Qualification process development for metal additive manufacturing

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MASTER THESIS

Qualification process development for metal additive manufacturing

A study for the establishment of additive manufacturing at Alfa Laval

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Abstract

The process of additive manufacturing and qualification of components in metal is complex, and the manufacturing method is still not fully understood. Therefore, the purpose of this thesis is to gather knowledge of the qualification procedures connected to additive manufacturing in metal and to develop sustainable qualification for additively manufactured parts at Alfa Laval. The qualification procedures aim to ensure that the additive manufacturing procedures operates and performs as expected. The research was conducted through a literature study and a case study consisting of interviews within the industry and data collection at Alfa Laval.

No general qualification process for additive manufacturing was found in the literature study. Instead, the result showed complex qualification needs for both part and process. The conducted interviews showed that the qualification processes for additive manufacturing within the industry differs between companies. It was also highlighted that additive manufacturing should be considered as any other manufacturing method.

Based on the research, a qualification framework was developed and presented in this thesis. In the concept, there are four steps of qualification required: raw material, equipment, part and process and performance. This general concept was developed into a strategy based on Alfa Laval's interests, concerning qualification based on part criticality. Another strategy regarding product families is also presented. The presented work was validated by feedback from experts within additive manufacturing.

In conclusion, a more standardised approach of qualification and way of working with additive manufacturing would be in order across the industry. Qualification procedures are also involved in product development which demands early involvement of different functions within an organisation.

Keywords: additive manufacturing, qualification process, laser powder bed fusion, metal AM, 3D-printing, qualification of AM

Sammanfattning

Den additiva tillverkningsprocessen och kvalificeringen av komponenter i metall är komplex och tillverkningsmetoden är inte ännu fullständigt förstådd. Syftet med detta examensarbete är därför att förvärva kunskap om kvalificeringsprocesser kopplade till additiv tillverkning i metall och att utveckla en hållbar kvalificering för additivt tillverkade komponenter hos Alfa Laval. Kvalificeringsprocedurerna avser att försäkra att de additiva tillverkningsprocesserna fungerar och utförs som förväntat. Forskningen bestod av en litteraturstudie och en fallstudie uppdelad i intervjuer inom industrin och datainsamling hos Alfa Laval.

Inga generella kvalificeringsprocesser för additiv tillverkning upptäcktes i litteraturstudien. Istället visade det sig finnas komplexa kvalificeringskrav på både komponent och process. Från intervjuerna uppdagades det att kvalificeringsprocesser för additiv tillverkning inom industrin skiljer sig åt mellan företag. Dessutom underströks vikten av att behandla additiv tillverkning likt andra tillverkningsmetoder.

Baserat på forskningen utvecklades och presenterades ett kvalificerings-ramverk i detta examensarbete. I konceptet ställs krav på fyra kvalificeringssteg: råmaterial, utrustning, komponent och process samt prestanda. Det generella konceptet utvecklades till en strategi baserad på Alfa Lavals intressen, avseende kvalificering baserat på komponenters kriticitet. En andra strategi angående produktfamiljer presenterades också. Arbetet som presenterades validerades genom återkoppling från experter inom additiv tillverkning.

Sammanfattningsvis så hade ett mer standardiserat förhållningssätt till kvalificering och arbetssätt inom additiv tillverkning varit till nytta för industrin. Kvalificeringsprocesser är involverade i produktutveckling vilket kräver tidig inblandning av olika funktioner inom en organisation.

Nyckelord: additiv tillverkning, kvalificeringsprocess, laser-pulverbäddsfusion, metall-AM, 3D-printning, kvalificering av AM

Acknowledgments

First, we would like to thank Alfa Laval for the opportunity to take part of their road towards implementing additive manufacturing as a core technology. It has been an adventure, challenging and exiting. Further we would like to thank our supervisor, *Per Gabrielson*, and rest of the AM-team at Alfa Laval, especially *Joakim Öhlin*, *Lindsay Leach* and *Oskar Bruce*, which has provided us with great support.

Secondly, we would like to thank the interviewees for taking part in the study. Without them sharing their knowledge and expertise, this thesis would not have been feasible.

Lastly, we would also like to thank *Axel Nordin*, our supervisor at the Lund University from the department of Design Sciences, for supporting us throughout the project and leading us through unclarities.

Writing this thesis has been challenging, with many lessons learned along the way. The experience and knowledge learned through the process will be valued greatly in the future!

Lund, May 2020

Anna-Klara Svensson and Josefine Bang Laurén

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List of abbreviations & acronyms

Abbreviation/Acronym	
AM	additive manufacturing
AMF	additive manufacturing file format
APQP	advance product quality planning
CAD	computer-aided design
CT	computed tomography
DfAM	design for additive manufacturing
EB-PBF	electron beam powder bed fusion
FE	finite element
FEA	finite element analysis
L-PBF	laser powder bed fusion
NDT	non-destructive testing
PBF	powder bed fusion
PBFT	powder bed fusion techniques
PDCA	plan-do-check-act
STL	stereolithography

1. Introduction

This chapter describes the scope of this thesis including an introduction to the subject, the focus company, the purpose of the thesis, the formulated research questions and the delimitations within the project.

1.1 AM

In additive manufacturing (AM) physical components are built up layer by layer. For every layer, the material is bonded to the previous layer. In contrast to subtractive manufacturing such as milling and sawing where material is removed from a workpiece, the principle of AM is to add material to achieve desired designs of components. (Diegel, Nordin & Motte, 2019)

3D-printing is a more common term for AM. The term is often used for non-commercial usage and AM is rather referring to the technique used in industrial contexts. AM can be divided into several different methods, e.g. binder jetting, directed energy deposition, material extrusion, vat photopolymerization and powder bed fusion (PBF). These methods are based on different principles used for building the components. (Diegel, Nordin & Motte, 2019)

AM can also be categorized by type of feedstock used, polymers or metals are the most commonly used in AM processes (Diegel, Nordin & Motte, 2019). For metal AM the most common feedstock is metallic powder that is fused together. The machines required for fusing metal are expensive and therefore metal AM is suited for the industry rather than the private sector (Yang et al., 2017).

Compared to other manufacturing methods, AM is a relatively new technique. The AM techniques are still under development and lots of research is made in the area (Gibson, Rosen & Stucker, 2015). AM has several advantages in comparison to subtractive manufacturing. First, AM reduces the amount of waste material (Diegel, Nordin & Motte, 2019).

Furthermore, it enables another level of design freedom and complexity in the design of the component. For example, assemblies can be merged and built as one part only and complex geometries such as lattice structures can be manufactured. Another benefit of the design freedom is the possibility to optimize it after desired properties, e.g. to create as lightweight but still strong components as possible (Gibson, Rosen & Stucker, 2015). Additionally, since AM is a manufacturing method that is flexible for changes in the design of the part it enables mass-customization. Every component can be individually adjusted without affecting the manufacturing cost or time. On the other hand, additive manufacturing is considered as an expensive and slow manufacturing method suited for low-volume production (Diegel, Nordin & Motte, 2019).

The benefits of additive manufacturing are utilized in many different applications. For example, the possibility to optimize weight while retaining strength makes AM valuable in the aerospace industry. In the medical industry, the ability to customize every component is of interest. (Diegel, Nordin & Motte, 2019)

1.2 Challenges with qualification of AM

As with any new technology, the maturity of AM is questioned. The understanding for the relationship between processing, microstructure and properties is still under development. There are several other knowledge gaps for AM and it is stated that the AM process chain is less understood than conventional processes. For example, the characteristics of the defects in AM-parts are still being researched, leading to difficulties in defining the needs for inspection. (O'Brien, 2019)

One identified risk with AM is the lack of governing requirements and standards since the knowledge gaps are problematic when developing standards for AM (O'Brien, 2019). Further, the lack of understanding affects the development of qualification procedures for the AM-process which obstruct the adoption of AM in the industry. Another concern with qualification processes of AM is the requirements on extensive empirical testing. Today a statistical-based qualification method is used, where thousands of individual tests are needed for qualifying a part. It is a non-feasible method from economic and time-consuming perspectives, obstructing qualification of AM parts by the industry. To counteract this

approach and enable the use of AM by the industry, there are needs for developing sustainable qualification processes for AM (NIST, 2019).

1.3 Alfa Laval

Alfa Laval is the focus company this master thesis is written for. Alfa Laval is a worldwide organization with key technologies within heat transfer, separation and fluid handling. The company produces products treating water, reducing carbon emission and minimizing water and energy consumption. Products involved in heating, cooling, separating and transporting food is also one of Alfa Laval's core skills. The company is divided into three main divisions: *The Energy Division*, *the Food & Water Division* and *the Marine Division*. Alfa Laval is a company with over 17 000 employees that helps customers with their needs in over 100 countries. (Alfa Laval, 2020)

Alfa Laval as a company is known for focusing on innovation and new ways of thinking (Alfa Laval, 2020). Alfa Laval is creating a technology center for AM in Eskilstuna. This is an important step on their disruptive technology journey and work to improve competitiveness. The technology center has the goal to build strong R&D knowledge in Design for AM (DfAM) and the vision to establish AM as a new core production technology in *Operations*. This master thesis is part of the division *Operations* within *Operations Development* at Alfa Laval. The thesis is written in Lund but is defined to be a part of the build-up of the technology center in Eskilstuna.

1.4 Swerim

This thesis is also a project within the Swedish Arena for Additive Manufacturing of Metals, which is an arena created as a part of Swerim. Swerim is an industrial research institute within mining engineering, process metallurgy, materials, manufacturing engineering and application. (Swerim, 2018a)

The goal of the Swedish Arena for Additive Manufacturing of Metals is to make Swedish industries competitive and leading through high-value manufacturing. The arena consists of several companies and universities

within the area of metal AM which offer a great network within the community of metal AM. One of the arena's focus areas is on *Quality considerations of additive manufacturing*. (Swerim, 2018b)

1.5 Research aim and purpose

The overall purpose of this thesis is to gather understanding about the qualification process for metal AM and the qualification issues connected when introducing AM as a new manufacturing technique in industry today. The thesis will also aim to develop a sustainable qualification process for additively manufactured parts as a new manufacturing method at Alfa Laval. Three research questions (RQ) were formulated to proceed with this thesis:

- RQ1 - What is qualification of AM and which process steps need to be taken into consideration to achieve qualification for AM parts?

- RQ2 - How are qualification processes for metal AM configured and executed at companies in industry today?

- RQ3 - What aspects of qualification of AM does Alfa Laval need to consider and how could a qualification process for AM parts be configured?

To answer RQ1 a literature study is needed to understand how qualification procedures are developed and which specific qualification processes relate to AM as a manufacturing technique. The issues with AM as a manufacturing method and the trends and developments within the area of AM are also handled to support this research question.

To answer RQ2 a case study with interviews of companies using or involved in metal AM is conducted. The aim of this research question is to understand the issues and possibilities regarding qualification processes of metal AM in industry today to gather deeper understanding of the subject.

To answer RQ3 the knowledge reached through RQ1 & RQ2 is analysed and applied. A deeper understanding of qualification at Alfa Laval is gathered through collection of data at the company. The collected data also enables introduction of a qualification process for AM at the company.

1.6 Delimitations

This thesis is constricted to metal AM, hence when referring to AM in this thesis it is understood metal AM is implied. Within the case study at Alfa Laval the focus AM technique is laser powder bed fusion (L-PBF), the material is stainless steel 316L and the AM machine *Trumpf TruPrint 5000*.

The general focus of the thesis is companies within industries, working to industrialize the AM technique for non or medium-critical applications. This is since the focus company Alfa Laval does not produce highly critical components such as components used in the aerospace and medical industries. All the qualification procedures necessary to achieve a successful qualification framework within a company are not handled throughout this thesis. The focus will be restricted to the specific qualification processes necessary for AM. Furthermore, the focus of this thesis is not evaluation of the appropriate DfAM, evaluation of different techniques within AM nor selection of appropriate machine or powder suppliers. The length of this thesis was limited to 20 weeks.

1.7 Outline of thesis

An outline of this thesis and short descriptions of each chapter are presented in Table 1.1. The table presents an overview of the contents of this thesis.

Table 1.1. Outline of the thesis with short description of each chapter.

Chapter	***Description***
1. Introduction	This chapter contains the introduction and describes scope of this thesis.
2. Methodology	This chapter describes the methodologies followed during the thesis project.
3. Results from literature study	This chapter contains a theoretical framework. The literature study includes theory of the AM technique delimited to this thesis, material, quality processes and the process steps of AM.
4. Results from case study	In this chapter, the results from the conducted case study is presented. The results from the case study includes results from the interviews conducted in the industry and the data collection at Alfa Laval.
5.Recommendations and discussion	In this chapter the recommended general concept of qualification and the qualification strategy of dividing products into criticality levels according to Alfa Laval's interests is presented. An option to qualify products in product families is also discussed and short chapter of the future of qualification of AM parts is presented. In the end, the methodology and presented concept and strategy is evaluated.
6. Conclusion	To be found in this chapter are concluding descriptions of how the research questions were answered. Further research to be conducted is also mentioned.

2. Methodology

This chapter describes the methodologies followed during the thesis project. The chapter includes description of the pre-project planning, the research approach, the data collection methods, the methods of data analysis and the quality of the research.

2.1 Pre-project planning

To enable a well performed master thesis project, deliberate planning was carried out before the project started. The planning of the work mainly consisted of composing a project plan which included the overall content of the master thesis, delimitations applied to the project, the method used through the project and a time plan covering the project's deadlines. The time plan was configured and presented through a Gantt chart which is a traditional method to plan and present timing of tasks (Ulrich & Eppinger, 2012). The time plan and the actual project timeline can be viewed in Appendix A — Project timeline. The actual timeline corresponds to the time plan in general but differ slightly. The main difference is to be found for the empirical study at Alfa Laval, the reason was to improve the project from Alfa Laval's perspective by continuous discussions and research. Furthermore, the workload and project tasks of this master thesis was distributed equally between the authors.

In parallel with writing a project plan of the master thesis, a pre-study of the subject was conducted to gather the sufficient background to carry out the project. The pre-study included studying theory, arranging contact with universities working within the subject and arranging meetings with people within Alfa Laval to gather organizational knowledge.

2.2 Research approach

There are different methods of conducting and gathering data for research, including differences between ways to collect quantitative and qualitative data (Yin, 2015). In this project a qualitative approach of collecting and analysing data was chosen since a variety of topics of real-world settings can be studied through qualitative research (Yin, 2015). In other research the difference between qualitative and quantitative is referred to the handling of gathered data and not the research method (Denscombe, 2010).

There are different strategies of research methods, e.g. surveys, case studies, experiments and action research. The strategy for this thesis should be chosen based on the questions:

- Is it feasible?
- Is it suitable?
- Is it ethical? (Denscombe, 2010)

With discussions around these questions the chosen research strategy concluded to case studies. This strategy was also chosen since the purpose of the thesis' research was to understand complex factors connected to one specific setting, which connects to the strategy of case studies. (Denscombe, 2010)

To collect data to answer RQ1, a literature study was conducted to obtain a theoretical framework. The method of data collection chosen for the case study was primarily interviews as it would gather understanding regarding RQ2. To answer RQ3 the case study based on interviews and the theoretical study was analysed. These conclusions in combination with data collected from Alfa Laval was used to give the company recommendations for a qualification process of their AM parts. Within Alfa Laval, a project group working with AM within the company was constantly a part of the master thesis project contributing with information, guidance and feedback. This in order to assist answering RQ3 and compile the thesis with a conclusion and recommendation for Alfa Laval. In Figure 2.1 below, the outline of research strategy and data collection methods are presented.

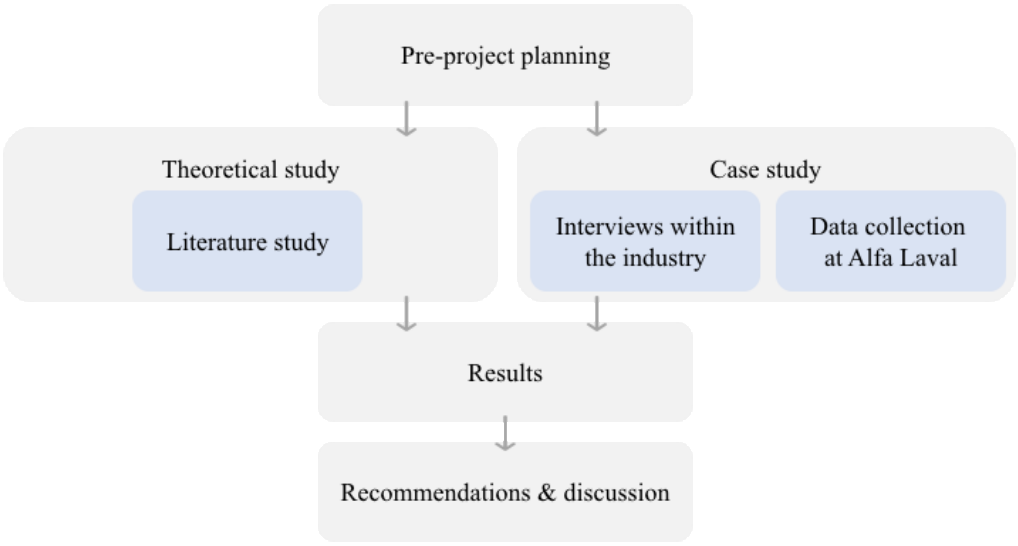

Figure 2.1. The outline of the research strategy.

