Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Mechanical and Industrial Engineering

Kristian Bru

A mathematical model for evaluating spare parts qualification costs considering different manufacturing technologies

Master's thesis in Mechanical Engineering
Supervisor: Mirco Peron
Co-supervisor: Alessandra Cantini
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I would like to thank my supervisors, Mirco Peron and Alessandra Cantini, for their ideas, comments, and contacts throughout the semester.

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Summary

Ideally, companies store a sufficient amount of spare parts to avoid downtime while keeping the number of spare parts as low as possible to avoid high storage costs. However, efficient spare parts management can be challenging because it involves high-mix, low-volume parts and is often characterized by high service requirements coupled with unpredictable demand patterns. Additive manufacturing (AM), also known as 3D printing, has been identified as having the potential to overcome some of the above challenges thanks to a "print on demand" approach.

So far, however, the impact of qualification costs on when metal AM is economically convenient compared to conventional manufacturing (CM) has been overlooked. This lack of qualification assessment is a problem because costly and time-consuming non-standard testing is deterring the wider applications of metal AM, especially for critical end-use components.

Thus, this master thesis proposes an easy-to-use mathematical model for evaluating spare parts qualification costs for AM and CM. The developed model is based on the DNV-ST-B203 qualification standard, and it calculates costs for nine different qualification routes for both manufacturing technologies. The nine options are derived from 3 levels of criticality and their 3 case scenarios, ranging from best to worst-case.

A mixed-method approach was performed using qualitative and quantitative methods to develop the qualification model. The qualitative phase consisted of a literature review and a focus group meeting, which led to the qualification standard and assumptions underlying the model. This was followed by the quantitative phase, i.e., the development of the model itself and its application to two case studies.

The qualification model developed herein represents the main contribution of this master thesis since no tool has been developed so far to support managers and practitioners in evaluating qualification costs for AM and CM. Additionally, the two case studies demonstrated that the DNV-ST-B203 standard is, in many cases, too rigid and expensive. Consequently, promising metal AM spare part candidates were not necessarily as promising anymore by applying the qualification model.

Sammendrag

Ideelt sett lagrer bedrifter en tilstrekkelig mengde reservedeler for å unngå nedetid. Til gjengjeld er det ønskelig at lagerstørrelsen ikke overskrider hva som er nødvendig, da dette fører til høye lagerkostnader. Det å håndtere reservedeler på en god og effektiv måte kan imidlertid være utfordrende fordi det involverer deler med høy kompleksitet og lavt volum. I tillegg preges reservedeler av høye servicekrav kombinert med uforutsigbar etterspørsel. Additiv produksjon (AM), også kjent som 3D-utskrift, har blitt identifisert som en mulig løsning på flere av disse utfordringene takket være "print on demand" funksjonen ved slik teknologi.

Så langt er det imidlertid ikke kjent hvordan kvalifiseringskostnader påvirker evaluering av økonomisk lønnsomhet ved metall AM sammenlignet med konvensjonell produksjon (CM). Denne mangelen er et problem fordi kostbar og tidkrevende testing hindrer metall AM i å ha ett større nedslagsfelt i industrien, spesielt for kritiske reservedeler.

Målet med denne masteroppgaven var derfor å utvikle en brukervennlig matematisk modell for å evaluere kostnadene for kvalifisering av reservedeler for AM og CM. Modellen som ble utviklet er basert på kvalifikasjonsstandarden kjent som DNV-ST-B203, og den beregner kostnader for ni ulike kvalifiseringsveier for begge produksjonsteknologiene. De ni alternativene er et resultat av at en reservedel kan gjennomgå 3 ulike scenarioer for hver av de 3 nivåene av kritikalitet.

Modellen ble utviklet ved å kombinere kvalitative og kvantitative metoder. Den kvalitative fasen bestod av et litteraturstudium og et møte med eksperter innenfor fagfeltet. Dette resulterte i at nevnte kvalifikasjonsstandard ble valgt, samt at forutsetningene som lå til grunn for modellen, ble formulert. Deretter fulgte den kvantitative fasen hvor utviklingen av selve modellen ble gjennomført. I tillegg ble den anvendt på to casestudier.

Kvalifikasjonsmodellen representerer dermed det unike bidraget til denne masteroppgaven siden det så langt ikke er utviklet verktøy for å evaluere kvalifikasjonskostnader for AM og CM. Dette kan komme til god nytte for både bedrifter og forskere innenfor det aktuelle fagfeltet. I tillegg demonstrerte casestudiene at DNV-standarden i mange tilfeller er for omstendelig og derav dyr. En konsekvens av å bruke kvalifikasjonsmodellen var at det som opprinnelig ble sett på som lovende reservedeler for metall AM, ikke nødvendigvis var like lovende lengre.

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Abbreviations

AM	Additive Manufacturing
CM	Conventional Manufacturing
CAD	Computer Aided Design
PBF	Powder Bed Fusion
DT	Destructive Testing
NDT	Non-destructive Testing
BPQ	Build Process Qualification
PQ	Part Qualification
PT	Production Testing

1 Introduction

Ideally, companies store a sufficient amount of spare parts to avoid downtime while keeping the number of spare parts as low as possible to avoid high storage costs (Kretzschmar et al. 2018). However, efficient spare parts management can be challenging because it involves high-mix, low-volume parts and is often characterized by high service requirements coupled with extremely sporadic and unpredictable demand patterns (Chaudhuri et al. 2021; Frandsen et al. 2020; Sgarbossa et al. 2021). Furthermore, the strong dependency on suppliers and long procurement lead times makes spare parts planning even more complex (Peron et al. 2021). The situation is even worse for companies operating in remote geographical locations where investments in spare parts inventories can be huge. To illustrate, the US coast guard keeps more than 60000 spare parts in stock with an inventory value of more than $700 million (Westerweel et al. 2021).

Additive manufacturing (AM), also known as 3D printing, has been identified as having the potential to overcome some of the above challenges. Holmström et al. (2010) reports, among others, the following unique benefits of AM: tool-less manufacturing, short setup times, and economic "batch of one" production. Consequently, spare parts with high-mix can be produced on-demand or at least with substantially shorter lead times, reducing the need for high inventory levels (Kretzschmar et al. 2018). Moreover, utilizing decentralized and in-sourced AM may relax the dependency on suppliers and thus decrease the impact of supply disruptions (Cestana et al. 2019; Knofius et al. 2019).

The basic principle of this technology is that a model, initially generated using a 3D Computer-Aided Design (CAD) system, can be fabricated layer by layer directly without the need for process planning (Gibson et al. 2015). Several AM processes are available for the fabrication of metals, where Powder Bed Fusion (PBF) is the most common one (Gokuldoss et al. 2017). While the same benefits mentioned for AM apply to metal AM, the technology is less mature and currently limited to a few industry sectors such as dental, medical, construction, and aerospace (Redwood et al. 2017; Vafadar et al. 2021).

Despite the potential of AM, it is doubtful whether AM will replace conventional manufacturing (CM) methods. It appears more likely that they will complement each other (Zijm et al. 2019). Many studies address the dual sourcing problem where AM is used as the second source, including Liu et al. (2014), Song and Zhang (2020), Knofius et al. (2021, 2019), Cestana et al. (2019), Westerweel et al. (2021), Sgarbossa et al. (2021) and Lolli et al. (2022). These studies are mainly focused on the economic viability of AM. This is to be expected when both researchers and practitioners refer to AM parts' high production costs and uncertain failure rate, as the two main limitations that might hinder the transition from CM to AM (Peron et al. 2021).

However, an overlooked problem in the studies above and traditional cost modeling literature is that they do not account for qualification costs. Indeed, in AM and CM approaches, most models developed to assess product costs have focused on quantifying direct and indirect production costs without including, however, relevant cost components such as the cost of qualification (Verna et al. 2022).

This lack of qualification assessment is a problem because costly and time-consuming non-standard testing is deterring the wider applications of metal AM, especially for critical end-use components (Kandukuri and Le Gallo 2020). For instance, the combined cost of part qualification can reach almost as much as the part manufacturing and its associated costs in the case of metal parts (Romero et al. 2019). Thus, by not incorporating the qualification costs into the overall part cost, it is difficult to determine whether and to what extent metal AM is economically convenient compared to CM. This implies that an easy-to-use tool to support managers and practitioners in calculating and comparing qualification costs for AM and CM is highly warranted.

One way of addressing this need would be to develop a mathematical model based on a metal AM qualification standard. However, the inconsistency and complexity of each AM system have made it challenging to establish a standard set of rules for the technology (Pereira et al. 2019). Furthermore, standards development has always been a slow process since it is a voluntary option requiring multiple participants in a field to collaborate. At the same time, it is also difficult and time-consuming to obtain consensus on both general and technical aspects (Malkawi et al. 2021).

