as an example. The authors note that while AM also has its own manufacturing constraints, and attention needs to be focused similarly, a large difference is that it can radically reduce these before mentioned costs and difficulties, by eliminating the need for these operations altogether. With great focus on the utilization of the unique design possibilities of AM, this can be achieved.

![Figure 3. Parts consolidation example of an aircraft cooling duct. [2, p.404]](image-url)
In the example, 16 parts and fasteners along with multiple manufacturing operations were both reduced to 1, all while improving the performance of the part. [2, p.400-404]

Therefore, AM can bring value to the manufacturer with reduced manufacturing efforts. Additionally, AM can allow completely new performance enhancing features into the design, which add value for the customer. They are both enabled by a shift of focus to maximally utilize the design potential. In their book, the authors divide AM unique capabilities into four different complexities. Along with them, the most common design potentials, considerations and limitations of SLM are explored in chapter 3.2.1 and 3.2.2

As demonstrated by the previous paragraphs, the change from design for traditional manufacturing methods to DFAM requires a change of thought. However, in her article C.C. Seepersad states how research has demonstrated that designers experience powerful tendency to adhere to traditional designs and design guidelines related to conventional manufacturing methods, and often fail to come up with marketable solutions that cannot be substituted with conventional methods. [3, p.1], Such a perspective change is therefore not easy, but the change can be accelerated with tools and methods which are suggested in chapter 3.3.2

Of course, DFAM depends not only on the designer, but heavily on the designable product. As stated in a journal article by M. K. Thompson et al. It must also be considered that not all products are possible, or cost effective to be produced with AM, and an understanding of when, why and how to redesign for the possibilities and limitations of AM is necessary. [4] It should also be questioned whether AM will be utilized better with a partial redesign, or a completely new design started from a blank canvas. Methodology for selection of potential part candidates for AM, and criteria to evaluate their potential are introduced and applied to the handle in chapter 3.3.1 and 3.3.3.

### 3.2 Dependency on the SLM method

#### 3.2.1 Division of capabilities for AM

The unique capabilities of AM and specifically the benefits and limitations of SLM are very important knowledge for a designer to gain value for a design effectively. The following division for AM capabilities is concluded by I. Gibson et al. [2, p.404-410], which is acknowledged in other literature [5] as well.

Shape complexity, provides the capability to build parts of any shape, since material can be deposited anywhere in the layer cross section of a part. It enables the use of shapes such as lattice structures or hollow cavities which optimize the part in terms of weight or stiffness for example. Further advance is that unique customized geometry containing parts are also possible, and integration of design changes and increasing shape complexity in general is easy. Design changes do not typically make related manufacturing operations
more complex, unlike in traditional manufacturing methods. Lot sizes of one are therefore economically feasible. [2, p.404-405]

Hierarchical complexity, provides the capability to produce parts with features of multi-scale. The material structure can be controlled in multiple detail levels of length. This capability is most commonly utilized in highly optimized cellular geometries. [2, p. 405-407] The creation of surface textures, such as basic texturing demonstrated by P. Kokkonen et al. in their report [6, p.119-120] can be considered also as a benefit of hierarchical complexity.

Functional complexity, which stems from the fact that the inside of the buildable part is accessible during buildup, enables the capability to insert embedded parts or build functioning assemblies and kinematic joints within one part. [2, p.407-409] Parts consolidation is therefore often achievable with AM. This includes reducing the number of parts or fasteners and the production activities and costs associated with them.

Material complexity depicts the possibility to place different materials or alter material properties in different parts of a layer by altering process parameters based on which area of the part is in question. Subsequently different regions in a part can perform differently based on structural density for example. [2, p.409-410]

Based on the division made by I. Gibson et al. [2] a comprehensive network visualization of the dependencies between AM opportunities in design (referred to as levers) and their respective benefits (referred to as value propositions) was distinguished by M. Kumke et al. and is shown in figure 4. [5]

![Figure 4. Network of AM dependencies between levers and value propositions, compiled by M. Kumke et al. [5]](image_url)
This visualization can help the designer to realize a comprehensive vision of what values could possibly be strived for with a redesign for AM methods.

### 3.2.2 Design rules and considerations

As can be seen from the previous division, complexity is the main possibility enabled for parts by AM. However, it must be noted that different AM manufacturing methods such as SLM have their own details regarding the benefits and limitations they contain, and not all value propositions found in the network of figure 4. are achievable to the same extent. The benefits and limitations of SLM differ from most AM processes mostly since the materials used are dense metals instead of other lightweight materials, and the material joining method is based on a high temperature melt pool as opposed to lower temperature joining methods. This sets specific design rules for the manufacturable components.

In technical reports such as [6] and in the design guide compiled by J. Lehtimäki [1, p.48-63], valuable knowledge and insight is available for the designer from a more technical point of view. They consider these design rules and how component geometries should be designed to ensure successful prints.