2.2.1 **Literature study**

As mentioned, a literature study was conducted to answer RQ1 and obtain relevant background and theory for the project. A theoretical understanding is an important aspect of the beginning phases of a case study as well as it is an important aspect in generalizing the results and conducting a conclusion after the case study is completed (Yin, 2014). The literature study also offered support to the RQ2 and the RQ3. Furthermore, the literature study offered significant knowledge about the subject and was also an important aspect of the preparation of an interview template for the data collection through interviews.

2.2.2 **Case study**

Case studies are used to gather in-depth information about experiences or processes occurring in a particular instance. Multiple methods of gathering research data are available within the strategy and encouraged when working with it. The main advantage of the strategy is its ability to focus on one or a few instances to deal with features and complications within a complex situation. The main weakness is the method's vulnerability to generalizations of findings. This needs to be taken into consideration throughout the study. (Denscombe, 2010)

Case studies can be divided into two categories of either *Discovery led*, including description, exploration and comparison, or *Theory led*, including explanation, illustration and experiment. However, using a case study as a research strategy does not restrict the research to one of these categories (Denscombe, 2010). Within this thesis exploratory and comparable studies within the *Discovery led* was used to answer RQ2. These categories explore key issues within a case study setting and compare settings to learn from similarities and differences between them (Denscombe, 2010). This facilitated well with the foundation of RQ2.

2.2.3 **Applied case at Alfa Laval**

To be able to answer RQ3, the benchmarking interviews and literature study needed complement information regarding Alfa Laval's purpose of AM, the company's way of working and current state of using AM as a technology. This information was collected by discussions, meetings, observations and document studies to be able to apply a qualification approach to Alfa Laval's interests and adapt the strategy according to the company's prerequisites.

2.3 Data collection

2.3.1 **Literature study**

Literature studies are recommended to be used as the foundation in good scientific research, to create a holistic view of the subject (Höst, Regnell & Runeson, 2006). Further, literature studies were used for several other tasks in the research for this thesis. According to Höst, Regnell & Runeson (2006), literature studies provides:

- Gaining basic knowledge about the topic
- Researching within subproblems and delimitations
- Deeper studies of specific focus areas
- Comparing the result with other research

The literature studies were conducted iteratively. The repeated process of literature studies should be the following; determining keywords to use, searching, selecting and assessing data to be able to conclude it. (Höst, Regnell & Runeson, 2006)

When searching for data to collect, it is important to evaluate if the information is relevant. It is also important to evaluate if the sources are reliable, since a search portal can only search for sources and not evaluate the quality of the found information (Höst, Regnell & Runeson, 2006). Therefore, effort was put in finding trustworthy literature for this thesis. Mainly published and reviewed journals, articles, encyclopaedias and books from well-known publishers were used to gather data for the literature study. The searches were principally made at Lund University search portal *LUBsearch*, *Google Scholar* and *Springer Link*, a platform for scientific publications by the publisher Springer. Springer is a world leading publisher within science (NE, n.d.c) and their book-series *Springer Series in Advanced Manufacturing* was used as the foundation in the literature study about AM.

Documentation of a literature study should consist of both compilations of the collected data and references to the literature used. (Höst, Regnell & Runeson, 2006) The compilations are presented in several parts in this report, with references to the sources. The references are presented in a list in the chapter References.

2.3.2 **Interviews**

To qualitatively collect data in the case study, interviews were used. The decision was motivated by the objective of the case study, to investigate how the industry reasons about qualification processes within AM.

Interviews are stated to be a useful method when the aim is to gain insights into experiences and opinions. Moreover, in-depth interviews can provide data collected from privileged information, value-adding data from important persons in the field. (Denscombe, 2010)

Not only usefulness, but also feasibility should be motivating the choice of data collection method. Feasibility includes both accessing the right persons to collect the aimed information and viability in terms of time and travel (Denscombe, 2010). To make time and travel feasible in this case, the interviews were chosen to be performed over the internet.

Interviews can be structured, semi-structured or unstructured depending on the freedom of the interview's plan. A structured interview follows a strict setup of questions, while during an unstructured interview the interviewee is

allowed to speak freely about a topic. Semi-structured interviews are a combination of them both where listed issues and questions are used, both flexible in order of topics. It is stated that semi- and unstructured interviews are preferable when discovering complex issues and developing ideas (Denscombe, 2010), therefore the interviews in the case study were semi-structured.

Interview templates with questions were assembled for the semi-structured interviews. The templates included both main and follow-up questions with open ends, to allow the interviewees to develop ideas and speak freely. The questions were developed from this thesis' research questions and can be found in Appendix B – Interview questions and Appendix C – Interview questions for powder suppliers**.** There was a small variation of the questions prepared for each interview, since the companies in the case study were involved at different levels of AM. The companies were divided into three sections:

- Supplier of AM powder
- Manufacturer of AM parts
- Manufacturer of AM parts and supplier of AM powder

The execution of the interviews was repeated, keeping the same attitude to structuring the interviews, asking the questions and documenting the answers through all the cases. The documentation was made by taking notes on every answer and during all the discussions.

When selecting who to interview, the feasibility aspect was kept in mind. By selecting companies practically working with AM, their knowledge about AM was assumed to be adequate. To further ensure that the interviewee had enough competence within the subject, effort was put in finding the right person to interview at every company.

The number of interviews to be held was not determined in advance. Contrary, it was to be decided when the amount of data collection was satisfying. There were five interviews held with four companies, one company was classified as *Supplier of AM powder*, one company was classified as *Manufacturer of AM parts* and two companies were *Manufacturer of AM parts and supplier of AM powder*.

An option for enabling data collection from companies located at distances, was digital interviews. With viability in terms of time and travel in mind,

digitalizing the interviews was a well-motivated choice. One drawback of online interviews is the loss of the visual clues, but on the other hand it reduces the interviewer effect, occurring when the interviewee is influenced by the interviewer (Denscombe, 2010). To be mentioned is that one of the interviews was carried out in person at the company instead of online.

One-on-one-interviews, with only one interviewee at the time, are useful to focus on one person's ideas and experiences (Denscombe, 2010). Therefore, it was decided to, if possible, only interview one person at one time. For the interview held at the company and not online, there were three people interviewed at the same time. The interviews were held in Swedish. This appeared naturally, since Swedish was the mother's tongue for everyone involved in the interviews.

2.3.3 **Information from Alfa Laval**

The collection of information about Alfa Laval's interest and way of working was performed during meetings and individual discussions. These were held with persons working within AM and/or qualification at Alfa Laval. As a complement, a study of internal documents was performed to further investigate the company's work procedures. Areas of interest for the applied study was Alfa Laval's way of working with AM.

2.4 Data analysis

2.4.1 **Literature study**

For the literature study, both broad and deep searches were performed. The collected data was analysed, and the relevant information was compiled and presented in the literature study.

2.4.2 **Interviews**

To analyse gathered material from the interviews there are different methods and approaches to conduct. There is no general way of analysing data according to one generalized recipe, however it is important to present

sufficient evidence and apply careful consideration of different interpretations of the data. (Yin, 2014)

The chosen approach to analyse the raw interview data is based on a four-step schematically process described by Höst, Regnell & Runeson (2006):

1. Data collection
2. Coding
3. Categorizing
4. Conclusions

The *Data collection* is performed and documented in the form of summary transcriptions. The next step is *Coding* where important statements or subsections are underlined and connected to several chosen keywords of importance within the study. In the next section of *Categorizing* the different paragraphs are categorized to enable a study of the different statements regarding a specific keyword. Based on the categorized data, *Conclusions* can be drawn. (Höst, Regnell & Runeson, 2006) This method of analysing raw interview data was used.

2.5 Research quality

Credibility of the conducted and demonstrated research needs to be taken in consideration during the research process itself. The researchers need to demonstrate in which way their research is credible and therefore of good quality. The difficulties with analysing the quality of the qualitative research refers to the inability to reproduce the method in comparison to quantitative research, e.g. experiments. However, the qualitative research quality still needs to be addressed. The credibility of research is mainly focused on *reliability*, *validity* and *objectivity*. (Denscombe, 2010)

2.5.1 **Reliability and objectivity**

Reliability of a case study explains the consistency and repeatability of the performed research procedures and the ability to reproduce such research (Yin, 2014). To achieve as high reliability as possible all the procedures and evidence gathered during this project were carefully documented and could therefore be traced back to.

Objectivity refers to the extent to which the researchers can produce findings without their own influence. However, qualitative data is always in a process of interpretation which will affect the findings in some way (Denscombe, 2010). To deal with objectivity during this project the researchers always aimed to have an open mind and evaluate alternatives and competing explanations of data. When analysing raw data, methods were followed in as large extent as possible, e.g. as described in chapter 2.4.2 Interviews, to obtain objectivity.

2.5.2 **Validity**

The validity of a study is ensured if the results are valid and if the studied phenomena is presented from an objective perspective. The five points to take into consideration for the validity of a project are:

- Log
- Feedback
- Third-party review
- Triangulation
- Long term studies (Höst, Regnell & Runeson, 2006)

Documenting the work, decisions and thoughts in a log can ensure a well-implemented and reliable study (Höst, Regnell & Runeson, 2006). To ensure validity by logging in this thesis, a weekly journal was written, and all meetings were documented.

Furthermore, feedback is to be provided from experts and respondents to ensure validity (Höst, Regnell & Runeson, 2006). In this case, this was fulfilled by sending the collected data from the interviews to the respectively interviewee. The feedback was then to be used for ensuring validity in the collected data. Similar to the feedback aspect was third-party review conducted. The report was sent to the supervisor at Lund University during the project, to ensure that the studied phenomena was presented objectively and correctly. Further third-party reviews were conducted by AM-specialists within Alfa Laval and externally.

The point concerning long term studies implies that the length and extent of a project is crucial for the validity. In a shorter study the risk is that the problem's complexity is misunderstood. On the other hand, for a longer project the risk lies in losing objectiveness (Höst, Regnell & Runeson, 2006).

Since the length of this thesis was standardized to 20 weeks, this part of validity is not to be further discussed. With the earlier mentioned motivation for validity in this project, the conclusion is that the method for gathering and processing results are valid.

3. Results from literature study

This chapter contains a theoretical framework of the subject within this thesis. The literature study includes theory of the AM technique delimited to this thesis, material, quality processes and the process steps of AM. The theoretical framework will be used to support the data collection in the case study, draw conclusions and submit recommendations.

3.1 Powder bed fusion

As earlier mentioned, one AM technology is powder bed fusion. There are three different powder bed fusion technologies (PBFT): laser powder bed fusion (L-PBF), electron beam powder bed fusion (EB-PBF) and multi jet fusion. The basic principle in PBFT is fusing powder in a powder bed. Additionally, the PBFT share three mechanisms. Firstly, a thermal source is used to fuse powder particles and secondly, they have methods for controlling the fusion of powder to restricted areas in every layer. The third mechanism in common is a recoat-mechanism for adding a new layer of powder to the powder bed. L-PBF and EB-PBF are similar techniques, differing in the thermal sources. In L-PBF the source is laser, and an electron beam is used in EB-PBF. (Diegel, Nordin & Motte, 2019)

3.2 Laser powder bed fusion

The building process in L-PBF is an iterative process starting with a layer of powder which is spread over a building platform. The thermal energy source, a laser beam, scans a pattern and melts the material in the restricted area. A lowering movement of the building platform enables spreading of a new layer of powder in the powder bed. The laser melts a pattern in the new layer, fusing it with the layer below. These steps are continuously repeated until every layer of the part is built. (Gibson, Rosen & Stucker, 2015) The procedure of L-PBF is shown in Figure 3.1. The process of L-PBF will be

further described and discussed in chapter *3.5 The process steps of additive manufacturing.*

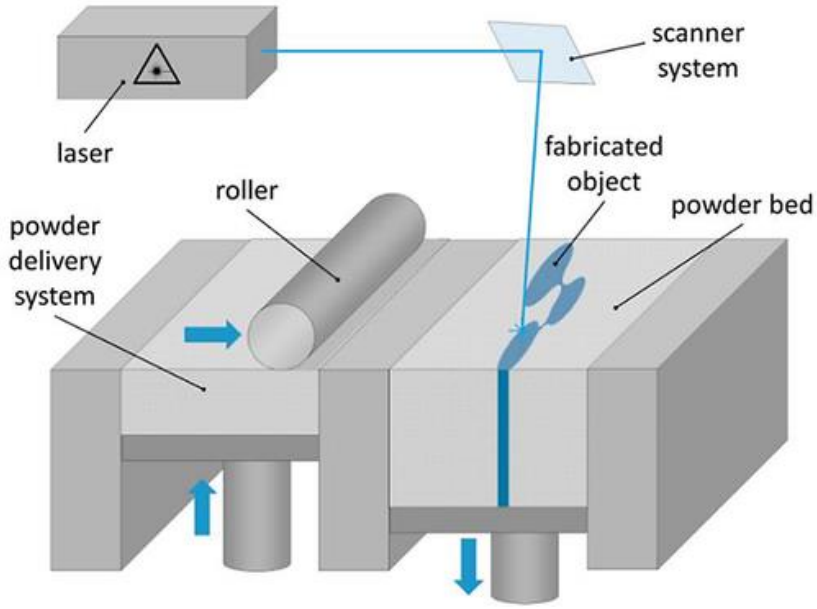

Figure 3.1. The procedure of L-PBF. (Mao et al., 2019)

L-PBF is a full-melting method, meaning all material beneath the laser spot is melted and the melt goes through the whole layer of thickness. An advantage with L-PBF is the possibility to adjust the wavelength of the laser for the absorptivity of the metal powder (Gibson, Rosen & Stucker, 2015). Several other parameters are adjustable in L-PBF, these process parameters are further discussed in chapter 3.5.5 Machine setup – process control. Since this technology induce health and safety concerns, it is executed in controlled environments where inert gases or vacuum are used (Yang et al., 2017).

L-PFB results in well bonded and high-density components that are strong and durable even if a small amount of anisotropy is noticeable in the z-direction, implying isotropy in the x-y-plane. Due to the rapid melting and solidification in the process, the tensile properties are good in AM-parts. On the other hand, it also results in residual stresses which can cause warping. Furthermore, the components have poor surface roughness, leading to lower fatigue properties. (Diegel, Nordin & Motte, 2019)

3.2.1 **Terminology**

To be able to comprehend the terminology of the processes connected to AM in this thesis and the different terminology applied to it, a couple of the used terms are described or defined below:

- *Building* is a L-PBF process of building up a part layer by layer. In this process, the post-processing steps are not included. Building could also be referred to as *printing* in other contexts.

- *Build job* is the building of one or several part or samples. The build job includes the whole process of building up one or several parts layer by layer.

- *Build process* is a build job including the settings and parameters.

- *Build* is referring to an output of a build job, i.e. the part, the test sample or the test artifact.

- *Manufacturing* means all procedures of producing a part, including the post processing steps.

- *Test sample* is a built geometry used for testing.

- *Test artifact* is a collection of test geometries built for testing, evaluation, diagnostics or development. *Test geometry* is referring to a shape of a test artifact feature.

3.3 Material

The PBFT allow processing in various materials such as plastics, elastomers, metals, ceramics and composites. Generally, all materials that can be welded and re-solidified can be used in the processes of PBF. (Gibson, Rosen & Stucker, 2015) For this thesis, only metal powders are considered and covered for the L-PBF process.