Nonetheless, several international and national standards organizations are actively involved with such matters (Chen et al. 2021; Malkawi et al. 2021; Seifi et al. 2017; Vendra et al. 2020). Consequently, the following research question will be answered first through a literature review:

> **RQ1)** What is the best metal AM qualification standard to use as a basis for a qualification model?

The literature review was part of the mixed-method methodology used for this thesis. An exploratory sequential design was the preferred choice, where the qualitative results from RQ1 were used to develop the quantitative mathematical model and thus answering RQ2:

> **RQ2)** How does a qualification model evaluate spare parts qualification costs differently for AM and CM?

An additional part of the qualitative phase, besides the literature review, was a discussion with experts within the applied AM domain. This discussion led to useful information for developing and validating different assumptions used in the mathematical model. Next, a python script was made based on the model to address this thesis's primary objective; to develop an easy-to-use mathematical model for evaluating spare parts qualification costs for AM and CM.

The remainder of the master thesis is organized as follows. In section 2, a literature review is provided, and RQ1 is answered. Additionally, the thesis is positioned within the literature, and the contribution is clarified. Section 3 describes the research design and the methodology followed to obtain the qualification model. Afterward, in section 4, an application of the model to two case studies is demonstrated. This is followed by section 5, where the results and limitations are discussed. Finally, Section 6 concludes the thesis.

2 Literature review

2.1 Qualification - Challenges with AM and how it is different from CM

Currently, metal AM part producers are applying the same destructive and non-destructive testing (DT and NTD) that are in place and required by industries like casting, forging, and metal injection molding, to name a few (Weaver 2019). However, this approach is not always suitable nor efficient for AM, especially for more complex parts. This is due to the vast capability of AM, referring to material variety and manufacturing process differentiation, which has resulted in multifaceted qualification requirements. For this reason, CM continues to dominate AM in quality, precision, and reliability (Pereira et al. 2019).

The multifaceted qualification requirements of metal AM are hindered by critical challenges in the aspects of design, materials, in-situ monitoring, post-processing, repeatability, traceability, standards, etc. (Thomas-Seale et al. 2018). The primary challenge is that the qualification process is underdeveloped and lacks adequate standards for many applications (Chen et al. 2021), especially for critical end-use components (e.g., parts facing corrosion in the oil and gas industry). From a business perspective, this challenge burdens them with high costs and prolonged lead time, making the adoption of metal AM less attractive. For instance, AM projects with rigorous and prolonged qualification processes have been reported to be millions of dollars in approximately a two-year period (Kandukuri and Ze 2021). Therefore, standards development is a key enabler for large-scale industrial application of metal AM (Vendra et al. 2020).

However, standards development has always been a slow process since it is a voluntary option requiring multiple participants in a field to collaborate, and it is difficult and time-consuming to obtain consensus on both general and technical aspects (Malkawi et al. 2021). This development is further exacerbated by the inconsistency and complexity of each AM system (Pereira et al. 2019). Firstly, an AM system has more dependent variables than CM (see Figure 1). For example, there are roughly 250 process variables for Direct Metal Laser Melting alone (Malkawi et al. 2021).

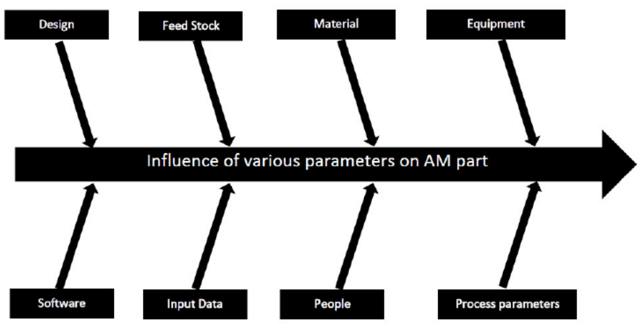


Figure 1: Aspects of the process chain and their influence on parameters of additive manufacturing process (DNV 2021).

Secondly, the point-by-point, line-by-line, and layer-by-layer fashions to print a part coupled with the complicated metallurgical process brings great difficulty in the consistency of each printable layer (Chen et al. 2021). Consequently, batch-to-batch, inter-batch, and machine-to-machine variabilities are possible, and this imposes an immense challenge to standardize the reliability and repeatability of the process (Kandukuri and Le Gallo 2020).

So given that qualification is usually achieved through reliability and repeatability of a manufacturing technology, the current indication is that batch testing cannot be applied to AM. This is different from CM, where batch testing is predominantly the most used qualification technique. With batch testing, one test piece within a batch can be tested as a reflection of the properties of the remaining parts. Consequently, this means that the more parts being manufactured for testing, the more favorable CM is (Pereira et al. 2019).

2.2 Qualification standards

Despite the mentioned difficulties of developing standards, several international and national standards organizations are actively involved in the development of standards, rules, and regulations for metal AM (Chen et al. 2021; Malkawi et al. 2021; Seifi et al. 2017; Vendra et al. 2020). Table 1 reports several test methods and qualification standards that have been published so far. However, most AM standards are still under development (Chen et al. 2021).

With standards in flux, using an independent testing laboratory (i.e., qualification is outsourced) experienced with metal AM can be very helpful. This is because it prevents the need to purchase and learn how to use expensive testing equipment. Additionally, customers expect service providers of spare parts to adhere to standards and strict testing, especially for high-critical parts (Hagan and Somrack 2018). Unless the service provider is certified for a particular part, a third party will likely be involved for qualification. Consequently, outsourcing qualification is likely to be the best option for most companies in the service business today.

Table 1: Published qualification standards for metal AM.

Published qualification standards	**Organization**
ISO/ASTM F2971, F3122, 52902	American Society for Testing and Materials (ASTM) and International Organization for Standardization (ISO)
VDI 3405-2	Verein Deutscher Ingenieure (VDI)
MSFC-STD-3716, 3717	National Aeronautics and Space Administration (NASA)
AWS D20	American Welding Society (AWS)
GB/T 35022	Standardization Administration of China (SAC)
DNV-CG-0197, CP-0267, **ST-B203**	Det Norske Veritas (DNV)
NI662 DT R00 E 2019	Bureau Veritas (BV)
API 20S	American Petroleum Institute (API)

Almost all the standards share similar definitions of risk and risk assessment needed to qualify a metal AM process and part (Malkawi et al. 2021 and author's reading of the standards available). They have adopted a 3-tier approach which spans from least critical to most critical (or versions of this), while NASA uses a more complex tier/class system (NASA 2017). This is referred to as risk-based qualification or part classification in the literature. The more critical the part is, the more rigorous the testing and qualification process is to reduce the risk of failure (Malkawi et al. 2021). For instance, a model toy plane would have an extremely low risk compared to a landing gear assembly printed for a commercial aircraft (Pereira et al. 2019). In the context of this thesis, *criticality* is being defined by the purchaser on a case-by-case basis.

2.2.1 DNV-ST-B203

Out of all the standards, the one highlighted in Table 1 (DNV-ST-B203) seems to be the best option as a basis for a qualification model. First and foremost, DNV is one of the world's largest accredited classification and certification societies, with a long history as a trusted independent partner to the maritime and oil and gas industries (Vendra et al. 2020). They are currently taking the lead in offering various services related to assurance of metal AM (Kandukuri and Ze 2021). Within these services, the mentioned standard specifies requirements and guidance for the qualification of metal parts made by AM (PBF process) for the oil and gas industries (DNV 2020). Moreover, the requirements are precise and easy to quantify compared to those in the other standards. For instance, Table 2 presents an overview of testing requirements depending on part criticality and qualification steps. For every test method in Table 2, there are clear instructions on how many test specimens are required and what ASTM/ISO standards you should adhere to for performing the specific test.

Table 2: Overview of quality control steps and testing depending on the AMC (DNV 2020).

Control step	Test method	AMC 1	AMC 2	AMC 3
Build process qualification	Tensile testing	x	x	x
	Impact testing	x	x	x
	Hardness measurement	x	x	x
	Microstructural assessment	x	x	x
	Porosity measurement	x	x	x
	Chemical analysis	x	x	x
Part qualification	Tensile testing			x
	Impact testing			x
	Hardness measurement			x
	Microstructural assessment			x
	Porosity measurement			x
	Visual testing			x
	Surface NDT			x
	Volumetric NDT			x
	Dimensional check			x
Production testing	Tensile testing		x	x
	Impact testing		x	x
	Hardness measurement			x
	Microstructural assessment			x
	Porosity measurement			x
	Visual testing		x	x
	Surface NDT		x	x
	Volumetric NDT		x	x
	Dimensional check		x	x

As we can see from Table 2, DNV's risk-based approach is called additive manufacturing categories (AMC). The three categories reflect increasing criticality and will from now on be referred to as criticality 1,2, and 3. Before continuing, some terms need to be clarified:

Build process qualification (BPQ) is the building of a pre-defined geometry or set of geometries, referred to as a standard qualification build, from which test specimens are extracted and tested.