As is shown in figure 5, specific design rules, limitations and recommendations regarding manufacturable geometries are set from analyzing numerous test pieces. Further beneficial knowledge provided by these kind of reports is the discussion made of the effects design choices have on other areas of the process.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Test geometry design</th>
<th>SLM test pieces</th>
<th>Key remarks</th>
<th>Design limit values</th>
<th>Design recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclined surface</td>
<td></td>
<td></td>
<td>Every 40° unsupported plate prints fine at small SLM plate thickness. Surface quality.</td>
<td>40° for materials with good hot conductivity. Small layer thickness and small parts.</td>
<td>40° possible, but follow the 45° rule for large components. Minimize heat conduction and melting phenomena.</td>
</tr>
<tr>
<td>Round holes</td>
<td></td>
<td></td>
<td>Round holes print fine. Hole forms at inclined holes. Finishing is required.</td>
<td>0.1 mm is practical minimum for holes. Transverse holes print fine up to 0.25 mm.</td>
<td>Supports are not needed at least up to 0.25 mm diameter. Having 45° drill bit. Finishing is needed to remove stress.</td>
</tr>
<tr>
<td>Self-supporting holes</td>
<td></td>
<td></td>
<td>Self-supporting cross sections should be used. Sharp ray shapes lead to less stress at top of holes.</td>
<td>Avoid small holes for long internal channels. Sharp rays should result in top location.</td>
<td>Small holes are formed at top of the cross section. Use diamond or taper drill for best surface quality.</td>
</tr>
<tr>
<td>Overhangs</td>
<td></td>
<td></td>
<td>Large overhang length leads to receiver imperfections. Fillers support the overhang.</td>
<td>Use fillers to support overhangs and avoid stress. Improve heat conduction for low stress.</td>
<td>Maximum unsupported overhang length is a few millimeters. The rule of thumb, 0.75 hole diameter or break is possible.</td>
</tr>
<tr>
<td>Island junctions</td>
<td></td>
<td></td>
<td>Island type parts print fine, but stress and transverse shrinkage increase as open length increases.</td>
<td>Use 45° inner angle and 0.625...1.0 fillers at top for minimum stress. Mind the effect of transverse shrinkage in design.</td>
<td></td>
</tr>
<tr>
<td>Fillers</td>
<td></td>
<td></td>
<td>Fillers print at a rough surface quality and require finishing for structural parts.</td>
<td>The staker effect limits the mini. radii. R&lt;sub&gt;max&lt;/sub&gt; = 0.3. Modest stress at diagonals.</td>
<td>Stair step effect leads to poor surface quality at near flat and at the fill. Downward stress suffers from stress.</td>
</tr>
<tr>
<td>Effect of angular orientation</td>
<td></td>
<td></td>
<td>Angular orientation does not affect the print quality at large extent.</td>
<td>Angular orientation sets the limits due to printing quality. Consider the material selection for print orientation.</td>
<td></td>
</tr>
<tr>
<td>Wall thickness</td>
<td></td>
<td></td>
<td>All test pieces print fine. Cracks develop in thickness &gt; 0.15 mm. Possible, but slightly irregular.</td>
<td>Vertical wall print fine at quite small wall thickness. Avoid excessive gap length and height.</td>
<td></td>
</tr>
<tr>
<td>Elliptic channels</td>
<td></td>
<td></td>
<td>Elliptic channels prevent fine at all directions. Fracture formation at any locations.</td>
<td>Use self-supporting cross sections for internal channels. 90° turns are possible and no supports are needed.</td>
<td></td>
</tr>
<tr>
<td>Small details</td>
<td></td>
<td></td>
<td>SLM resolution limits the quality of small details. Fracture at sharp edges.</td>
<td>Functional small grooves are best done by machining. Use small fill radius of min. 0.625...1.0 mm to avoid burr at sharp edges.</td>
<td></td>
</tr>
<tr>
<td>Dross at channel</td>
<td></td>
<td></td>
<td>Abusive flow reaching may be used for dross removal and welding of the inner surfaces.</td>
<td>Avoid small holes for long internal channels. No supports needed. Dross removal may be needed.</td>
<td>Slag drip is formed at top of the cross section. Use diamond or taper drill for best surface quality.</td>
</tr>
</tbody>
</table>

Figure 5. Summary of SLM design recommendations, compiled by P. Kokkonen et al. [6]
Additional insight can be gained from SLM machine manufacturers and service providers design guides and case studies [7-11], which demonstrate realizations of concrete design possibilities. Knowledge of the manufacturing steps of SLM production can be found in the technical report [12] by A. Vaajoki and S. Metsä-Kortelainen.

While SLM and AM in general are still in their infancy, developments appear quickly. It is therefore beneficial to recognize the common advantages of AM along with process specifics, to be prepared to use them when technological advances make them available for the specific manufacturing method in question.

When creating their design guidelines for SLM, P. Kokkonen et al. reviewed casting and welding design guidelines as a basis. They argued for this, due to the similarity between SLM and multipass welding. The effects of issues such as heat input and transfer, thermal stresses and distortions, metallurgy and defects need to be considered heavily in SLM also. [6] A diverse compilation of things to consider regarding different aspects of the SLM process was compiled by P. Kokkonen et al. and is shown in figure 6.

![Figure 6. Things to consider in SLM, compiled by P. Kokkonen et al. [6, p.7]](image)

When discussing the effective utilization of AM, the focus is most often on the design aspect. Like in this thesis, it is encouraged to fully utilize the design freedom provided. However, when looking at figure 6, it should be observed, that the designer must not forget the implications and dependencies that design choices might have on other aspects of the process and vice-versa. The things compiled in figure 6 are important to keep in mind by the designer.
3.3 Dependency on the part

3.3.1 Part potential

Searching through literature, the matter of part potential has been most thoroughly considered by C. Lindemann et al. in their journal article. [13]

They suggest that in most cases, it’s not sufficient to take a traditionally manufactured part and think of directly switching to manufacturing with AM, or SLM in this case. They argue that the limitations brought by the AM process, such as the design rules and other process specific aspects such as build orientation, need to be considered early in the design phase, along with the fulfillment of requirements regarding geometrical or mechanical properties of the part. And a direct switch in most cases would not produce additional value. It is also noted that a detailed look at the whole life cycle of a part is worthwhile to realize full benefits of a redesign. [13, p. 217]