3.3.1 **Characteristics of powder**

The metal AM powder used for L-PBF is most often produced through a gas atomization process. This results in a powder with a spherical shape, good powder density and good reproducibility of particle size distribution. In metal powder the ideal shape is spherical since it increases powder flowability and the ability to create equal layers of powder in the powder bed fusion layers. The powder size is normally distributed with smaller and larger particle grains to enable denser layers of powder being spread in the process. (Diegel, Nordin & Motte, 2019*)*

There are several specifications that are important to have in mind regarding the powder, including powder particle size distribution, average particle size and flowability. The powder size distribution modes, powder spreadability and chemistry are also important factors regarding the metallic powder for usage in PBF. The mechanical properties of metallic powders are dependent on the microstructure of it. The microstructure of the material is affected by inherent chemistry, the manufacturing process and the heat treatment applied to it. (Yang et al., 2017)

The quality of the powder is of highest importance in AM. The supplier of the powder should obtain a certificate, e.g. ISO 9001. This provides the AM-company insurance of regular quality controls. The company and the supplier could agree on a so-called fixed process, this is presented by a document identifying the powder manufacturing step-by-step. The fixed process also provides documentation of the powder certification, how the powder is handled, the machine's process parameters and the digital files used for the build process. (Yang et al., 2017)

The powder morphology, which includes the powder size distribution and the shape of the powder particles affects the mechanical properties of parts produced by additive manufacturing. The morphology affects the optical penetration depth of the laser, the thermal conductivity and the density of the layers in the L-PBF process (Dowling et al., 2020). Irregular shapes and small grains make it harder to spread even layers of the powder and hollow particles can explode or entrap gas in the part during the melting process (Diegel, Nordin & Motte, 2019).

The usage of recycled metal powder as feedstock can also affect the properties of the powder and therefore the manufactured part. The main consequences for the reused powder are deviating size distribution and that

the powder particles become less spherical. However, in some studies the reused powder showed no undesired characteristics. If the reused feedstock leads to repeatability and reproducibility issues of built parts, powder variation could be determined in the feedstock and the process parameters could be adapted to fit the powder instead of generalized processing parameters (Dowling et al., 2020).

3.3.2 **Material characteristics of built part**

The material characteristics of built parts in metal AM are dependent on the AM system manufacturer and the material used. There are many different areas of the process and parameters that will affect the resulting quality of the build.

A general assumption for metallic materials designed and processed through AM is that they achieve the same or slightly higher mechanical properties in wrought parts. However, some mechanical properties, such as creep and fatigue strength are not as well figured out when it comes to the AM process. (Yang et al., 2017)

According to Seifi et al. (2017) the AM parts cyclic load behaviour is the largest issue regarding validation of mechanical properties. Cyclic load could lead to fatigue and fracture issues due to presence of defects, anisotropy and surface roughness. Similitude between test samples and actual parts is also an issue, since local properties in the material depends on specific parameters which can vary between part and test sample. (Seifi et al., 2017)

3.4 Qualification

3.4.1 **Terminology**

To be able to comprehend the subject of quality within this thesis and the different terminology applied to it, a couple of the used terms are described or defined below according to ISO:

- *Quality* is defined as the degree to which a set of inherent characteristics of an object fulfils requirements.
- *Verification* means confirmation, through the provision of objective evidence, that specified requirements have been fulfilled.

- *Validation* is confirmation that the requirements for a specific intended use or application have been fulfilled.
- *Requirement* is defined as a need or expectation that is stated, generally implied or obligatory. (ISO 9000:2015)

Qualification procedures are different depending on application and industry. However, qualification could generally be described as the collection of data to guarantee that a material or a process will function as intended. Extensive testing to fully qualify a material can conclude in thousands of individual tests which results in long and expensive procedures. (NIST, 2020)

Qualification can be applied to both product and process development. Process qualification includes the procedures which validate that a manufacturing technique meets specific requirements. Process qualification provides a guarantee that a process is under control and can produce acceptable products. Product qualification refers to the parts quality, function and reliability under specified operational and environmental conditions. (Wang, Azarian & Pecht, 2008)

3.4.2 **Qualification procedures**

The qualification of a product and/or procedure should be considered early in a development project to obtain cost- and time-efficiency. The end qualification of a product is time-critical since you want to decrease the time to market. Integrated qualification into the development process therefore offers a more efficient way of qualifying. (Gerling et al., 2002)

Qualification of products includes:

1. *Verification* of their function and performance
2. *Validation* in the system application
3. Qualification for *processability* and *reliability* (Gerling et al., 2002)

Regarding the qualification procedures, it is important to reflect about *how* the requirements on the product and the expectations from the customer are fulfilled and *why* a specific qualification measure is in place (Gerling et al., 2002).

Technology qualification can be seen as a way to guarantee a process or new technology that is not covered by existing standards or certifications (Samindi et al, 2017). When developing new or adapting existing

qualification procedures it is also important to revise what present abilities are within the company or project regarding similar products and processes (Gerling et al., 2002). Risk-based technology qualification, which bases on the end risks of a product and a process, could be used to minimize uncertainties or deviating factors in a novel technological process (Samindi et al, 2017).

3.4.3 **Qualification of additive manufacturing**

As industry is moving towards implementing AM technologies into production, the need for appropriate qualification procedures for the whole AM process is increased. Since AM is a relatively new manufacturing method for many companies, the need to evaluate and develop new procedures, standards, specifications, testing methods, documentation and monitoring to ensure a stable process of AM-parts are of importance. (Lu & Wong, 2018)

Quality procedures are established since reliability and reproducibility in the process needs to be obtained. L-PBF is a process containing complex physics and heating to fuse layers of material together during a build, which causes variability in parts. The variation can therefore appear in two identical building runs in the same machine. This aspect of AM will be difficult to eliminate without in-process monitoring offering closed-loop control of the building process. (O'Brien, 2018)

A framework for qualification of AM is proposed by Yeong and Chua (2013). The framework is developed for medical devices but aiming to ease technical advancement in AM for other regulatory industries as well. The qualification framework is divided into five categories:

- *Software and data input,* including format and quality of the file.
- *Product understanding,* including manufacturing process aids such as DfAM and risk assessments.
- *AM equipment qualification,* including validation for software, equipment performance and materials.
- *Process understanding,* including material management and process characterization such as process capability and reliability.
- *Continuous process verification,* including process controls and material characterization by performance verification by testing. (Yeong & Chua, 2013)

O'Brien (2019) presents different processes for development and qualification for AM in the aerospace industry. The objective is reducing variability, increasing repeatability and reliability in AM. The first process is developed by NASA's Marshall Space Flight Center and includes two standards for L-PBF for controlling the metallurgical fusion process, part process, equipment process and vendor process. The metallurgical process consists of feedstock controls, fusion process controls and thermal process controls which are to be qualified and then frozen.

The second process presented by O'Brien (2019) is *The Space and Missile Center's* strategic plan to develop and mature AM. The development consists of three phases. Phase 1 is understanding the AM technology, including application and design of the part. Phase 2 is developing the production process. It is an iterative process of design, production controls and testing that is executed until the prototype satisfies its requirements. Phase 3 is part production and integration, including qualifying the parts and the production process' reliability and repeatability.

3.4.4 **Standards and certificates for additive manufacturing**

Standards provide a guarantee that procedures and methods are followed correctly. Standards therefore add reliability and stability to quality of processes and products. (Slotwinski & Garboczi, 2015).

Currently there are 14 ISO/ASTM standards published for AM and 23 standards under development (ISO, 2020). 12 of the issued ISO/ASTM standards have been edited and issued by SIS (SIS, 2020). The industry's growing demand to enable equal and stable processes has pushed the development of standards. Many of the issued AM standards today are referring to conventional methods as a way of testing the materials or parts in AM (Slotwinski & Garboczi, 2015).

Several steps of the AM process are a part of the certification process, e.g. the machine, the material, the build location on the build platform, the process parameters, the post-processing and sometimes test samples. When the parameters are in place and fixed, additional testing must be conducted if they are changed (Diegel, Nordin & Motte, 2019). The company Lloyd's Register offers their certification mark *LR* to companies that ensure part quality (Lloyd's Register, 2020).

3.5 The process steps of additive manufacturing

In order to evaluate the specific steps of a qualification process for L-PBF, a process map of the steps of manufacturing a part through L-PBF was established, as seen in Figure 3.2. The process map was influenced by the process described by Yang et al. (2017).

The steps included in the process map are *CAD-model*, *preparation of file*, *feedstock*, *machine setup* (further divided into *hardware* and *process control*), *building*, *build removal*, *post processing* and *inspection and testing*. The qualification steps assigned to the different steps of manufacturing a part are further described in the correspondingly sections.

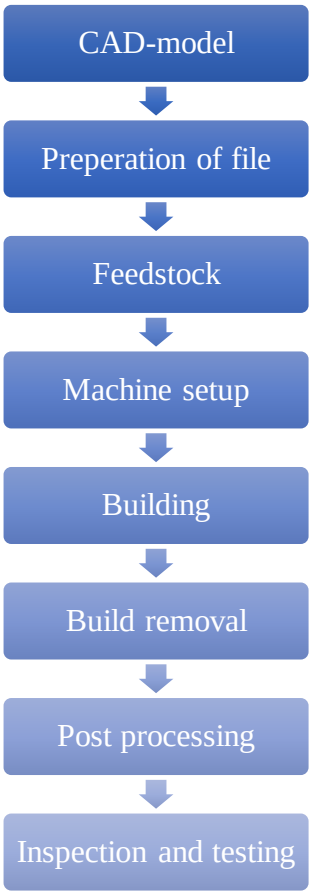

Figure 3.2. The AM process steps of building a part.

3.5.1 **CAD-model**

3.5.1.1 The Process

A 3D model of a component is created in a computer-aided design (CAD) software. The CAD-file is a virtual representation of the part to be manufactured providing information about the geometrical shape, dimensions, material etc. (Yang et al., 2017).

For AM, the design of the part can be divided into three categories depending on the possibility to adapt the design for AM. The lowest flexibility of design changes is *Direct Part Replacement*. In this category, no changes of the design are allowed, and the aim is to reproduce the exact model of an old part. This usage of AM is often to shorten lead time for spare parts. Furthermore, there is *Adapt for AM*, making the part easier to produce with AM but not changing the part's function or fit. *DfAM* on the other hand allows total redesign of the part to optimize the advantages of using AM. (Diegel, Nordin & Motte, 2019)

DfAM can also be design guidelines to use when designing a component. These are specific for different materials and different machines (Yang et al., 2017). When designing a part for AM there are limitations. For example, in PBF, holes and overhangs require support material. Further, sharp corners are recommended to be replaced with fillets to avoid stress concentrations (Diegel, Nordin & Motte, 2019). The staircase-effect is another limitation of the building, happening due to the layer thickness on surfaces that are neither vertical nor horizontal (Yang et al., 2017).

In addition to the design limitations it is important to consider the post processing of the part during the design stage. The removal of support material depends on the construction. Also, the design must enable other post processing steps. With optimal design of an AM part, stress concentrations and residual stresses can be minimized, requiring minimal post processing such as heat treatment. Simple design examples for this intent are filleting sharp corners and evening wall thickness. (Diegel, Nordin & Motte, 2019) A further discussion about post processing methods is to be found in the chapter *3.5.8 Post processing.*

3.5.1.2 The Qualification

The design is qualified when buildability is ensured. This depends on the implementation of DfAM-guidelines. Furthermore, the buildability of critical

design features depends on the machine and the feedstock, meaning that the performance of the AM-system needs to be verified for these critical design features. If buildability is insufficient, a redesign of the part is required (Yang et al., 2017). Testing of critical design features in the AM system can be done with test artifacts. For some common critical design features the standard *Additive manufacturing – Test artifacts – Geometric capability assessment of additive manufacturing systems* (SS-EN ISO/ASTM 52902:2019) compiled by SIS is available.

3.5.2 **Preparation of file**

3.5.2.1 The Process

The CAD-file representing the component has to be converted to a format acceptable for the AM-machine. Which format the machine uses depends on the machine, but the two most common formats are Stereolithography file format (STL) and Additive Manufacturing File format (AMF). AMF is the standard file format recommended by ISO and ASTM. (Yang et al., 2017)

Before start of the build job, the component has to be arranged on the build platform. The placement is important since the properties of the build might differ within the build chamber. Since it is possible to build several parts in one build job, their placement if of concern (Yang et al., 2017). Further, the orientation of the component is also to be determined at this stage. Different orientations can affect the properties of the manufactured part due to anisotropy. It can also change the building time, depending on the number of layers to build which is directly linked to the height of the part (Diegel, Nordin & Motte, 2019). In this part of the process, support material is added to avoid warpage and ensure that the design features are created as intended. When the preparation of the file and support structures is performed in a pre-process software program, a slicer program is used to dividing model into layers (Yang et al., 2017).

3.5.2.2 The Qualification

To verify this process, the quality of the AMF or STL file is to be analysed after conversion from the CAD file. The AMF or STL file is to be repaired if any errors occurs (Diegel, Nordin & Motte, 2019). Examples of file errors can include missing triangles, inverted triangles, open edges and contours and shells (Yang et al., 2017). For AMF, the SIS-issued standard *Specification for additive manufacturing file format (AMF) Version 1.2* (SS-EN ISO/ASTM 52915:2017) can assist.

The building process with the setup of the build can be simulated through computer software. A build process simulation uses finite elements (FE) models to predict residual stresses and distortion from the building. Build process simulations can also be used to better understand the performance of a material and part geometry. It can also simulate post processing such as heat treatment and removal from the building plate. This enables compensating the geometry for distortion. There are two versions of build process simulations, both layer-by-layer simulation and scan-pattern simulation. The former is used to analyse the heating and cooling of every layer and the latter is used for analysing the scan pattern of every layer, resulting in more accurate results but on the other hand are more time consuming. There is some commercial software available for this today, including ANSYS exaSIM, MSC Software Simufact Additive, Autodesk Netfabb, among others. (Diegel, Nordin & Motte, 2019)

3.5.3 **Feedstock**

3.5.3.1 The Process

In general, any metallic material that can be welded can be used in L-PBF. The powders shape, size and distribution influences laser absorption characteristics, the powder bed density, the powder bed thermal conductivity and the powder spreading (Gibson, Rosen & Stucker, 2015). More detailed information about the characteristics of metal powder is described in the section 3.3 Material.

After a build is completed, the left-over powder from the building can be collected and reused. There are two types of loose powder left after a build process, unused powder in the powder supply stock and overflow powder in the building chamber. As earlier mentioned, the handling of feedstock powder must be a controlled process to avoid contamination. The handling of the recycled powder differs from the handling of virgin powder. Further, the management of the powder differs between the unused and the overflow powder since the overflow powder is exposed to heat during the build job. The used powder is processed through several sieving steps to remove impurities and unwanted particles that can affect the final properties of the final part. To be able to reuse the recycled powder, it is mixed with virgin powder to enable the necessary volume. (Gibson, Rosen & Stucker, 2015)

3.5.3.2 The Qualification

In the Swedish issued Standard *Additive manufacturing – Feedstock materials – Methods to characterize metal powders*, different methods of characterizing and measuring metal powders are explained. In the standard, technical specifications or methods are often referred to conventional developed material standards. The standard encounters the importance of a pre-decided testing plan between customer and supplier based on customers' requirements. (SS-EN ISO/ASTM 52907:2020)

The quality verification of feedstock could also be applied through a material specification between powder producer and customer which contains the requirements for the primary input material used to fabricate a product element. A material specification could contain information about a fraction or all the following areas:

1. Approved uses for the material.
2. Composition requirements.
3. Material properties requirements.
4. Microscopic structure requirements.
5. Surface condition requirements.
6. Allowable defects.
7. Analysis methods for evaluating the properties and features of the material.
8. Referenced documents. (Pfeifer, 2009)

The powder delivery system, i.e. the recoater, is also an important aspect of the powder handling. The delivery system must fulfil the criterions of correct volume to enable a whole building process and sufficient coverage of the layers. The system should spread a thin, smooth and repeatable layer and the spreading cannot add shear forces to the already built layers of the build. The delivery system must therefore be considered in the process of choosing a machine supplier. The delivery system of powder also includes other issues related to powder, such as airborne particles that have a higher tendency to explode or burn. (Gibson, Rosen & Stucker, 2015)

In the section 3.3.1 Characteristics of powder, factors regarding the quality verification of metal powder are described further. The factors related to quality validation of the metal powder are listed below:

- Storage and handling routines.
- Allowed reuse cycles regarding recycled metal powder as feedstock.
- Regular quality controls, e.g. with testing methods.

- Powder certification, e.g. chemical composition, homogeneity, morphology, flowability.
- Control of new batches, e.g. with test artifacts or test samples.
- Sampling and traceability.

Since the final properties of the builds are affected by powder characteristics, which can change when the powder is reused, it is important to verify the powder before usage. Also, powder verification is important to avoid reducing the repeatability of the build process. Therefore, it is necessary to set up working methods for the operators and specifications for the powder reuse. The standard ASTM 3049-14 is recommended for characterizing metal powder for AM to determine the condition of the powder to ensure repeatability. (Tang, Qian, Liu et al., 2015)

3.5.4 **Machine setup – hardware**

3.5.4.1 The Process

Preparing a build job includes setup of the AM machine. The machine setup consists of two parts, hardware and software. The software is explained in chapter 3.5.5 Machine setup – process control. The hardware-setup covers cleaning of the AM system (Diegel, Nordin & Motte, 2019) and loading feedstock into it. Preparations of the build chamber are also made, including placing the build plate in it (Gibson, Rosen & Stucker, 2015) and preheating the build plate (Diegel, Nordin & Motte, 2019).