- The purpose of the BPQ is to ensure that the build process used for manufacturing parts is suitable for obtaining specified material properties.
- It provides a basis for comparison for similar types of tests used for part qualification and production testing.

Part qualification (PQ) is the testing of a specific part or similar parts of representative geometry.

- The purpose of the PQ is to ensure that the part(s) have the required and expected properties.
- Parts with criticality 3 shall undergo sacrificial qualification testing.

Production testing (PT) is the testing of a specimen or part that is being produced at the same time, or during the same build job, as a part.

- The PT aims to ensure that the manufacturing results in parts with the intended properties.
- All build jobs with criticality 2 and 3 shall contain production test specimens.

Both BPQ and PQ are one-time qualifications. They are valid for a calibrated and well-maintained machine as long as the essential parameters are within a pre-defined limit used during the BPQ. An example of an essential parameter would be the manufacturing site, meaning that if the AM equipment is moved to a different location, both BPQ and PQ are likely to be required again (DNV 2020).

Another aspect of the DNV-ST-B203 standard that makes it a good fit for a qualification model is the possibility of introducing different case scenarios for each criticality. One way of accomplishing this would be to define three case scenarios, from best to worst, in the following manner:

- **Best-case:** BPQ and PQ are already done, which means that only PT is necessary.
- **Medium-case:** BPQ is already done, which means that both PQ and PT are necessary.
- **Worst-case:** Nothing is qualified in advance, meaning that BPQ, PQ, and PT are necessary.

This would make the qualification model more flexible because service providers of spare parts could realistically be in every scenario. A prior customer of a given spare part would be an example of a best-case scenario, considering that both part and process are likely already qualified.

2.3 Cost models in the literature

As mentioned in the introduction, traditional cost models typically lack qualification costs. Up to now, when evaluating the possibility of adopting metal AM for spare parts, many studies have focused only on the production phase and some supply chain characteristics (Cantini et al. 2022). The first studies on AM cost modeling proposed generic models focusing on rapid prototyping and series production of polymer parts (Colosimo et al. 2020). Within the framework of metal AM, studies dealing with cost models or other forms of economic evaluation are discussed below.

Atzeni and Salmi (2012) presented a redesign for metal AM, where a landing gear assembly was selected as a case study. Their cost model compared metal AM with CM (high-pressure die-casting) by evaluating pre-process, process, and post-process costs. The comparison demonstrated that AM could be economically convenient and competitive for small to medium batch production of metal parts. Lindemann et al. (2012) on the other hand, presented an analysis that accounted for all product life cycle costs. The study did not formulate a cost model in the traditional sense but instead focused on the main cost drivers of AM. Lindemann et al. (2012) are among the first researchers who included quality control in their analysis, though the extent of quality control was not specified. However, it is safe to assume that it is not comparable to the DNV-ST-B203 standard because the quality control had a minuscule contribution to the overall part cost. Rickenbacher et al. (2013) generalized and extended previously presented non-metal cost models with particular focus on pre- and post-processing operations. A contribution of this study was the ability to calculate the cost per part in a mixed-build job.

Three studies leaned more toward the question of under which conditions is a transition to an AM option economically profitable for spare parts management. Knofius et al. (2016) focused on a top-down approach by introducing a multi-criteria AHP framework to identify suitable parts for AM. The framework was applied to the aerospace industry and evaluated safety stock cost, manufacturing/ordering cost, number of suppliers, supply risk, remaining usage period, and demand rate. Heinen and Hoberg (2019) used a combination of cost model and design science framework to leverage AM in spare parts manufacturing. The framework included cost, monthly demand, EOQ, and inventory model. 8% of SKUs and 2% of total parts could be produced via AM in a Material Handling Equipment company. Finally, Sgarbossa et al. (2021) presented a decision tree to compare the best-suited process between four AM and five CM technology for spare parts manufacturing. The reorder model for Poisson demand used the following criteria: mean time to failure (MTTF), holding cost, backorder cost, failure rate, lead time, production cost, review period, order up to level, dimensions, and complexity (to a degree).

Another life cycle costs analysis which included energy demand, was done by Ingarao and Priarone (2020). The comparative assessment between AM and CM revealed that, for the considered case study, AM could be more energy-efficient than CM due to the higher efficiency in raw material usage. Regarding cost, AM was only the preferred solution when they included the cost savings during the use phase. On the supply chain note, Cantini et al. (2022) developed a decision support system to assist managers and practitioners in determining their spare parts supply chain configuration and the manufacturing technology to adopt. The mathematical model included the cost of purchasing spare parts from external suppliers, placing replenishment orders, inventory, outbound transportation, and backorder costs.

All the aforementioned studies aim to determine whether and to what extent metal AM is economically convenient compared to traditional technologies. To date, however, only two works have tried to incorporate qualification costs into their cost models (Colosimo et al. 2020; Verna et al. 2022). The authors treated qualification as an in-house operation instead of outsourced in both these cost models. The total cost of quality inspection included operator cost and cost of the meteorological equipment used, multiplied by the time needed to inspect the part. Moreover, Colosimo et al. (2020) included only visual testing or dimensional check depending on the case studies, while Verna et al. (2022) at best, included dimensional check, hardness test, and surface NDT in their case study. These assumptions could be considered realistic for the low criticality cases. Still, they are insufficient when dealing with more critical parts because they do not comply with modern qualification standards such as DNV-ST-B203. However, the problem was mitigated to a degree since both studies leveraged scrap fractions/defect probabilities in their cost models.

Consequently, to the best of my knowledge, there exists no tool to support managers and practitioners in calculating and comparing qualification costs for AM and CM. This gap is overcome in this thesis, where a mathematical model is developed based on the DNV-ST-B203 qualification standard. The mathematical model is also given as an easy-to-use python script.

3 Research methodology

3.1 Research design

The research methodology for this master thesis has been a mixed-method using qualitative (literature review and focus group meeting) and quantitative methods (mathematical modeling and case studies). An exploratory sequential design was used because essential variables (RQ1) were unknown, and instruments (RQ2) were unavailable. In this design, qualitative data collection and analysis occur first, followed by quantitative data collection and analysis (George 2021). In other words, the qualitative results from RQ1 were used to develop the quantitative mathematical model and thus answering RQ2.

The perceived strength of this research design is that combining quantitative and qualitative approaches provides a better understanding of research problems and complex phenomena than either approach alone (Molina-Azorin 2016). Furthermore, it is a flexible method by being less tied to disciplines and established research paradigms (George 2021).

On the other hand, the main disadvantage of mixed-method research is the workload (George 2021). This disadvantage is the reason for the scope of the thesis, namely that the mathematical model only incorporates the qualification process. Additionally, deciding which qualitative findings to use for the quantitative phase in a mixed-method approach is challenging.

3.2 Literature review

The choice of search engine was based on Falagas et al. (2008) comparison of *PubMed*, *Scopus*, *Web of Science* and *Google Scholar*. This comparison evaluated the usefulness of these databases in the biomedical field. However, given that the comparison was mainly of general characteristics, it was deemed applicable to all subject areas.

It was considered appropriate to use a curated database of journal articles and an open web-based database to have a wide field of impact. Including more databases in each category would not be feasible for the literature review's scope. *Google Scholar* emerged as the obvious choice for an open web-based solution, while the reputable *Scopus* was chosen because it has the largest curated database in the world (Falagas et al. 2008).

Prior to the literature review, a non-structured explorative literature search was conducted to identify important topics and keywords. The following main search query was used in *Scopus* as a starting point:

- TITLE-ABS-KEY((”additive manufacturing” OR ”3d printing” OR ”rapid manufacturing”) AND ”qualification” AND ”certification”)

This search query resulted in 59 documents. Based on Chen et al. (2021) review on qualification and certification for metal AM, it was decided to put more emphasis on the available AM standards as well. The information gathered from DNV, ASTM, and NASA's standards, combined with cited reference search and citation search on key papers, was used to find more keywords (and synonyms).

The following list of main and secondary keywords was used during the literature search:

Table 3: Keywords used for literature review.

Main Keywords	**Secondary Keywords**
Additive manufacturing	Qualification, certification, verification, evaluation, testing,
3D printing	validation, inspection, approval
Rapid manufacturing	
Powder Bed Fusion	+ cost, time, duration
Electron Beam Melting	Test specimen, non-destructive testing,
	NDT, destructive testing, CT
+ metal	Qualification standard
	Modeling, digital twin, in-situ monitoring

Papers were chosen through a three-step process:

1. The abstract was read.
2. If the abstract seemed relevant, the introduction, first few paragraphs, and conclusion of the papers were read. References to these papers were stored in *Zotero* reference manager.
3. Lastly, a thorough reading of each paper was done. Papers were excluded if they did not contribute to qualification and certification efforts/problems, both current and future.

