Some aspects on designing for metal Powder Bed Fusion
Thanks to Saab Dynamics for funding my studies. Thanks also to Vinnova and KK-stiftelsen for financial support. Thanks to my supervisors Lars Pejryd (main supervisor) and Jens Ekengren (second supervisor) at Örebro University who helped me in many ways through these years of intensive full-time studies. Thanks to Torbjörn Holmstedt and Karolina Johansson at Lasertech for helping me with all sorts of things related to additive manufacturing and Powder Bed Fusion. Thanks to Stopek Burton at Saab Dynamics for proofreading this licentiate thesis. And finally thanks to all those who paid interest in what I was doing and so helping me in direct and indirect ways.
Some aspects on designing for metal Powder Bed Fusion
Abstract

Additive Manufacturing (AM) using the Powder Bed Fusion (PBF) is a relatively new manufacturing method that is capable of creating shapes that was previously practically impossible to manufacture. Many think it will revolutionize how manufacturing will be done in the future. This thesis is about some aspects of when and how to Design for Additive Manufacturing (DfAM) when using the PBF method in metal materials. Designing complex shapes is neither easy nor always needed, so when to design for AM is a question with different answers depending on industry or product. The cost versus performance is an important metric in making that selection. How to design for AM can be divided into how to improve performance and how to improve additive manufacturability where how to improve performance once depends on product, company and customer needs. Using advanced part shaping techniques like using Lattices or Topology Optimization (TO) to lower part mass may increase customer value in addition to lowering part cost due to faster part builds and less powder and energy use. Improving PBF manufacturability is then warranted for parts that reach series production, where determining an optimal build direction is key as it affects many properties of PBF parts. Complex shapes which are designed for optimal performance are usually more sensitive to defects which might reduce the expected performance of the part. Non Destructive Evaluation (NDE) might be needed to certify a part for dimensional accuracy and internal defects prior use. The licentiate thesis covers some aspects of both when to DfAM and how to DfAM of products destined for series production. It uses design by Lattices and Topology Optimization to reduce mass and looks at the effect on part cost and mass. It also shows effects on geometry translation accuracies from design to AM caused by differences in geometric definitions. Finally it shows the effect on how different NDE methods are capable of detecting defects in additively manufactured parts.

Keywords: Additive Manufacturing, AM, DfAM, lattice, Powder Bed Fusion, Topology optimization, Selective Laser Melting, Electron Beam Melting, Design for manufacturability

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### List of abbreviations

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<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tr>
<td>AM</td>
<td>Additive Manufacturing</td>
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<tr>
<td>BJ</td>
<td>Binder Jetting</td>
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<td>CAD</td>
<td>Computer Aided Design</td>
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<td>CDR</td>
<td>Critical Design Review</td>
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<td>CT</td>
<td>Computer Tomography</td>
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<td>DED</td>
<td>Directed Energy Deposition</td>
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<td>DFM</td>
<td>Design For Manufacturing</td>
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<td>DFAM</td>
<td>Design for Additive Manufacturing</td>
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<td>DMLS</td>
<td>Direct Metal Laser Sintering</td>
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<td>DMD</td>
<td>Direct Metal Deposition</td>
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<td>EBM</td>
<td>Electron Beam Melting</td>
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<td>EDM</td>
<td>Electric Discharge Machining</td>
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<tr>
<td>ETO</td>
<td>Engineer To Order</td>
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<tr>
<td>FEA</td>
<td>Finite Element Analysis</td>
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<td>GD &amp; T</td>
<td>Geometric Dimensioning and Tolerance</td>
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<td>GMS</td>
<td>Global Management System</td>
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<td>HIP</td>
<td>Hot Isostatic Pressing</td>
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<td>HSM</td>
<td>High Speed Machining</td>
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<td>IGES</td>
<td>Initial Graphics Exchange Specification</td>
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<td>IP</td>
<td>Intellectual Property</td>
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<td>IPC</td>
<td>Integrated Product Creation</td>
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<td>IRQ</td>
<td>Industrial Research Question</td>
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<td>LSH</td>
<td>Lasertech AB</td>
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<td>MJ</td>
<td>Material Jetting</td>
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<td>MBD</td>
<td>Model Based Definition</td>
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<td>ME</td>
<td>Material Extrusion</td>
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<td>MRR</td>
<td>Material Removal Rate</td>
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<td>NC</td>
<td>Numerically Controlled</td>
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<td>NDE</td>
<td>Non Destructive Evaluation</td>
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<td>NDE</td>
<td>Non Destructive Testing</td>
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<td>NURBS</td>
<td>Non-Uniform-Rational-Bspline</td>
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<td>PBF</td>
<td>Powder Bed Fusion</td>
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<td>PDR</td>
<td>Preliminary Design Review</td>
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<td>PCA</td>
<td>Physical Configuration Audit</td>
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<td>Ra</td>
<td>Surface Roughness, arithmetic value</td>
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<td>ROI</td>
<td>Return of Investment</td>
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<td>RP</td>
<td>Rapid Prototyping</td>
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<td>RQ</td>
<td>Research Question</td>
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<td>SBD</td>
<td>Saab Dynamics AB</td>
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<td>SEK</td>
<td>Swedish krona</td>
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<td>SL</td>
<td>Sheet Lamination</td>
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<td>SLM</td>
<td>Selective Laser Melting</td>
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<td>STEP</td>
<td>Standard for The Exchange of Product data</td>
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<td>STL</td>
<td>Stereo Litography</td>
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<tr>
<td>TO</td>
<td>Topology Optimization</td>
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<td>TTC</td>
<td>TillverkningsTekniskt Centrum</td>
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<tr>
<td>VP</td>
<td>Vat Photopolymerization</td>
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List of published research papers
Four papers are included as a part of this licentiate thesis.

In paper I, II and III the author performed all the work. Guidance was provided by the two supervisors during bi-weekly meetings. The supervisors also provided help with reading paper drafts before submitting them for peer review. Build time simulations in Paper I and II were performed by Lasertech. In Paper IV the student created the design and documentation for the component and foresaw distribution of data to both manufacturing of the component that was tested, and for nominal-actual defect analyses.


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1 Introduction to metal Powder Bed Fusion

This licentiate thesis describes when and how to design for Additive Manufacturing (DfAM) specifically referring to the Powder Bed Fusion (PBF) process, including associated cost aspects. Additive Manufacturing (AM) is a method that manufactures a part by adding material to it and the phrase is used as a family name to differentiate the method from subtractive manufacturing methods such as milling or turning. Metal Powder Bed Fusion is one of several AM methods and it works by melting successively deposited layers of metal powder to a solid body by an in-plane moving energy source. This gives PBF some advantages over subtractive manufacturing methods as categorized by Klahn et al. [1] including lower product mass and better product efficiency. More advanced shapes may create value by reducing product mass or by making the product more efficient by the use of, for example, internal cooling channels as shown by Pejryd et al. [2].

Two ways of creating more advanced shapes that might create additional customer value, which in turn motivates a higher part cost, are Topology Optimization (TO) and Lattice design. Topology optimization involves defining loads, boundary conditions and optimization goal and let an iterative computational process find the best solution by modifying the geometry within an allocated space. Lattice design involves the substitution of a solid volume by the use of repeating pattern of smaller, less dense structures of a unit cell. Lattice design tools are available in many AM build processors and are becoming available directly in many commercially available Computer Aided Design (CAD) packages.

However, mechanical design from an industry perspective involves cost to performance tradeoffs. Part and assembly costs can be predicted using experience and similarity to existing parts with known cost, or asking suppliers for cost quotes. Predicting part and product performance may be done by analyses or tests and is product specific. The cost-to-performance ratio can then be established and if multiple design alternatives compete, the most cost-effective solution can be selected. The customer value could however be more difficult to calculate as different products have different customer expectancies of cost. In that regard, comparing mass reduction to possible cost increase that a more advanced part shape may create is warranted.

A part of doing design work in an industrial environment is to get the design manufactured. Currently, AM service providers are fewer than for
example High Speed Machining (HSM) service providers. Another difference between AM and HSM is how 3D geometries that are used for both processes to drive path planning are defined. AM uses triangles to describe the geometry approximately, whereas almost all other types of traditional manufacturing uses exact geometry definitions. In triangle based geometry definitions, curved surfaces are replaced by a number of planar or curved triangles. The number of triangles is usually controlled by user modifiable settings with different names depending on the mechanical design tool used. This deviation from the expected end part dimension is an error that will exist in the data before any manufacture errors are added. This needs to be taken into account when sending data from design to additive manufacturing.

When parts are designed for lower mass, the margin for error is reduced. Errors may consist of deviations between assumed loads and loads applied in use by the customer. There may be deviations between assumed material properties and material properties of the individual part or material batch. There may also be deviations between as-designed dimensions and the manufactured part from a certain supplier’s batch or it may be caused by defects in the individual part. For AM parts that are designed for low mass, it becomes important to know the actual material properties, actual dimensions and possible defects, perhaps for all individual parts in a batch. Non Destructive Evaluation (NDE) is a family of methods that serve to verify a part or product for deviations from an expected, nominal outcome. Some NDE methods are more capable of detecting internal defects that could occur during additive manufacturing or by design intent where lattices could replace the internal volume of a seemingly solid part.

This licentiate thesis is laid out as follows.

Chapter one contains a brief description of AM processes and the metal PBF process in particular. It also describes the industrial context in which this research has been performed. It states the research questions that are explored in this licentiate thesis and the attached research papers.

Chapter two describes the research method used. The attached research papers’ respective research questions are summarized with main contributions.

Chapter three handles design for AM from a when and how perspective. It also describes the PBF process capabilities of Electron Beam Melting (EBM) and Selective Laser Melting (SLM) in respect to shape and material properties. This chapter serves as a State-of-the-Art for Design for
PBF from a manufacturability perspective. The chapter may be used by a mechanical design engineer as an introduction to how to design for metal PBF to improve manufacturability and product quality, in addition to talking to an AM service provider.

Chapter four describes some aspect of what affects the cost of PBF parts and summarizes results and contributions from paper I where AM was compared to High Speed Machining for manufacturing costs and lead time in an effort to support when to design for PBF from a cost perspective.

Chapter five gives a short introduction to Topology Optimization and Lattice Design as two ways for a mechanical design engineer to create shapes that can both improve product performance and give AM an advantage relative to traditional manufacturing. It also summarizes results and contributions from paper II where an existing part was redesigned for AM using these methods and the effect on mass reduction and cost were compared.

Chapter six describes the process of geometry translation from exact surfaces to tessellated surface approximations and the effect on geometric accuracy. Paper III, where different CAD tools were evaluated for AM geometry translation accuracy, is summarized for results and contributions.

Chapter seven describes Computer Tomography (CT) as a Non Destructive Evaluation (NDE) method that may be used to verify both external and internal defects. It then summarizes results and contributions from paper IV that showed NDE defect detection capabilities on a PBF part in aluminum.

Chapter eight handles challenges on designing for metal Powder Bed Fusion by summarizing both academic research and insights gained by the author during these studies.

Chapter nine summarizes the different licentiate thesis chapters, topics and research questions.

1.1 Metal Additive Manufacturing

Additive manufacturing or 3D-printing or rapid prototyping are, or have at least been, synonyms for defining a manufacturing process where a part is built in an additive, layer-by-layer process [3]. The word Additive is used as a family name for manufacturing processes that add material instead of removing material (as subtractive manufacturing does, for example milling and turning). Additive Manufacturing machines capable of building parts in non-metallic materials such as polymers have been
around for almost 30 years [3]. The technology was used to create prototypes of plastic parts during product development so that lead time could be shortened and costly tooling could be avoided until the design had reached a certain level of maturity. Design for AM using plastic material was usually unnecessary for prototype parts as the series production method was almost always another manufacturing method. Additive manufacturing using metal powder was initially done by firstly solidifying a mix of metal powder mixed with a thermoplastic binder that was melted to hold the part (“green” body) together. The part was then heated to remove the plastic binder (“brown” body) and the metal sintered together. Some additional metal alloy was then introduced to fill the porosities left from the polymer binding to create the final part [3]. Later, methods that involved producing end parts directly in metal materials appeared.

ASTM and later ISO/ASTM52900-15 proposes a common terminology for AM processes [4] where Powder Bed Fusion is one type of process. Other AM processes are Directed Energy Deposition (DED), Vat Photo polymerization (VP), Material Jetting (MJ), Binder Jetting (BJ), Material Extrusion (ME) and Sheet Lamination (SL). Some of these processes are currently unable to produce parts in metal materials, however PBF can. PBF processes, a very common metal AM process when considering the number of commercially available machines, may be divided into two groups depending on what source of energy they use to melt the powder; Laser-based processes and Electron-Beam based processes. This licentiate thesis only includes the Powder Bed Fusion process and the SLM and EBM process in particular.

Figure 1 shows a schematic view of different Powder Bed Fusion processes and the other AM processes as defined in ISO/ASTM52900-15 with information of business model differences regarding process parameters employed by the AM machine manufacturers. Some manufacturers allow free-of-charge user modification of process parameters and others do not.
All PBF processes are similar in the way a part is manufactured; they use thin layers of metal powder which an energy source successively “prints” across, melting the powder into a solid body. Before manufacturing can start, a 3D model is needed. The 3D-model also needs to be prepared for manufacturing and the first step in that process is to select a build direction.

1.2 Manufacturing by Powder Bed Fusion

PBF builds parts by successively melting thin layers of deposited powder into solid form. After a layer is processed the build platform is moved downwards, a new thin layer of powder is added and the process is repeated. Before manufacturing can begin, a 3D model is imported into a PBF build preparation tool. The model is then oriented in a virtual build chamber and prepared for manufacturing. Then the machine is set up, the part is printed, removed from the machine and the PBF machine is set-up for a new job.
1.2.1 PBF build preparation, software side

A build preparation tool is used by the PBF service provider to prepare a part to be built. This software tool usually consists of several functions, some of them being a virtual representation of the PBF machine in terms of build volume, layer thickness and when and how support structures are to be added. Support structures serve to support the part during build and at the same time improve heat conductivity. For some processes, solid supports are needed to secure the parts to the build plate to avoid part warping. These supports are usually defined and placed manually by the PBF service provider as a part of the PBF build preparation step.