3.5.4.2 The Qualification

To ensure that quality is preserved in this part of the process it is important to specify working methods and routines for the operators, e.g. cleaning of the chamber (Yang et al., 2017). Instructions for sieving the feedstock when loading it into the machine is for example important to ensure the quality of the powder. There should also be instructions for maintenance of the machine and scheduled calibrations of critical components, such as the laser. Further, test artifacts containing test geometries can be built to diagnose and calibrate the machine (Gibson, Rosen & Stucker, 2015). These performance assessments should be made according to the SIS-standard *Additive manufacturing – Test artifacts – Geometric capability assessment of additive manufacturing systems* (SS-EN ISO/ASTM 52902:2019).

3.5.5 **Machine setup – process control**

3.5.5.1 The Process

The settings used to control a build job are called process parameters. These parameters are specific for the machine, including the technology used, the manufacturer and the model. Additionally, they depend on the material and the part. The objective of adjusting these parameters is to suit the part and improve the build, by optimizing the quality or build time. Developing suiting process parameters is complicated due to interaction between the parameters since they are interdependent. (Gibson, Rosen & Stucker, 2015) This leads to several ways of categorizing the parameters. One example of dividing the parameters are:

- Build process parameters
- Material parameters
- Part parameters (Yang et al., 2017)

Build process parameters includes settings relevant for the entire build, e.g. gas injection, material recoated motions and ventilation. Further, the material parameters specify the powder dosing behaviours and chamber environment. Part parameters on the other hand control the parameters assigned to the part and can vary during the build job. (Yang et al., 2017)

It is also possible to divide the parameters into four groups:

- Laser-related parameters
- Scan-related parameters
- Powder-related parameters
- Temperature-related parameters (Gibson, Rosen & Stucker, 2015)

The laser-related parameters for example include laser power, spot size and pulse properties such as duration and frequency. The speed and pattern of the laser spot movement on the other hand is covered by the scan-related parameters. The scan pattern is important to control the melt pool characteristics and build-up of residual stresses. Powder-related parameters are connected to both the powder characteristics and material properties but also the powder bed, e.g. its density and layer thickness. Further, the temperature-related parameters include settings such as temperature of powder bed and powder feeder. (Gibson, Rosen & Stucker, 2015)

Another important input in the process is the energy density. The amount of energy applied to one spot determines if particles will fuse, both melting in

the top layer and joining it with the layer beneath. By increasing the energy input, the density is improved but the surface roughness is impaired and key porosities could occur. The energy density depends on laser power, scanning speed, hatch spacing and layer thickness. (Diegel, Nordin & Motte, 2019)

3.5.5.2 The Qualification

The process parameters assigned to the build process of L-PBF are of highest importance to the end quality of the part or several parts built on the build plate.

The different ways of determining the process parameters are for now:

- Trial and error, where an experimental process of building and adjusting determines the parameters. This method can be time-consuming and expensive.

- The second method is using a computational software tool, e.g. physic based finite element analysis (FEA), melt pool monitoring or build process simulation of the AM process. The computational tools can predict the build process, the temperatures and the cooling rates for a set of parameters. These methods can in some cases be a faster and cheaper option than trial and error, however there is often a need for some experimental trials in combination with the computational tools. (O'Brien, 2019)

- The third method is buying predetermined "proven" parameters from a supplier. These parameters are set for a specific machine and/or material that can have specific functional intention for e.g. surface finish or building time. (Gibson, Rosen & Stucker, 2015)

3.5.6 **Building**

3.5.6.1 The Process

The process of building a part or several parts begins with the AM system machine accepting and processing the build files. The building process starts with a layer of powder coated across the building plate, usually by a wipe, roll or blade mechanism. One or multiple lasers fuse regions of powder together in the specific layer. The height of the powder layer is an important parameter to the process, since it will affect the quality of the fused layers. (Yang et al., 2017)

The laser, or the multiple lasers, fuses the layer along the powder surface in a specific pattern with the area defined by the 3D model converted file. The build platform moves in a negative Z-direction and a new layer coats the platform for a new repeatable process until the part is completely built up. (Yang et al., 2017)

3.5.6.2 The Qualification

Many commercial AM systems offer some kind of in-process monitoring which enables the ability to pause a build if there are errors appearing, e.g. in the powder coating process, overheating or issues regarding the thermal radiation or melt-pool. Some of the in-process monitoring systems also offer an ability to analyse data of the melt pool size, shape and temperature after a build as feedback control input. (Gibson, Rosen & Stucker, 2015)

In-situ measurements offer a method to optimize part reproducibility to the process. The techniques could also offer a closed-loop system, which means the measurements can be used to predict structure properties and defects in builds (Lu & Wong, 2018). The most appropriate in-situ measurement technique should be identified regarding the specific AM machine. A couple of the commercial methods available according to research are presented in following chapters.

3.5.6.2.1 Melt-pool monitoring - In process diagnostic tools

Melt-pool monitoring consists of a beam coaxial to the process beam that does an analysis where the intensity of the thermal radiation is measured, the melt-pool size and the radiation spatial distribution. This analysis can offer an indication of the quality of the part. (Yang et al., 2017)

3.5.6.2.2 In process feedback tool for the powder re-coating

The in-process feedback tool for the powder re-coating process takes an optical image of each layer and analyses the picture to determine if the layer of powder was fully coated in the correct way. The method could determine if the building needs to be stopped due to defects in the process. It could also be relevant to prevent overheating of the machine. (Yang et al., 2017)

3.5.6.2.3 In-situ defect detection

In-situ defect detection is a method that combines high resolution images during the building process of each layer with machine learning of typical defects of the material or defects regarding the condition of the build. The information regarding abnormalities or flaws are in current research obtained

from 3D computed tomography (CT) scan data post build. (Gobert et al., 2018)

The method of *Thermography* which uses infrared light to detect detection and *Acoustic emission testing* could also be used as inspection methods for in-situ monitoring. The data obtained from the methods are primarily used for qualification and certification of AM parts. However, the methods can be adjusted to apply in feedback control systems. (Lu & Wong, 2018)

3.5.7 **Build removal**

3.5.7.1 The Process

After the build job is finished, the build platform is unpacked from the powder bed. The build platform is taken out of the building chamber and the loose powder is removed (Yang et al., 2017). Methods based on blasting or vibrations are used to remove the remaining powder from the part, preparing it for post processing (Diegel, Nordin & Motte, 2019).

3.5.7.2 The Qualification

To ensure that the build removal is performed correctly and that the powder is well handled, it is necessary to set up working methods for the operators and specifications for the powder reuse (Tang, Qian, Liu et al., 2015). The handling and reuse of powder is further discussed in chapter 3.5.3 Feedstock.

3.5.8 **Post processing**

3.5.8.1 The Process

After the build is taken out from the building chamber and the powder is removed, the next step in the manufacturing process is post processing. The aim of post processing is to improve and prepare the manufactured part for its application. The needs for post processing differ from part to part and the demand depends on the PBFT, the application and the requirements on the finished part. (Yang et al., 2017)

A general process flow of post processing for L-PBF could be the following:

1. Residual stress relief
2. Removal from build plate
3. Heat treatment
4. Removal of support structures

5. Surface finish (Diegel, Nordin & Motte, 2019)

It should be stated that the only required step is removal from the building plate, even if residual stress relief is highly recommended. The remaining steps are optional and the configurations of them depend on the design and the requirements of the part. (Yang et al., 2017)

All metal AM parts are required to be processed with thermal stress relief to remove all residual stresses due to rapid melting and solidification during the building. These residual stresses can cause warpage but by eliminating residual stresses in the part, the risk of distortion when removing the build plate is minimized. Therefore, the residual stress relief is performed before the removal of the support structures. The removal of support structures implies the removal of the building plate. (Gibson, Rosen & Stucker, 2015)

Other heat treatments than the residual stress relief, e.g. hot isostatic pressing, are optional and due to economic aspects often only performed if required for application (Gibson, Rosen & Stucker, 2015). These heat treatments are performed to improve material properties, e.g. increase density by removing defects. (Yang et al., 2017).

The final step in post processing is surface treatment, finishing the outer layer of the part for aesthetic or performance reasons. There are several different methods available for surface treatments, resulting in different properties (Diegel, Nordin & Motte, 2019).

3.5.8.2 The Qualification

The qualification is partly focusing on the execution of the process, but also on the part quality. Qualification of the part quality is further discussed in chapter 3.5.9 Inspection and testing.

It is important to ensure that the setup of post processing is developed with regards to the part's requirements. To be able to achieve the requested properties the post processing methods have to be chosen carefully. (Gibson, Rosen & Stucker, 2015)

Validating one post processing method of AM-parts is not different from validating the same method for post processing of a conventional manufactured part. This does not include AM specific procedures e.g. support removal. According to the standard *Additive manufacturing* -

General principles - Requirements for purchased AM parts (SS-EN ISO/ASTM 52901:2018) the processes should be performed in accordance with applicable standards, standards which are non-customized for AM but are rather general for the post processing method.

3.5.9 **Inspection and testing**

3.5.9.1 The Process

The process step of inspection and testing could offer reassurance of the feedstock material, the product and the process. The inspection and testing of the part depend on the requirements of the part and its end application. Standardized tests for mechanical properties, e.g. tensile strength and fatigue resistance can be used to ensure quality of AM parts. (Seifi et al., 2017)

In the SIS issued standard *Additive manufacturing – General principles – Part 3: Main characteristics and corresponding test methods* (SS-EN ISO 17296-3:2016), the quality characteristics for different areas of requirements of AM are described and referenced to the corresponding ISO standards for testing. It is stated that tests should be performed in accordance with standards developed for the material and the requirement rather than for AM, e.g. validating surface finish by measuring the surface texture according to *Geometrical product specifications (GPS) - Surface texture: Profile method - Rules and procedures for the assessment of surface texture* (ISO 4288:1996). This standard is not specific for AM, it is focused on the measurement independent of manufacturing methods.

The available test methods for inspection and testing of parts are divided into non-destructive testing (NDT) and destructive testing, where the destructive testing method will break or damage the test geometry and in non-destructive testing, the material or sample will not be harmed (NE, n.d.b).

NDT is primarily used for inspection and guarantee of product quality. This is applicable to the built part or raw material of powder. NDT methods especially applicable for L-PBF include:

- Visual inspection and measurements
- Liquid penetrant testing
- Eddy current testing
- Radiography (CT)
- Thermography
- Ultrasonic testing (Lu & Wong, 2018)

Destructive testing is executed to verify the material properties of the built part. According to the parts requirements destructive testing can be applied to test samples or test artifacts (Lu & Wong, 2018). Examples of destructive testing are tensile testing, impact testing and fatigue testing. As understood, the destructive testing of a specific part or sample, destroys the specific geometry hence it cannot be used in another application (NE, n.d.b).

3.5.9.2 The Qualification

The quality verification of *Inspection and Testing* is to perform the correct and appropriate testing for the end application of the produced part. NDT can be performed on built parts, to guarantee the quality without sacrificing the parts. Test artifacts and test samples are geometries that can be used to evaluate a build process and collect efficient testing data. (Rebaioli & Fassi, 2017)

3.5.9.2.1 Test artifacts

Test artifacts could be divided into two different categories that are described below.

- Standardized or machine-specific test artifacts

A test artifact is a built geometry, or several geometries, that can evaluate and compare characteristics of AM machines and processes (Rebaioli & Fassi, 2017). Test artifacts could be standardized to apply to different kinds of AM system machines or techniques. The SIS issued standard *Additive manufacturing – Test artifacts – Geometric capability assessment of additive manufacturing systems* (SS-EN ISO/ASTM 52902:2019) offers a standardized collection of geometries that allows testing of the abilities of a manufacturing system, e.g. holes, wall thickness and angles. Test artifacts could also be included or purchased as a standard for a specific AM machine.

- Company, industry or machine-designed artifact

A specific company or industry could also design their own test artifact consisting of geometries that enable testing of a specific function of a feature, part or process. The design artifact could also show how the process of building a part or several parts will develop and the specifics regarding the building process. (Dordlofva, 2020)

3.5.9.2.2 Test samples

Test samples can be in various shapes, from simpler geometrical shapes to more complex geometries. They can also be in a shape resembling or replicating a component. (Dordlofva, 2020)

Test samples, also called test coupons, can either be built for material testing e.g. according to ISO standards, customer requirements, or to provide for quality and statistical process control. The samples used for statistically based control could for example be specimens used for tensile and fatigue testing or density cubes for microstructural analysis (Brandão et al., 2017). The test samples could also be of pyramided structure in order to sample and seal an amount of powder to achieve traceability (Orme et al., 2017).

The issued concern with test samples is similarity in mechanical properties between the test samples and the actual component because of the different size, geometry and sensitivity of changed process parameters. This is because their differences will change the thermal history which could affect different components' microstructure and defects in the material. (Seifi et al., 2017)

The actual testing of the samples should preferably follow standards for the material and manufacturing process, e.g. according to the SIS issued standard *Additive manufacturing – General principles – Part 3: Main characteristics and corresponding test methods* (SS-EN ISO 17296-3:2016). Since specific testing methods are not fully developed for AM, standards for conventional production testing could be performed. Testing and inspection could also be executed to gather knowledge and data about material or the process. According to the SIS issued standard - *Additive manufacturing – General principles – Requirements for purchased AM parts* (SS-EN ISO/ASTM 52901:2018), the inspection and testing of purchased AM parts, should be predetermined in an *Inspection plan* including test methods and acceptance criteria for the application of the part in prior to manufacturing.

To further ensure the quality of the testing methods, it is important to apply correct measurements for the end parts application. It is also to ensure well-working and calibrated measuring instruments. Calibration is an important step of quality assurance. (NE, n.d.a)

4. Results from case study

In this chapter, the results from the conducted case study are presented. The results from the interviews conducted in the industry are presented in categories of subjects and as a summarising result. The result from the data collection at Alfa Laval is presented in terms of qualification and criticalities.

4.1 Interviews within the industry

Presented in this section are answers from five conducted interviews. The interviews were held with engineers with expertise in AM. The participants are working in the industry, with positions as researchers or managers within research and development and/or qualification of AM. As AM is a relatively new manufacturing method, the amount of companies working industrially with AM is restricted. This limited the research possibilities. The number of interviews was stopped once the data collection deemed to be sufficient, also taking into account the time limit of the thesis.

In Table 4.1, every interview (I) is described with a number of participants and a company reference (C). In general, every company had one interview with one interviewee present, but it should be noted that in I1, three persons participated. Furthermore, I4 and I5 were conducted with interviewees from the same company. The interview abbreviations will be used to present the result from the conducted interviews.

Table 4.1. Interview and company reference to conducted interviews.

Conducted interview	*Abbreviation*	*Company reference*	*Participants*
Interview 1	I1	C1	3
Interview 2	I2	C2	1
Interview 3	I3	C3	1
Interview 4	I4	C4	1
Interview 5	I5	C4	1

The following result is based on each of the individual interview's statements. In Appendix B – Interview questions the questions asked in the interviews of C2, C3 and C4 can be viewed. In Appendix C – Interview questions for powder suppliers the questions asked for C1 can be viewed. The questions for C1 are slightly altered in regard to different expertise of the interviewed company.

4.1.1 **Results from the interviews**

4.1.1.1 Advantages and disadvantages of AM

In I4 it was expressed that the cost of AM is a problem when introducing it as a new manufacturing method. In I1, the opinion was also that the cost of AM is problematic. One of the interviewees expressed the technique is only useful and profitable if the application can pay for it. The company's perception of AM was however that it has a short lead time. One of the interviewees in I1 had the opinion that there will be a batch size of serial production advantageous for AM and the method should be adapting towards it.

In I4, a troubled transition period was expressed when a company shifts from researchers working with development of AM to serial production. The interviewee expressed that another competence is needed when this transition is taking place and the interviewee believed this competence is shortcoming. In I2, the opinion was that AM as a manufacturing method is yet not a success and it is difficult for AM to compete with traditional manufacturing methods that have been around for over 100 years.

One expression in I3 was the shift in responsibility of the quality of the end product, since AM manufacturers have a higher responsibility of the microstructure of products, compared to classic steel mills. The perception in I1 was that all machines are different which concludes in different building results of the same part and that the material can behave differently in different machines. In I1 it is also expressed that they do not believe the process of PBF is completely understood. On the other hand, the opinion of the interviewee in I4 was that there has been a general concern about the quality of AM parts, however this scepticism is starting to disappear.