It was considered necessary to include industry knowledge directly from AM manufacturers in conjunction with academic research. This was done because it is reasonable to assume that the understanding of metal AM is more mature in the industry compared to academia, especially when you account for the ”lead time” of journal articles. Consequently, literature deemed relevant consisted of journal articles, conference papers, a book chapter, website articles, presentations, and the standards.

A brief bibliographic analysis was also performed on the papers available at *Scopus*. This was done to visualize better what keywords, authors, and journals were most prominent in the literature review (see Figure 2 and 3). The open-source *bibliometrix* R-package was used with the *Biblioshiny* app for the analysis (Aria and Cuccurullo 2017).

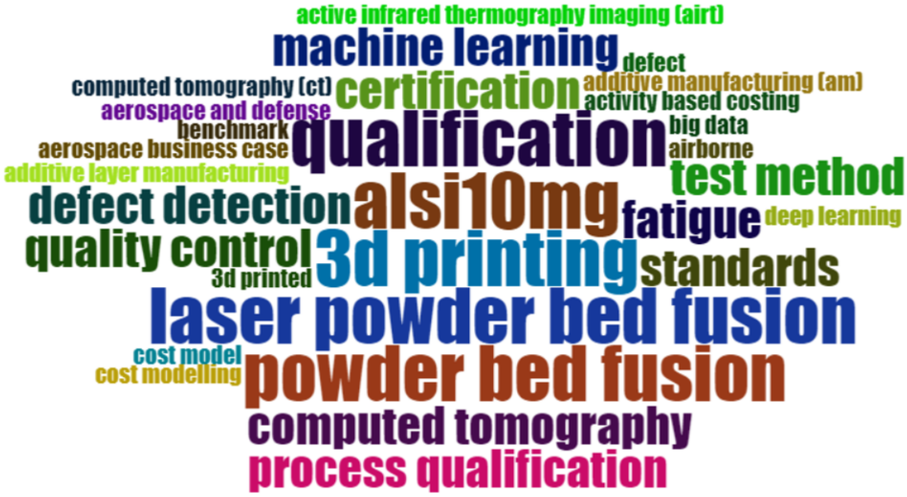


Figure 2: World cloud with main keywords connected to the papers.

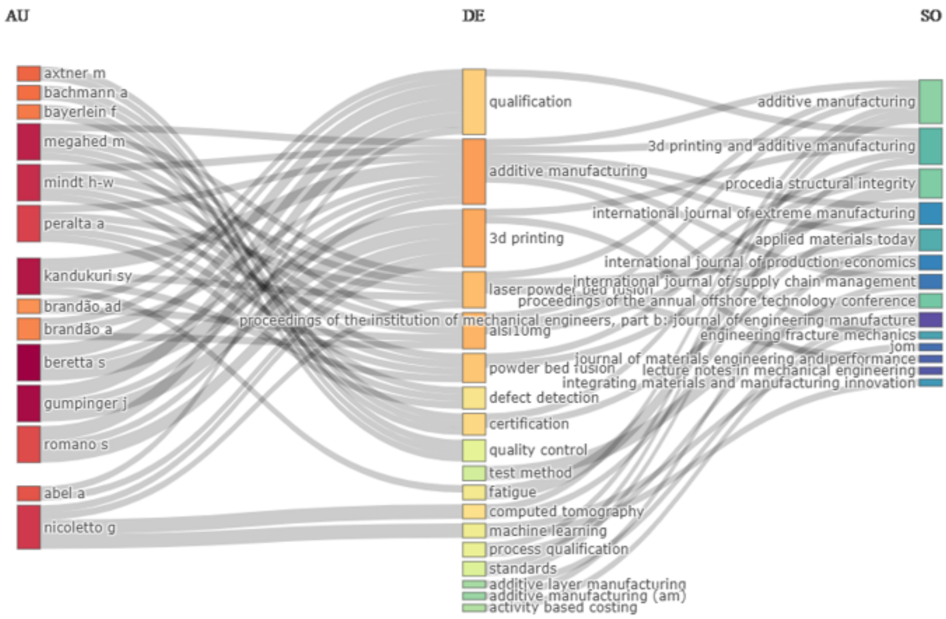


Figure 3: Three-Fields Plot with keywords, authors and sources.

3.3 Focus group meeting

A discussion with experts was conducted through a focus group meeting with Fieldmade. They are a deep tech company working within the applied AM domain to develop technology and services for the *Digital Era* (Fieldmade 2021). The representatives from Fieldmade were the Product and Process Development Engineer and the Head Of Digitalization.

The findings from the literature review were given as a presentation. Discussion and questions from both parties emerged during the presentation. This allowed for an informative meeting where the findings were compared to their understanding of the topic. The discussion led to useful information for developing and confirming different assumptions used in the mathematical model.

3.4 Developing the mathematical model

The main objective of this thesis is to develop an easy-to-use mathematical model for evaluating spare parts qualification costs considering different manufacturing technologies. The proposed model combines two decision trees (one for AM and one for CM) with the same qualification scenarios (best to worst-case scenario for three levels of part criticality). Based on the model, a python script is given to support managers and practitioners in calculating and comparing qualification costs for AM and CM. However, some key characteristics and assumptions must be clarified before describing the mathematical model.

Dealing with key characteristics, the model only studies the qualification process (i.e., cost of qualification tests and transportation to and from the testing facility). Hence, the model does not include supply chain aspects such as purchasing from external suppliers vs. in-sourced production, centralization vs. decentralization, and customer distribution. However, later, the two case studies will demonstrate how you can incorporate the qualification costs from this model with production-related costs.

Concerning the assumptions made in the development of the model, these are based on information from the literature review and the meeting with Fieldmade. The literature review established why the DNV-ST-B203 standard is the best option as a basis for a qualification model. Consequently, a lot of the assumptions emerge from this standard. The following list is the assumptions underlying the mathematical model:

1. A spare part can assume three criticality values (1-3) and three case scenario values (1-3). That means that there are a total of 9 qualification options for both AM and CM (DNV 2020). The tests required for the different options are based on Table 2.

2. The same qualification tests are assumed to be used for AM and CM (Weaver 2019). Fieldmade echoed this assumption saying that qualification costs for one-off production are likely similar for AM and CM.

3. Spare parts with criticality 1 and case scenario 1 or 2 are expected to undergo visual inspection. However, the cost is assumed to be negligible since the inspection can be done in-house.

4. Each qualification test refers to the cost of one test. A test usually consists of test specimens. Notice that the number of specimens for tensile and impact testing is different for BPQ compared to PQ and PT (see Equation 2).

5. It is assumed that batch testing cannot be applied to AM, only CM (DNV 2020; Pereira et al. 2019). Allowing batch testing means that one PT is sufficient for CM. For AM, however, PT

depends on how many parts (build jobs) are up for qualification. In other words, the $\#parts$ parameter only applies to AM, thus answering RQ2.

6. Both BPQ and PQ are one-time qualifications and are not affected by the number of parts.

7. The model includes the unitary transportation cost of one part/test job to and from the testing facility (uT) because qualification is treated as an outsourced operation (Fieldmade 2021; Hagan and Somrack 2018). One test job (a build job with the necessary test specimens) is assumed to be either BPQ, PQ, or PT. Consequently, a qualification where they are all required would equate to three test jobs ($3 * uT$). For AM, this means that one extra unitary transportation cost is added for every additional PT performed.

8. One testing facility is assumed to be able to do all the different qualification tests.

9. The model does not directly include the cost of handling a test job (i.e., preparing for shipping and receiving). This cost is not necessarily negligible but can indirectly be included in the unitary transportation cost if desired.

10. Since the focus of this thesis is not the problem of sustainability but rather the qualification costs alone, no environmental effects are assessed. For example, CO2 emitted during the transportation is neglected. The cost of producing the test jobs is also omitted from the model for the same reason.

Now that the key characteristics of the proposed model and the assumptions made have been described, two decision trees were developed for better visualization. They are presented on the following two pages and illustrate the nine qualification options for AM (Figure 4) and CM (Figure 5). A short qualification cost formula for each option is also given in the figures. It is worth mentioning that the 2/3 fraction used for medium criticality is only for illustration purposes (to show that PT is less extensive in this case).