At this stage, total build time may be analyzed using computer simulations in order to accurately give a cost quote of one or several PBF blank parts. It may take hours to plan the build of a single part depending on part complexity. The PBF service provider may duplicate the part to be built or add other parts, improving build chamber utilization, further reducing lead times and costs.

With build preparation finished, the data is sliced in equally thin layers, matching the powder being used. Different processes use different powders and size distributions and the slicing thickness differs accordingly. Then the paths for the energy source are generated for each layer and the work file can be sent to the PBF machine and the build can start.

Figure 2 shows how support structures are generated by the PBF build preparation tool Magics for an EOS M290 and an Arcam A2X in titanium. Supports are generated from all down-pointing surfaces when the surfaces are angled less than a certain value relative the build direction, and with a longer distance than a certain value. The EOS supports are generated down into the build plate whereas the Arcam support lengths are limited in length. The supports may act as both structural supports and heat transfer supports and are generated by topological rules within the PBF build preparation tool.
Figure 2. Supports are generated by the PBF build preparation tool, in this case Magics. In this case, only default supports as generated from the machine vendor supplied support setting file, which is unique for each machine type, are shown. The EOS M290 supports reaches all the way down to the build plate whereas the Arcam A2X generated ones only reach down a defined distance.

1.2.2 PBF build preparation, hardware side
The build process involves different steps depending on machine type but some steps are common. Firstly, a PBF service provider prepares the build by adding powder into powder feeder containers, calibrates the equipment and loads the work file including all the information needed to produce the end part. Information herein controls energy output, energy beam in plane movement and traversal speed among others. If one machine is used with many different powder materials, the machine needs cleaning and sometimes even replacement of some parts before using a new material. The cleaning time may be substantial. The machine can then begin to manufacture new parts with no further PBF service provider input.

1.2.3 PBF part build process
The build starts by preparing the build chamber to reduce the risk for material oxidation which otherwise could affect the part and material. This may be done using vacuum for the EBM process or through the use of some inert gas for laser based processes. Powder is deposited from a reservoir by a moving arm or re-coater so that an even, thin layer of powder is deposited. Then an energy source moves across the powder bed, melting the powder to a solid metal layer.
Different materials, processes and layer thicknesses need different energy levels to melt the powder correctly; too low energy could cause lack of fusion between powders or layers whereas too much energy could cause evaporation of material. Different energy levels may also be utilized by the manufacturing process depending on where on the part melting takes place. A part’s outer surface (or contour when it has been sliced and processed in a layer-by-layer fashion) is usually printed with a certain set of process parameter whereas the internal volume (or fill) of the part uses other process parameters.

The platform with the first layer of the part, just solidified and rapidly cooling, is moved downwards a distance correlating to the layer thickness. A new powder layer is deposited and the process repeats itself, however with slightly new information on both melt paths and process parameters. The new layer of powder is melted to a solid on top of the previous layer, fusing them together to a solid part. It is not uncommon that the bulk of the part is melted by changing the vector of the energy source for the new layer so that it is melted by fill lines in an angle relative to the previous layer in order to improve material properties. Powder that is not melted and included in the part build may be collected and reused during post processing. Manufacturing of large and tall parts or a full build chamber with many tall parts may take days.

Figure 3 shows schematically how the PBF and the DED process in metals relate to each other, both capable of building parts in metal. PBF feeds material by repeatedly depositing thin layers of powders that are subsequently melted by an in-plane moving energy source, during which the build platform is lowered. DED feeds both material and energy from a multiple-axis deposition head onto a part attached to a platform that may move in more than one direction. DED typically allows for faster material deposition rates and larger parts.
1.2.4 PBF build post processing

After the build is complete, a PBF service provider removes the part from the build chamber. Non melted powder is brushed aside and recycled by mixing it into a batch of unused powder. If non melted powder is attached to the part like for the EBM process, it is first blasted away, then sieved and reused together with new powder for the next build.

After powder removal, support structures are removed from the part. Depending on support type, material, process and location of the supports, this task can be time consuming. It is often done manually with standard hand tools like files and pliers. Sometimes the part needs further heat treatment or Hot Isostatic Pressing (HIP) to improve material properties. Often the AM part needs surface finishing on fit surfaces or other functionally important surfaces and as such an AM part can be compared to a cast part. Such operations may include milling to improve fit tolerances. After post processing is done, the part is ready for delivery.
1.3 Electron Beam Melting

So far, the PBF manufacturing processes have been described where they are similar. Differences include the type of energy source used and how that in turn affects the build process and the end product.

The company Arcam develops and markets Electron Beam Melting (EBM) powder-bed-fusion machines that use a magnetically controlled electron gun in a vacuum environment to melt metallic powder. The electron gun makes it possible to use a high energy to penetrate relatively deep into the powder bed, making it possible to melt thicker layers than many laser melting systems, typically resulting in faster material deposit rates.

When build begins, each deposited powder layer is pre-sintered to a firm (but not melted) shape. This reduces powder movement during processing. Otherwise the powder can become electrically charged creating a cloud (called “smoking”) inside the machine during build. The EBM process may be called a “hot” process due to the elevated build temperatures created by the pre-sinter step. The pre-sintered powder bed also provides some structural support to the part which is to be built although Arcam states their process “need no supports” [5]. However, support structures are generated during build preparation by AM build preparation tools using similar mechanisms as those for laser machines, although not all the way to the build plate as shown in figure 2. These supports are needed to improve heat conductivity and reduce part overheating which can cause part swelling or material evaporation with dimensional inaccuracies as an end result.

After the pre-sintering step, the 2D layer slice of the part geometry is traced by the electron beam, melting the pre-sintered powder to a solid part. The part and platform move downwards and the process repeats itself until the part is built completely.

The solidified part, surrounded by a pre-sintered powder “cake” volume, must cool down inside the machine before post-processing can begin. The part needs to be sufficiently cool to enable handling and reduce oxidation once the part leaves the vacuum chamber. This cool-down step may take several hours.

During post-processing, the pre-sintered powder block is removed usually by the use of blasting equipment using the same powder as the part was built with.

The process parameters that drive the automatic manufacturing process differ between materials. Arcam provides process parameters where customers have the possibility to alter them if needed. Different process pa-
parameters may be specified by the PBF service provider to be used within the same part to improve quality or reduce build times.

1.4 Laser Melting

EOS develops and markets Direct Metal Laser Sintering (DMLS) machines that instead of an electron gun use actuated mirrors to guide a laser beam across a powder bed in an inert atmosphere. EOS machines typically use Argon gas as a consumable which adds to part cost. Similar laser-powered powder bed machines are manufactured by SLM Solutions who use the trademarked process name Selective Laser Melting (SLM). Other PBF machine suppliers also exist.

Laser PBF processes may be called “cold” as they do not pre-sinter the powder bed and the non-melted powder can be brushed off instead of blasted off during post processing. It is usually required to firmly anchor the part that is being built to the build plate to avoid heat stress induced warping. This can cause the part to collide with the re-coater during powder deposition, stopping the build process. Laser PBF supports tend to be generated from a certain area on the part all the way down to the build plate. Depending on part shape this can result in a more voluminous support structure when compared to EBM.

Post processing otherwise includes similar steps to the EBM process with the addition of heat treatment of the part while still attached to the build plate to alleviate thermal stresses that the rapid cooling could induce, causing the part to warp out of shape or crack as it is removed from the build plate.

EOS licenses process parameters separately for both machines and materials. This typically means that a company that uses EOS PBF machines need to purchase process parameters separately for every machine, for every material, and for every layer thickness in that material. Typically, different process parameters are used for the part (bulk parameters) and another set for the supports. For example, if one wanted to reduce build time for lattices by using other process parameters than for the bulk of the part, currently you would have to develop them by firstly licensing an open process parameter set from EOS, and then develop your own process parameters to improve manufacturability of such structures.
1.5 Industry context
This licentiate thesis on some aspects of design for PBF is the outcome of studies in an industrial environment. Saab Dynamics (SBD) develops and sells military equipment for Sweden and other countries. As SBD does not manufacture parts themselves, AM needs for this licentiate studies were supplied by Lasertech, a company in Karlskoga with connections to Tillverkningstekniskt Centrum (TTC).

1.5.1 Saab Dynamics
This licentiate thesis and studies in design for the PBF process has been funded by the student’s employer SBD. SBD is a company that develops military equipment, often in an Engineer To Order (ETO) method preferably with a launch customer that may both fund the development and become the first important customer of the new product. Many products from SBD are carried by actual soldiers in the field and as such have low mass requirements.

All individual parts are procured from outside suppliers and assembled and tested by SBD in SBD facilities. This method requires cooperation between the design team and the manufacturing company where different manufacturers of the same part may be used after some sort of validation or qualification of the supplier has been done. This approach also makes it possible for SBD to have intermittent production for certain products and share manufacturing costs with other companies. This may come at the expense of possibly longer lead times when production needs to re-start and suppliers may be engaged with other customers.

Some of SBD products are manufactured in low annual volumes. These products are often high-cost, high-value products within the missiles or torpedoes business areas. These products usually consist of several thousands of components of different materials. Not all of these products are man portable but a reduced product mass may create opportunity for a larger payload which creates additional customer value. SBD also has products within non-guided systems. Ammunition for these systems is typically comprised of hundreds of components and sometimes has annual sales volumes exceeding tens of thousands of units. These products have very different cost expectations than guided systems, and thus the performance/cost ratio is different.

A reduction in mass on some components may create an opportunity for longer range or a larger warhead which improves system performance. AM is capable of creating parts with new properties in both the shape and
material domain. How to design for PBF to improve product performance by reducing product mass at a cost that is accepted by a customer is thus a high-level research question of interest for SBD.

1.5.1.1 The Mechanical Design process at SBD

The mechanical design process at SBD is similar to the development processes taught to the author while studying at university during the 1990’s. SBD currently has approximately 110 employees at the mechanical engineering departments. Of these about half are dedicated to mechanical design and the other half are doing different kinds of mechanical analyses, project management, methods development or other mechanical development tasks. Structural analyses are usually done by special competences and approximately ten employees work mainly with analyzing and addressing those topics.

SBD is a matrix organization where a line organization is based on engineering skill (like mechanical design) with responsibility to assure that the project organization, which is responsible to develop new products at a certain time, cost and quality, receives the appropriate competence.

A mechanical design engineer at SBD is responsible for creating parts, assemblies, material selection, allocating tolerance requirements to improve assembly and that requirements in the development specification are fulfilled by the proposed design. The mechanical design engineer is also heavily involved in discussions with a chosen supplier to manufacture the part and adapting the design to improve manufacturability based on a cooperation between design and outside manufacturing.

Due to the relative smallness of the mechanical design group, and the broad product portfolio, SBD’s mechanical design engineers tend to be broad in skills and capable of solving problems in very different development phases and areas. As such, the research questions presented in papers attached to this licentiate thesis are all on areas that the author has been required to learn as a mechanical designer for SBD, however for other parts and manufacturing methods than AM.

Designs are reviewed at certain formal events called Preliminary Design Review (PDR) and Critical Design Review (CDR) with the major difference being CDR status being more mature. At these formal design reviews, all resources involved with the development work participate. These are mostly analysis based during the PDR and sometimes complemented by tests prior to and after CDR. For example, stress analyses, safety analyses, support analyses are all performed by people from other line organiza-
tions. A Physical Configuration Audit (PCA) serves to verify that manufacturing is capable of producing working parts and is the last formal review of the SBD development process of new products. After the product is released to production, it is maintained and upgraded for obsolescence issues for many years. Since SBD products have a long service life and many products designed in the 1970’s are still sold, about a third of the mechanical engineers work with product maintenance tasks which include for example updating drawings that use out-of-date material specifications.

About twenty years ago, SBD sometimes added a redesign step after a design had been tested using prototype hardware. This phase was called Seriekonstruktionsfas, freely translated to Series Production Design phase. This was an additional design iteration step where the initial (functional, prototype part) design was modified to fit mass production. In this step, manufacturing method could be changed from short lead time manufacturing like HSM to casting plus machining. This step is currently seldom performed due to time and cost constraints and is usually integrated in the design work leading up to the CDR. As a result, manufacturing methods today rarely change dramatically during development and HSM from rod blanks is often used throughout development and production.

There are many service providers for HSM in close proximity to SBD development sites. Casting is currently used to fabricate larger parts in certain alloys. There has been a transition from casting to HSM from rod as costs to machine parts have become cheaper. Carbon fiber reinforced composite materials are used as low-mass, high-strength solutions mainly in guided systems. Development of these is mostly done using suppliers in an ETO fashion, where SBD writes a development specification with an interface specification and environmental requirements. A supplier then designs, manufactures and qualifies the part before delivering hardware to SBD final assembly.

Titanium is used in approximately one new part design per year. The other close to thousand newly designed parts are produced mainly in aluminum or other metals. Superalloys like (Inconel) 718 are used even more seldom.

Figure 4 shows the SBD Global Management System (GMS) development process generally and the mechanical development specifically. Support processes are shown as individual boxes above and below the three main workflows. Mechanical development is included in the Integrated Product Creation (IPC) workflow.
There are currently no plans for SBD to begin manufacturing parts themselves. So SBD needs an Additive Manufacturing supplier that builds-to-print. For PBF, SBD currently uses Lasertech which is a part of TTC.

**1.5.2 Tillverkningstekniskt Centrum**

Close to SBD facilities in Karlskoga is a local, cooperation group called Tillverkningstekniskt Centrum (freely translated to “Manufacturing Technology Center”) that focuses on Additive Manufacturing and it was established in 2015. TTC comprise of, among others, Örebro University, Saab Test Center and Lasertech. Pejryd et al. described TTC and their role in participating in AM research in both industries and academia in Sweden [2]. SBD participated in creating TTC and contributes by funding part of their activities.
Saab Test Center sells services and provides facilities for testing purposes of both civil and military equipment. For TTC they are providing NDE services using a Computer Tomography (CT). They currently use a Nikon XTH 225 which is capable of creating x-ray images of objects in size up to approximately 0.18x0.25x0.6m in size, however smaller objects allow higher resolution images. If the object is rotated and many images from different directions are collected, a 3D-object can be built during post processing [6]. During post processing analyses, many different investigations are possible to perform, for example measure the size of internal defects in an additively manufactured component or investigating if a warhead fuse is in its locked position.