In general, regarding the difficulties with process understanding and qualification procedures of AM, one interviewee in I1 said:

"All technologies have these problems."

These kinds of statements were commonly expressed during the different interviews. Even if AM has its issues, several of the interviewees believed AM should be considered as any other manufacturing method regarding development of the process and qualification procedures.

4.1.1.2 Qualification

The perception of the interviewee in I5 was that to use a quality management system such as the one used for other manufacturing methods, in their case based on the seven principles of quality management in ISO 9001. The foundation of ISO 9001 is extended by certifications, AM standards and other requirements from the customers. Their AM qualification process and quality assurance are divided into three parts: concerning equipment, development of product and production processes and production.

In I5 it was explained that a large part of the quality work is performed before the start of production with risk analysis and quality tools for validation. The interviewee explains that the quality of a product is ensured when the product is validated and when the requirements are fulfilled. In their production the quality and requirements are controlled, maintained and developed constantly through the model PDCA, plan-do-check-act (American Society for Quality, 2020).

The interviewee in I4 perceived three needs for qualification of the AM process, including product development, material properties and geometrical shape.

In I2 it was stated that the company uses artificial intelligence in combination with in-process monitoring to rate the severity of defects in every layer in a build. This enables qualifying a build if the evaluated layers have acceptable defects.

The opinion of the interviewees in I1 was that powder suppliers are important in the qualification of AM, since the process chain starts with them. They experienced problems qualifying AM-powder, due to improper requirements and difficulties ensuring them. They had the opinion that stability in the continuous process will be achieved when it is possible to put relevant specifications and ensure repeatability in the building process. Further, they stated the importance of qualifying the personnel.

4.1.1.3 Standards

In I4, the interviewee's opinion was that standards offer a structured way to work with quality processes, files, assurances of processes and testing. In I1, the interviewees also believed standards offer reassurance in a process. In I4, the interviewee expressed they do not use AM specific standards. However, they use ISO 9001 and for specific requirements they use AS9100. Their perception was also that companies use their own standards within their industries.

The interviewee in I5 was positively set to AM specific standards developed by e.g. ISO and ASTM. However, the perception of the interviewee was that the AM standards are not complete at the moment. If standards for AM are not available, the interviewee's opinion was that regular standards for testing can often but not always be used. In the end, the requirements from the customers are the most important, as stated in I5. Just as the interviewee in I5, the interviewee expressed in I3 that they perform tests that the customers require.

The opinion expressed in I3 is on the other hand that material testing within AM does not have to be applied to specific AM standards since the material testing is comparable to material testing of conventional manufacturing. However, the interviewee in I3 experienced that standards developed for particular testing of complex AM geometries could be used.

In I1, a belief that general standards written for other technologies are not always applicable to AM, was expressed. They also believed certification of powder suppliers are very important for companies' survival and they also wish for standard materials within the industry.

4.1.1.4 Simulations

In general, almost all companies' perception of simulation software within AM was that it would be a great support for the qualification processes in the future. The general opinion was that some developments of current commercial simulation software would be in place to make it more valuable and easier to use. More detailed explanations from the different interviewees are stated below.

In I4, the interviewee explained that their company partly uses simulation software in connection with AM. However, the interviewee expressed that there are needs for development of the commercial simulation software

available for AM today. In I5 it was explained that the company uses simulation tools in their product development process to predict failure, simulate support structures and predict geometrical- and material-related issues of builds.

In I3 it was stated that the company uses build process simulation that does not predict the melting, only the time of the build. On the other hand, in I2 it was mentioned that the company uses build job simulations based on FE to predict heat distribution and deformation in a build. In I1 the interviewees stated that the company does not use simulation for the time being. The interviewees expressed their opinion about AM simulations as too expensive and time consuming at the moment.

4.1.1.5 Monitoring

In I1, I3, I4 and I5 it was stated that the companies do not use continuous in-process monitoring for the moment. However, the interviewees expressed it could be a future possibility. The interviewee in I5 wanted to use melt pool monitoring to develop their process parameters but this was not possible for the time being. The opinion expressed in I1 was that since melt pool monitoring does not enable closed loop control, it is not developed enough to be useful for the moment. In I3 the interviewee also believed that closed loop control with continuous feedback will be relevant in the future, but a lot of testing is needed first.

The interviewee in I3 expressed that the current possibility of in-process monitoring is taking pictures of every layer and by combining the data with algorithms detecting flaws in the building process. One possible issue was highlighted in I1; the handling of big amount of data connected to the pictures taken of every layer in a building process. The interviewees also expressed the need to have an appropriate method to use the data.

The company in I2 stated that they use statistical process monitoring to rate the defects occurring in every layer with a machine learning-evaluation system. The data is processed through machine learning and therefore an operator only has to assess a few critical layers within the build. This monitoring and analysis can define characteristic features and acceptable limits in the building process. This method is an artificial created analysis and not scientifically based but works well according to the interviewee.

4.1.1.6 Powder

I5 it was stated that the company develops their own powder, and the interviewee's experience was that it provides a greater control for the AM process. The interviewee's opinion was that feedstock should be validated throughout the process and that a powder should be validated for the application, the specific process and the specific AM-machine. For powder verification, it was stated in I2 that the company takes samples of every powder batch.

In I1 the requirements on feedstock material was further discussed and the interviewees' perception was that the methods to characterize metal powder for AM are not sufficient. They argued that some common requirements are not of interest for AM-powder. One example used to illustrate the issue was flowability, a common property to demand, but since flow does not occur in all PBF-machines the requirement might be unnecessary. Further, they stated that requiring properties impossible to measure is another common problem. This occurs for example when particle shape is specified, e.g. with a photo of a particle, since there are millions of particles in the powder and analysing each particle is not feasible.

On the other hand, homogeneity is of greatest interest according to the interviewees in I1. Their experience was that homogeneity has to be ensured during all the handling, e.g. during storage, in the powder supply and powder bed. It was also stated that the company as powder suppliers do not provide handling instructions for the powder, but they give their customers storage advice. They also stated that an AM-manufacturer should have 2-3 powder suppliers, to ensure production even if one delivery of powder is cancelled or incorrect.

The reuse of powder was also mentioned. In I3 it was stated that the company does reuse powder, but it must be sieved beforehand to remove melt flakes, pins or similar. In contrast, the opinion expressed in I1 was that reuse of powder could be problematic because the powder could get contaminated when removing it from the chamber after a build job. During that process, the system is not fully closed. Therefore, the perception expressed in I1 was for now to always use virgin powder for AM, to be able to qualify the powder in the process.

4.1.1.7 Development of part and process

The interviewees had different perceptions of their development processes in regard to AM, e.g. depending on their use of the technology. The interviewee in I4 explained that their company is in the middle of a product development process, as the company is working towards serial production. In I5 it was explained that their company for instance follows the method Advance Product Quality Planning (APQP) for product development within AM, similar to development of manufacturing using a different technique. As for any other manufacturing method, the interviewee in I5 believed a development process must be in place for AM. The interviewee also believed it is common that people think they can skip the product development phase of AM and just build, which the interviewee did not agree with.

The company of I2 stated that the company is within serial production of AM parts and the interviewee explained the difficulties with adapting the technology to existing processes and manufacturing within the company. The interviewee believed it would be easier to start over and establish new procedures.

In I1, the interviewee mentioned that production and development is aimed to understand the process and the materials behaviour. In I3, the interviewee emphasized the ability that design changes in early product development can provide improvement in application and can also be used to minimize post processing of details.

4.1.1.8 Development of manufacturing process and process parameters

The interviewee in I5 experienced that the development of a manufacturing process is qualified partly in the product development, but also by risk analysis and development of process parameters. Other stages than the build process, e.g. post processing, in the manufacturing process are also to be qualified.

In I3, the development of a build process was discussed as the development of a melt theme, i.e. the setup of process parameters used in a build job. By qualifying the melt theme, the company stated to experience great control of the build process. The first stage in developing a melt theme is adjusting the sintering parameters and the second stage is adjusting the melt technical parameters. These settings are tuned in until desired properties are achieved and then the settings are frozen, just as with any manufacturing method according to the interviewee. The company in I2 divided this development

into two parts. First, the build process is determined, and the process parameters are developed iteratively. The adjustments of process parameters and part geometry continues until every layer in the build reaches acceptable values from the machine learning-evaluation system. Then the setup of process parameters is frozen, and the second stage is ensuring robustness and repeatability of the process.

It was stated in I1 that it is important to remember that building is only one of the processes included in the manufacturing, e.g. post processing and powder removal from the build also has to be developed and qualified.

Moreover, the interviewees in I1 experienced that during the development of a manufacturing process, it is difficult to develop the process parameters. The reason is the complexity and the number of parameters involved, requiring a very structured development process. The interviewees stated that the company does not sell process parameters for their materials, but they stated to have researched within the area since they held the opinion that a powder supplier should be able to answer questions about their materials. Further, they stated that machine-retailers are the ones developing the process parameters for the company's powder. Their experience was that buying powder from the machine-retailer is more expensive, but the price difference is the guarantee that the powder and the machine works well together. On the other hand, they highlighted the risk of buying process parameters from a machine-retailer. They questioned the reliability in the method, since the machine-retailer might not have enough competence within powder.

4.1.1.9 Continuous manufacturing process

The interviewee in I4 believed there were two options when qualifying the repeatability of a manufacturing process. One alternative is to build several test samples and measure the dispersion. The other alternative is to monitor the process and ensure continuous quality in the process. In I5, the interviewee explained that the company qualifies the continuous manufacturing process in two ways, by qualifying both production and performance of the part.

The interviewee in I3 experienced AM as a very repetitive process, unless the machine gets damaged. The company verifies the repeatability with the log from the process-monitoring and uses this to qualify continuous manufacturing processes.

To qualify a continuous manufacturing process, the interviewee in I2 explained that they use upper and lower limits for the layers evaluated by a machine learning system. The company perceived that a build job can be qualified if the values are within the restrictions.

In I1, the powder aspect of the qualification of a continuous manufacturing process was brought up. The interviewees stated that it is not the same thing to once fulfil the requirement for the powder and to continuously produce the same powder. And for the building process, it is important to ensure repeatability in the powder-spreading procedure for every layer, in their opinion.

4.1.1.10 Test samples

In I4, the interviewee explained that they use built test samples to ensure the metallurgy of the material by inspecting the microstructure of a test piece. With building and examination of the test samples, conclusions can be drawn if the material is acceptable. The interviewee in I5 explained they build at least four test cubes, one for each laser, in every corner of their build plate to ensure no variation occurs. They cut the cubes and study their cross sections with light optical microscopes. The interviewee in I5 explained they also build test samples in the shape of test specimens if needed, often based on customer requirements. It is stated in I1, that they also build four cubes in one build. They examine a cross section of the cubes showing porosities and microstructures. Up until now the company explained they have not seen any effect of different placements of the test samples on the building plate. In I2, the interviewee explained that they build witness coupons in every commercial building job.

In I3, it is explained that the company uses test samples in the shape of test specimens. They build a lot of test specimens in one build job to test the settings before building the actual part, the aim is to verify the melt theme. The building of test specimens is statistically motivated, and the specimens are built in and vertically towards the building direction. The interviewee in I3 explained that test samples can be applied to the same build job as the actual part as well, if the customer requires. Their perception is that it is not expensive to add a test samples in a build. The advanced part is the measurements that should be applied to it.

4.1.1.11 Test methods

When asking the companies questions regarding material testing, different answers were presented from the interviewees. In I4, the interviewee explained that testing to obtain the material- and geometrical quality in built parts was an important part of testing and qualification of AM.

The opinion expressed in I5 was that some testing methods specific for AM are missing today. The interviewee explained there are some testing methods for AM, however there are areas that need to be complemented and improved. The interviewee's opinion was also that a lot of people are unsure about the result of a build job and therefore a lot of unnecessary testing is performed.

The interviewee in I3, on the other hand, believed that material testing of AM components is just as for any other manufacturing method with regular testing methods applied. The interviewee did not believe specific standards for testing within AM is necessary but if so, maybe just for specific designs with advanced geometries of AM parts.

In I2, it is explained that NDT is executed on built parts, in suitable execution and scope. In I1, they explained that they also use NDT to verify issues in the material, whereof they mostly use visual inspection and CT scanning.

4.1.2 **Summarizing result of interviews within the industry**

In order to present a compilation of the interviews, the result was compressed and divided into four different categories: *Similarities*, *Differences*, *Issues* and *Future possibilities*. The compiled result is presented in each category below.

4.1.2.1 Similarities

There were expressed statements regarding similarity between AM and conventional manufacturing methods. Even if AM has the issues of low process understanding and qualification procedures of AM, many of the interviewees believed one should consider AM as any other manufacturing method in regard to development of the process and qualification procedures.

All of the companies use some sort of test samples. Either in the actual build of the part or in a build job before production. The test samples could be

placed on different areas of the building plate or be chosen in regard to the number of lasers. If cubes are built, they are usually cut and examined. Usually more test samples are built on customer requirements. Test specimens could also be built to verify the parameters of the machine.

Similarities between the companies' methods for developing process parameters can be seen. The companies stated to use development in an iterative process, changing the parameters until desired properties are achieved. When that occurs, the process is frozen, and the settings are used for production.

4.1.2.2 Differences

One expressed opinion is that material testing within AM does not have to be applied to specific AM standards since the material testing is comparable to material testing of conventional manufacturing. However, another interviewee's perception was that standards developed for particular testing of complex part geometries could be useful. In another interview a belief was expressed that general standards written for other technologies are not always applicable to AM.

In the interviews, there were different opinions regarding reusage of powder. In I3, it was explained that the company reuse powder, but it has to be sieved in beforehand. The opinion expressed in I1 was that reusage of metal powder can be problematic, and the quality of the powder cannot be verified if not tested further.

Not only similarities can be seen between the companies' methods for developing process parameters. It could be part specific or exclusively for the material and the machine. The latter option enables qualifying the parameters for more than one part.

4.1.2.3 Issues

In I4 and I1, it was expressed that the cost of AM is problematic. In I2, the opinion was that AM as a manufacturing method is yet not a success and it is difficult for AM to compete with traditional manufacturing methods that have been around for over 100 years.

In the interviews there were statements that AM standards are not complete at the moment and need development to be fully applicable.

Several problems concerning the powder were stated, regarding both the handling and storage but also specifications and testing. In I1 it was stated that irrelevant specifications on the powder are a common problem. Moreover, the interviewees in I1 highlighted the importance of requesting feasible tests to be able to ensure the quality of the raw material.

Another problem is the insufficiency of understanding AM. The interviewee in I5 stated that this has resulted in a common, but faulty, perception of lower needs for product development when working with AM. In contrast to that perception, the interviewee highlighted the importance of the product development phase for AM-parts.

4.1.2.4 Future possibilities

The general perception of computational tools for analysis within AM is that they need to be developed and improved. The interviewees agreed that there are future possibilities within simulations and monitoring, but percept needs for development for current software's. For monitoring, the interviewees were interested in closed loop monitoring and the ability to develop process parameters. Further, it was stated that the current main issue of monitoring is handling the huge amount of data to process. Therefore, the next development of monitoring would be artificial processing of the data.

4.2 Data collection at Alfa Laval

The collection of information about Alfa Laval's interest and way of working was performed during meetings and individual discussions, as well as through internal documents. Areas of interest for the applied study was Alfa Laval's way of working with AM and criticality. This information was collected to be able to apply a qualification approach to Alfa Laval's interests and adapt the strategy according to the company's prerequisites.

4.2.1 **AM within Alfa Laval**

Alfa Laval has the vision of AM becoming a new production technology in their new AM Technology Center in Eskilstuna. In Eskilstuna, the first implemented AM technique is L-PBF with the usage of the material stainless steel 316 L and the AM machine *Trumpf TruPrint 5000* equipped with three lasers. AM is a new manufacturing method for Alfa Laval, hence process

understanding of the technology and gradual build up for gathering knowledge and experience is needed.

As Alfa Laval is gradually building up their competence and AM production, their start-up phase includes manufacturing of components in different sizes, volume and criticality levels.

The production includes manufacturing of spare parts to their systems. Manufacturing spare parts could be a one-time manufacturing where the company wants to be able to rely on the manufactured end product with as strong reliability as with other manufacturing methods used within the company. When manufacturing individual spare parts, the aspect of reducing cost and minimize time for development of procedures comes in place. The company wants to be able to make AM a competitive manufacturing method with minimal lead time.