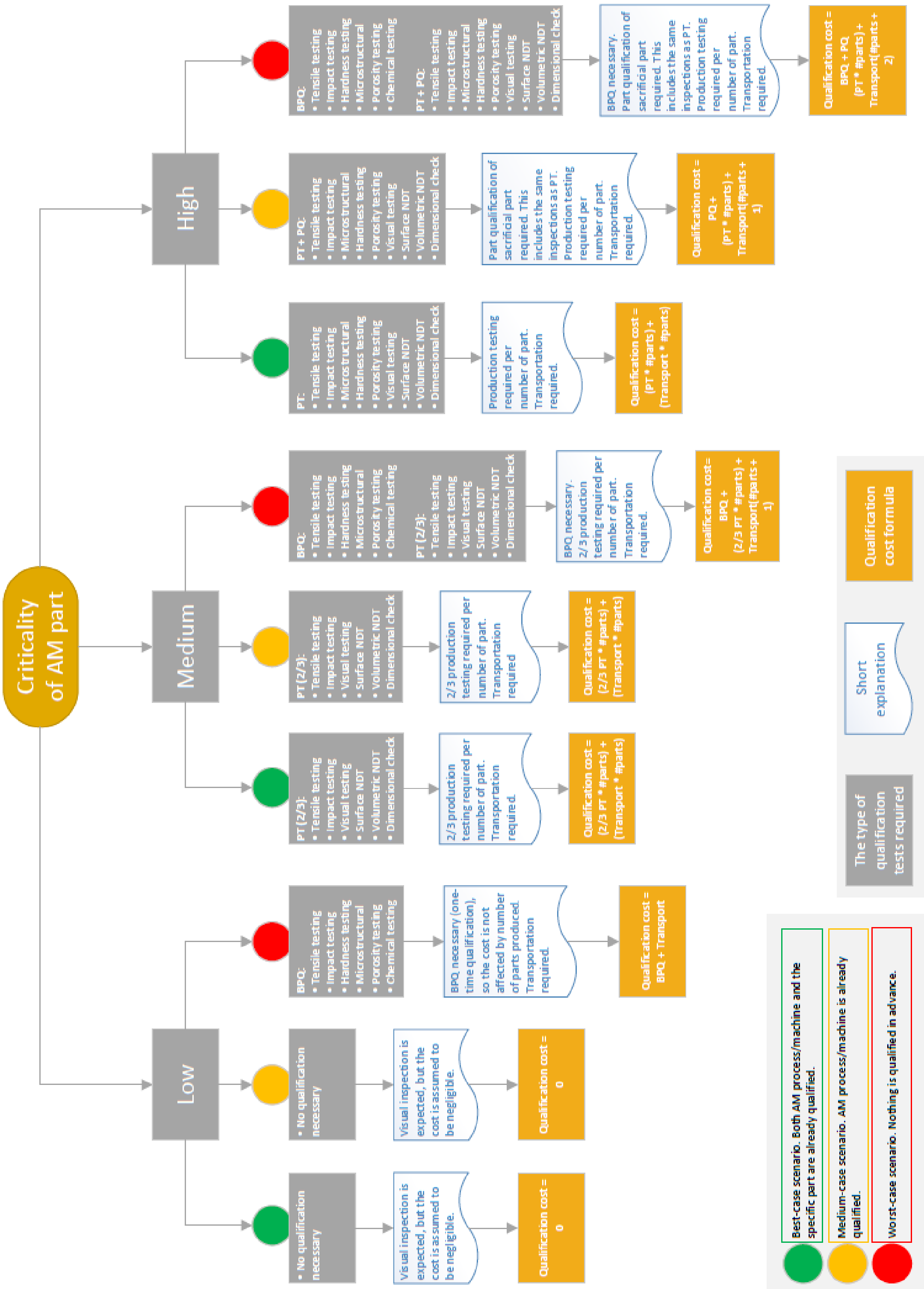


Figure 4: Qualification tree for AM.

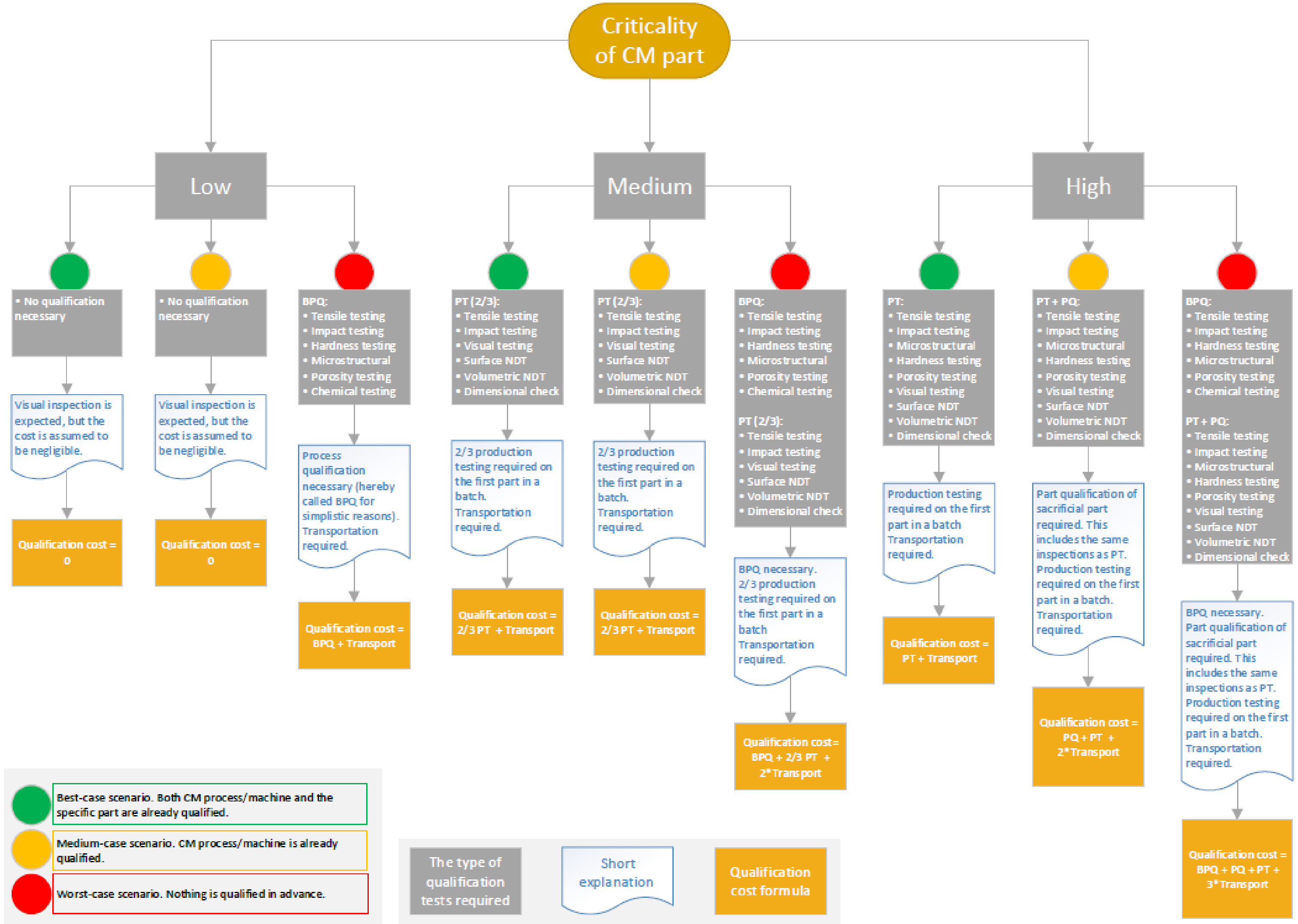


Figure 5: Qualification tree for CM.

The input parameters for the mathematical model were decided based on the two qualification trees. The goal was to formulate an equation considering the nine qualification options for AM and CM (see Equation 1).

Table 4: Input parameters for the mathematical model.