Lasertech AB (LSH) is a company connected to TTC that has invested in PBF using both plastic and metal materials. LSH began using an EOS M290 metal PBF machine in 2014, and added an Arcam A2X during late 2015. The build chamber size on these and other PBF machines may be too limited for some parts. An M290 machine is 250x250x350mm in width x depth x height size. The A2X has a build chamber size of 200x200x380mm. Lasertech currently has a subset of material licenses from the EOS catalogue for the EOS machine. The Arcam machine is currently using Ti6Al4V powder only due to business reasons although Arcam provides process parameters freely for other materials. Lasertech have built extensive tacit knowledge on how to manufacture PBF parts especially on the EOS platform and has contributed to cost predictions presented in this licentiate thesis list of papers.

When the Arcam EBM machine was acquired and placed in Lasertech’ s facilities, Saab sponsored the investment by pre-purchasing annual manufacturing time for a certain amount of hours. This pre-allocated machine time in the Arcam machine was split between different companies within the different Saab companies, including Saab Dynamics. In effect, this makes it possible for Saab projects to get hardware “for free” as long as there are still funds left in the pre-allocated pool.

Other parties involved in TTC are Örebro University, Siemens Turbomachinery to name a few. Pejryd et al. interviewed Lasertech to present their “most appreciated” PBF parts by their customers in [2] and which advantages of AM they used as defined by Klahn et al. [1] showing that currently, Lasertech produces mainly prototype PBF parts where the series production method is known to be another manufacturing method. This reduces the need for designing for PBF specifically and the AM advantage
being used is mostly to reduce lead time as compared to the tool-based solution to be used in series production.

Companies are visiting Lasertech on a regular basis to learn more about what AM and PBF can do for them and their products. Many are interested in learning more about how to design for AM.

1.6 Research questions

Five different research questions (RQ) are addressed in this licentiate thesis and in the attached list of papers. This chapter shows how these were initially stated and how they were refined. In the attached papers, more refined research questions may exist.

SBD funded a licentiate study on the Industrial Research Question (IRQ) “How to design for AM?” (industry research question 1; IRQ1) and due to the cooperation with Tillverkningstekniskt Centrum, the question was early on refined to how to design for PBF in metal materials. RQ1 was divided into “When to design for AM” and “How to design for AM” from a general point of view. As the SBD design process combines the designer’s knowledge of manufacturing with the designer’s capability to generate shapes, this first IRQ created RQ1b “What are the manufacturability capabilities/constraints of EBM and SLM in regards to shape capabilities and material properties?” These two research questions resulted in a literature study of EBM and SLM process capabilities of different mechanical design areas such as material properties, dimensional accuracy and surface roughness.

IRQ2 was “What affects PBF part costs?” At this stage in the studies, initial cost quotes had been received and were found to be much more expensive than traditional mass manufacturing. From this point, two research questions were created. RQ2 relates to “How does PBF compare to HSM for series part costs?” During research, build time for different PBF parts in different materials were simulated in a case study of eight SBD parts and compared to HSM cost quotes to find what shapes and materials affect cost. A mathematical model was created to predict PBF part cost of several existing SBD designs. The results from the study are presented in paper I. It was then discovered that the same model could be used to predict PBF blank cost by replacing the simulated build time with an experience-based and estimated one. This created RQ2b of “How to use SLM cost prediction modelling to support when to design for AM” and was then suggested in paper II. This part of the RQ2b has been used by the
author to support SBD design choices more than once during the two years of studies.

IRQ3 was “How to design for metal PBF to lower product mass?” After a literature review and looking into how other companies designed PBF parts, research question RQ3 “What mass reductions are possible using TO and lattice design and what effect does lower part volume have on part cost” arose. Results from this study using a SBD part as a case study are presented in Paper II.

IRQ4 was “How to improve AM tolerances?” As SBD currently does not intend to manufacture AM machines or manufacture PBF parts internally, how to improve tolerances was refined to study the effects of geometry translations from design (that SBD are doing internally) to PBF manufacturing. RQ4 thus became “How to improve geometric accuracy of AM geometry translations”. The results from a case-study using three different round part shapes and translated to AM using six different CAD tools are presented in paper III.

IRQ5 was “How to know if the AM part performs is built to and performs according to specification?” This question was refined and limited to include Non Destructive Evaluation only. As AM can manufacture complex shapes, one solid and one latticed part were designed by the author as test objects for evaluation of defect detection capabilities by three different NDE methods. RQ5 was thus “How can PBF defects be detected using commercially available NDE methods?” and the results are presented in Paper IV where the author contributed component design and data for post processing comparisons.

Table 1 summarizes the IRQ’s and RQ’s.
Table 1. Industrial research question and research question summary.

<table>
<thead>
<tr>
<th>IRQ</th>
<th>RQ</th>
<th>Industrial Research question (IRQ)</th>
<th>Research Question (RQ)</th>
<th>Chapter / Paper</th>
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<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>How to Design for AM?</td>
<td>How to design for metal PBF?</td>
<td>Chapter 3</td>
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<tr>
<td></td>
<td>1b</td>
<td></td>
<td>When to design for metal PBF?</td>
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<tr>
<td>2</td>
<td>2</td>
<td>What affects PBF part cost?</td>
<td>How does SLM compare to HSM for series part cost?</td>
<td>Chapter 4 / Paper I</td>
</tr>
<tr>
<td></td>
<td>2b</td>
<td></td>
<td>How to use SLM cost prediction modelling as a way to support when to design for PBF?</td>
<td>Chapter 4 / Paper II</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>How to design for metal PBF to lower product mass?</td>
<td>What mass reductions can Topology Optimization and Lattices provide and how is PBF part cost affected by lowered mass?</td>
<td>Chapter 5 / Paper II</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>How to improve AM tolerances?</td>
<td>How to improve geometric accuracy of AM geometry translations?</td>
<td>Chapter 6 / Paper III</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>How to know if the part is built to specifications?</td>
<td>How can PBF defects be detected using commercially available NDE methods?</td>
<td>Chapter 7 Paper IV</td>
</tr>
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</table>

Figure 5 shows how the industry research questions (as specified by SBD) gave rise to academic research questions. The figure is inspired by the industry-as-laboratory research method as described by Potts [7]. This research started in the top left corner with a high-level industry research question (IRQ1) that was refined to RQ1 and RQ1b. Subsequent IRQ’s arose as results from initial studies which in turn became RQ’s. Many questions arose almost simultaneously and were not researched in the exact order the figure shows. However, the industry-as-laboratory method is familiar to the author and the model is used to create a logical flow of research questions as they could arise in the context of a development project. That is also why this licentiate thesis presents the RQ’s in this order. The grey box to the left is inspired by the industry-as-laboratory approach. The right box shows where in this licentiate thesis and which attached paper contributes new knowledge. Bold boxes indicate research questions contributed to with own work.
As a student financed by industry, it was possible to some extent to use existing SBD parts as a base for PBF research. However, SBD has no product currently under development that is to be manufactured by PBF so different parts were used as possible case studies for different RQ’s. In
addition, some research methods are more fitting in an industrial context and that is the topic of the next chapter.
2 Research methods and contributions

This chapter describes the research methods used for the five research questions. It also summarizes the contributions for each paper attached to this licentiate thesis. It begins by showing different possible design methods that are relevant for the author as an industrial PhD student and then describes which method was used for each of the research questions and for the four attached papers. It also summarizes main contributions from the attached papers.

2.1 Research methods

SBD has currently no part that uses PBF as the chosen series production manufacturing method. This made it hard to take advantage of both internal co-funding and spin-off research questions in an industry-as-a-laboratory approach as described by Potts [7]. Pejryd et al. describes different approaches to research AM in by describing a component-centric AM research approach used at Örebro University [2]. Here, investigations on certain properties that AM provides are done on parts produced by existing process parameters using existing AM machines and AM service providers. Industries may however deploy, and SBD does so, what Pejryd et al. describes as a product-centric approach which is similar to the demonstrator based approach as defined by Marie Jonsson in her dissertation [8]. Here, both a product and knowledge of how to produce it, and knowledge of why things work the way they do are generated at the same time in an integrated manner. Teegavarapu et al. compares the method by case studies to experiments and argues that both these methods are possible to use for design research [9].

In the research for this licentiate thesis however, different parts for different papers were used as a bases for experimentation, as case studies or as product- or component centric research methods, in order to investigate different aspects of design for PBF.

To answer RQ1 on “manufacturability capabilities/constraints of EBM and SLM” a literature review was performed. The result from this study is presented in chapter 3 as shown in table 1 and figure 5.

RQ2 on “How does SLM compare to HSM for series part cost” was presented in paper I. Eight existing SBD parts that are possible to mill from solid rods were used in a comparative case study were PBF build times were simulated and total PBF part cost predicted. A mathematical model was established to predict post-processing machining needs to cal-
alculate the final PBF part cost and to predict the PBF manufacturing speed increases needed to compete with HSM part cost. All parts had existing HSM cost quotes available and the parts reflected both shape and material selections typical for SBD designs with annual sales volumes less than 1000 units. Since the result showed higher costs for PBF blanks than for HSM, no parts were chosen for change of manufacturing method and thus no parts were manufactured or tested for performance. No actual cost quotes were requested for the post processing machining step due to the high PBF blank cost, highlighting the importance of adding extra customer value by designing more advanced shapes in more capable materials as ways to motivate the often expensive PBF parts. RQ2b was addressed in paper II which also handles RQ3.

RQ3 on “How to design for metal PBF to lower product mass” was presented in paper II where an existing SBD part was used as a case study for redesign for lower mass and PBF using Topology Optimization and Lattice patterns. The part was chosen because it was relatively easy to reverse engineer its purpose and design intent. It also had a relatively simple shape and it was easy to divide into different geometries for both methods to work on. The resulting shape result was compared for cost and mass to an existing design solution cast in magnesium. Due to lack of business case the new less heavy design was not manufactured or tested, highlighting the importance of knowing the value of performance and finding suitable parts for PBF redesign efforts. Paper II brings up the point of using cost prediction to support when to design for AM as a part of RQ2b.

RQ4 on “How to improve geometric accuracy of AM geometry translations?” was researched in paper III. Here, three geometries with two being downloaded from the Internet and one primitive tube geometry, were used in a comparative case study to see how six different CAD packages (four of which SBD use to some extent) approximated round surfaces to planar triangles as a part of the AM geometry translation process. The parts were chosen specifically to show translation accuracy effects on circular surfaces with large diameters as they would create larger form deviations if measured. The results were compared to an assumed form requirement and a method of combining form requirements plus an exact geometry translation method was suggested as ways to interface to AM. The translation effects on form requirements were shown in hardware using another company’s prototype part which showed that these effects are visible in the physical parts.
RQ5 on “How can PBF defects be detected using commercially available NDE methods?” was researched in paper IV. Two new components were designed with internal slits to simulate the defects caused by lack of fusion between powder layers in a component-centric case study and then manufactured in AlSi10Mg using an EOS M290. The part was then used as base to perform physical experiments of defect detection of three different NDE methods.

2.2 Contributions
This licentiate thesis contributes some new knowledge that has not been contributed previously by the attached papers. This is mainly the literature review in chapter 3 (RQ1, RQ1b) and the further explanation of the research questions RQ2-RQ4 in chapters 4-6. Contributions of new knowledge as shown in the attached research papers are summarized in table 2 in addition to being summarized in respective sub paragraph.

<table>
<thead>
<tr>
<th>RQ</th>
<th>Paper</th>
<th>Research question</th>
<th>Research method</th>
<th>Contributions</th>
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</table>
| 1  | -     | What are the manufacturability constraints/capabilities of EBM and SLM in regards to shape capabilities and material properties? | Literature study | i) Collection of literature supporting when and how to design for AM in chapter 3.  
ii) Collection of some characteristics of SLM and EBM in respect to shape capabilities and material properties in chapter 3. |
| 2  | I     | How does SLM compare to HSM for series part cost? | Case study, SBD parts used | i) Mathematical model separating PBF costs in per-build costs and per-part costs in paper I.  
ii) Showing that when it is possible to mill, that cost is seemingly much less expensive than PBF suggesting that more advanced shapes and materials are needed to motivate PBF. |
<p>| 2b | II    | How to use SLM cost prediction modelling as a way to support when to design for PBF? | Case study, SBD part used. | i) Suggesting a cost-prediction step before performing design work to verify business case of a more expensive but possibly better performing part in paper II. |</p>
<table>
<thead>
<tr>
<th>RQ</th>
<th>Paper</th>
<th>Research question</th>
<th>Research method</th>
<th>Contributions</th>
</tr>
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</table>
| 3  | II    | What mass reduction is possible using TO and lattice design and what effect does lower part volume have on part cost? | Case study, SBD part used.                                                                            | i) Dividing of design processes into process-driven (TO) and designer-driven (lattices) methods in paper II with some process similarities and differences.  
ii) Cost comparison of new lower mass designs to existing design and the cost effect of reducing mass using SLM for one case study part. |
| 4  | III   | How to improve geometric accuracy of AM geometry translations                       | Case study, non-SBD parts used.                                                                       | i) User modifiable accuracy settings are named differently between CAD packages.    
ii) Some CAD packages tessellates worse than others, with possible facets being visible in the end product despite maximum accuracy setting.  
iii) AM build preparation tools can read exact geometry formats and tessellates data at higher accuracy than some CAD packages.  
iv) Suggestion of using exact geometry formats plus form requirements as input to metal AM processes. |
| 5  | IV    | How can PBF defects be detected using commercially available NDE methods?          | Case study, component-centric, new original design                                                   | [by research paper]  
i) CT generally provided better defect detectability than Eddy Current (EC) and ultrasonic inspection (UI)  
ii) Defects in lattice patterns could not be detected using EC or UI but indicated on by CT when using actual/nominal comparisons.  
[by student]  
i') Design of component, distributing of engineering data, ordering and distributing of manufactured part |
3 DfAM; when and how to improve performance and additive manufacturability

This chapter contains a literature review on when to design for AM and how to design for AM. How to design for AM is in this licentiate thesis divided into how to improve performance and how to improve manufacturability. The manufacturability aspect includes shape capability (what is possible to build, surface roughness and tolerance capabilities of EBM and SLM respectively) and material properties (static and fatigue load capabilities of both SLM and EBM in titanium and aluminum).