They continue to introduce a methodology that aims to help designers identify feasible part candidates for AM production. The methodology they developed consists of three main phases. Information, assessment and decision. The structure of the methodology is illustrated in figure 7. [13, p.217]

![Figure 7. Illustration of the methodology for identifying feasible part candidates for AM production, by C. Lindemann et al.][13, p. 218]
In the first phase, a basic understanding of the manufacturing technology needs to be developed. Based on this knowledge, a large selection of parts that currently suffer from problems and will potentially benefit from the AM technology are collected and entered in to a trade-off matrix for phase two. [13, p.218]

In the second phase, the matrix is first used to rank and narrow down the number of collected parts by assessing the parts against several rating criteria of part manufacturability and design potential with the AM method. Once a rating has been defined for each candidate, few of the most promising parts are selected for further evaluation in the second segment of the matrix. [13, p.218]

In the third phase, the parts potential in terms of redesign is discussed further. The parts are assessed in terms of criteria relating to the costs of manufacturing with the AM method in the second segment of the matrix. A rough economic analysis is performed on the parts, and the most suitable candidates should be distinguished from the trade-off matrix shown in figure 8. [13, p.218-221]

![Figure 8. Example of a trade-off matrix used for selection of potential part candidates for AM, by C. Lindemann et al. [13, p.219]](image)

In the case usage of the methodology in the article, emphasis was drawn mostly on the weight savings aspect. This was due to the parts originating from the aviation industry. The authors argue however, that the methodology is also suitable for different industries, and different strategies of companies, if the criteria, definitions and ratings are defined accordingly. [13, p.218]
Therefore, with some adjustments the methodology might prove potential for ABB’s uses when searching for the next part candidates for redesign and manufacture with SLM. Additionally, like in this thesis, the rating criteria listed in table 1. can be used to help explore the potential redesign targets in a part such as the handle, after its structure is analyzed in the end of this chapter.

Table 1. Suggested rating criteria to evaluate part potential. [13]

<table>
<thead>
<tr>
<th>No.</th>
<th>Rating criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>How does the size of the part compare to the available build chamber?</td>
</tr>
<tr>
<td>2.</td>
<td>Can multiple instances of the part be nested next to each other or supported by each other?</td>
</tr>
<tr>
<td>3.</td>
<td>How complex is the manufacturing of the part with traditional methods, compared to AM methods?</td>
</tr>
<tr>
<td>4.</td>
<td>Does the part need to contain specific geometries that will have difficulties to produce with AM, such as large solid blocks that suffer from residual stresses, or overhangs that produce dross or need support structures and their subsequent removal?</td>
</tr>
<tr>
<td>5.</td>
<td>How many external interfaces are forced to be assembled due to current manufacturing constraints? Can they lead to assembly suppression or function integration?</td>
</tr>
<tr>
<td>6.</td>
<td>Does the part have potential for improvement from topology optimization or weight reduction?</td>
</tr>
<tr>
<td>7.</td>
<td>Does the part contain typical problems for the company, can another part benefit similarly?</td>
</tr>
<tr>
<td>8.</td>
<td>How demanding are the material requirements, can they be served with AM materials?</td>
</tr>
<tr>
<td>9.</td>
<td>How many post processing treatments such as surface finishing or heat treatment will the part need?</td>
</tr>
<tr>
<td>10.</td>
<td>How much material is needed to manufacture the part with traditional methods compared to AM methods?</td>
</tr>
<tr>
<td>11.</td>
<td>How will the manufacturing time differ between traditional methods and AM manufacturing methods?</td>
</tr>
<tr>
<td>12.</td>
<td>How will the costs differ between traditional and AM manufacturing methods?</td>
</tr>
</tbody>
</table>

3.3.2 Tools and methodologies

In their journal article [5, p.2] M. Kumke et al. concluded that currently existing DFAM approaches usually only describe which AM-specific opportunities in design can be utilized to achieve which benefit for the product. According to them, comprehensive methodological guidance on executing the utilization is rarely found for design goals, other than for lightweight design by topology optimization.

Due to this, the authors argue, that general design theory is still suitable and should be used for other DFAM goals, until more suitable and comprehensive methods are developed. Kumke et al. state that while the general design theory doesn’t naturally lead to AM design complexities, the usefulness of the general methods can be increased significantly when they are enriched by DFAM tools. [5]

Based on the results and feedback from their workshop experiments, their research suggests that, as method suitability is highly context specific, it is recommended to use a general design methodology which the designer is comfortable with, and enrich it’s use with such tools as the following [5].
• The designer should use the previously introduced network visualization of AM opportunities and their respective benefits as basic tool, to provide insights into the DFAM process and what value propositions could be pursued in the design by using which levers provided by SLM. [5]

• Understanding the benefits from text alone will prove difficult, and therefore the designer should seek visual examples of design features and associate them with all the textual descriptions found on the network. Subsequently a DFAM feature database tool would be formed. These visual examples could be physical parts, pictures or 3D CAD models for example. [5] Additionally, even SLM optimized shapes resulting from technical analyses could be used as a basis of form giving as stated by P. Kokkonen et al. [6]

• Similarly, a collection of case studies associated with the value propositions would help the designer to grasp the concrete benefits provided by AM. [5] It is also a good way to draw inspiration and gather a more extensive understanding of the process of implementing the AM-specific benefits, and how the specific part and its requirements as a whole are taken into consideration.