Input parameter	**Description**	**Unit measure**
i	Manufacturing technology. i can be AM (1) or CM (2).	[-]
j	Criticality of part. j can assume integer values between 1 and 3.	[-]
k	Best to worst-case scenario. k can assume integer values between 1 and 3.	[-]
$\#parts$	Number of parts (build jobs) being tested. $\#parts$ only relates to AM.	[units]
uT	Unitary cost of transportation of one part/test job to and from testing facility.	[$/unit]
Ten	Cost of 1 tensile test.	[$/unit]
Imp	Cost of 1 impact test.	[$/unit]
Mic	Cost of 1 microstructural assessment.	[$/unit]
Har	Cost of 1 hardness test.	[$/unit]
Por	Cost of 1 porosity test.	[$/unit]
Che	Cost of 1 chemical test.	[$/unit]
Vis	Cost of 1 visual test.	[$/unit]
Sur	Cost of 1 surface NDT.	[$/unit]
Vol	Cost of 1 volumetric NDT.	[$/unit]
Dim	Cost of 1 dimensional check.	[$/unit]

The total qualification costs can be calculated according to Equation 1.

$$QC_{i,j,k} = BPQ_k + PQ_{j,k} + PT_j * parts_{i,j} + uT_{j,k} \tag{1}$$

where BPQ_k is

$$BPQ_k = \begin{cases} (12 * Ten) + (3 * Imp) + Har + Mic + Por + Che & \text{if } k = 3 \\ 0 & \text{if } k = 1, 2 \end{cases} \tag{2}$$

and $PQ_{j,k}$ is

$$PQ_{j,k} = \begin{cases} Ten + Imp + Mic + Har + Por + Vis + Sur + Vol + Dim & \text{if } j = 3, k = 2, 3 \\ 0 & \text{else} \end{cases} \tag{3}$$

Whereas, costs related to production testing are given as a product between PT_j and $parts_{i,j}$. These are defined by Equations 4 and 5.

$$PT_j = \begin{cases} Ten + Imp + Mic + Har + Por + Vis + Sur + Vol + Dim & \text{if } j = 3 \\ Ten + Imp + Vis + Sur + Vol + Dim & \text{if } j = 2 \\ 0 & \text{if } j = 1 \end{cases} \tag{4}$$

$$parts_{i,j} = \begin{cases} \#parts & \text{if } i = 1, j = 2, 3 \\ 1 & \text{if } j = 1 \\ 1 & \text{if } i = 2 \end{cases} \tag{5}$$

Finally, $uT_{j,k}$, is given by the following expression

$$uT_{j,k} = \begin{cases} uT(parts_{i,j} + 2) & \text{if } j = 3, k = 3 \\ uT(parts_{i,j} + 1) & \text{if } j = 3, k = 2 \text{ or } j = 2, k = 3 \\ uT * parts_{i,j} & \text{if } j = 3, k = 1 \text{ or } j = 2, k = 1, 2 \\ uT & \text{if } j = 1, k = 3 \\ 0 & \text{if } j = 1, k = 1, 2 \end{cases} \tag{6}$$

A python script was also made from the developed mathematical model, which can be found in Appendix A. In the python script, the first four parameters in Table 4 are inputs from the user. By running the script, the user is presented with the following statements:

- Please enter manufacturing technology (AM or CM):
- Please enter the number of parts being produced:
  - If AM is entered by the user. Please enter the number of parts per build job:
  - If CM is entered by the user, no extra statement is given.
- Please enter criticality of part (1,2 or 3):
- Please enter case scenario:
  Type 1 for best-case (BPQ and PQ already done).
  Type 2 for medium-case (PQ already done).
  Type 3 for worst-case (nothing is pre-qualified).

The total qualification costs are then calculated and presented to the user based on their inputs.

4 Results

4.1 Application of the mathematical model

Here the two case studies (A and B) are provided to illustrate different use cases of the mathematical model. The parameters i, j, k, and $\#parts$ were treated as variables and were assigned different values depending on the case studies.

Table 5: Parameters and values used in both cases.

Input parameter	Values	Unit measure	Sources
uT	20	[$/unit]	(Posten 2022)
Ten	35	[$/unit]	(Test Metals 2022)
Imp	65	[$/unit]	(Test Metals 2022)
Mic	85	[$/unit]	(Test Metals 2022)
Har	150	[$/unit]	(Test Metals 2022)
Por	75	[$/unit]	(Test Metals 2022)
Che	70	[$/unit]	(Test Metals 2022)
Vis	10	[$/unit]	(Colosimo et al. 2020)
Sur[1]	15	[$/unit]	(Worman 2011)
Vol[2]	150	[$/unit]	(Plessis and Waller 2018)
Dim[3]	50	[$/unit]	(Colosimo et al. 2020)

[1] Surface NDT: Penetrant testing.
[2] Volumetric NDT: X-ray Computed Tomography (CT scan).
[3] Dimensional check: Coordinate Measuring Machine (CMM).

The value for uT in Table 5 assumed a Norwegian setting, meaning a hypothetical scenario where a service provider qualifies their spare part at a Norwegian testing facility. The value, which included some handling cost, is reasonable because the maximum dimension of a parcel package at Posten is sufficient for the size of test jobs produced by PBF (Frandsen et al. 2020).

4.2 Case study A

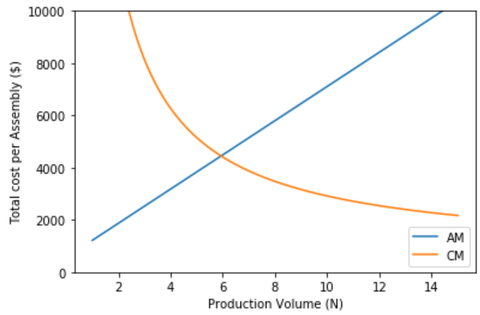
As briefly mentioned in the literature review, Atzeni and Salmi (2012) did a redesign for AM, where a landing gear assembly was selected as a case study. For a 1:5 scale model of the Italian aircraft P180 Avant II by Piaggio Aero Industries S.p.A., with an estimated five years of useful life, the AM process cost per assembly was $560.55[1]. Compared to CM, the process cost per assembly were $22.68 + $22 366/N (N = production volume). A breakeven analysis estimated that AM was the preferred choice for production runs of less than 42.

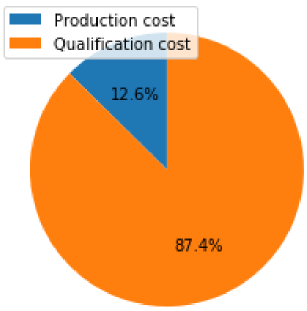
By applying the qualification model to this case, it was possible to study how it affected the breakeven point. Even though it is reasonable to assume that a landing gear has criticality 3, every criticality was included. These breakeven points are presented on the following pages, together with cost breakdowns for each case scenario. For more information about how the results were obtained, see the python code in Appendix B.

[1] The currency has been converted from EUR to USD using exchange rate 1€= 1.07$.

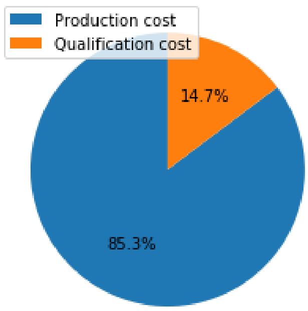
4.2.1 Criticality 3

Figure 6: Breakeven point for AM and CM with criticality 3.

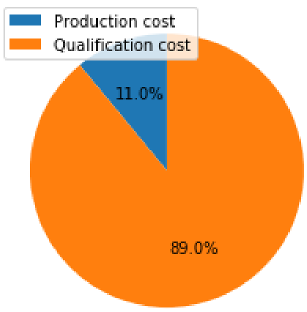




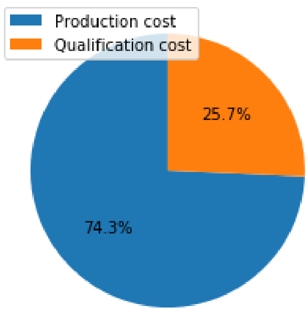
(a) Best-case scenario with AM



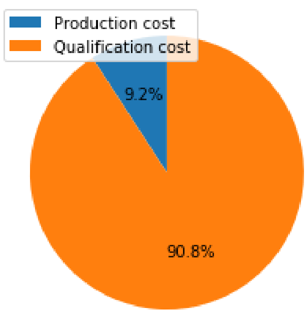
(b) Best-case scenario with CM



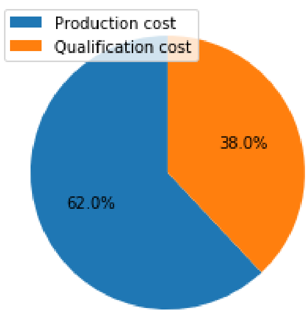
(c) Medium-case scenario with AM



(d) Medium-case scenario with CM



(e) Worst-case scenario with AM

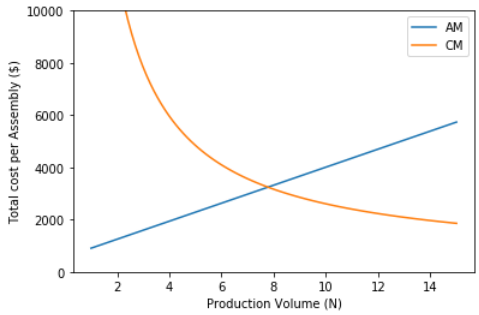


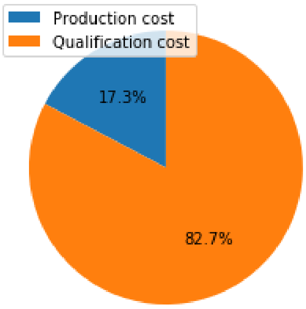
(f) Worst-case scenario with CM

Figure 7: Cost breakdown at the breakeven point of 6 assemblies (5.93) with criticality 3.