This content was collected during 1st half of 2015 and complemented during a PhD course in Additive Manufacturing during late 2015 to spring 2016. It was complemented during the writing of this licentiate thesis by the addition of some recent review papers on material properties. It serves as responses to RQ1 and RQ1b. The chapter may thus be used by a mechanical designer to learn about some of the EBM and SLM manufacturing capabilities as a complement to discussing directly with a PBF service provider.

How to design for AM and how to design for Powder Bed Fusion are relevant questions especially when PBF has been chosen as a series production manufacturing method. Different manufacturing methods have different advantages, capabilities and possibilities in addition to having different effects on lead time and costs. When to design for AM and PBF is a relevant question, perhaps especially in the early phases of development since designing for improved performance or reduced part cost are different processes. The answer on when to design for PBF differs between industry and product but some suggestions are given in literature.

3.1 When to design for AM

When to design for AM is perhaps more relevant in an industrial setting but has been studied to some extent in academia as well. Lindemann et al. suggest a part selection process for additive manufacturing, highlighting the importance of mass reduction for faster build and having access to requirement specifications in the reengineering task [10]. Kerbrat et al. describe a way to combine AM with machining using topology analysis code based on the octree geometric model [11]. Part areas with lower surface derivatives create the initial part blank onto which areas with high
surface derivatives are suggested to be additively manufactured. Merkt et al. suggest using the number of facets on the geometry file to diagnose geometric complexity [12] and if comparing relative facet density within a part, the facet density could be an indicator of surface complexity that could favor AM. But since tessellation accuracy usually can be modified at export, using the number of facets to compare complexity between different parts may not identify suitable AM parts correctly.

Other ways of finding parts suitable for design for PBF is from an economic perspective. Paper I shows that when hard-to-cut materials are needed, especially for shapes with large surface-to-mass ratio or buy-to-fly ratios, PBF may be a cost effective solution even when compared to HSM for manufacturing of the part. In Paper II a process is proposed where an assumed volume reduction due to using PBF advantages of shape may be used to predict PBF part cost and compared to alternative designs and the business case.

Klahn et al. define four areas where additive manufacturing might be advantageous [1]; integrated design, individualization, lightweight design and efficient design. If a part makes use of many simultaneous advantages of AM, the chance of an AM part reaching series production increases. Integrating an existing assembly design may remove or reduce the number of assembly steps which may reduce assembly cost as shown in studies by Corney et al. [13], Selvaraj et al. [14] and Schmelzle et al. [15] for example. The three other areas are categorized in this licentiate thesis as ways to improve product performance.

3.2 How to Design for improved performance
How to improve performance depends on the product. The customer value of increased performance needs to be known to be able to decide if the performance vs. cost trade-off is tolerable. Tang et al. review different DfAM methods to improve functionality (such as lower mass) in [16]. They divide design methods into what dimensional scale they operate on; macroscale, mesoscale and microscale and assign the method of Topology Optimization (TO) to the macroscale domain, lattice design to the mesoscale and material structure design to the microscale domain. Doubrovski et al. also use the geometry scale division of DfAM methods and add visual performance (aesthetics) and thermal performance in their review paper as examples of what AM can do to improve performance [17]. They also raise the question of what role the designer will have when design methods are changed from manufacturing-first to performance-
first. Richards et al. combine topology optimization and lattices in a product-centric warhead design to reduce mass, wall thickness and improve fragmentation while displacing less than the original design [18].

The field of individually designed parts is apparent in the medical implant industry. The combination of body-compatible materials with biological shapes and a high customer value of an individually shaped implant are combined to give AM an advantage over traditional manufacturing. In addition, it is possible to use Computer Tomography (CT) scans of the surrounding tissue to develop the implant around, to print the implant and the surrounding tissue in plastics and practice surgery. It is possible to scan bone tissue, create a tessellated dataset that can be modified directly in the AM build preparation software, and additively manufactured as shown by Cronskär et al. in [19], making it a “scan-to-print” design process with reduced manual design needed. This significantly reduces computer modeling time, which also lowers part cost since when producing only one; the single part carries all manufacturing and development costs.

Improving heat transfer by taking advantage of the freedom of shape to create curved, part conforming, internally located channels is a design feature perhaps limited to laser PBF processes since EBM pre-sinters powder making it hard to remove from curved channels. Schmelzle et al. redesigned a hydraulic valve in laser PBF manufactured titanium by using part consolidation to reduce part count and remove assembly steps, which resulted in curved internal channels for the fluid. They tried different cross section areas to make the channel self-supporting [15]. Part consolidation may also reduce mass since adding non-moving parts to one may make it possible to remove material where parts are joined. Otherwise, it may be one way of reducing part cost by eliminating assembly steps.

Pejryd et al describe and show images of a Saab Surveillance part designed for PBF with internal cooling channels [2]. The part was designed for laser PBF in aluminum and came into existence by first adding existing parts designed for assembly into a single part (part consolidation) and sent to a PBF service provide for manufacturability analysis. The response was that it was feasible to manufacture using SLM in AlSi10Mg and manufacturability could be improved further by some changes of the geometry. Manufacturability improvements were done in cooperation with the PBF service provider to make the part easier to build, reduce material use (and part mass) and reduce post processing needs. The outside surface is machined to improve heat conductivity but the internal conforming cooling channels are not post processed other than the removal of non-melted
Some aspects on designing for metal Powder Bed Fusion

3.3 How to Design for improved additive manufacturability

Once a design fulfills functional requirements and a manufacturing method has been chosen, the design may be modified to improve manufacturability to lower part cost. In the case of the previously mentioned cooling plate, the functional aspects of the part included the size and shape of the cooling channels and the external interfaces. Changing the geometry outside these areas to improve manufacturability is warranted when a part is going into series production. Sometimes, design for function and performance and for manufacturability are iterated at the same time and could be hard to separate or reverse engineer if the manufacturing method was to change.

Design-for-manufacturing methods serve to reduce part cost and improve quality and are manufacturing method dependent. When cutting metal rod blanks to manufacture a part, strict tolerances are possible. If the blank part is cast however, one would like the tolerances to be achievable by casting directly, reducing the need for further machining to lower both lead time and cost. A part that can be built using AM with post-processing steps that the AM service provider can do internally, for example heat treatment, blasting and polishing, will probably also reduce lead time and AM part cost.

Depending on how a part is rotated within a PBF build chamber relative to the build plane and build direction, build support need is changed. PBF build preparation tools often use PBF machine supplier settings to know when and how to generate supports during build preparation. Choosing an “optimal” build direction is therefore important as it affects how supports are created during build and need to be removed during post processing. In addition, having good knowledge of the capabilities of the different PBF process in regards to typical manufacturing method properties such as material availability, material properties, typical dimensional accuracy, surface roughness and lowest possible wall thickness is vital in order to design parts well suited for PBF series production.

3.3.1 AM build direction effects on manufacturability

All PBF manufacturability improvement possibilities are derived from a chosen build direction. Changing build direction may make the part invalid from a manufacturability point of view in respect to support build up.
and post processing needs. Das et al. show a build direction selection method using form requirements and AM process knowledge of surface properties (including slicing effects on surface roughness) and tolerances that are achievable to suggest a best build direction to reduce post processing needs [20].

However, there are more trade-offs that are made when selecting the “best” build direction from economic point of view in series production. For example, a part with a selected build-direction that has the lowest possible need for support structures to make the part possible to build, may create a very large build height which in turn needs more layers to build which takes more time to deposit. And similarly, a build orientation that creates more supports (which will cost more and take longer time to post process) may instead make it possible to print more parts inside the chamber at the same time, lowering per-part printing cost. A full build chamber could be more important for per-part cost when using PBF processes that require many hours of pre-heating and/or cool down of the build chamber before and after build. It is only after the PBF process has been chosen and a build direction selected that a PBF build preparation operator and a designer can jointly discuss possible geometric changes of the part so that it would still perform all functional requirements but become easier and cheaper to manufacture with repeatable and predictable quality.

Surface roughness can also vary depending on build direction. Up-surfaces and vertical surfaces are usually better than angled and down-facing surfaces. Angled surfaces contribute to perceived surface roughness due to stair step effect during slicing as shown by Snyder et al. [21] and others.

Most PBF build preparation software gives some support to analyzing different kinds of possible build problems caused by the part shape and build orientation. However, only some of the design guidelines as documented by Kranz et al. in [22] are supported by most PBF build preparation tools. Discussions between design and manufacturing are thus equally warranted for PBF as it is for all other types of manufacturing. Understanding the capabilities of the selected manufacturing method is a key knowledge for a designer of metal PBF parts but also for a PBF manufacturer to suggest a suitable PBF process for a given part.
3.3.2 Metal Powder Bed Fusion capabilities and constraints

One way for a designer to improve manufacturability is to understand the manufacturing method and capabilities it has including tolerances, material properties and other engineering characteristics. Academic research results on engineering design characteristics for SLM and EBM PBF processes are described below, including what shapes can be built, dimensional accuracy, thin wall capability, surface roughness and material properties. These findings can be used by a designer of PBF parts as information on what performance it is possible to get, and to improve manufacturability of their designs. However, these metrics are constantly changing as PBF machines and powder alloys continue to evolve.

3.3.2.1 SLM capabilities

SLM manufacturability has been researched by building common topological shapes in different materials. The idea is to be able to reuse this information when doing subsequent builds. Kranz et al. created several topologically different primitive shapes and built them using an SLM machine in titanium [22]. They categorized the different shapes and recommend certain boundaries to follow when designing and building parts. Daniel Thomas shows results from similar buildability tests using other primitive shapes in his PhD thesis [23]. Atzeni et al. investigated self-supporting shapes in [24] using aluminum powder. Adam et al. compared different PBF processes capabilities on shape accuracy and overhangs with different materials, among them steel 316L on a SLM 250 machine [25, 26]. A similar study was done by Kruth et al. however with different shapes, different processes and different materials [27]. Other efforts to create design guidelines for additive manufacturing have been done by PBF machine vendors [28]. Some, but not all of these findings are included as decision support in current PBD build preparation software tools.

Dimensional accuracy was investigated by Bauza et al. using stainless steel powder [29]. They found that the circularity of one printed specimen was approximately 0.05mm but also found large flatness deviations due to warping. Pessard et al. used DirectMetal powder in an EOS machine and evaluated dimensional accuracy to 0.2mm which they state is above the 0.05mm tolerance of requirements of molds [30]. One SLM machine supplier states a typical tolerance grade depending on materials of ±0.05mm for titanium [31] and ±0.1mm for aluminum [32] powders.

The thinnest buildable wall section was also tested by Kranz et al. in titanium, finding it to be >0.3mm [22]. This compares well to PBF machine
Some aspects on designing for metal Powder Bed Fusion supplier guidelines [31] using the same material. The thinnest buildable wall thickness is also affected by the geometrical shape. Powder is dispensed as a flat, even layer by the use of a mechanical arm. Thin, unsupported structures have been shown to break in some laser based processes due to re-coater arm collisions during powder addition, or that the collision causes disturbance of the powder bed causing build failure. An experienced PBF service provider use mainly experience to select part orientation relative re-coater in order to reduce such problems.

Surface roughness of printed surfaces before physical post process differs between materials and is also affected by build chamber orientation. Surfaces facing up get finer surface roughness than down facing surfaces. Angled surfaces in relation to build direction contribute to surface roughness due to stair effect of slicing, as investigated by Das et al. [20], Snyder et al. [21], and others. Up facing or vertically built surfaces typically show a surface roughness of $R_a$ 9-12 using titanium powder [31]. Yang et al. used a copper powder to measure surface properties on top surfaces when printer parameters where changed, stating that powder layer thickness and low laser power in combination affects surface roughness heavily [33].

Material properties have been researched abundantly by both PBF machine vendors and academia. PBF vendors publish results in material data sheets for respective materials [31, 32 as examples]. Xu et al. found results close to those documented by the PBF machine vendor for titanium [34]. Kasperovicha et al. used a Concept Laser M2 to print Ti6Al4V specimens. They tested both machined and as-printed and post processed specimens by Hot Isostatic Pressing (HIP). Elongation did not improve substantially for any of the two heat treatments when compared to the as-built specimens [35]. The HIPed specimen failed at 19% elongation, very similar to the reference wrought material, improving elongation from roughly 12% (as-built). Fatigue properties were investigated using High Cycle Fatigue (HCF) at 600MPa, for which the as-built parts failed after $2.3 \times 10^3 - 5.6 \times 10^3$ cycles and machined $1.2 \times 10^4 - 2.0 \times 10^4$ cycles. When heat treated, the number of load cycles before failure did not improve significantly, but when using HIP this increased to $1.5 \times 10^5 - 3.0 \times 10^5$ cycles. They conclude that heat treatment does not increase ductility or fatigue properties very much. Instead, HIP should be used, and the as-printed surface is to be considered a crack initiator when machining or polishing cannot be done, for example with lattice designs and possibly even topology optimized shapes. Recently there have been several review papers published that summarizes material properties for different PBF processes, for example
Beretta et al. for titanium and aluminum [36] and by Trevisan et al. for aluminum [37].

3.3.2.2 EBM capabilities

PBF manufacturability of primitive shapes has not been investigated as thoroughly as for SLM in academia using the EBM process. Since powder evacuation could be problematic using EBM this capability has been researched by Vayre et al. They found a linear relation between powder removability and hole diameter suggesting holes deeper than 3*diameter would begin showing problems in removing powder [38].

Dimensional accuracy of parts manufactured using EBM show lower accuracy than SLM due to the larger energy spot diameter and thicker layers. The accuracy of the energy beam allows for a ±0.15 to ±0.2mm dimensional accuracy [39].

Thinnest buildable wall section was included in the Vayre et al. study of EBM design parameters. They state the minimum buildable diameter of support structure to be 0.6mm [38]. As for laser based PBF processes, the lowest wall thickness is partly affected by part shape and material.