One example of a more comprehensive DFAM methodology is set by M. Orquéra et al. in their journal article [14]. The methodology is specified as an eleven-step process for multifunctional optimization of mechanical systems. Its structure is shown in figure 9.

![Figure 9. Structure of optimization methodology, by M. Orquéra et al. [14]](image-url)
As the name suggests, this methodology also focuses more on the optimization of a current design with AM capabilities, rather than a full redesign utilizing AM. As is noted in the article [14], the choice of the solutions still come from classical designer thinking, experience and knowledge. The solutions choice is improved radically however, thanks to the AM capabilities providing complexity and setting fewer limits on shape giving.

While the methodology is not ideal, it was the most useful guideline found in literature during the writing of this thesis, for redesigning a mechanical system such as the handle for SLM. The methodology is divided in to the following steps shown in table 2.

**Table 2. Design methodology steps as suggested by M. Orquéra et al. [14]**

<table>
<thead>
<tr>
<th>No.</th>
<th>Steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Drafting specifications for the system. What are its required functions and context it must work in, and how are they achieved mechanically? What functions or properties are targeted for improvement?</td>
</tr>
<tr>
<td>2.</td>
<td>Conducting the functional analysis on each part of the system and verifying which interfaces are truly necessary for the functions, and requirements needed. The necessary interfaces are then represented with ideal shapes provided by AM, along with external components such as fasteners if needed. Together they define the allowable design space for further steps.</td>
</tr>
<tr>
<td>3.</td>
<td>The skeletal architecture, such as the location of joints or other functions is optimized with respect to the functional analysis and design space. Topological optimization can be used to provide optimized shapes.</td>
</tr>
<tr>
<td>4.</td>
<td>The preliminary design is realized in CAD. The design being a close interpretation of the optimized architecture, including the previously specified functionality. Design solutions are developed with classical design approach, but the solution space is extended and improved by capabilities provided by AM and adjusted by considering the manufacturing constraints set by the specific AM method.</td>
</tr>
<tr>
<td>5.</td>
<td>The preliminary design of the system and its parts are checked to provide the functionality and properties specified earlier. If not met, the process is continued from step four.</td>
</tr>
<tr>
<td>6.</td>
<td>Finite element analysis is performed to check for required mechanical behavior. If not met, the process is continued from step four again.</td>
</tr>
<tr>
<td>7.</td>
<td>The design is analyzed in CAD to verify non-interference of parts during assembly and other usage situations.</td>
</tr>
<tr>
<td>8.</td>
<td>The resulting design is assessed for possible improvements and steps from 4. to 8. are iterated. Resulting in a complete model of the redesigned system.</td>
</tr>
<tr>
<td>9.</td>
<td>Design for the manufacturing phase is conducted to optimize the production quality, quantity and such, by optimizing build orientation and support design for example.</td>
</tr>
<tr>
<td>10.</td>
<td>The previous step typically leads to implementing changes in the design to decrease overhangs, to reduce supports, or to consider for post-processing steps by leaving a machining allowance for example.</td>
</tr>
<tr>
<td>11.</td>
<td>The final step is to verify that all requirements set during the systems lifecycle are met.</td>
</tr>
</tbody>
</table>

The introduced methodology could work as a suitable guideline for the redesign of the handle, and similar parts in ABB Oy product development processes in the future. If not as introduced, it could be combined with current design guidelines and processes that have been used effectively for traditionally manufactured parts, and a suitable guideline for design of SLM parts could be developed.
In the following chapter the handle is analyzed with the help of the rating criteria from the previous chapter along with the tasks set for step 1. and partially for step 2. in the methodology.

### 3.3.3 Analysis of the handle

The structure of the handle is shown in exploded view in figure 10. The parts of grey color are alloys. Parts of orange color are plastic. Parts in blue and red are various springs and seals which control the motion and waterproofness of the handle. The handle is assembled with bolts shown in green.

![Figure 10. Structure of the handle in exploded view with the main parts numbered.](image)

The parts numbered in figure 10 are named and their material and current manufacturing methods are specified in table 3. As can be noted, the handle is highly complex, and it consists of multiple parts, materials, and manufacturing methods.

**Table 3. Names, materials and current manufacturing methods of numbered parts.**

<table>
<thead>
<tr>
<th>Part name</th>
<th>Part number</th>
<th>Material:</th>
<th>Manufacturing method:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Locking latch</td>
<td>1.</td>
<td>X5CrNiMo1912 stainless-steel</td>
<td>Sand casting</td>
</tr>
<tr>
<td>Latch hinge</td>
<td>2.</td>
<td>X5CrNiMo1912 stainless-steel</td>
<td>Sand casting</td>
</tr>
<tr>
<td>Rotation lock pin</td>
<td>3.</td>
<td>X5CrNiMo1912 stainless-steel</td>
<td>Sand casting</td>
</tr>
<tr>
<td>Top handle structure</td>
<td>4.</td>
<td>X5CrNiMo1912 stainless-steel</td>
<td>Sand casting</td>
</tr>
<tr>
<td>‘Snap’ pin</td>
<td>5.</td>
<td>CYBD8M1 plastic</td>
<td>Die casting</td>
</tr>
<tr>
<td>Middle structure</td>
<td>6.</td>
<td>X5CrNiMo1912 stainless-steel</td>
<td>Sand casting</td>
</tr>
<tr>
<td>Stop plate</td>
<td>7.</td>
<td>St 01 Z 200 S steel</td>
<td>Plate pressing</td>
</tr>
<tr>
<td>Slide</td>
<td>8.</td>
<td>CYBD8M1 plastic</td>
<td>Die casting</td>
</tr>
<tr>
<td>Lower structure</td>
<td>9.</td>
<td>ZAMAK5 zinc alloy</td>
<td>Precision casting</td>
</tr>
</tbody>
</table>
Proceeding with the tasks suggested in the first steps of the previously introduced methodology, the required functions for the whole handle-system were specified. The following functions defined in table 4. were identified.