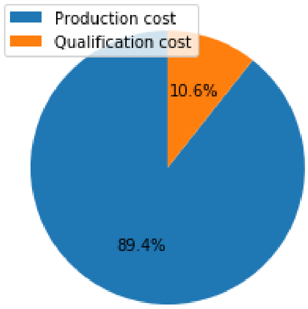
4.2.2 Criticality 2

Figure 8: Breakeven point for AM and CM with criticality 2.

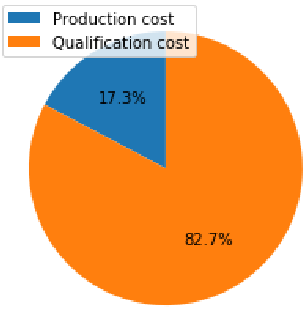




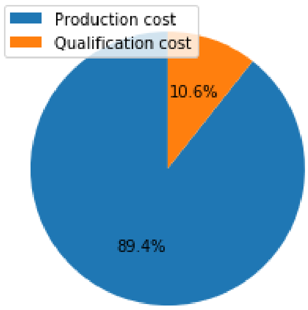
(a) Best-case scenario with AM



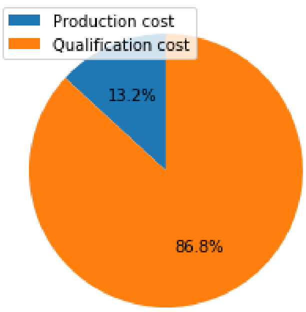
(b) Best-case scenario with CM



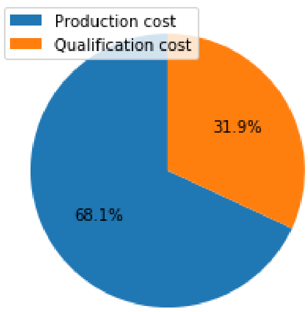
(c) Medium-case scenario with AM



(d) Medium-case scenario with CM



(e) Worst-case scenario with AM

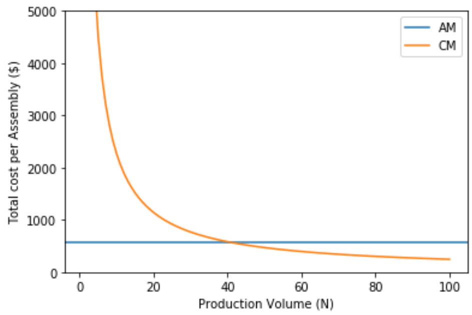


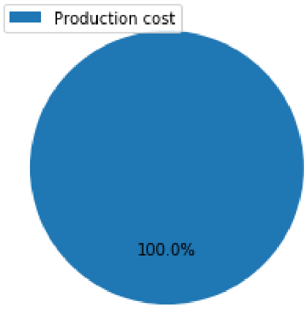
(f) Worst-case scenario with CM

Figure 9: Cost breakdown at the breakeven point of 8 assemblies (7.78) with criticality 2.

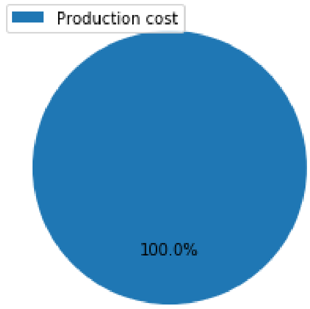
4.2.3 Criticality 1

Figure 10: Breakeven point for AM and CM with criticality 1.

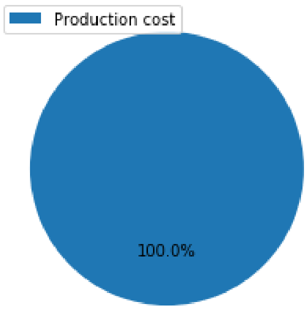




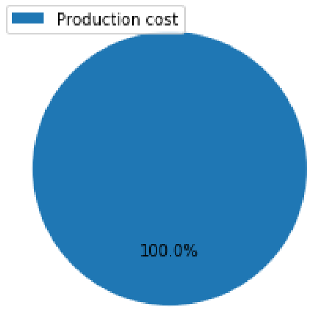
(a) Best-case scenario with AM



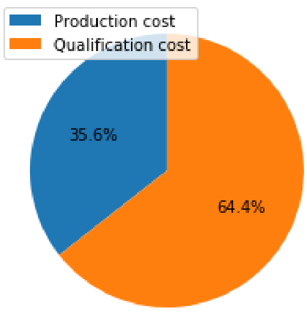
(b) Best-case scenario with CM



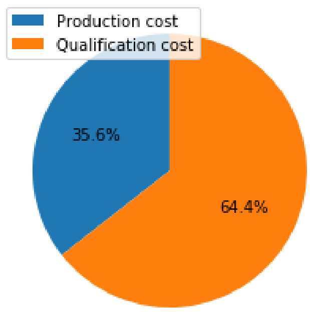
(c) Medium-case scenario with AM



(d) Medium-case scenario with CM



(e) Worst-case scenario with AM

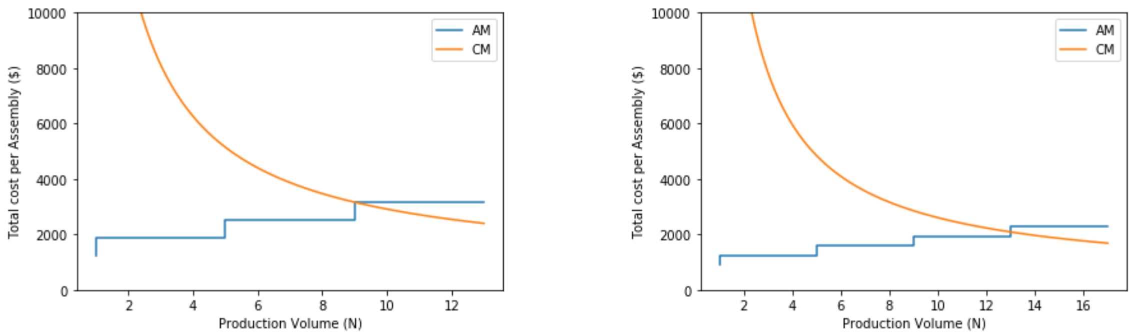


(f) Worst-case scenario with CM

Figure 11: Cost breakdown at the breakeven point of 42 assemblies (41.58) with criticality 1.

The Atzeni and Salmi (2012) case study reported that the number of parts produced per build job was four. This information was not accounted for on the previous pages. Those figures assumed PT per part produced. Therefore, two additional breakeven analysis was also done to account for the number of parts per build job (see Figure 12). Notice that the total cost per assembly for AM is a step function for both criticalities. Furthermore, the breakeven points have also shifted in AM's favor compared to Figure 6 and 8.

Figure 12: New breakeven points for criticality 3 and 2 if using 4 assemblies per build job.



(a) Criticality 3: Breakeven point = 9 (b) Criticality 2: Breakeven point = 13

4.3 Case study B

Colosimo et al. (2020) did three real industrial case studies in order to evaluate their proposed AM cost model. This model adopted the main framework of previous studies and extended it by considering the contribution of scrap fractions and in-situ monitoring tools to the process and material costs, including pre- and post-processing operations.

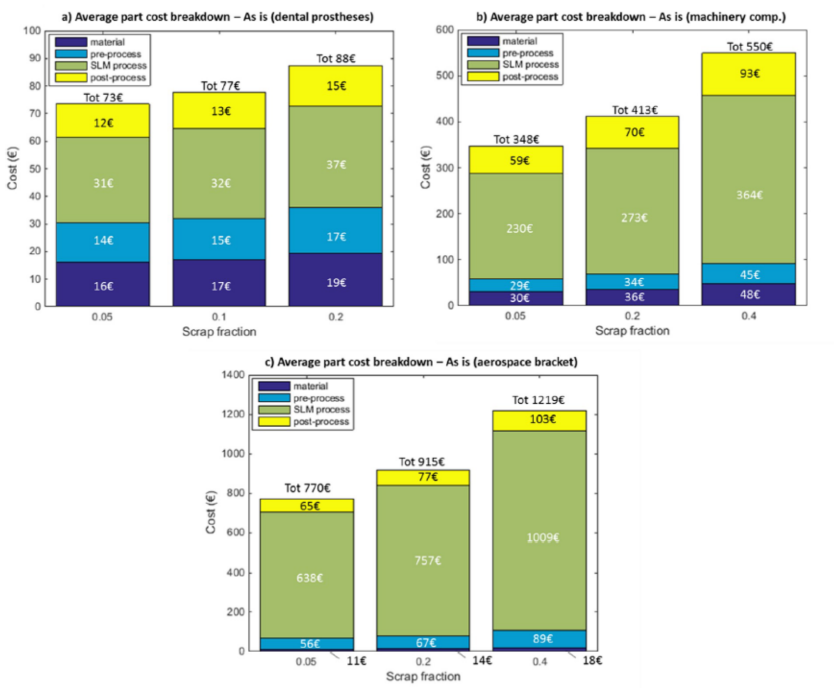
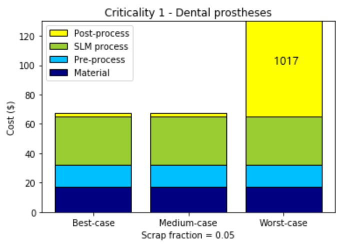


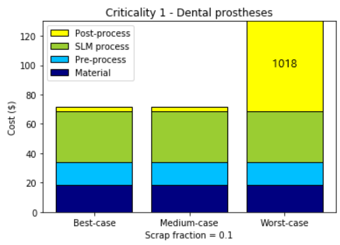
Figure 13: Average part cost breakdown in the dental prostheses case study (a), machinery component case study (b), and aerospace bracket case study (c). Retrieved from Colosimo et al. (2020).