An expressed desire from Alfa Laval is a sustainable strategy to qualify components of different geometry and size. As Alfa Laval is not yet using AM for developing new products designed for AM or as a serial manufacturing method, this aspect had to be considered in this thesis and the recommendations for the company. The production in use right now will be applicable to one-time manufacturing or smaller series, with existing or adapted products. Another expressed desire from Alfa Laval, is to not evaluate the raw material in depth or their working methods and routines in the factory.

4.2.2 **Criticality within Alfa Laval**

Classification of a part's criticality is based on a risk assessment at Alfa Laval. It depends on the impact on the product or system emerging if the part is damaged. The impact on the system could be physical damage and/or contamination of the customer's product in the system. The classifications at Alfa Laval differ between the product groups and are primarily established for conventional manufacturing methods. Therefore, the AM-specialist at Alfa Laval has the intention to redefine the criticality classification to better suit AM. In the AM-based configuration there are three classes of criticality: high, medium and low. High criticality is for safety critical parts and medium criticality are for functional parts that are not safety critical, meaning lower severity of failure. Low criticality is for static parts without dynamic loading. The low criticality parts are equally important to fulfil required performance;

however, the consistency can be established through a reliable build process and therefore not with extensive part-specific testing. Therefore, only geometrical dimensions are to be inspected after the manufacturing of a low critical part at Alfa Laval.

5 Recommendations and discussion

In this chapter the recommended general concept of qualification and the qualification strategy of dividing products into criticality levels according to Alfa Laval's interests is presented. An option to qualify products in product families is also discussed and short chapter of the future of qualification of AM parts is presented. In the end, the methodology and presented concept and strategy is evaluated.

5.1 General concept of qualification steps

The four step qualification is a concept developed for the general qualification process of AM and aims to qualify the input, the AM process and the output. The concept is developed from the material collected in the literature study and the interviews. The concept's content is based on analyses of the results. Therefore, the concept is applicable for L-PFB in metal AM. Other prerequisites for the concept are to be found in chapter *5.1.1 Presumptions and limitations of the concept.*

The qualification process is divided into four steps in *The four step qualification.* The steps are:

- Qualification of raw material
- Qualification of equipment
- Qualification of part and process
- Qualification of performance

The sequence of these steps can be seen in Figure 5.1. The qualification of raw material and equipment is to be performed before the build job is started, regardless of building a test artifact or a part. Qualification of part and process is a step to be fulfilled before the building of the part. After the build process is finished, the qualification of performance is to be accomplished. The qualification of performance focuses on qualifying the AM process and manufacturing output. The qualification of the post processing activities will not be handled in this concept for qualification although they are included as

the last section of the manufacturing. Validation of the product development and the manufacturing process are not a part of the qualification steps.

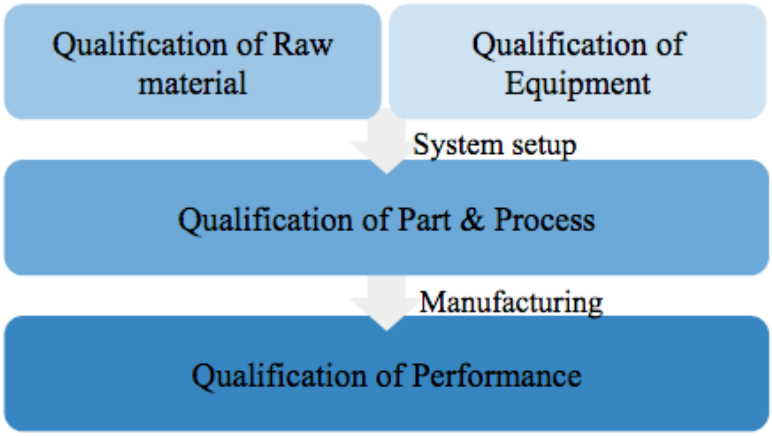

Figure 5.1. The sequence of the four qualification steps.

Every step in the concept is to be fulfilled in a qualification process. How it is fulfilled is not determined since there are several different methods to qualify a step and the aim of the concept is to be general. Therefore, options of approaches to fulfil the qualification are mentioned. In chapter 5.3 The four step qualification concept, the purpose of each step is described and followed with explanations of what to qualify and approaches for the performance. Since the concept is general, it is possible to adjust the method to use within the qualification of a step, enabling possibilities to adapt strategies in the qualification process to suit the interest of the additive manufacturer.

5.2 Presumptions and limitations to the concept

Since qualification of AM covers large amounts of activities and parameters, the concept of *the four step qualification* has to be limited to make it manageable and usable. Some actions have to be predefined and predetermined in order for the concept to work. Validation of the development procedures, that are heavily anchored to qualification of AM, are also handled as a separate procedure when presenting the concept. Since the concept is developed based on results from the literature study and interviews, there is reservation for overreaching specific details of

qualification for AM within this concept. Below actions are presumed in order to use *the four step qualification*:

5.2.1 **Predetermined actions**

The predetermined actions should be as follows:

- Assess risks and establish manufacturing plan

In order to determine the right strategy of qualification for an AM part, a risk assessment of the part should be performed, to establish which level of criticality the AM part should have and therefore what strategy or actions that should be carried out throughout the qualification procedures.

In order to be able to have repeatable processes and traceability throughout the AM process, inspection-, test- and process-plans should be configured and set up. The plans could include test methods, acceptance criteria, instructions, routines and execution according to companies' individual preference and regular routines.

- Validation of development phases

Another presumed action is the development phases of product development, process parameter development and continuous improvements. The development phases are as mentioned connected with the qualification procedures, since the more time and effort that is put into development, the more reliable will a process and its outcome be. The development phases can also be processes executed simultaneously with the qualification steps. Within the development phases are also continuous improvements by failure analysis and the usage of the PDCA-cycle. The improvements are important in both development phases, but also within the qualification steps in order to improve the processes.

- Qualification of personnel

Another presumption for the qualification steps is qualified personnel. The personnel should have the right competence or training for the manufacturing and the different actions included in qualification. Experienced personnel are also an advantage, as with any other manufacturing technique.

5.2.2 **Consistency in working methods**

Consistency in working methods by the usage of standards are important since companies and industries should follow similar paths for qualification of AM to improve reliability in the processes. AM standards are not fully developed for industry application today, however many new AM standards are currently under development. Customer requirements on components will in the end determine the requirements of AM parts. In conclusion, consistency in working methods can be fulfilled by ISO standards, application specific standards, AM specific standards and customer requirements and/or generally implied or obligatory requirements.

5.2.3 **Continuous documentation throughout the process**

Another important action to be carried out throughout the qualification steps is continuous documentation. This offers traceability and reliability of the process. The continuous documentation could be performed according to company's individual preferences and regular routines.

5.3 The four step qualification concept

5.3.1 **Step 1: Qualification of raw material**

Included in the first step of qualification, *Qualification of raw material*, is powder verification. The qualification step is to be fulfilled before the powder is used, i.e. before the building process starts, to ensure quality of the used feedstock.

5.3.1.1 Powder verification

Verification of the powder improves reliability in the AM process. Furthermore, reproducibility can be improved since the verification ensures that the powder in every build has the desired properties. When verifying the powder, the results from the tests performed on the powder provide data for traceability.

5.3.1.1.1 Approaches to achieve powder verification

- Material specification and test plan

The foundation of powder verification is the material specification. With procedures according to a test plan, the powder is to be verified for the material specification to ensure correct properties. The powder can either be produced by the company or bought from a supplier. This does not affect the material specification but can affect the amount of testing required to ensure correct powder characteristics. If the powder is supplied, its requirements are agreed on and feedstock controls are only made to verify the delivery. Furthermore, certification of the supplier, e.g. according to ISO 9001, can improve its reliability and the quality of the delivered powder.

- Verification of virgin powder

The powder in an AM-system is either virgin or reused. Virgin powder delivered from a supplier has to be verified at arrival. These feedstock controls can be performed for samples of every batch to ensure the material specification is met. Sampling can also be used for traceability.

- Verification of reused powder

If the powder is to be reused it has to be analysed after the sieving procedure but before the reusage. The verification is performed by feedstock controls according to the test plan. Sampling of powder is also to be used for traceability reasons, even if the traceability is reduced by reused powder since the powder is mixed with virgin powder. Mixing the powder requires extra sampling and testing since the mixture is unique for every build job.

- Handling and storage routines

The powder is stored between the supplier's delivery or own powder manufacturing upon the production of AM components. Therefore, storage and handling routines are required to maintain the powder characteristics. If uncertainties about the preservation of the material properties arise during storage or handling, the powder is to be verified according to the test plan again.

5.3.2 **Step 2: Qualification of equipment**

Included in the second qualification step, *Qualification of equipment,* is verification of the AM-system. Included in the verification of the AM-system

is both hardware and software related activities. The qualification of equipment has to take place before the building of a part to enable a reliable result.

5.3.2.1 Verification of the AM-system

The purpose of the verification of the AM-system is to generate reliability, reproducibility and traceability throughout the process. The verification of the AM-system includes maintenance of the machine, tools and physical equipment connected to producing an AM part. Included in the verification of the AM-system is also the machine setup, which connects hardware and software related setup.

5.3.2.1.1 Approaches to achieve verification of the AM-system

The verification of the AM-system is mainly achieved by continuous maintenance of all equipment involved in the process, which involves:

- Diagnosis of equipment

To ensure the quality of the AM-system, diagnosis of e.g. the AM-machine can be carried out through a test artifact. The standardised test artifact can be built on a regular basis, e.g. every third month or with every new batch of material and be compared to a test artifact built under optimal conditions. The test artifact would serve as the basis of a failure analysis and therefore the diagnosis of the system.

- Calibration of system

Regular calibration of all the components of the AM-system including measuring instruments and tools is an important step of verification of the AM-system. This to ensure well working and reliable components used in the process in order to enable a reliable result. The calibration should be executed by qualified personnel.

- Routine control

Routine controls of all components and physical equipment involved in the AM process is also important to enable reliable results. The routine controls should include instructions and documentation for the personnel to ensure that the controls are carried out in the right way and documented for possible traceability. The routine control includes regular cleaning of the AM-system.

The verification of the AM-system is also achieved by qualifying the machine setup. The machine setup includes all the activities connected to

setting up the machine for a build job, including the software system and quality of the CAD-file. The set up could include the following activities:

- Levelling the build plate, the initial layer and the recoater.
- Controlled feedstock loading.
- Software control, e.g. file quality or control of the software system.

5.3.3 **Step 3: Qualification of part and process**

Included in the third step, *Qualification of part and process*, is qualification of the process and qualification of the part requirements. This step takes place before the manufacturing of the end product is initiated to ensure buildability and reliable results in advance. Depending on criticality of the end product, different actions can be taken in this qualification step.

5.3.3.1 Qualify process

The qualification of the process is performed to ensure that the manufacturing process is feasible. Not all actions in this qualification step are part-specific, therefore a qualified process could in theory be used for manufacturing of different parts if the process remains frozen. However, since AM is dependent on every built part's geometry and the specific process parameters assigned to it, a successful manufacturing process could not always be guaranteed even if the process is frozen. If any of the input parameters of the process are changed the qualification should be repeated.

5.3.3.1.1 Approaches to achieve a qualified process

To achieve buildability, four different approaches can be used:

- Build job simulations

It is possible to predict whether a build job will be successful or not with simulations. By using build process simulation, properties such as warpage and failures can be predicted. The disadvantage of using simulations is the difficulty in verifying the result by ensuring similarity between the actual build process and the simulation. Furthermore, this approach could be expensive since it requires investments in software and validation of the simulation result. The simulations demand great computational power and can be time consuming.

- DfAM, design guidelines and limitations

DfAM guidelines is the simpler procedure that can be used to evaluate the equipment constraints and appropriate and buildable designs. It can be based

both on experience and the guidelines of DfAM. By following the limitations and guidelines in DfAM when qualifying the design, buildability of the design in the AM-system can be ensured.

- Test artifacts, to evaluate critical design features

Test artifacts can be used to evaluate if critical design features are buildable. The artifact can be designed with simple geometries or specific details of one or several common part designs. When the artifact is built, it is to be measured and tested to evaluate if the build satisfies the requirements on the critical design features. This method could be time consuming, because both building and testing takes time. In addition, designing a specific test artifact could also be time consuming. One option to reduce time is to purchase a standardized test artifact, with the risk of reducing the similarity between the actual part and the test artifact, which is also a disadvantage of this method.

- Evaluate material properties - build, test and evaluate test samples

Another approach to qualifying the process is to evaluate the material properties of several test samples. This is to test and evaluate the process in accordance to a material and a set of process parameters. The test samples are built and evaluated according to specific testing methods, and therefore a process can be qualified.

5.3.3.2 Qualify part requirements

Validation of part specific requirements are executed to ensure that the part will have the correct mechanical, surface, density, physical/physicochemical and geometrical/dimensional properties. This step of qualification will not be relevant to all components since it can be expensive and time-consuming. The application will therefore mostly apply to highly critical components where it is crucial that the component meets the requirements.

This step of qualification will be achieved just before the manufacturing of the end component. If the evaluated result is as predicted all the parameters associated with the process and product should be frozen to ensure the predicted quality of the later produced end component.

5.3.3.1.1 Approaches to achieve qualified part requirements

- Computational tools for design analysis

Computational tools in the form of FEA can be used to partly validate part specific requirements, however the process parameters and characteristics of each AM machine will affect the materials properties of the end product.

Build process simulations can also be used to gather better understanding of a function of a material, part geometry and process parameters.

The usage of computational tools could eliminate the costly aspect of manufacturing and testing samples. However, as mentioned in the interviews, the commercial software available today may still be time-consuming and the results may not always be as sufficient as wanted. For this purpose, test samples may still have to be built to gather an understanding of an AM process and to achieve validation of part specific requirements, especially when building highly critical components.

- Build test samples, to test and evaluate

Validation for part specific requirements can be achieved by building one or several test samples. This would be used to test and evaluate part properties and part performance. The test sample could be in the shape of the actual part or shapes with similar critical features of the part. Testing and evaluation of test samples can offer validation of the parts' requirements and therefore part qualification. The testing of the test samples could include controls of geometrical, dimensional and material properties. The material properties could include surface, mechanical, density and physical and physicochemical properties.

The disadvantage of building test samples is that it can be time-consuming and therefore costly, depending on the extent of the shape. If the shape is not a replica of the actual component, it can also be time-consuming to develop the suitable geometry and to achieve confidence in similarity between the geometry and the end component, since AM components highly depend on design and geometry. The evaluation of the result could also be an issue in this process.

5.3.4 **Step 4: Qualification of performance**

Included in the fourth step, *Qualification of performance*, is both qualification of a manufacturing process and of a continuous manufacturing process. Moreover, this includes quality controls of part performance and process. The qualification step is to be performed after the manufacturing of parts starts and the aim is to qualify the AM process and the output. The scope of this qualification step is heavily dependent on the part's criticality.

5.3.4.1 Ensure quality of manufacturing process

By ensuring the quality of a manufacturing process it is possible to qualify the part after it is built. This is to be achieved with quality controls of part performance and control of the build process. The scope of these controls depends on the criticality of the part, especially the controls of part performance depends on the importance for the part to fulfil its requirements. When ensuring quality and approving variations in the build process, the result is reliability in the manufacturing process. Furthermore, data from this qualification step can be used for the traceability of a part.

5.3.4.1.1 Approaches to achieve a qualified manufacturing process

The qualification is divided into two parts:

- Quality controls of part performance

The objective is to evaluate the part by dimensional and material testing according to the test plan. This qualification step is to be performed after post processing is executed, to test the final properties of the part. The testing is either destructive or non-destructive. NDT can be performed on test samples or on the built part in contrast to destructive testing, where only test samples are applied. The shape of test samples varies from test specimen for standard testing methods, to replicas of the part for sacrificial testing. The disadvantage of using test samples is the difficulty of verifying the result by ensuring similarity between the actual part and the test samples. It is also costly to perform testing and to build test samples. The NDT-methods can be advanced and provide data about the material's interior structure. The negative aspect is that it requires investments in expensive NDT equipment and qualified personnel for this testing. For less expensive NDT, such as visual inspection and measurements, testing applies only to the outside of the built part.

- Quality controls of process

Test samples can also be used for quality control of a process, the so-called statistical process controls. This qualification is to be performed when the build process is executed, only evaluating the AM process and excluding the aspects of post processing. The objective of the test samples is to determine variations in the process, e.g. variations due to drifting of the process parameters or due to differences between the lasers. The variation can be compared within one build or between several builds. As earlier mentioned, the disadvantages of test samples are the cost of testing and the difficulty of verifying the result by ensuring similarity between the actual part and the test sample. On the other hand, it is a method to evaluate the process without

destroying the built part and without using expensive NDT methods.