<table>
<thead>
<tr>
<th>no.</th>
<th>Function</th>
<th>Additional consequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>To turn the axle and handle 90° between the OFF- and ON -position.</td>
<td>Operation of the switch-disconnect - mechanism to turn power off and on.</td>
</tr>
<tr>
<td>2.</td>
<td>To release the axle in the OFF -position, and to secure the axle in the ON -position.</td>
<td>Opening and closing of the housing door.</td>
</tr>
<tr>
<td>3.</td>
<td>Provide a state where the axle is secured in the OFF position and turning the axle is prevented.</td>
<td>Turning on the power by the handle is disabled.</td>
</tr>
<tr>
<td>4.</td>
<td>Provide possibility to secure the handle in the locked state with three pad locks.</td>
<td>Require input from all electricians, to control if the handle is in the disabled or enabled state, when working on the system.</td>
</tr>
<tr>
<td>5.</td>
<td>To be able to release the axle when the handle is in the ON -position with a special tool when necessary.</td>
<td>Ability to open the housing door in the ON -position if necessary for measurements.</td>
</tr>
<tr>
<td>6.</td>
<td>Provide audible and tactile feedback on exact positioning of the handle.</td>
<td>The user knows that the handle is positioned exactly in a determined position.</td>
</tr>
<tr>
<td>7.</td>
<td>Provide visual feedback on current positioning of the handle.</td>
<td>The current state of the whole handle, axle and switch-disconnector mechanism is known for the user.</td>
</tr>
</tbody>
</table>

To continue the step, the identified 6 functions were analyzed further to specify how they are achieved mechanically in the current design. The identified mechanisms were listed in table 5.

<table>
<thead>
<tr>
<th>no.</th>
<th>Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>The latch hinge, which provides rotation to the locking latch, which in turn presents the locations for padlocks and simultaneously presses down on the rotation lock pin.</td>
</tr>
<tr>
<td>2.</td>
<td>Movement of the rotation lock pin through the middle structure to prevent rotation of the handle.</td>
</tr>
<tr>
<td>3.</td>
<td>Movement of the rotation lock pin onto the slide, which gets pushed in front of the axle, and subsequently secures it to the handle.</td>
</tr>
<tr>
<td>4.</td>
<td>The extension of the spring around the rotation lock pin, which returns the latch and the pin into their default position.</td>
</tr>
<tr>
<td>5.</td>
<td>The spring and snap pin mechanism, which gives tactile and audible feedback on the handles movements when moving over holes in the middle structures top surface.</td>
</tr>
<tr>
<td>6.</td>
<td>The stop plate, which together with the middle structure geometry defines the handles rotational limits, and additionally secures the middle structure to the handle structure.</td>
</tr>
<tr>
<td>7.</td>
<td>Manually actuated movement of the slide mechanism with a tool through the hole in the middle structure to release the axle.</td>
</tr>
<tr>
<td>8.</td>
<td>The compression and extension of the springs around the slide, which position it to the default position.</td>
</tr>
<tr>
<td>9.</td>
<td>Visual markings on the middle and top handle structures, which display the current position of handle.</td>
</tr>
</tbody>
</table>

Along with the functions, the context in which the handle must operate in needs to be defined as well. It was specified in table 6.
**Table 6. The handles operating context.**

<table>
<thead>
<tr>
<th>no.</th>
<th>Context in which, and how the handle must operate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Have the same mounting geometry onto the housing, the same space to guide and house the axle, and similar outer proportions as in current design.</td>
</tr>
<tr>
<td>2.</td>
<td>Contain a durable and clear locking mechanism that secures the axle, and a durable mechanism that contains space to attach three padlocks, to secure the whole handle mechanism.</td>
</tr>
<tr>
<td>3.</td>
<td>The exterior parts need to be made of stainless steel to withstand operation conditions.</td>
</tr>
<tr>
<td>4.</td>
<td>Be dust and waterproof in class IP66.</td>
</tr>
<tr>
<td>5.</td>
<td>Be easily washable with minimal amount of dirt collecting shapes.</td>
</tr>
<tr>
<td>6.</td>
<td>The design must minimize material use and post processing such as machining, to enable efficient series production.</td>
</tr>
<tr>
<td>7.</td>
<td>Have a robust, ergonomic and high-quality feel, and capability to be used with working gloves on.</td>
</tr>
</tbody>
</table>

In the end of step 1. of the methodology, the current functions and properties that will be targeted for improvement should be defined. In its current design, the handle suffers from multiple issues consisting of the following:

- The handle has a very high mass, which results in excess material usage and raises environmental and cost related concerns. Additionally, it results in impracticality during its handling and logistics.
- The use of conventional manufacturing methods results in challenges with varying surface quality and failures to meet dimensional tolerances. Both challenges result in problems with the fit of parts, smooth movement in mechanisms and leakage of seals, thus losing the waterproof ability of the handle. Subsequently, a lot of post processing is needed to fix problematic parts, and when not possible, high number of parts end up as waste.
- The complexity and high number of parts in the current design, result in requirements for many separate manufacturing and assembly steps. Subsequently, high amounts of resources are needed to complete production.