The surface roughness of parts built in EBM is generally larger than that of SLM. Arcam, the EBM machine vendor, states an $R_a$ of 25/35 in titanium [39]. However, continuous enhancements in printing parameters and powder alloys are improving both surface roughness capabilities and dimensional accuracy.

Material properties of EBM manufactured test specimens in titanium Ti6Al4V are documented by the machine supplier [40] and are similar to those of SLM. Since EBM build parts in a chamber with elevated temperature the main difference is increased ductility when compared to non-heat treated SLM parts. De Formanoir et al. printed 2mm flat tensile plates in different build directions in Ti6Al4V in two different layer thicknesses (50µm and 70µm) and heat treated them for 1h in 950 °C or 30min at 1040 °C. The parts were polished prior testing. The $R_a$ value was not stated. They found vertically built plates from 50µm powder, non-polished, non-heat-treated failed at 3.6%±1.2% elongation and when polished 4.58%±0.78% [41]. Plates that were built lying flat performed worse due to build defects. 70µm powder layers provided better elongation values for the vertical build direction. The lower elongation values are discussed and attributed to the smaller build dimensions binding more oxygen. They also state that a part of outer surface, approximately 0.15mm, may not carry load due to surface roughness. When this was taken into account, less
difference in strength between the as-printed vs. polished specimens were shown. Abele et al. found pores that went completely through thin metal plates when manufactured using EBM for wall thicknesses below 0.15mm [42] providing additional information that thin wall properties may be reduced due to the surface roughness or porosity effect at the surface level. De Formanoir et al. conclude that heat treatment did not improve ductility much; instead focus should be placed on keeping oxygen out of the powder. Gong et al. compared an EOS machine to an Arcam machine using Ti6Al4V to build a rod ø10mm in vertical direction, varying process parameters between those as suggested by the AM machine supplier to modified ones. Non-heat-treated SLM parts failed at elongation 8%-10% and EBM at 7%-12% with larger variation when comparing supplier suggested parameters [43].

Fatigue properties show large variation in results for both processes. SLM managed 350MPa for 10 million cycles, lower than in other studies. This is thought to be due to the differences in powder and printer parameters. The EBM process produced similar results where the large variation between specimens made it difficult to see the differences. Larger powder particles and rougher surfaces were noted on the EBM specimens, probably contributing to the lower-than-expected fatigue properties when compared to other studies.

Tong et al. summarizes both SLM and EBM processes for Ti6Al4V material properties in their review paper [44], stating that AM cannot be assumed to achieve material properties equivalent to a wrought material due to difference in material structure. They also highlight that AM shape freedom may cause surfaces to be inaccessible for surface finishing post build.

Summarizing both these PBF processes, material properties for PBF parts of different shapes and in different materials have been extensively researched, and the build direction effect on buildable shapes has been more researched using laser based PBF process than EBM.

Figure 6 summarizes this chapter on how to design for PBF. Design for PBF may include development of new alloys that improve material properties or manufacturability and is a researched in both academia and industry as shown by Pejryd et al. in [2] for Swedish industries and universities. Dashed lines indicate not being included in this licentiate thesis.
If a part has been designed considering function, performance and cost and PBF is the chosen manufacturing method, then it is possible to get an accurate part cost quote from a PBF supplier. This cost includes build time costs, consumable costs including powder, and costs for post processing. In many cases, the PBF service provider can provide an accurate cost quote within some hours. Input to the cost quote is a 3D model, material choice, PBF process selection and how many parts are needed. This is the content of the next chapter.
4 Cost of PBF parts

This chapter contains a description of what affect series production has on PBF part costs. PBF part costs may be divided into those attributed to the individual part, and those that are shared between parts built in one build chamber in order to be able to predict at what series size PBF might be competitive. This chapter describes some of the costs attributed to PBF manufacturing.

In paper I, a comparison between High Speed Machining by milling from rod and PBF is done. Eight parts that had cost quotes for milling were selected from a list of about 40 with different part shapes and sizes to find how PBF compares to HSM in cost. A build chamber was filled with parts and melt speeds of the different parts were simulated and used to calculate PBF blank cost. Costs for milling the PBF blank part to meet specifications are derived from the existing HSM cost quotes and added to the PBF blank part. From the melt speed results, a PBF blank cost prediction step was proposed in paper II to support when to design for PBF.

The study was performed during 2\textsuperscript{nd} half of 2015 to 1\textsuperscript{st} quarter of 2016 as a result from RQ2 and created a derivative research question RQ2b which is expanded on in this chapter. The PBF cost prediction model derived from RQ2 to create RQ2b has been used to predict PBF blank cost of other SBD parts since the study was made and compared to build time simulations. When a good medium melt speed is estimated by experience from similarly shaped parts, PBF blank cost predictions are fast and accurate enough to make preliminary manufacturing decisions. As long as the build time is a large contributor to part cost, predicting build times captures a large portion of the total part cost.

PBF part costs are comprised of material cost and other consumables for the part, the machine time cost to build the part and costs from post processing for the part. Since the PBF machines are currently expensive and need skilled operators, the combined hourly cost for a PBF machine and operator can become the largest portion of a PBF part cost.

Costs may be divided into costs related to the part and costs related to the build (that may comprise of many parts). This division makes it possible to see cost build up between different PBF machines but also see the effects of cost in a series production perspective where the build chamber would be used at its full capacity in order to reduce per-part cost. Baumers et al. created a cost model for PBF blank parts [45] and compares EBM to
SLM for build cost. For a specific build chamber and powder they found that EBM managed to build the part in 25% of the time of the SLM machine, although the material deposition rate in gram/hour being two times larger for EBM than SLM for that specific powder and part setup. They also state that machine productivity contributes to a large portion of part cost. They used a longer write-off period, lower total machine cost and lower operator wage to create about 60% lower hourly machine cost than paper I suggests. Otherwise, the Baumer model and the model in paper I are similar in how costs are separated and both look at PBF cost from a series production perspective.

When the number of parts needed exceeds the build chamber capacity, a new chamber with the remaining parts is built, and the parts in that build share costs between fewer parts, raising the per-part cost, creating a saw tooth shape cost per part curve as shown by Ruffo et al. [46] where cost per part suddenly jumps up due to cost build up due to a new build chamber being needed.

4.1 Per-build PBF costs

Since many parts may be built at the same time, some costs are shared between all parts built at the same time. Such shared costs include the time to deposit powder, pre-sintering of the powder bed if needed, pump vacuum or flood the build chamber with inert gases and post build cool-down.

Powder is deposited in thin layers (often in the range 20-70µm depending on PBF process and material) and thousands of layers might be needed to build the part. If every layer takes 9-50 seconds to deposit (when pre-sintering is needed the powder deposit times become longer), the powder deposit step in itself could cost several thousand SEK when using an hourly machine cost of approximately 1000 SEK/h as suggested in paper I. EBM machines pre-sinter the powder bed which increases the time spent on depositing powder.

Machine reset costs include start-up time to flood the build chamber with inert gas (Selective Laser Melting) or pump a vacuum and pre-heating the build chamber (Electron Beam Melting). This time may be minutes to some hours. Machine shut-down time includes the time to prepare the part for build chamber removal. For EBM this includes cooling down from an elevated build temperature to one that allows handling. This time may be several hours. The part is removed from the build chamber and the machine is prepared for a new build. If one machine is used for many differ-
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Different powders, a cleaning step which can take between some hours and some days depending on machine, could add significant cost to the part.

Other consumables include inert gas for laser based PBF processes. Even EBM may sometimes consume inert gases to reduce cool-down times.

In the case of EOS, parts are melted onto a build plate of the same material as the part. This induces a need for both cutting off the part from the build plate by saw or wire Electrical Discharge Machining (EDM) and then milling the build plate flat which reduces the thickness thus consuming a part of it. Build plates in Titanium cost several thousand SEK and need to be replaced after a number of reuses.

4.2 Per-part PBF costs

The per-part cost typically includes material costs, print time per part costs and post processing costs.

Powder costs differ between materials and quality. Some PBF vendors sell powders themselves which when used with recommended process parameters ensures “good” builds. Powder may however be bought from other suppliers, but the time and effort to qualify them for actual use in an industrial environment may be large. Different powders are also melted at different speeds and may need different layer thicknesses. Non melted powder is reused a number of times to reduce material costs.

Different process parameters may be employed on different places on the part. Surfaces of a part may have different process parameters than the inside of a part. Two parts with the same volume, but with different surface to volume ratio and differently shaped, will thus not take the exact same time to print. During a build time simulation, this shape aspect is taken into account to accurately predict the build time. When shapes are somewhat similar, like some of those investigated in paper I, melt speeds are more comparable and possible to use in an experience and volume based cost prediction model as suggested in paper II.

A build time simulation includes reading the sliced dataset and analyzing how long it would take to actually build the parts within the build chamber. This task requires PBF build preparation knowledge including part orientation selection and support generation and access to a printer with special software, and in some cases, software licenses for the process parameters for a given material. Some AM build time simulation processes are more automated whilst others require several manual steps to provide accurate build time responses.
Machine costs are typically above one million SEK even for smaller PBF machines, and a medium sized machine like those mentioned in this licentiate thesis that includes support equipment like vacuum cleaners and blasting equipment are closer to ten million SEK. This cost is then written off over some years and depending on usage profile this cost can be treated as an hourly machine cost. This cost is largely affected by the predicted annual usage hours and the depreciation time.

Post processing includes support removal and for EBM blasting off the pre-sintered powder surrounding the part. This is usually done manually by the PBF service provider. It also includes post heat treatment/HIP and post machining which is often needed. Post processing in many cases also includes some sort of machine cutting of the part’s interface and fit surfaces. If machining to specification is not done by the PBF service provider, an additional supplier is needed and both the cost and the manufacturing lead time increases.

Figure 7 summarizes the costs for PBF parts, roughly comparing laser to electron-beam melting. EBM usually has a larger combined per-build cost than the EOS process. In turn, EBM deposits material faster than the EOS process making per-part build times shorter. This difference in cost buildup could favor EBM when parts are larger and bulkier and in series production, whereas the EOS process is better suited for low series production of less bulky parts.
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Figure 7. The figure depicts some differences between SLM and EBM from an approximate cost perspective. Box sizes are not in scale relative to actual costs but reflect general cost differences between laser melting and electron beam melting processes. The former usually melts powder slower and causes build time related per-part costs to be higher than the EBM process. Powder costs are similar or lower for the EBM process. Post processing time due to support removal is usually higher for SLM. The EBM machine takes longer to reset due to pumping of vacuum and cool down post build. It also takes longer to deposit powder due to presintering. These differences in combination usually result in a higher per-build cost for EBM but lower per-part cost.

In order to learn more about how costs were generated for PBF relative to other manufacturing methods with low initial tooling costs like HSM, a case study on eight SBD designed parts with existing cost quotes available was made in order to see what they would cost if built by PBF instead of being milled from blank rods. The model was then used to see what shapes and what materials were closer in cost to the milled part. The paper was presented at the 26th CIRP Design Conference in Stockholm 2016 by the main author.
4.3 How does SLM compare to HSM for series part cost?  
(paper I)

How do part cost and lead time compare when using HSM or PBF? What shapes and materials affect PBF cost? How efficient do PBF machines need to become in order to make them more cost effective than milling from blank rod? Those were the questions that were investigated in paper I.

Paper I compares manufacturing cost of eight real parts from SBD that were designed for milling as a case study. Milling had already been chosen as the manufacturing method. Not necessarily because it was the cheapest method, but for the combined effect of part cost, lead-time, functional requirements and company culture, which together suggested that milling from rod is the best solution. The same parts were cost simulated for PBF manufacturing using an EOS M290 machine in different materials.

Milling costs for the parts existed and were already separated into machining time, material costs and surface treatment costs which made it possible to compare to PBF. For each part a batch size was established based on how many fit within one build chamber so that the per-build costs could be shared among as many parts as possible, reducing the PBF part cost, mimicking series production. Allowance was added to the original geometry to be able to predict milling costs. However, this added material was not used to simulate AM blank build times, in effect reducing the AM blank cost at some extent.

Machine reset time and support removal induced per-part costs were included in the machine hourly cost and derived from an assumption that two operators in co-operation can both prepare the machine for a new build and remove support structures. Their salary costs were added to the PBF machine cost written off over three years and an assumed annual usage time. This created a total hourly machine cost of about 1000 SEK/h. Cost for consumables other than powder were neglected.

Per-part costs could then be generated by build time simulations using licensed process parameters from one part a full batch and compared to HSM in order to see if and when the lines crossed, indicating a possible batch size when PBF or HSM is cheaper. The model also tries to predict cost of post process machining by reusing the Material Removal Rate (MRR) from the cost quotes to calculate removal of the added allowance to certain fit surfaces post printing.

The results were that PBF blank part costs were much higher from one part and upwards than HSM. The largest contributor to part cost was the
Some aspects on designing for metal Powder Bed Fusion printing-time costs due to the low material deposit rates of the EOS M290 machine. If few parts were printed, powder deposit time induced costs per part become large. Smaller PBF parts were closer in cost to HSM, partly because that made it possible to print many at the same time but also tended to have low HSM material removal rates. Switching materials from aluminum to titanium made PBF cost increase relative cutting cost increases of HSM lower, decreasing the cost premium of PBF. When post process machining is needed to meet form requirements was added this effect was reduced. If printing time induced costs were to be reduced by roughly ten times, some parts became cheaper to print than to cut from rod.

The conclusions were that smaller parts which are needed in some volume (so that a build chamber can be fully utilized), makes PBF costs closer to the cost of milling. Also, a material that is tough and hard to cut, such as titanium vs aluminum, show better promise being printed rather than cut from rod blanks when the buy-to-fly ratio (mass of blank divided by mass of finished part after subtractive manufacturing is finished) is large. The paper shows the importance of sharing per-build-chamber costs to reduce per-part cost and if the part needs post process machining, the possible lead time advantage compared to machining from rod may disappear. When recoating time was removed from the total build time, the shape- and material effects on print times were easier to see. Print times in AlSi10Mg were fairly stable for the analyzed parts indicating that it could be possible to use an experience-based melt speed per material in order to faster predict part cost when a part is designed for low mass.