Another technique for quality control of a process is in-process or in-situ monitoring. From an in-situ monitoring it is possible to watch the build in real-time, which enables pausing an incorrect build or qualifying a correct build. In process monitoring and logging provides the operator with data which can be analysed after the build process is complete. From the analysis it is possible to qualify the build process. As pointed out in the interviews, the handling of the data is problematic due to the huge amount. Therefore, qualifying the build from monitoring data is rather a future possibility, when software has been developed to handle and evaluate the data.

5.3.4.2 Ensure quality of continuous manufacturing

The main objective of ensuring quality of a continuous manufacturing is to achieve reproducibility of the manufacturing process and to ensure consistent results of the builds. In addition, it improves the traceability of the manufactured parts.

5.3.4.2.1 Approaches to achieve a qualified continuous manufacturing

Ensuring quality of continuous manufacturing is similar to ensuring quality of a manufacturing process, including similar quality controls of part performance and process. The difference is the possibility to compare data from quality controls between several repeated build jobs and use statistical qualification in continuous manufacturing. Further, with continuous manufacturing it is possible to do quality controls with a frequency instead of testing every build. The frequency can differ, depending on the criticality of the part or reliability in the developed process. For lower criticality, the less frequent sampling for quality controls. On the contrary, for higher criticalities the quality controls need to be performed more regularly to ensure high quality in every build. This also affects the cost, since it increases with higher frequency of testing.

5.4 Recommendations for Alfa Laval

5.4.1 **Qualification strategy**

The four step qualification presented in chapter 5.3 The four step qualification concept is recommended to be implemented and adapted as a

qualification strategy at Alfa Laval. *The four step qualification* offers a broad and adequate approach to working with qualification of AM. From the results gathered throughout this thesis, it is important to have a systematic approach in working with qualification of AM and constant improvements, which the concept could offer.

The four step qualification is a general concept that can be adapted and optimised according to different prerequisites. The prerequisites within companies will probably differ in the near future as AM is a maturing technology and therefore the concept can be adapted accordingly.

A qualification strategy can make the concept more useful, by optimizing the fulfilment of each qualification step according to the prerequisites. By developing a strategy, the qualification process is to be adjusted for the interests of the company and making the qualification economically viable. In the following chapter, recommended strategies for Alfa Laval are presented based on the mentioned objectives for AM in chapter 4.2 Data collection at Alfa Laval.

5.4.2 **Criticality**

The choice of implementing the three criticality levels high, medium and low has the basis in an AM adaption of Alfa Laval's current system of dividing parts into five different criticality levels. To simplify the division, make it more applicable for AM and follow the intentions of future work at Alfa Laval, three levels were chosen. The choice of three levels of criticality was also strengthened by the division used in the AM standard *Additive manufacturing – General principles – Part 3: Main characteristics and corresponding test methods (ISO 17296-3:2014).*

The recommendation is therefore to perform a risk assessment of AM parts that can result in three different criticality levels at Alfa Laval: high, medium and low criticality. High criticality applies to safety critical parts, medium criticality applies to functional parts that are not safety critical and low criticality applies to non-functional parts.

The usage of the general concept *the four step qualification* could be optimized for Alfa Laval’s classification of criticalities and applied to each criticality level. Even if the concept is kept general, not every step is to be adjusted for a strategy. In this recommended strategy for Alfa Laval, the steps

of *Qualification of equipment* and *Qualification of raw material* are not adapted since minor changes will apply according to the parts' criticality. Therefore, the strategies presented only concern the steps of *Qualification of part and process* and *Qualification of performance*. The need of fulfilment of these steps varies with the criticality levels, how it varies will be presented in following chapters. A summary of the qualification stages needed for each criticality is presented in Table 5.1. This strategy development is based on the results from the literature study and the interviews within the industry, but the main aspect when determining the needs for different criticality levels is Alfa Laval's perception of qualification needs.

Table 5.1. The qualification strategy for each criticality.

Criticality	*Qualify process*	*Qualify part requirements*	*Production control of process*	*Production control of part*
High	Yes	Yes	Yes	Yes
Medium	Yes	No	Yes	Yes
Low	Yes	No	No	Only dimensional testing

5.4.2.1 High Criticality

The category *High Criticality* applies to parts that are highly or safety critical. The parts that apply to this category have critical application and demands. With the safety critical parts, it is of highest importance that every individual part fulfils its requirements. Within this category the recommendation is therefore that Alfa Laval applies the highest level of qualification strategy to the manufacturing of their parts. Within the qualification of this category, part specific testing is required before and after the manufacturing, complemented by process control of the build. For the time being, the part specific testing will require sacrificial testing of replicas of the part geometry to qualify the part requirements.

The strategy of qualification for highly critical components is demonstrated in Figure 5.2. The strategy is composed according to step 3: *Qualification of part and process*, and step 4: *Qualification of Performance*, with representing sub-steps. The four sub-steps included in the qualification strategy for highly critical parts are:

- Qualify process - qualifying the process to ensure that the manufacturing process is feasible.
- Qualify part requirements - qualifying the part requirements to ensure that the part specific requirements are met before manufacturing.

- Production control of the process - qualifying the build process by ensuring that the manufacturing process was performed as expected.
- Production control of part - qualifying the part by ensuring that its part requirements are fulfilled.

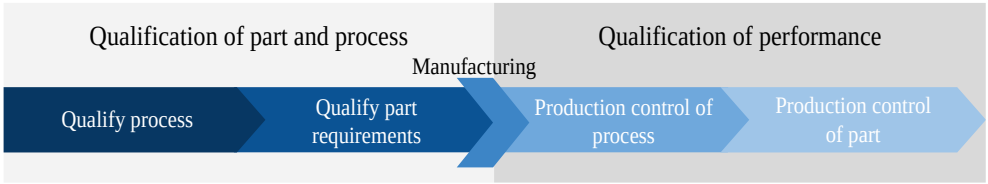

Figure 5.2. Qualification strategy for high criticality.

5.4.2.2 Medium Criticality

Parts of medium criticality are functional but not safety critical parts. This implies that the demands are not as high as for highly critical parts. It is less important to ensure that all the part's requirements are fulfilled, even if it is essential to meet the requirements. Part specific testing is required, but not before manufacturing as with the highly critical. Therefore, the difference between the qualification strategies for highly and medium critical parts is that the qualification of part requirements before manufacturing is not applied to the latter. Production controls are to be performed after manufacturing.

The qualification strategy for medium critical parts can be seen in Figure 5.3. From step 3: *Qualification of part and process,* and step 4: *Qualification of Performance*, are the three sub-steps included in this qualification strategy:

- Qualify process - qualifying the process to ensure that the manufacturing process is feasible.
- Production control of the process - qualifying the build process by ensuring that the manufacturing process was performed as expected.
- Production control of part - qualifying the part by ensuring that its part requirements are fulfilled.

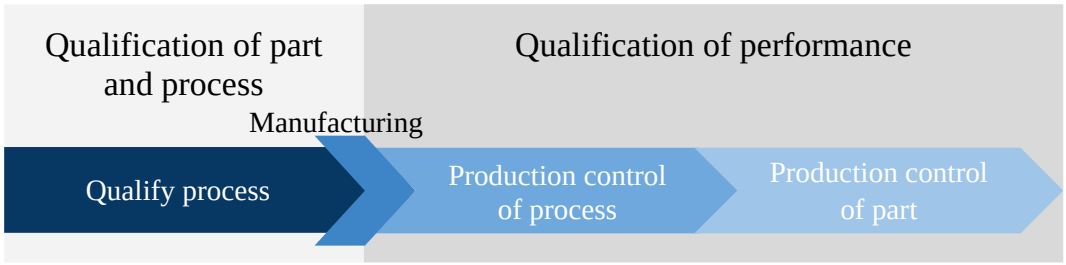

Figure 5.3. Qualification strategy for medium criticality.

5.4.2.3 Low Criticality

At Alfa Laval, non-functional parts classify within the category low criticality. For these parts, it is not as important that all part requirements are fulfilled in comparison to the higher criticality levels. Therefore, the only process that needs to be qualified in advance. The only required testing after manufacturing is dimensional testing. This is the lightest applied production control of parts and performed by visual inspections or measurements.

The qualification strategy for low critical parts can be seen in Figure 5.4. From step 3: *Qualification of part and process* and step 4: *Qualification of Performance* are the two sub-steps included in this qualification strategy:

- Qualify process - qualifying the process to ensure that the manufacturing process is feasible.
- Dimensional testing - qualifying the part by ensuring that its dimensional or geometrical requirements are fulfilled.

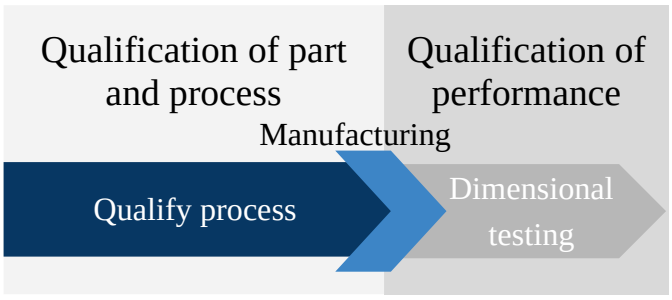

Figure 5.4. Qualification strategy for low criticality.

5.4.3 Product Family

As earlier mentioned, Alfa Laval is planning to use AM to manufacture several parts with low production volumes of each. Their objective is to minimize the cost of manufacturing by being able to qualify the first build of a part. To achieve this, the company has discussed qualifying several parts in one qualification process. The implementation could divide similar parts into product families and developing one common manufacturing method for the whole product family. The purpose of dividing products into families and enabling qualification of a groups with similar attributes is to reduce the cost and time for qualification. The method of qualifying a product family would also contribute to making AM a competitive manufacturing method if the method and results are reliable.

From the results gathered throughout this thesis, a possible solution to qualify product groups is to qualify a designed family-specific artifact with similar design attributes as defined by a product family. The family-specific artifact would undergo the earlier mentioned qualification steps to enable adequate qualification. If the artifact covers qualification for a whole group of products, sacrificial testing would not be needed for every individual part and a one-time manufacturing of a part would be possible. The important aspect of this possible solution would be to validate similarity between a family-specific artifact and the design attributes identified for the product groups. To enable reliable results, the family-specific artifact would have to be proven to be similar to the individual parts which would demand a lot of development and testing.

For the family-specific artifact of a product family it would be possible to adapt a qualification strategy from *the four step qualification*. The steps *Qualification of raw material* and *Qualification of equipment* would not be adjusted for this strategy. However, from the chapter 5.3.3 Step 3: Qualification of part and process, the qualification of process would be performed by the mentioned family-specific artifact. For highly critical parts, part qualification would be required as well. Depending on the similarities within the product family and between the developed family-specific artifact and the product family, this qualification could also be family specific. Otherwise, this step is to be performed part specific. When Step 3, *Qualification of part and process* is fulfilled for the product family, the step *Qualification of performance* is to be accomplished. The quality control of processes would be very important in this strategy to ensure correct output from the build process. Low variability, both within one build and between

builds within the product family, would qualify the build process and its output. On the other hand, this step would not be performed for low criticality products as mentioned in chapter 5.4.2.3 Low Criticality.

5.5 Feedback validation

5.5.1 **Feedback from Alfa Laval**

In order to validate the material presented and recommended in this thesis it was presented to three members of the AM project group at Alfa Laval. The collected material was compiled into the paragraph presented below. The validation was based on following questions:

- Are there any sections or facts presented that are unclear or incorrect?
- Do you have comments on the usefulness?
- Which areas are of interest for further development?

After a discussion with an AM-specialist within the project group at Alfa Laval, sections of the presented material were rearranged, clarified or changed. Smaller facts were also adjusted according to mentioned comments from the other members. In general, the majority of the presented material was perceived to be correct.

The concept seems to be useful for AM as a new technology at Alfa Laval according to one feedback provider. It was stated to be very broad, however the areas in focus were admitted as the most beneficial for the company. Another person agreed on the great focus areas and stated that it was good that the recommendations mainly concerned the AM process instead of post processing. In addition, it was mentioned that no further development of continuous manufacturing, e.g. for serial manufacturing, was of interest for the company. The most important aspect for the company was how many times a build is repeated, since it will probably be a one-time manufacturing or smaller series. With that stated, the possibility to adjust the concept was highlighted as great since optimizing the qualification would be very useful.

The importance of qualified personnel was emphasized. Alfa Laval has departments with distinctive expertise that can handle different aspects of the AM qualification process. To look further into the special expertise of personnel within Alfa Laval, would be interesting. Working with risk

assessments to strategize the general concept was well received and it could be further developed. Risk assessment is not regularly performed on every component at Alfa Laval, which could be a further development within the organisation. It was also mentioned that ishikawa diagrams could be used to assess the possible failure modes of different manufacturing processes. However, it was emphasized that it is broad and more practical examples on how to use it would be relevant.

5.5.2 **Third-party review**

Contact has been made to three external parties working and/or researching within AM for an external review of the presented material in this thesis. Two of the external parties did not answer. The third person works with advanced manufacturing processes in academia. The details of this third-party review were unfortunately not submitted in due time. However, some feedback was provided, and the person acknowledged that the presented work was clear and correct. Regarding the strategies the person expressed:

"I like the order you followed and I really like and agree the strategy presented for the case of Alfa Laval."

5.6 The future of qualification within AM

From the results gathered through research within this thesis, the opportunities of qualification of AM may be greater in the future with AM maturing as an industry applicable manufacturing method. The development of related technologies such as connected software programs are also to provide opportunities and support for qualification of AM in the future. AM as a computational manufacturing method also provides great conditions for digitalization, optimal for Industry 4.0.

In-process or in-situ monitoring was also a common future prospect expressed in the interviews. The in-process monitoring connected the usage of either machine learning for qualifying parts or closed-loop feedback would offer a great control of the AM process. With the development of this AM connected monitoring, the qualification of AM would most probably be very different and closer to all a software-controlled process. Simulations and FEA used for AM are also in current development and could therefore offer

considerable assistance in the development and qualification procedures of AM in the future.

For AM to become a mature manufacturing method, it was shown in the literature study as well as in the case study that it is important to improve the general understanding and reliability of the process. Furthermore, better understanding of the output from AM processes and the required testing have been stated as important steps for improving qualification of AM. One opportunity to achieve this is the development of AM standards. During the research of this thesis it was shown that both industry and academia is putting effort into development of AM standards.

5.7 Evaluation and discussion

5.7.1 **Evaluation of methodology**

The chosen methodology for this thesis was performing a theoretical study and a case study. The case study included a study of the industry and data collection at Alfa Laval. The research for the case study at companies working with AM consisted of semi-structured interviews. At Alfa Laval the data collection consisted of meetings, individual discussion and studies of documents. The choice of using a case-study approach as a method was well in regard to the purpose and task within this thesis, where the goal was to relate instances to a complex situation. However, the methodology could be evaluated and improved in some aspects.

The results from the theoretical study were collected before the empirical study commenced. Since the subject of AM and qualification for AM is a substantial subject, a lot of time was employed in the theoretical study. The theoretical study was carried out broad, which both had advantages and disadvantages when working with the results gathered from this thesis.

The methodology of the case study could have been improved in different ways. For the interviews, the amount of interviews was restricted due to the time limit of this thesis and the amount of companies working industrially with AM. With additional interviews, the understanding of AM in the industry could have been improved. Furthermore, the interviewees' responses were divergent in several questions. With a focus group or a

workshop with the interviewees, discussions could be held to provide nuanced answers on these complex questions. A more extensive case study could be achieved by interviewing international companies working with metal AM. This would lead to better representation of the technology worldwide.

For the research collection at Alfa Laval, a study visit to Alfa Laval's Technical Center in Eskilstuna was planned. The aim of the visit was to gain understanding of Alfa Laval's way of working by observations and discussions. Due to the current situation of the coronavirus outbreak, this visit was cancelled, and the needed information was collected differently. The study visit and a workshop at Alfa Laval could also have improved the quality of the applied case.

5.7.2 **Evaluation of the four step qualification**

The recommended concept presented in this thesis, is based on the results from the theoretical study and the interviews with companies working with AM. The concept is not practically applied at a company or established and tested step for step. Therefore, validation of the concept is gathered through feedback and third-party reviews. Although this offers points for validation, the concept should preferably be tested in practice to be fully validated.

The practical testing of an implementation could be difficult, since the concept would probably have to be used and tested during a longer period of time. The concept should also be used as foundation for developing qualification procedures, and therefore it could be difficult to apply a practical independent validation of the concept. The preferable validation of a successful concept would be a comparison to current procedures at a company. However, since AM is a new manufacturing method for Alfa Laval, fully comprehensive methods for qualification of AM are not implemented and the comparison cannot be performed.