These issues in conjunction with the small batch -type production drive the costs of the handle very high and they should be foremost targeted for improvement. Fortunately, the issues seem to be such which a redesign for the SLM method could potentially fix, and possibly produce additional value in the process.

However, the issue of minimizing post processing requirements, can likely not be fixed. According to the technical report by A. Vaajoki and S. Metsä-Kortelainen, SLM manufactured parts usually need post processing at least for the removal of excess powder, removal of support structures, heat treatment, machining, polishing and other treatments depending on the requirements of the part. Comprehensive information of post-processing can be found in their report. [12, p.9-22]
Using the rating criteria and value proposition network introduced previously, the following potentials are identified:

- **Additional value for the customer:**
  a. Improvement in comfortable use, through weight reduction, which makes handling easier.
  b. Improvement in reduced maintenance requirements, through a design with less dirt collecting shapes, which reduces the need for cleaning efforts.
  c. Improvement in reliability and function, through a more suitable design for stainless-steel mechanisms.
  d. Improvement in aesthetical and ergonomic design, through less limitations on form giving.

- **Additional value for the manufacturer:**
  a. Development cost reduction, through easier implementation of design changes for SLM manufacturing.
  b. Reduced logistics, through possibility of manufacturing multiple parts in the same locations, possibly closer to the customer, with less storage due to configurable batch size and manufacturing faster on demand.
  c. Reduced manufacturing and assembly steps, through parts consolidation and one-part built assemblies.
  d. Reduced number of different manufacturing methods due to being able to manufacture all parts excluding the springs and seals with SLM.
  e. Increasing the amount of parts manufactured in-house and decreasing reliance on external manufacturers.
  f. Less material waste, through SLM process characteristics and lightweight designed geometry.
  g. Quality assurance cost reduction, through a new more suitable design for stainless-steel, with reduced part count and reduced number of function-critical interfaces through parts consolidation.
  h. Gains made with the handle could be replicated in other similar products at ABB Oy, such as the terminal lug which was mentioned in the master’s thesis by J. Lehtimäki [1, p.93].

As can be seen from the previous list, a high amount of potential can be identified. However, a full redesign would likely be required to achieve all of them. The complexity of the handle means, that performing a full redesign will be a highly demanding task, and it would not be realistic in the context of this thesis. Therefore, in the following chapter the most potential redesign targets are defined, and design examples for optimizing the current design are displayed in chapter 4. They act as examples from which they can be evolved from or used to draw ideas for the full redesign in the future.
3.4 Derived redesign targets

From the mapping of potentials that SLM provides, and defining the issues calling for redesign in terms of the handle, the following redesign targets could be derived:

- **Weight and material usage reduction:**
  a. Implementing hollow cavities into the top handle structure, by utilizing shape complexity provided by SLM. High potential exists, which could be achieved with low effort. This redesign target is explored in example 1.

- **Parts consolidation:**
  a. It is unsure how much of the current designs complexity and requirement for a high number of structural parts and seals is forced by constraints of conventional manufacturing methods. At least in theory, both could be reduced by utilizing all the four design complexities provided by SLM. This could lead to a more efficient and radically different design of the whole handle, provided by the extended design freedom. High potential with very high effort exists, particularly in the parts contained in the middle and lower structures of the handle. This however, could not be explored in a redesign example in the constraints of this thesis.
  b. Manufacturing the top handle structure, locking latch and rotation lock pin mechanism as a one part printed assembly, by utilizing the functional complexity provided by SLM. Some potential exists in the current design for reducing dirt collecting geometries, but high effort would be needed to design suitable tolerances and to find a solution that addresses the problems implicated by the consolidation of the latch hinge. This redesign example is explored in example 3.
  c. Integration and consolidation of the snap-pin mechanism into the top handle structure as a flexure design might be achieved, by utilizing the shape and hierarchical complexities provided by SLM. Some potential exists, but it would likely require the effort of considerable amount of trial and error. This redesign target is explored in example 4.

- **Optimized geometry:**
  a. High potential with low effort exists in the handles outer geometry. The geometry could be refined to reduce dirt collecting shapes and improve its ergonomics, by utilizing shape complexity provided by SLM. This redesign target is explored in example 2.

- **Additional benefits:**
  a. High potential exists in integrating the ON and OFF markings currently produced by a separate laser marking process into the actual build process of the handle. Thus, the need for one manufacturing step could be eliminated. This redesign target is explored in example 5.
  b. During the final redesign, the nesting of the components during part build up should be taken into consideration. Due to the handle and its parts relative sizes compared to the build platforms of modern SLM machinery, the parts can be potentially nested next to each other or supported on top of each other during build up. Considerable potential with considerable effort will exist in making the manufacturing highly efficient this way.
4. REDESIGN EXAMPLES

As a conclusion to this thesis, five examples of the derived redesign targets were made in the following chapters. The examples were made mostly on an idea-level from which they can be evolved or used as inspiration in the full redesign made in the future. They represent some of the main potentials gained by designing for and manufacturing with SLM.

4.1 Weight reduction and optimized geometry

4.1.1 Implementation of hollow cavities

The handle contains multiple parts made from heavy stainless-steel material. Most parts are already designed to minimize weight, but high amounts of potential still exist in the top handle structure. Weight reduction has not been able to be utilized due to manufacturing with conventional casting process. By taking advantage of the shape complexity provided by SLM, hollow structures could be integrated into the part. This is explored in this first redesign example.