The contribution is the mathematical model and the separation of printing time costs into per-build chamber related (including the powder deposit step) and per-part related (including melting time and powder cost) which makes it possible to better highlight the cost difference between the EBM processes versus the laser melting processes as expanded on in this licentiate thesis, as shown in figure 7. It also gave insight to a cost-prediction model that can be used as a part selection process to find part types favorable for PBF manufacture. This cost prediction model was included as a step in paper II to predict part cost before initiating re-designs for AM efforts.
Figure 8 summarizes the cost-prediction method as an output from paper I. The right track uses a volume based cost prediction that could be used early in a design phase to select manufacturing method for cost.

Figure 8. AM and PBF cost prediction. Dashed lines indicate costs not included in the volume based cost prediction model created as part of paper I.

Figure 9 shows an expansion of how the cost-prediction can support the question of when to design for AM. It uses insights from paper I and paper II to quickly provide an approximate part cost to compare to the business case. Currently, PBF deposits material slowly which creates expensive parts. However, if larger part performance is valued more than lower part cost, the part may currently be warranted for being designed for PBF, firstly by using the capabilities of PBF to improve performance (for example using TO) and then improve manufacturability.
Figure 9. The figure shows an expansion of how to use a cost-prediction model to support when to design for PBF as suggested in paper II for RQ2b. Predicting PBF blank part cost related to build time captures a large portion of the total part cost. The workflow proposes using predicted part costs (derived from an experience-based estimate of melt speed) as a support process to find if a part is suitable for AM design and manufacturing in early design phases.

Two types of designs that use the shape advantage of AM and as such are often connected to AM are Topology Optimization and Lattices. Both these methods may lower a product’s mass, both may create shapes that are advantageous to AM and both methods are beginning to appear as functions in traditional parametric 3D-design tools, making design for AM directly in the CAD tool more available. During this research however, the author applied both these design methods outside the normal mechanical design software tools.
5 DfAM: Topology Optimization and Lattices

This chapter covers a description of design through Topology Optimization and through Lattices. Both these methods are frequently mentioned as ways to improve part performance and being realizable by AM. As TO is an advanced area in itself, the scope of this chapter is not to describe TO in detail, but describe the process capabilities for a mechanical designer to be able to create shapes that are optimal in some aspects. Design by lattices is also described and differences and similarities are described. The end shape result may reduce part volume in addition to creating an advanced shape that might give PBF a manufacturing advantage relative to traditional manufacturing.

Paper II shows how these two design methods were applied to a SBD part to reduce part volume as much as possible and to see what effect that had on part cost. The results from Paper II highlights the importance of knowing the value of increased performance in order to decide if the possible cost increase is motivated. The work was performed during 2nd half of 2015 to 1st quarter of 2016 as a response to RQ3.

Improving product performance is usually product specific and/or company specific. Values like lightweight design are of interest in many products to improve performance (win the race), improve efficiency (consume less fuel during the life span of the product) or to lower cost (less material use).

Design for PBF can be easy or difficult depending on the designer’s experience, product requirements and the type of industry the design is made for. Companies with products and customers that value increased performance, perhaps due to lower product mass needing less fuel over a long product lifespan, are more likely to find use of PBF even if part cost is increased relative traditionally manufactured parts.

Design for lower product mass is a common and cross-industries design goal. Lower mass improves performance and may reduce fuel consumption during the products lifespan, reducing operational costs for the customer. It could also lower part costs due to lower print times and reduced powder and energy needs. The part volume and part height (as derived from a PBF build direction selection process) are two important inputs to make PBF part cost predictions [paper I].

Two ways where DfAM can create a shape advantage (defined as a part shape that cannot be realized by other manufacturing methods at a lower
cost or at all) for AM are Topology Optimized shapes and lattice design. These two ways of designing were explored for mass reduction and effect on part cost in paper II. In this paper, the shaping of parts by TO was called a process-based design method whereas shaping by Lattices were called designer-based processes. They differ in the type of input needed to start the process. TO needs more precise input in order to start shaping a result that is some sort of optimal solution. Lattice design is similar to traditional mechanical design in that shaping is done by direct human input. Lattice patterns are designed or selected, intersected or cut with some designer-driven shape to create a less dense, high-surface-derivative part.

Design by lattices or topology optimization to lower product mass are currently mostly done outside the Computer Aided Design (CAD) domain and outside the mathematically exact surface domain although they are beginning to appear as functions in traditional commercial CAD tools. Finite Element Analysis (FEA) which is used to calculate stresses within 3D CAD models when loads and boundary conditions are applied live in the triangle-domain, as do current PBF build preparation tools like Magics.

In a workflow that combines the design domain (where geometry is often defined by exact surfaces) with a triangle-based domain (including PBF build preparation and FEA), work begins by defining a simple and exact shape, often by designing a maximum allowed volume and interface volumes. This data is then sent to other design tools that are capable of further reducing part volume by the use of design methods that work in a triangle based domain. Finally, the part can be sent directly to manufacture without converting triangles back to exact surfaces as AM uses the same triangle-based method to describe a part’s shape as TO and lattices do.

Figure 10 shows an expansion and some examples of process-driven shaping and designer-driven shaping methods. The process-driven shaping processes define a set of rules or equations that may change or create a shape that fulfils certain requirements. Designer-driven shapes consist, in this breakdown, of traditional design for manufacturing methods where a mechanical designer’s knowledge about a chosen manufacturing method affect design choices resulting in a solution that trades-off performance versus cost. In this breakdown, TO is a subset of Simulation Based Design which is a subset of a type of Generative Design which can be defined as a “form finding design method”. 3D fractal based algorithms can create
advanced shapes using a mathematical framework (for example Mandelbulb 3D) with low effort and they are possible to manufacture using PBF. Optimized Lattices is the process where parts of the lattice dimensions are driven from FEA calculations. Scan, modify and print is the process where a physical part is scanned and a copy can be printed with no need for re-engineering to translate the point cloud result to a mathematically accurate surface, reducing lead time and engineering costs. Designer driven shapes are here exemplified here with Design for Manufacture (DFM) and examples of DfAM methods are given.

Figure 10. Process driven shaping may not only consist of simulation based design methods like TO but also other rule or math based shaping processes. 3D fractal design is one example of a rule driven shaping process that can create abstract shapes that could be challenging for traditional manufacturing to realize. Designer driven shaping is here exemplified here with typical Design for Manufacturing (DFM) methods. Here, knowledge about manufacturing inside the mind of the mechanical designer creates a design solution that both fulfills requirements and is possible to manufacture. Dashed lines indicate that these methods have not been studied as a part of research in this licentiate thesis.
Figure 11 illustrates the main difference between designer driven shapes and process driven shapes where the former need less structured and exact information to produce a possible result and the latter needs more exact input to produce an optimal solution to that specific problem.

5.1 Topology Optimization

Topology optimization is a finite element analysis (FEA) based process where a part is iteratively modified by removing material that is not needed to carry the applied loads to meet the required design margin or requirement and to fulfill a specified optimization goal. Usual optimization goals are to reduce mass or optimize stiffness given a maximum allowed volume and a load set. Inputs to the process are usually boundary conditions (external loads, optimization criteria) and some sort of geometry. The geometry is often divided into a design space and an interface space.

The design space is the largest allowable volume for the part and may be changed by the iterative solver process. The interface spaces are volumes that may not be changed as they serve as interfaces to other parts in
the product and the external loads are often applied on these volumes. An optimization criterion is set, often being to reduce mass or optimize stiffness for a certain volume reduction goal.

Sometimes, additional constraints may be defined to simulate certain characteristics of a preferred manufacturing solution. This creates a combined optimization goal that can create optimal solutions for a specific manufacturing method. For AM, such research is on-going [47-51] and may appear in commercial codes so that mechanical engineers can use them to develop parts optimized for function and PBF manufacturability at the same time.

This licentiate thesis however does not cover all the aspects of TO but only its use as a design method to create abstract, optimal shapes motivating PBF manufacturing even though it might be costlier. A general understanding from the student on how TO codes might work to find a geometric solution to the loads and additive manufacturing constraints follows. When competing design goals exist, a trade-off is needed. Such trade-offs can be made by designers or manufacturing engineers based on experience. If the manufacturing method can be described as some sort of function that shapes geometry, it can be added to the FEA-code to create a combined design goal together with the FEA-based algorithms. In this case, additive manufacturability aspects may be called penalty functions for the optimal functional solution. As an example, a goal can be to reduce design space volume with 30% but also, create less than 5% of design space volume as support structures. This effectively reduces the solution space in order to improve additive manufacturability; more of the material is spent on building the end-part and less material is used to build supports. These competing goals usually create a design space solution that is not of the lowest possible mass, neither is it optimal for manufacturing, but it is optimal from a compromised view where some sort of weighting of the different design goal seeking algorithms has been done.

Design by lattices also begins by defining a design space that then has its volume reduced by replacing the solid volume with a repeating pattern of a small unit cell of less dense structures. The size of the struts of all or individual lattices may be selected by a designer or in some cases be determined by a TO process.

Figure 12 visualizes the idea of letting the optimal non-manufacturability-constrained solution of a certain load case and resulting design space volume ($m_1$) as it is competing against algorithms that shapes the part to be more self-supporting and need less supports during PBF
build. As supports are created depending on overhang distance and angle to the build direction, and material properties also vary according to build direction, the results are valid for a given build direction. Note that the penalty functions to describe the PBF process effects on the allowed design space solution are only suggested to exemplify how they could be described to mimic an additive manufacturing process.

Figure 12. The figure illustrates a combination of TO and additive manufacturability optimization from the authors understanding of it. The optimal solution from functional perspective generates mass $m_1$. The best solution from manufacturing point of view generates mass $m_2$. From a mathematical description of the PBF process with regard to material properties as a function of build direction, lowest allowable wall thickness and how supports are generated due to overhang distances and angles relative the build direction (“penalty” functions), a compromised solution may be derived by the TO algorithm. The end result is possible to manufacture using the PBF process at the expense of larger mass $m_3$ relative the lowest possible.

5.2 Lattice design

Lattice design is a designer-driven process where a part of the design space is intersected or cut with a repeating and conforming pattern of smaller strut-like structures that could provide better stiffness/mass ratio than a solid part would. Lattice patterns use less material than a solid representation of the same design space and may thus cost less to print which makes it a possible way of improving manufacturability and to lower series part cost. Due to the complex shape that lattices create, a faster in-plane moving energy source like that of EBM together with optimized process parameters could lower print cost even further relative a solid part.

Many PBF build preparation tools contain such design tools with different functionality. Commercial codes exist (for example Autodesk’s Within, nTopotology’s Element or Meshify Pro) that structurally analyze the selected
lattice pattern and dimensions for stresses when an external load is applied. A user selects a lattice pattern with a certain instancing distance and truss shape. The truss dimensions (or cross section of the trusses) are then individually optimized according to stresses and varied across the pattern, possibly reducing mass further. Areas with large stress become (almost) solid as the truss cross section area needs to be large. Areas with low stress will still have a basic lattice structure in place that can make the part self-supporting in a given build direction and PBF process, and possibly more robust.

Lattice designs can be used as lightweight structures within a part as shown by Schmelzle et al. [15] or combined with TO designs as done by Richards et al. in [18]. The lattice pattern can then replace the support structure and increase robustness against overloading of the final part. Depending on the geometric shape of the lattice, it might or might not be self-supporting using all PBF processes and materials. PBF build preparations for the specific process and material would reveal if that is the case.

These two design methods, TO and lattices, were applied in a case study on a cast magnesium part designed at SBD and compared to the original design for cost and mass and was presented at the 26th CIRP Design Conference in Stockholm 2016 by the main author.

### 5.3 Design for PBF using TO and lattices to reduce part mass and the effect of part cost (paper II)

Paper II shows a product-centric case study of a redesign for PBF of a beam attached to the ground equipment of a missile system. The original design was developed during the 1970’s in cast magnesium to be both light (since the system is man portable) and cheap to mass produce. Saab Dynamics missile products have rather low series production quantities due to complexity and cost of the systems. However, the products are manufactured for decades, creating a substantial total production volume until the product is taken off the market. This creates a need to trade-off cost vs performance, with more emphasis on cost than for example satellites and race cars. How much can mass be reduced and how is cost affected by using DfAM methods such as lattice design and topology optimization? That was the research question that was studied in paper II.

Lattice design and topology optimization methods were used to redesign a beam originally manufactured by cast magnesium to instead be manufactured using PBF in aluminum AlSi10Mg. Lattice design was categorized as a designer-driven shape to highlight the difference in the shap-
ing process from that of Topology Optimization which was categorized as process-driven. Lattice type was chosen so that the part could be built with reduced need for internal support structures to improve additive manufacturability. TO was used to create the lowest possible beam mass.

The result was a volume reduction for the TO based design, however the increase in material density made the end result similar in mass. Also, the TO part generated significant support structure needs during build that would add to the post processing cost. The lattice design did not reduce part mass due to material density increase but also because the chosen lattice pattern was too dense and the design tool lacked functionality to improve the lattice pattern further. The cost of the PBF design exceeded 30x of the original design when cost-analyzed for AlSi10Mg manufacturing in an EOS M290 with default process parameters. However more importantly, the cost increase could not be compared to any acceptable cost increase due to better performance. This contributed to the fact that the part did not go through to manufacture, requalification and series production. Results for this part showed that it might be difficult to reduce the mass of parts that already are designed for low mass and use a less dense material than those currently available in powder form. The original part was designed for a combination of low mass and low part cost since it is a part of a man portable product manufactured in medium series volume. The results also show that the cost reduction due to further volume reduction was diminishing due to the per-build related costs.

The conclusions are that it is possible to take advantage of process-based designs to create complex, hard-to-predict shapes, especially for non-symmetric load cases and design spaces in hardware using PBF. Designer-driven part shaping through lattices as a step of the PBF build preparation process is an efficient way of reducing the volume of otherwise bulky design spaces. However, the way lattices conform to the actual part shape and type of lattices and dimensions available are largely dependent on the software capabilities and were lacking in this case. Designing lattices in the CAD design tool using traditional patterning techniques proved a challenge with large geometry file sizes and long rebuild times. When the knowledge of customer value is missing or hard to predict or when requalification costs are high, the difficulty to change manufacturing method for an existing part increases. This indicates it is important to select PBF early in the design phase when designing new parts.