The usability of the concept could be evaluated from different aspects. *The four step qualification* is a broad and general concept and one can question the usefulness of its broadness. First of all, the wide scope of the concept could lead to difficulties in understanding the varying importance of different parts. One problem could be different depths of details described. In addition to that, the coverage of the concept should be mentioned. With a broad

concept there is a risk of missing single important considerations. To reduce this risk, the concept was validated by several AM experts.

The concept presented in the chapter 5.3 The four step qualification concept is not to be used directly by a company. It should rather be used as a foundation for a qualification process, providing guidelines about needs and possibilities for qualifications. The concept should be adapted and adjusted to be useful, therefore it is more valuable when developed according to strategies. An advantage of the broadness is the ability to adapt the concept to different qualification processes with different objectives and prerequisites.

Furthermore, the usefulness of the concept for the industry could be discussed. For a thesis developed on the basis of academia, there is a risk that the outcome is not practical enough for the industry. To avoid this problem the concept was discussed and validated with several employees at Alfa Laval.

5.7.3 **Evaluation of recommendations for Alfa Laval**

The recommended strategy for Alfa Laval is based on *The four qualification steps* with adaptation according to the results from the data gathered through Alfa Laval. The general concept can be optimised according to recommended criticality levels and/or according to division of parts into product families.

Regarding the presented strategy of adapting the general concept according to criticality levels, there is a trade-off in the presented strategy since the goal is to not under-dimension nor over-dimension the procedures of qualification. The validation of the strategy according to this trade-off is based on feedback from employees at Alfa Laval. The criticality strategy is also validated by AM-specialists and employees at Alfa Laval working with quality management. However, practical testing of the strategy would be preferable to optimise the strategy to the right dimension of qualification procedures. As mentioned for the concept, practical testing of an implementation of the strategy could be difficult.

Within the secondly presented strategy regarding product families, different aspects of the solution with family-specific artifacts should be discussed. The main issue is to validate that the family-specific artifact corresponds in similarity to the built parts. However, this problem is not unique for this

solution since it occurs between every built part and test artifact or test sample. Another problem is to validate that the artifacts are family specific and correspond to every part in a product family. These validations will require comprehensive testing, increasing the time and cost for qualification. In addition, developing the family-specific artifacts would be time consuming. Since the aim of this strategy is to reduce the cost and the lead time, whether this solution satisfies the objectives is to be considered. From the results gathered throughout this thesis, it could be difficult to develop a strategy to qualify highly critical, one-time manufactured parts without sacrificial testing.

6. Conclusion

To be found in this chapter are concluding descriptions of how the research questions were answered. Further research to be conducted is also mentioned.

6.1 Achieving qualification of AM

In this section, how to achieve qualification of AM components is described through answering research question 1:

- RQ1 - What is qualification of AM and which process steps needs to be taken into consideration to achieve qualification for AM parts?

Research question 1 was answered through the presented literature study in chapter *3. Results from literature study.* The literature study presented in this thesis explains what qualification for AM is and existing fragments of research within the subject of AM. The question is answered in detail in the chapter 3.4 Qualification. To obtain the whole scope of qualification of AM, a study of the process steps of additive manufacturing and which qualification procedures that could be connected to each process step is presented in chapter 3.5 The process steps of additive manufacturing.

The literature study demonstrates that there are not a lot of established qualification procedures created for AM. The procedures or frameworks that were found, were seldom specialised for industry application. The most common research that was identified on qualification for AM, was for qualifying aerospace or highly critical components. The process steps of additive manufacturing explicate the complexity of AM as a manufacturing method and all of the crucial steps connected to the process. The steps identified for the AM process were: *CAD-model, preparation of file, feedstock, machine setup (further divided into hardware and process control), building, build removal, post processing* and *inspection and testing*. All of the steps have qualification procedures that can be connected to each step. The results from the literature study in combination with results from

the conducted interviews were used to build upon a concept for qualification, presented in chapter 5.3 The four step qualification concept. The qualification procedures were however rearranged to better suit qualification of AM components for companies with industry application.

6.2 Qualification of AM in the industry

In this section, how qualification of AM components is performed in the industry is described through answering research question 2:

- RQ2 - How are qualification processes for metal AM configured and executed at companies in industry today?

The case study answered research question 2 through interviews conducted with companies utilizing AM as a manufacturing method. The aim was to understand the issues and possibilities regarding qualification processes of metal AM in industry today. In chapter 4.1 Interviews within the industry, the answer to this research question is described with the results from the interviews. The results are presented in the subjects of *advantages and disadvantages, qualification, standards, simulations, monitoring, powder, development of part and process, development of manufacturing process and process parameters, continuous manufacturing process, test samples* and *test methods.*

From the interviews, conclusions can be drawn about qualification processes for metal AM in industry today. It has been shown that the companies often perceive AM as any conventional manufacturing method in regard to qualification of parts and product development. Further has the importance of product development in AM, as for any manufacturing method, been highlighted.

The results also showed that the qualification procedures were performed dissimilarly at the companies. For example, the qualification procedures of the interviewed companies differed depending on their area of using AM. Companies working towards using AM for serial production differed from companies using AM for building of single components. On the other hand, the concept for development of a manufacturing method was alike. Until desired properties were achieved the parameters were tuned in, thereafter the process was frozen.

In several questions, conclusions cannot be drawn based on the case study, since the interviewees disagreed with each other. One subject for disagreement was the reuse of powder. It was also stated that the understanding for the process of AM is currently insufficient and therefore the needs for qualification are not fully understood. There is still a need for conducting research within the area and applying it to the industry.

6.3 Qualification of AM at Alfa Laval

In this section, how to achieve qualification of AM components at Alfa Laval is described through answering research question 3:

- RQ3 - What aspects of qualification of AM does Alfa Laval need to consider and how could a qualification process for AM parts be configured?

With the gathered results from research question 1 and 2 as the foundation, combined with data collection at Alfa Laval the research question 3 was to be answered in chapter 5 Recommendations and discussion. In conclusion, the concept for qualification presented in chapter 5.3 The four step qualification concept, is recommended to be applied to Alfa Laval. The concept offers four main areas of qualification including: qualification of raw material, qualification of equipment, qualification of part and process and qualification of performance. The concept has its presumptions and limitations, presented in chapter 5.2 Presumptions and limitations to the concept, that have been taken into consideration if implemented. The concept would offer Alfa Laval a framework for qualification of their AM components.

With the objective to optimize the framework of qualification processes and increase its relevance for companies, strategies for the usage of the concept could be developed. The qualification process can be configured according to Alfa Laval's interests. In chapter 5.4.2 Criticality, a qualification strategy adapted after part criticality is presented. This is based on Alfa Laval's prospective criticality levels for AM parts and the qualification steps in the general concept are adapted for the criticalities: high, medium and low. For these levels, the qualification of part and process and qualification of performance are adapted. The qualification areas of equipment and raw material are not further developed for this strategy, since minor changes will apply.

Another presented area of interest in this thesis, is the possibility of qualifying product families, in order to obtain a sustainable qualification strategy for manufacturing of single spare parts. The subject is presented in the chapter 5.4.3 Product Family. The idea is to design family-specific artifacts that would cover critical design features of different products and would offer a sustainable way of qualifying single products. However, the development time and effort that this would take has to be taken into consideration and for the current state of AM within Alfa Laval, the possible strategy has to be investigated further in order to be recommended.

Gathered from the results of this thesis, a more standardised approach of qualification and way of working with AM would be in order. The procedures and organisational way of working with AM will probably differentiate from ways of working with qualification in traditional manufacturing methods. This aspect is important to have in mind when working, adapting or implementing qualification procedures for AM. A lot of the qualification procedures will also be a part of the product development procedures which demands early involvement of different functions within an organisation. Therefore, cross-functional competence sharing within an organisation and within industry is preferable to find effective ways of working with qualification of AM.

6.4 Recommendations for future research

As this thesis was limited to 20 weeks, it had to be restricted to a section of the possible research within the area. Within the subject of qualification of AM, many areas of interest are involved. The identified areas of interest that would preferably be a part of further research work within Alfa Laval or within the industry are listed below.

- Further validation

Further validation of the recommendations presented in this thesis is needed. As earlier mentioned, additional validation by implementation of the general concept and the strategies should be performed for a proper evaluation.

- Investigation of family-specific artifacts

To understand if the strategy regarding product families is applicable for Alfa Laval further research should be conducted. A family-specific artifact should

be developed and compared to the parts in a product family, to investigate if the strategy has potential.

- Serial production strategy

If the aim is to achieve serial production of AM components, other aspects are to be considered. The product development of AM components and the continuous manufacturing becomes more crucial. If this is the aim for Alfa Laval, more time and effort into investigating the strategy should be employed.

- Test samples and test methods

The appropriate test samples to be built for Alfa Laval's components and the test methods that should be conducted could be further investigated at Alfa Laval. As mentioned in this thesis, many believe unnecessary building and testing is performed due to uncertainty of the AM process. Therefore, this could be further practically investigated and developed in combination with different designed test samples. Test samples should also be compared to Alfa Laval's components to ensure similarity.

- Qualification of other AM methods

This thesis was limited to L-PBF and the result concerns only this method of AM. To widen the scope of qualification of metal AM and improve the understanding of other AM methods, similar research is to be conducted for other methods.

- Powder and powder reusage

The feedstock material of metallic powder has interest for further investigation both within Alfa Laval and within the industry in general. The suggested area of research would be how many times you can reuse powder, how much reused and/or mixed powder affects the quality of both the powder and built components and the health aspect of handling the powder. Another area of interest would be validation of different powders for different applications.

- Supportive software

In the research for this thesis, it has shown that the needs for simulation software and in-process monitoring are not fulfilled. The development needs for simulations are ensuring similarity between the simulation and the build. There is also a desire for optimizing development opportunities of process

parameters in the simulation software. For in-process monitoring, the main issues are lack of closed-loop feedback and handling large amounts of data.

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Appendix A – Project timeline

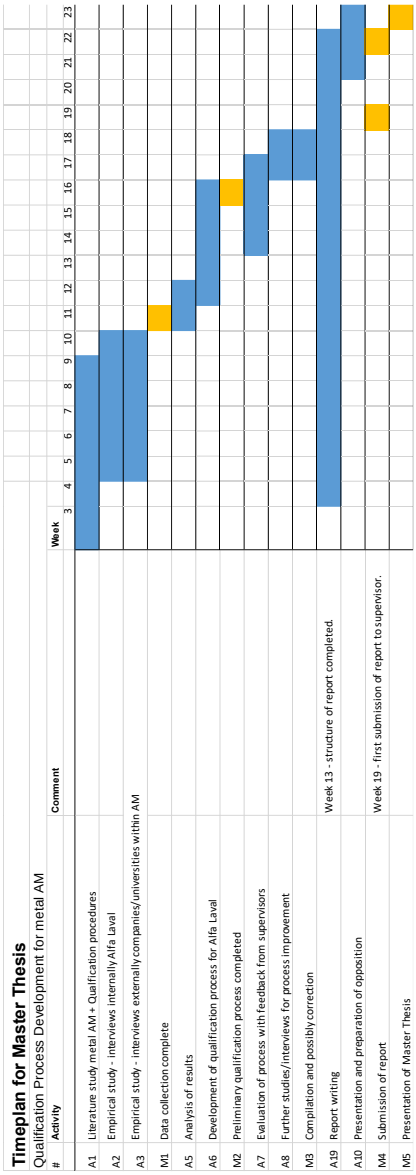

Figure A.1. The project time plan.

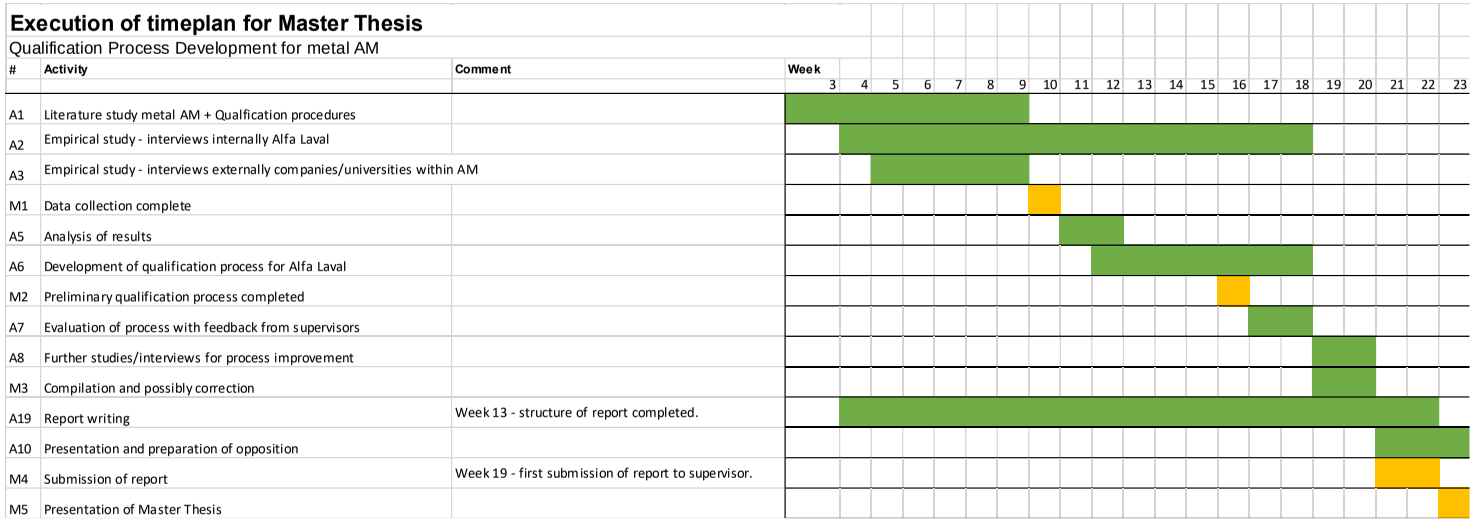

Figure A.2. The executed project timeline.

Appendix B – Interview questions

Interview topics and questions used for the C2, C3 and C4, companies divided into the group *manufacturers of AM parts* and *manufacturers of AM parts* and supplier of AM powder:

Main research questions for the interviews:

- How companies have developed or adapted their qualification processes for AM.
- How companies ensure stability in the AM process.
- Which are the main issues within qualification of AM.

General questions regarding qualification and AM-processes:

- Tell us briefly about yourself, you position at your company and your experience of AM.

- What is the purpose of your use of AM?
    - Do you have your own production? In which extent?

- Which techniques within AM are you using? And which material do you use?

- How do you company introduce and qualify new manufacturing techniques?
    - How does implementation of AM differ from other manufacturing methods?
    - What extra requirements does that imply to the qualification of AM?
    - Which steps of the manufacturing process for AM parts need to be qualified according to you?

- How is repeatability ensured in the AM process (parameters, material etc.)?
    - How do one understand when the process has stabilized?

- How has the qualification process for AM parts affected your product development phase?

- Accoring to you, what is the most important factor in the qualification process for AM?

- Which factor in the qualification process is the most difficult to control/monitor?

- According to you, what needs to be improved in the (qualification) process today?

- What is your opinion about:
    - Test geometries / test artifacts (reference objects)
    - Simulations
    - In process monitoring
    - AM-standards

Other:

- Do you have anything to add regarding AM or qualification processes?

Appendix C – Interview questions for powder suppliers

Interview topics and questions used for C1, *the supplier of AM powder*:
Main research questions for the interviews:

- Which role do supplier of AM powder have in the qualification process of AM.
    - What is their responsibility when going from powder to part.
- How companies ensure stability in the AM process.
- Which are the main issues within qualification of AM.

General questions regarding qualification, powder and AM-processes:

- Tell us briefly about yourself, you position at your company and your experience of AM/powder manufacturing for AM.

- What metallic materials for AM do you produce?
    - Which techniques are used for the manufacturing?

- What applications/industries are your powder mainly used in?

- Do you have your own additive manufacturing?
    - In what purpose do you use AM?
    - Do you work with test geometries and test artifacts?
    - How do you work with qualification of AM parts?

- How is your collaboration and exchange of information with customers and machine manufacturers regarding qualification of AM parts?

- Do you develop process parameters optimized for your material/machine?
    - What is taken into considerations then? What are the focus areas?

- What is your opinion about:
    - Reuse of powder
    - Handling and storage (recommendations?)
    - Powder characteristics

- What properties do you customers require?

- What requirements applies to powder for AM compared to powder used for other powder technologies for manufacturing?

- What is the challenge in qualification of AM powder compared to powder for other techniques (pressing, sintering, welding etc)?

- What is the most important factor in the qualification process for AM?

- Which factor in the qualification process is the most difficult to control/monitor?

Other:

- Do you have anything to add regarding AM or qualification processes?