On a first thought, the internal structure could be filled with a lattice structure which ensures structural strength while providing weight reduction. However, the removal of excess powder from inside the part would pose a problem, since unwanted open geometries would be needed in multiple locations on the parts surface. Additionally, the handle is not subjected to high loads, so the strength of a lattice structure is not necessary.

If the strength of the handle stays sufficient, self-supporting hollow geometry cavities as shown in figure 11. could be left inside the part. With empty cavities the excess powder would be easily removed from the large openings in the bottom of the handle structure.

Figure 11. Design example of utilizing hollow cavities.
The design example extends the existing geometries made for weight reduction in the current design of the part. The original weight reduction geometry is shown in green and the extended geometry in blue. This specific implementation is for demonstration only, and it might not be viable exactly as is. The shape of the cavity needs to be optimized depending on the parts print direction, and design rules regarding self-supporting structures need to be considered. For example, shapes such as shown in figure 12, should be used. They were studied by P. Kokkonen et al. [6] and deemed self-supporting.

![Figure 12. Self-supporting shapes, tested in H12 tool steel by P. Kokkonen et al. [6]](image)

In their research report, P. Kokkonen et al. note that while these shapes should print fine, slight dross will typically form at the top of the shape. According to them this can be reduced with sharper top shapes. Diamond and tear shaped sections are said to provide the best quality, and as a rule of thumb they suggest that a minimum 45-degree limit should be kept for the inclination angles of shapes that need to be self-supportive. [6] However, design rules could possibly be stretched in favor of more weight savings, since problems such as poor surface quality would not visible inside the part and since the part is not subjected to high loads.

Comparing the models of the original and redesigned geometries, it can be observed that an approximate 20% decrease of mass could be achieved by the proposed extension of the hollow cavities. This mass decrease would be significant, since the part is responsible for most of the weight of the whole handle assembly.
While the potential mass decrease might be reduced when the cavity shapes are optimized according to design rules, further mass savings could also be explored in the middle area of the handle part which is marked blue in figure 13. As an addition to the weight and material savings, the implementation of hollow cavities is also favorable, since if thick sections were left in the structure, they would concentrate heat and generate thermal stresses in the part during part buildup.

![Figure 13. Areas to further explore weight savings.](image)

### 4.1.2 Minimizing dirt collecting geometries

The second design example which is shown in figure 14, was made to explore possibilities to minimize dirt collecting geometries.

First, the padlock latch hinge was integrated into the handle structure to remove the two holes where the hinge is normally inserted. Secondly the area between the handle grip and the center area was reshaped to remove the geometries which were reported to accumulate the most dirt during use, and which are difficult to clean. A small hole was left to this area, to help rinse dirt from under the locking latch. Thirdly, to provide a smoother overall shape, the locking latch was reshaped to fully fit inside the top handle structure, and a small lip geometry was added on top of it to provide a new place to push open the mechanism. Additionally, the new location seems to be a more logical place to push open the latch.
Figure 14. Current design (left) and redesign (right) to reduce dirt collecting geometries.

4.2 Parts consolidation

4.2.1 Directly fabricated padlock mechanism

As already mentioned in the second design example, the rotation lock pin and the latch hinge along with the locking latch it holds, could possibly be integrated into the handle structure. With suitable tolerances and light structures to support them during printing they could be able to be manufactured as a one-piece assembly which is a unique design freedom provided by SLM. However, with this design the current mechanism would not fully function since the spring and seal would not be able to be inserted under the rotation lock pin anymore. Very high effort would therefore be needed to design a functional solution for this problem.
For SLM manufactured direct assemblies, suitable tolerances are particularly important as concluded in the research by X. Su et al. [15] and F. Calignano et al. [16]. In their research the direct fabrication of mechanisms with SLM and stainless-steel material was studied. Their results deemed it feasible by utilizing optimized clearances and build orientations which minimize roughness in the joint, allow the removal and prevent the melting of excess powder, and minimize support requirements in the clearance. F. Calignano et al. concluded however, that a finishing post-processing step would be needed to improve surface roughness in the joint inner surfaces to be competitive with traditional joints.

However, for undemanding joints like the one in the handle locking latch, the motion quality might suffice. An example of a universal joint manufactured in stainless-steel by SLM is shown in figure 15.

![Stainless-steel universal joint manufactured with SLM.](image)

*Figure 15. Stainless-steel universal joint manufactured with SLM. [16]*

As is pointed out by M. K. Thompson et al. [4, p.750] In the case of using directly manufactured joints, the designer must consider that these kinds of features cannot be disassembled for routine maintenance or repair, and the whole assembly will in these cases need to be replaced, creating waste and possible recycling difficulties during its lifecycle if multiple different materials are used.

### 4.2.2 Integrated snap-pin mechanism

In the fourth redesign example, the integration of the snap-pin mechanism is explored. The current design uses a separate spring and pin assembly which is inserted into a hole in the top handle structure. During use, the pin travels over holes on the top face of the middle structure and provides a tactile feedback on the positioning of the handle. By utilizing the shape and hierarchical complexities provided by SLM, the mechanism might be replaced with a flexural structure integrated directly into the top handle structure, and parts consolidation of two parts could be achieved in the process. The current design and the redesign example are shown in figure 16.
Figure 16. Snap mechanism of current design with pin and spring (left) and redesign with integrated flexure (right).

This redesign example works as a demonstration of the possibilities of shape and hierarchical complexity. It shows how features in one part's structure can be designed in multiple different scales of length and different areas of a part can be designed to function largely different. The end of the narrow flexure would travel similarly to the pin.