Contributions of the paper include the combination of mass and cost comparisons to an existing unique non-PBF design. It also contributed by
the categorization of design methods into process-driven and designer-driven shapes with some differences and similarities. Finally it suggested a workflow beginning with predicting part cost (using insights from paper I) of a predicted mass reduction of an existing part before doing the actual optimization work, in order to better select parts that are to be redesigned for PBF as expanded on in this licentiate thesis in figure 9.
6 Design and Additive Manufacturing accuracies

This chapter explains how some dimensional errors and form errors may appear in PBF parts. Traditional manufacturing often reuse an exact mathematical description of a part’s shape but AM currently approximates the part surfaces by using triangles by a process called tessellation. This creates an initial deviation between the design- and manufacturing representation of the geometry that is then added to by manufacturing tolerances. Depending on form requirements, the finished PBF part may then not fulfil geometrical requirements due to tessellation effects.

Paper III presents a comparison of tessellation capabilities from six different CAD tools and three different geometries and proposes a way of using exact data and form requirements as a bridge from design to PBF manufacturing to reduce form errors.

The work was performed during 2015 as a response to RQ4.

6.1 Design Domain, accuracy and errors

Mechanical designs are commonly created in 3D CAD software. The output from the designer-based shaping process is a solid model, capable of describing both the Boolean operations and in which order they are needed to produce the final part and, in addition, the exact mathematical volume definition of the end result. Many CAD programs use a data model to describe the resulting models mathematically exactly. In many cases, a drawing is created with the 3D-model as an associative reference which carries tolerance information. Tolerances of both form and dimension, often referred to as Geometric Dimension and Tolerance (GD&T), are used to describe within which limits a manufactured part needs to fall in order to be valid. Tolerances are also used by the mechanical designer to validate that parts will fit during assembly, enabling parts to be replaced during service and maintenance for example.

Errors in the design data are usually only due to designer error. When manufacturing is done by a supplier, it is common to export the source CAD data to some standardized format which is sent to the supplier for planning and manufacturing. Errors may occur in this step, either due to capabilities of the sending and/or receiving geometry translators, but also from differences in capabilities of the actual file format being used.
6.2 Manufacturing Domain, accuracy and errors

Different manufacturing methods have different capabilities of fulfilling dimension and form tolerances. Parts reaching series production tend to be designed for a specific manufacturing method and as such the final design is shaped from a mix of customer requirements, strength requirements, sometimes regulatory requirements and manufacturing requirements to name a few. Milling for example is capable of very high accuracy and fine tolerances with fine surface finishes whereas sand-casting typically gives lower dimensional- and form accuracy and higher surface roughness. Manufacturing using milling typically use the 3D-model as input to plan tool paths. The actual cutting operation then removes material from the work piece until the part is finished. This operation is never exact as positional errors of the cutting tool, tool wear, vibrations, work piece movement and other deviations may occur during manufacturing, slightly differently each time. As-manufactured part dimensions thus vary slightly from the exact, as-designed dimension.

A PBF manufactured part will also deviate from the information sent to the machine. Positional errors of the energy beam as it travels across the powder, is one possible source of errors. Tolerance capabilities of a specific PBF process are usually specified by the machine supplier material data sheets [31 for example] and also depend on which powder types and powder sizes are used. Other deviations can arise from insufficient bonding of powder particles and lack of fusion causing voids pores or even cracks. Larger dimensional deviations may occur from part warping due to the fast cooling of the part during build or from part swelling due to overheating of areas of the part during build. These errors are not included in the machine vendor specification and have to be solved before series production using PBF begins. Such errors could also be the source of significantly larger dimensional inaccuracies than those stated by the PBF machine manufacturer.

Manufacturing errors may also be due to geometry translation errors. These may even appear if different versions of the same CAD tool are used, but are more common when translating geometry between different systems. Some errors can easily be detected such as if a model is not a solid volume, whereas others might not be. When converting a model from an exact, mathematical definition to a triangle-based, approximate definition as used for AM, the model can still be used as solid definition in the AM domain, but the surfaces that create the boundaries of the solid
part are created by the sides of a triangle, adding dimensional errors already in the input data.

6.3 Geometry formats for manufacturing

3D file formats can be divided into exact and approximate types. Standardized geometry data formats capable of exporting exact geometry data are for example the Initial Graphics Exchange Specification (IGES) or Standard for The Exchange of Product (STEP, ISO 10303-21) with the latter being the most commonly used today for almost all types of manufacturing. These formats typically carry other types of engineering metadata that may be used in downstream applications. Both IGES and STEP carry the unit of measure to specify if the data points inside the file are in mm or inch. The STEP file format is capable of using Non-Uniform Rational B-Splines (NURBS) as a mathematical way to describe part surfaces exactly.

Additive manufacturing however uses an approximate data model to describe the 3D-model which is used to plan PBF tool paths in the PBF build preparation tool. Software tools such as Magics and Netfabb, commonly used for PBF build preparation do read exact geometry representations, however the results are immediately at import converted to a facet-ed, triangle-based dataset based on a user specified accuracy setting. The process where a collection of triangles creates an approximate description of the surface of an exact 3D-model is called tessellation.

6.3.1 Tessellation

Tessellation takes place when, for example, a mechanical designer exports some part’s geometry to be additively manufactured. Tessellation is a process performed by the CAD software that creates triangles along the outer surfaces of a part’s geometry. Often, user modifiable settings allow the creation of more triangles or fewer. Some tools allow specification of a maximum edge length which results in a drastically increased file size since it in addition restricts how large the triangle edge length can be. Most of the time, a larger set of triangles creates a better approximation of the exact surface.

Tessellation also takes place during the display of 3D-data on computer screens as a process in the graphics display driver. Many CAD tools can modify the display accuracy in ways similar to exporting data to AM. It may however give the impression that all 3D-data is approximate since round shapes may look like a hexagon or even a cube when displayed.
However, the mathematical description in the 3D-model is unchanged regardless of display accuracy.

The tessellated data when exported to a file is stored in a binary or ASCII based format where the latter may be very large in size. It is not uncommon for an approximate tessellated representation of a given geometry to have a larger files size than a mathematically exact representation of the same geometry. Since the triangles may be planar only, the accuracy cannot be further improved by dividing the triangles into more triangles; the curvature information is lost in translation.

One possibility of increased accuracy of triangle based geometry formats is to use curved patches or slicing source data directly [52-55]. Curved triangles can carry more curvature information and allow for subdividing an initially lower number of triangles into more triangles, providing better accuracy. The subdivision could then be located to the slicing step; keeping data load low during interactive use, and grow as needed during the computationally intensive slicing process. The XML structure within the AMF file has allocated space for this type of geometry definition.

Figure 13 shows the principle of tessellation on a tube and cube primitive. The curved circular edge of the top view tube and the corresponding side surfaces will be approximated data that may be perceived as manufacturing errors. The cube however can be exactly described by a subset of very few planar triangles. However if a max edge length smaller than the cube side length had been specified, the cubes planar surfaces would be accurately described with an unnecessary large number of triangles. The user cannot control the tessellation algorithm other than a few metrics, making it dissimilar from for example FEA meshing tools which often allows user specification on certain areas with need for shorter edge lengths.
Some aspects on designing for metal Powder Bed Fusion

6.3.2 Additive Manufacturing file formats

Stereo Lithography or Standard Tessellating Language (STL) is currently the most common AM file format. The STL file does not carry the unit of measure adding ambiguity. Some AM build preparation tools try to counter this effect by either asking the operator which unit of measure the file is in, or by warning the operator that the part is seemingly very small or large, and perhaps a switch between inches and mm is in place. In which unit the CAD tool exports STL data was included in the study presented in paper III.

Translation from NURBS to STL can be done by most CAD tools but also in some AM build preparation tools such as Netfabb or Magics. The STL file format uses planar triangles to define a solid part. Three points create three vectors and by using a right-hand-rule order, a material side is derived. Curved surfaces are thus approximated during tessellation whereas planar surfaces can still be exact in the part data definition. Lipson showed that using curved triangular patches makes it possible to reduce chord deviation errors [56].

Figure 13. Tessellations of curved surfaces create an approximation of the exact underlying surfaces. Tessellation of planar surfaces with non-curved edges may however be described exactly.
Other AM formats have begun to appear. They are however still based on the same principle of approximating the exact shape using triangles. The Additive Manufacturing Format (AMF) ISO/ASTM 52915:2013 [57] is a new additive manufacturing file format currently under development. It allows for curved triangle patches that can increase geometric accuracy by sub-tessellation. It also has data structures to allow different materials and different densities in the same part [58].

AM currently uses an approximate data definition as input to the build preparation process. This creates an initial deviation between the as-designed data in the design domain and the as-manufactured data sent to manufacturing. How to improve geometric accuracy was therefore investigated and presented at the 26th CIRP Design Conference 2016 in Stockholm by the main author.

6.4 Improving geometric accuracy of AM geometry translations (paper III)

How to improve geometric accuracy and reduce an initial error in the design data caused by tessellation, before manufacturing inaccuracies are added, was researched in paper III.

Three different geometries were used in a case study of how different CAD tools export tessellated and approximate geometry definitions. An initial form requirement was assumed based on experience from similar parts and the effect on that form requirement from tessellation errors was investigated. A manufacturing error derived from PBF vendor data sheets was added on top of this translation accuracy induced error and compared to the requirement. Six different CAD tools were used to translate the same geometries to STL using different accuracy settings. The tessellation results were then compared to those from the PBF build preparation tool used at a PBF service provider.

The result of the study was to propose a method to use the same geometry export for AM as for traditional manufacturing; an exact NURBS-based standardized dataset in combination with dimensional and form requirements, and let the AM service provider select an appropriate tessellation accuracy. The method of combining a nominal 3D model with form requirements is not new. It is currently used for many types of traditional manufacturing. In addition, it was shown that the PBF build preparation tool used (Magics), indeed tessellates STEP data very accurately (shorter triangle edge lengths were possible) and has more tessellation accuracy settings than most CAD software’s to increase accuracy even further. The
industrial benefit was immediate as the PBF service provider procured a STEP license for Magics and now does all translations using tessellation accuracies that they select themselves, keeping file sizes low and geometry exact during data exchange from design to manufacturing.

There are cases when STEP cannot be used to transfer data from design to manufacturing, like online 3d printer shops (mainly using plastic materials) that currently tend to only read tessellated data. If the design contains a mix of NURBS data and triangles, like in the case of lattices or TO, using STEP can currently be a challenge. Otherwise using accurate STEP data plus form requirements is the recommended way to transfer design data to AM today, especially for parts in series production using metal PBF processes.

The contributions were mainly the suggestion to use exact geometry plus form requirements as an interface to additive manufacturing. It also contributed by showing that visible facets in hardware (created by a low accuracy translation using one of the CAD software’s most accurate setting) disappeared when using the shorter facet edge lengths that Magics could provide. At 0.5mm edge lengths (as created by Magics when tessellating the STEP file) the facets disappeared into the parts general surface roughness when manufactured using an EOS M290 in steel powder.
7 Geometric verification

This chapter briefly covers the topic of Non Destructive Evaluation (NDE) specifically using the Computer Tomography (CT) method. From an industry point of view the author of this licentiate thesis realizes the importance of knowing that actual dimensions and material solidity are fulfilled, especially for optimized parts. However, NDE methods are not the author’s area of expertise and the chapter is therefore short in comparison to previous chapters and the chapter only contains a brief explanation of the Computer Tomography NDE method capabilities.

A PBF part was designed with existing defects and manufactured in AlSi10Mg and three different NDE methods were used to possibly detect and measure the size of these defects. Results from the study are presented in paper IV. The author’s contribution for this research question was the design of two the test components with defects, one including the addition of lattices. The design work was performed during 1st half of 2015, manufacturing of component design was done in the 3rd quarter of 2015 and defect detection experiments were performed late 2015 and early 2016. The chapter serves to investigate RQ5.

Parts optimized for low volume/mass in order to improve performance and efficiency, and also reduce part cost, have a lower tolerance for dimensional inaccuracies and thus might need 100% dimensional accuracy testing prior use. Methods that evaluate part performance for certain requirements without destroying the tested part are called Non Destructive Evaluation (NDE) or Non Destructive Testing (NDT). Such methods are for example Eddy current testing, liquid penetrant testing, radiographic and optical testing methods. In radiographic testing, x-rays or gamma rays may be used to penetrate into the material, detecting anomalies inside or dimensionally certify internally located features of a part.

Computer Tomography (CT) is a method where a series of x-ray images are taken while the investigated part is rotated within a machine enclosure [6]. Depending on among others, energy levels of the x-ray, material type and thickness and distance between the investigated object and the energy source, an accuracy level is achieved. The images can then be processed using special software and represented as a 3D-object defined by voxels. A voxel is a tessellated volume definition, somewhat similar to a FEA mesh, which describes the actual volume inside the part in addition to its surface. This makes CT particularly suitable for AM parts as these, similar to cast
parts, may contain small internal voids or areas with lack of fusion, or even intended internal voids.

PBF is capable of creating advanced internal shapes like lattice frameworks or internal, conforming channels to improve heat transfer. How can one geometrically certify internal non-visible structures? What methods are available and how do they compare to each other? Can small defects that might appear during the build process (for example due to lack of fusion) be detected? Those questions gave rise to Paper IV where the author’s contribution to that paper was the design of the tested component and providing datasets for computational comparisons. The paper was presented at the PM2016 conference by the main author.

7.1 Non-destructive evaluation of internal defects in additive manufactured parts (paper IV)

A component with internal defects was designed and manufactured by an EOS M290 machine in AlSi10Mg in both solid and latticed variants. Some surfaces were machined to allow three different types of NDE investigation; CT, electromagnetic inductive inspection using Eddy current and ultrasonic inspection. The differences in black/white contrast in the 2D-images were analyzed by special software to deduce material thickness and where the outer surfaces of the part reside using CT. A 3D model of the part was then created during post processing by using voxels. The two other methods created 2D-images only. The test part was modelled with internal defects designed as several vertical, part-internal slots from 0.1 to 0.4mm width, trying to simulate a part where material failed to fuse during printing and to see at what dimension the defects were detectable.