This specific implementation is for demonstration only, and it might not be viable. No direct case example usage of flexures made with SLM of stainless-steel material was found in literature. However, the manufacturing of helical springs made of Ti-6Al-4V alloy was explored in a conference proceeding by A. Mohamed et al. [17] Their research demonstrated it is possible, but with irregularities concerning mechanical performance of the springs. The springs tested in their research are shown in figure 17.

Figure 17. Helical springs manufactured with SLM in Ti-6Al-4V. [17]

Since the material used was not stainless-steel and the scale of the springs is much larger, no guarantee of similar feasibility can be argued. Therefore firstly, correct performance and reliable prediction of the flexures lifetime might not be achieved with design based on springs made for conventional manufacturing methods. Secondly, the shape of the flexure and design of functioning support structures which can be removed without breaking the flexure itself, would need extensive optimization. Some potential in consolidation exists, but high amount of effort is likely needed to achieve results.
4.3 Additional benefits

4.3.1 Removing the need for a separate laser marking process

In the fifth redesign example, the removal of the need for a separate laser marking process is explored. In the current design the ON and OFF markings on the handle are made by a separate laser marking process. With SLM, the markings could be produced as embossed geometry by utilizing the hierarchical and shape complexities provided. An example of the markings made as embossed geometry is shown in figure 18.

Figure 18. Design example of replacing laser markings (lower right) with embossed geometry.

As demonstrated in the research report by P. Kokkonen et al. [6] SLM should provide good enough accuracy to provide similar sized markings as in the current design. An example of a logo printed in Inconel 625 is shown in figure 19.

Figure 19. Text containing logo printed with Inconel 625 by SLM process. [6, p.31]

Another consideration is that the laser markings could possibly be manufactured with the laser used in the actual part buildup. However, by searching literature and manufacturers offerings of SLM machinery, no such machinery was found that can currently do this. However, it might be possible in the future since technical advances happen at a fast pace and a multifunctional SLM machine might appear on the market.
5. CONCLUSIONS

During the writing of this thesis and the practical efforts to derive the potential redesign examples of the handle, it was quickly realized that the greatest challenge is getting into the mindset of DFAM thinking. This includes, firstly realizing all the design possibilities and their value propositions, and similarly the design rules and considerations set by SLM. Secondly, identifying the potential of the part and the design targets for additional value on the part to be redesigned. Thirdly, lifting the mental block set by design guidelines for conventional manufacturing methods, and ensuring that the extended design solution space provided by SLM is explored to its maximum extent.

The thesis provides the reader with an overview of the capabilities of AM design, compilations of the SLM design value network, SLM design recommendations, and things to consider in design for SLM, which were found by literature review. Additionally, the reader was given direction where to find further valuable knowledge.

It was concluded that not all parts can benefit from a design for SLM, and that recognizing part potential is essential. A methodology found in literature was introduced, which helps to identify feasible part candidates for AM production, by comparing them against rating criteria of part manufacturability and design potential with AM. The author recommends, that with some adjustments the methodology can help ABB Oy identify parts similarly. In this thesis, the rating criteria were successfully used to evaluate and identify potential redesign targets in the stainless-steel handle.

It was also concluded, that comprehensive methodological guidance on executing the utilization of design opportunities is lacking. However, a methodology for the optimization of mechanical systems with AM capabilities was found in literature and introduced. The author recommends that parts of it could be combined with design guidelines for traditionally manufactured parts, and subsequently a suitable methodology for the design of SLM parts at ABB Oy could be developed. The steps of the methodology were partly used to analyze the handle’s structure, and successfully define functions and properties that should be targeted for improvement in the stainless-steel handle.

In the meantime, general design theory should be used and enriched with DFAM tools such as, the shown network of AM dependencies between levers and value propositions, and the suggested DFAM feature- and CASE-study database, to improve the designer’s awareness and confidence of utilizing the extended design solution space provided by SLM. Similar content as the tools, successfully helped the author derive the redesign examples for the stainless-steel handle.
As a result of this thesis, high amount of design potential for the stainless-steel handle was found. In total, 12 potentials of additional value that the SLM method could provide were identified, 7 redesign targets that could be achieved with a full or a partial redesign were derived, and 5 redesign examples for the optimization of the current design were made.

The biggest potentials were found in weight and material usage reduction in the top handle structure, in parts consolidation and reduced manufacturing complexity in the mechanisms of the handle, and in optimized geometry and better performance of the part in terms of reducing dirt collecting shapes and improving the ergonomics of the handle.

The redesign examples in this thesis demonstrated that on an existing design, some parts can surely benefit from the design freedom provided by SLM as optimization. However, as the complexity of the system increases, the more difficult it is to find areas to utilize SLM provided design freedom fully, without conflicting adjacent areas which are based on conventional design, since the design solutions are likely highly different.

Therefore, the benefits on design from using SLM and AM in general, are realized much more effectively with completely new designs started from a blank canvas, instead of just a partial redesign. If the final redesign is performed this way, attention should be focused on simplifying the main mechanisms of the handle, and on the possibility of reducing the number of needed seals between parts. In the context of this thesis, these redesign targets could not be explored further.

This thesis can function as a source of knowledge on approaching the redesign of stainless-steel parts such as the handle for SLM, and the redesign examples can function as a basis for the final redesign of the handle in a following more extensive thesis, or in product development processes at ABB Oy.
6. BIBLIOGRAPHY