The results were that CT scanning using 80µm voxel size for scans of the complete sample and 27µm voxel size for more detailed scans managed to visually detect defects down to 0.1mm in both solid and latticed designs. However, computer aided defect detection algorithms could not be used in the lattice case since a broken lattice was not automatically identified as a defect. A nominal vs. printed comparison could eventually be used to indicate such build defects. The size of defects that can be detected depends on the CT apparatus and the part size. Since scanning creates voxels, a large part scanned in high resolution creates very large datasets with a large, but manageable, impact on computer performance in regards to memory use and visualization performance. Ultrasonic inspection detected defects in the solid specimen however with lower visual clarity than CT. In the specimen with network structures defects, ultrasonic
inspection did not find any defects. Eddy current did not manage to find defects in any of the two types of test parts. This indicates that CT scanning, although slower, can achieve more accurate defect detection particularly for smaller, complexly shaped parts.

Contributions included the finding that pre-designed internal lattice defects could not be detected by software defect algorithms but hinted on by using actual-nominal comparisons in the same software, and that CT scanning was the only method capable of detecting defects in advanced shaped parts.
8 Challenges

This chapter summarizes challenges in the area of AM as identified in literature. It is complemented by the authors own views on challenges for designing for AM and PBF in particular as a result from doing mechanical design work for 20 years at SBD.

The work was done late 2016 and serves as summary of areas of possible future research.

Challenges for AM have been researched [59-61] from where the following points are selected as they are especially agreed upon by the author of this licentiate thesis;

- Build preparation tools need to increase first build success rates. Today, success is heavily dependent on the PBF service provider’s experience. In addition, fast analyses of heat transfer are needed to guide the PBF service provider in the placement of heat-conducting supports and to avoid swelling (EBM) or cracking (SLM) as well as to predict build chamber cool down for hot PBF processes.

- Modelling tools and processes for early conceptual design need to improve to make advanced/bio-inspired shaping easier to use and analyze parts for stresses. Also, CAD software need to be able to handle tessellated data so that TO and lattice designs can be handled or created directly in the main CAD tool. Although this is beginning to happen, it is far from widely used and not taught at traditional CAD training classes. The visualization of support structure is a function that needs, together with a user selected build direction, to be implemented directly into CAD software.

- Development of industry standards for powders, product documentation, file format etc. are needed so that engineering datasets can refer to them instead of making proprietary ones

8.1 Design Challenges (from the author’s point of view)

Designing complex shapes is challenging. There must be a reason to design complex shapes instead of simple ones. The performance advantage a complex shape brings to the customer must be quantifiable and justifiable. But even when those criteria are fulfilled, creating a complex, perhaps bio-
inspired TO shape using traditional CAD modelling tools is not easy. Most 3D CAD courses at university or from the CAD vendors only cover basic 3D modelling coupled with assembly design and drawing generation. Most mechanical designers have the knowledge and skill-set to create parts using those three basic functions.

Most minds have a limited ability to visualize a complex shape directly without doing some shaping either by creating a 3D physical model or by 3D CAD. Orthogonally placed sketch planes usually start such a design process, and commands like extrude or revolve are commonly used and may be argued to mimic traditional manufacturing methods like milling or turning. The statement “designers need to break free from the chains of traditional manufacturing and design more freely” as a way to increase AM adoption is thus only partly correct. Even if a designer works in an industry which can motivate high-cost part manufacturing using AM so that knowledge of traditional design for manufacturability would be less needed, there still is a challenge in directly visualizing AM-“favorable” shapes. If such a shape can be visualized, perhaps by looking at parts from an AM machine manufacturer’s part display case, the actual reverse engineering task by making 3D models that look similar requires more advanced modelling tools than most designers are aware of.

Design methods using lattices and designer oriented TO tools are beginning to appear directly in CAD tools, making it possible to create the complete design in one tool and in one dataset. However, most designs are documented by the use of 2D drawings, and if a part has a complex, curved shape with no apparent orthogonal views, or if it is created by the use of thousands of repeating small features in a lattice pattern, drawing creation will be challenging. Form requirements and dimensional tolerances are likely to be more important for serially produced AM parts once they leave the prototype stage where product documentation and tolerances might be of less importance.

Traditional designer skill-sets include design-for-manufacturability whereas optimization for strength is typically analytic, FEA-based skill-sets. In order to iterate design and design optimization as closely as design/manufacture is done today, the designer probably needs to have additional skills and additional software support in the design tools. Industries that develop products that are regulated such as aircraft, nuclear power plants or products where product tests are very expensive, tend to have skills and procedures to collect and use mechanical loads to analytically support the design process. Knowing FEA and loads are prerequisites to
do TO and knowing the correct loads is as important for TO shaping as 3D modelling skills for a mechanical designer. Some industries simply do not have the organization or engineering staff to start using TO even as a way to inspire a designer of the end shape of a loaded component destined for mass production. If a product can be easily tested, if it is hard to describe the physical condition in mathematical form that can help shape the part, a designer that knows traditional manufacturing will probably be faster at doing test-based design iterations and evaluations than trying to use process-based shaping methods. Design using lattices is mostly related to increased data complexity, as creating patterns of features is a standard 3D modelling skill.
9 Summary

This chapter summarizes this licentiate thesis and research questions. Research question RQ1 and RQ1b are answered through a literature survey and was presented in chapter 3 of this licentiate thesis. RQ2 was explained in chapter 4 of this licentiate thesis and studied in paper I. During studies of RQ3 as shown in chapter 5, a combination of research for RQ2 and RQ3 was presented in paper II as a way to use cost-prediction to answer when to design for AM (RQ2b). RQ4 was presented in chapter 6 of this licentiate thesis and in paper III. Finally RQ5 was described shortly in chapter 7 and in paper IV.

9.1 When and how design for AM? [RQ1]

A literature review performed by the author shows that some knowledge exists on when to design for AM. These methods try to identify shape and material advantages that AM provides over traditional manufacturing. Knowledge about when to design for PBF also exists inside companies that are using PBF today.

Improving performance is a good way to motivate the usually high part cost. Lowering product mass is a goal in many industries and for many PBF products this might also include lower part cost. Another method to improve performance is the use of conforming channels to improve heat transfer and this design task is usually done by a designer-driven shape. This might be a good way to find parts suitable for PBF design and manufacturing.

9.1.1 How to improve PBF manufacturability? [RQ1b]

Looking into how to improve manufacturability it is clear that a lot of research exists. In this licentiate thesis, research regarding material properties and shape capabilities of EBM and SLM are included under the chapter of improving manufacturability. As a rough summary, material properties are thoroughly investigated in literature and create a large database of information that can complement the PBF vendor data sheets, ready to use for the design for PBF parts. Shape capabilities of PBF processes have also been researched and for SLM several shape studies serve to explain the topological effects PBF manufacturing has on build possibilities. Some, but not all, build capabilities from literature are also captured during a PBD build preparation.
Design for improved additive manufacturability is partly guided from a chosen build direction. An initial build preparation and cooperation between an experienced PBF service provider and a designer with knowledge about what aspects of part shape may be changed to improve manufacturability while still maintaining part functionality, will in many cases provide many design insights in preparation for series production.

Using chapter 3 in addition to talking to a PBF service provider creates a good knowledge foundation on which further design studies can be done. How to design for AM from manufacturability point of view is as such covered to an extent that it shouldn’t hinder a mechanical designer from improving manufacturability of PBF parts. However, part cost could be a problem for some industries, and a low tolerance for deviations in mass properties might be difficult for others.

Figure 14 shows an expansion of the idea of process-driven shaping vs designer driven shape as described in chapter 5 and paper II. It maps process type to the design intent to improve performance or reduce part cost. Some of the different DfAM methods that have been explained in this licentiate thesis are then inserted and examples of software and methods are given.
Figure 14. Different design for AM/PBF methods are divided into improve function/improve manufacturability and designer-driven/process-driven shaping. Some design methods are currently performed inside traditional CAD tools, some are done in TO tools (ex: Altair’s Optistruct or SolidThinking’s Inspire) and some inside AM build preparation tools (Materialise Magics and Autodesk Netfabb). Dashed lines indicate currently missing functionality. However, many CAD tools are beginning to provide both TO and lattice design methods internally.

9.2 How does SLM compare to HSM for series part cost? [RQ2]

PBF part blank costs can be quoted very accurately by experienced PBF service providers given a 3D-model and an amount of parts needed in a specific material. A better understanding of what drives PBF part costs can provide the mechanical designer with information on when to design for PBF. PBF part cost can be divided into costs shared between parts during the same build, and costs for a single part.

Some of the costs, divided into per-build and per-part costs were described in chapter 4. A large contributor to PBF part cost is a low material
deposition rate in combination with it being done in an expensive machine. The melt speed in material deposition rate in volume/hour depends on PBF process type, material type but also part shape where parts with the same volume but different shape prints at different speeds. Depositing powder, in many cases several thousand layers, also takes time. Some PBF processes need to pre-sinter the powder before melting increasing per-build time, making build chamber utilization even more important as this time is shared between all parts produced during one build.

Selecting an optimal build direction is a multi-variable trade-off scenario that in many cases takes place in the mind of the PBF service provider with limited software support and automatization.

All this contributes to PBF parts of typical low-mass SBD designs in aluminum is less expensive to machine from rod than to build using PBF. The mathematical cost model created in paper I shows that build speeds or hourly machine costs must be reduced significantly to compete with HSM in aluminum. Further research need to be done to improve the predictive cost model for a combined AM blank plus machining costs and to compare results to real total cost quotes. The AM blank cost is possible to predict using a mean deposition rate to be used to support when to design for AM as suggested in this licentiate thesis and paper II as a response to RQ2b.

9.2.1 How to use SLM cost prediction modelling as a way to support when to design for PBF? [RQ2b]

PBF part cost can be predicted by knowing material cost, part volume, build height, layer thickness, powder deposit time and a mean melt speed for the part. The mean melt speed is usually derived from build time simulation but can be approximated to allow fast, rough cost estimates of a PBF blank part. If coupled with insights from research papers and insights from the case study in paper II (that mass reductions of some amount is possible using TO or lattice design methods) it is possible to make a quick, interface-driven bounding-box like design and predict series part cost if manufactured by PBF. This result can then be compared to other conceptual ideas or existing designs to determine if further time should be invested in a PBF design or not as shown in figure 9.
9.3 What effect on mass and PBF part cost does DfAM through TO and lattices have? [RQ3]

Design for PBF from a performance point of view has been researched in this licentiate thesis mainly by reducing mass using PBF-favorable shapes like lattices and shapes created through topology optimization processes. Process-based shaping or Simulation Based Design like topology optimization is a good way to increase customer value when low mass is favored. Especially when the design space and loads are asymmetric, the end shape may be very hard to predict and hard to manufacture using any other method than PBF. Since this design method improves part performance by making the shape optimal from a certain aspect, a mechanical design team employing this method can motivate why the part is complexly shaped and perhaps only realizable using PBF simply because the analysis says this shape is truly the optimal one.

Lattice design is another way of reducing product mass by replacing solid volumes with a repeating pattern of strut like shapes. The two methods can also be combined, either by firstly defining a lattice pattern and letting TO determine the strut cross section, or by letting TO shape the design space and a designer removes internal volume from the interface spaces by the using lattices as shown in paper II. The separation of design methods into process-driven part shaping and designer-driven shaping as mentioned in paper II were further explained in chapter 5 of this licentiate thesis.

It is not possible to answer RQ3 for all cases since it is very dependent on product, material, requirements and more. Similarities and differences between the TO and lattice design methods were established in the context of an existing part designed for low mass in cast magnesium in paper II. In this specific case, the initial cost increase of going to PBF was substantial and not reduced significantly when the volume of the PBF design was reduced even further. Reasons behind this cost effect are partly explained from research on per-build related costs in RQ2. More importantly, the increase in cost could not be compared to an accepted part cost increase for the improvement of performance the reduced mass contributed to. This contributed to that no parts were manufactured or qualified.
9.4 How to improve geometric accuracy for AM geometry translations? [RQ4]

Manufacturing today often uses a 3D-model as input to manufacturing planning and preparation. The AM process uses a faceted approximation of the often mathematically accurate design description to define part geometry. Exporting design data to current AM file formats is done by specifying some sort of accuracy setting and some information is lost in translation, like the unit of measure and in some aspects all of the mathematically exact geometrical definitions. This was explained in chapter 6.

Converting to a tessellated or faceted data format is done differently in all CAD tools that were tested in paper III where tessellation effects on geometric accuracy and printed appearance were investigated.

Curved triangle patches increase surface accuracy and makes it possible to subdivide triangles improving accuracy further without increasing file size. In many cases, using Magics and selecting a 0.01mm accuracy setting and not specifying any maximum planar triangle edge lengths, creates a fine enough “mesh” that add very small initial geometric errors and allows for facets to disappear within the general surface roughness of the manufactured PBF part.

As a response to RQ4 it is concluded in paper III that using an exact geometry representation like STEP together with the tolerance and form requirements on a drawing (similar to how mechanical design data drives other types of manufacturing) makes it possible for the AM service provider to select an appropriate tessellation accuracy based on geometric requirements, machine accuracy and visual performance during PBF build preparation.
9.5 How to detect defects in AM parts using NDE? [RQ5]

When complex shapes such as those achievable by lattices or TO are designed and manufactured using PBF, the importance of certifying dimensional accuracy and defect existence increases as the margin for errors are reduced as the design becomes more highly optimized. Non-destructive evaluation is commonly used as a way of examining certain aspects of a part without destroying it.

Computer Tomography is one such method combines a series of x-ray images from different angles to create a volume model of a part that can visualize internally located PBF build defects or features. Current limitations of CT are part size, resolution and costs. The part must fit inside the CT machine and commercially available machines with high resolution are currently limited in size. The resolution depends on many different things but generally, smaller parts can be scanned using a higher resolution. CT scanning and post processing into a usable 3D-model for further investigation is a time consuming process in addition to requiring large computer resources. Scanning a part, combining results to a 3D-model and performing analyses on that data may take days, contributing to part cost.

In the results from paper IV and RQ5 it is shown that defects like lack of fusion are best detectable by CT. However, such investigations take considerable time and contribute to a cost that could be on par with the PBF part cost itself.
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