For each case study, Colosimo et al. (2020) performed an average part cost breakdown (see Figure 13). From the perspective of this thesis, the three parts naturally lend themselves towards criticality; 1 for the dental prostheses, 2 for the machinery component, and 3 for the aerospace bracket. Before applying the qualification model, the visual inspection and dimensional check were removed from the post-process cost. The following figures present how the qualification model altered the average part cost breakdown for each case study and their scrap fractions. For more information about how the results were obtained, see the python code in Appendix C.

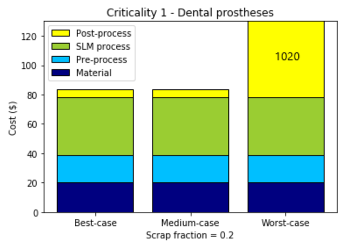
4.3.1 Dental prostheses



(a) Best to worst-case scenario with scrap fraction = 0.05



(b) Best to worst-case scenario with scrap fraction = 0.1

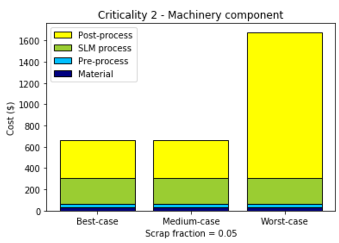


(c) Best to worst-case scenario with scrap fraction = 0.2

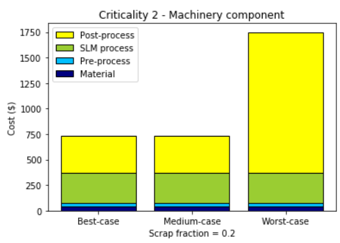
Figure 14: Average part cost breakdown for 1 build job of dental prostheses with the qualification model.

Notice that the stacked bar charts in Figure 14 have all been scaled (y-axis limit of 130). This was done to accommodate the high post-process value in the worst-case scenario. Without it, the charts looked nothing like Figure 13.

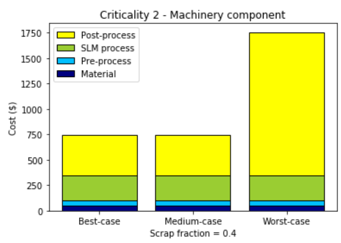
4.3.2 Machinery components



(a) Best to worst-case scenario with scrap fraction = 0.05



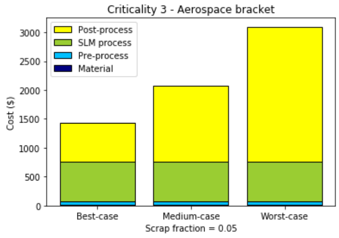
(b) Best to worst-case scenario with scrap fraction = 0.2



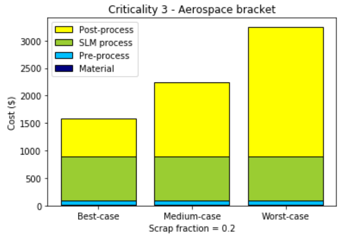
(c) Best to worst-case scenario with scrap fraction = 0.4

Figure 15: Average part cost breakdown for 1 build job of machinery components with the qualification model.

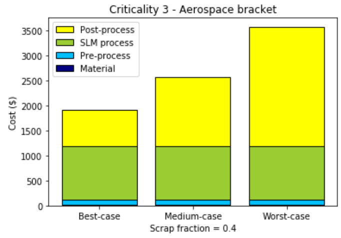
4.3.3 Aerospace brackets



(a) Best to worst-case scenario with scrap fraction = 0.05



(b) Best to worst-case scenario with scrap fraction = 0.2



(c) Best to worst-case scenario with scrap fraction = 0.4

Figure 16: Average part cost breakdown for 1 build job of aerospace brackets with the qualification model.

The results achieved by applying the mathematical model to both case studies will be discussed in Section 5.

5 Discussion

5.1 Case study A

Case study A demonstrated the first application of the qualification model. The results clearly stated that the qualification costs negatively impact AM significantly more than CM. For instance, Figure 6 showed that the breakeven point was six for criticality 3. This breakeven point is substantially lower than what Atzeni and Salmi (2012) found without considering qualification costs (42). Furthermore, the cost breakdown analysis at six assemblies in Figure 7 underscored this negative impact even more. In all the case scenarios for AM, the qualification costs contributed way more than 50% of the overall assembly cost, while for CM, it was the production costs. These figures illustrate what was initially considered a strong argument for small to medium batch production of metal AM is only reasonable for small batch production. This is because of how adversely the number of qualified parts impacts AM compared to CM. In other words, by incorporating the qualification costs into the overall part cost, an otherwise promising metal AM spare part candidate is not necessarily as promising anymore.

For criticality 2, the case study had similar results. The breakeven point was 8 for this case (Figure 8), and the differences in the cost breakdown between AM and CM were significant (Figure 9). Still, the same conclusions reached for criticality 3 are relevant to criticality 2. Naturally, though, the results are a little less skewed in favor of CM because there are fewer qualifications in this case.

On the other hand, assuming four assemblies per build job, the breakeven points were 9 and 13 for criticality 3 and 2, respectively. Although this is better for AM, the overall conclusions do not change. The total cost per assembly for AM is a step function (see Figure 12) because only the qualification costs are affected by the number of assemblies. Consequently, for every fourth assembly, there is a step.

Lastly, the case study also included criticality 1. Figure 11 illustrates that the qualification costs are the same for AM and CM. This is also the reason why Figure 10 has the same breakeven point as Atzeni and Salmi (2012).

5.2 Case study B

Case study B demonstrated the second application of the qualification model. The results showed how criticality and case scenario impacted qualification costs for metal AM. The average part cost breakdown changed drastically after applying the qualification model to the dental prostheses, machinery components, and aerospace brackets compared to what Colosimo et al. (2020) had done.

The best and medium-case scenarios were similar for the dental prostheses (criticality 1, Figure 14) because there are no qualification costs. However, the qualification costs for the worst-case scenario had a striking signal due to the BPQ. The qualification costs were more than tenfold the rest of the production costs. Moreover, for criticality 2 and 3 (see Figure 15 and 16), the qualification costs were between twofold and sixfold the rest of the expenses. Thus, it raises the question of whether the DNV-ST-B203 standard might be too rigorous for qualification, especially for criticality 1. On the contrary, it can also suggest that the topic of qualification costs is an overlooked problem in both case studies and the literature in general.

In my opinion, it is a combination of both. As stated by De Bernardi and Miller (2020), not having standards or guidelines increases the risk of products not meeting minimum requirements, in addition to increasing the part qualification cost. Therefore, having a modern standard is both valuable and necessary for the wider applications of metal AM. Still, ensuring that these additional considerations do not spiral into a massive cost consideration for AM part qualification is crucial. One can argue that this master thesis highlights this problem, as shown in the case studies, where promising metal AM spare part candidates were not necessarily as promising anymore by applying the qualification model. This is also in line with what Fieldmade assessed, namely that the current qualification standards are, in many cases, too rigid and expensive.

Hence, there is a need to implement faster and cheaper qualification methods based on, for instance, digital qualification. Building a bridge between the physical and virtual world of printing by creating a digital twin will reduce the number of trial-and-error tests, mitigate defects, reduce the time between the design and production and make metal AM more cost-effective (Megahed et al. 2019; Mukherjee and DebRoy 2019).

On the other hand, the topic of qualification costs is clearly an overlooked issue in the literature. This was demonstrated in the literature review and by applying the qualification model. Although the DNV-ST-B203 standard might exacerbate realistic qualification costs to a degree, the model still fulfills its objective of developing an easy-to-use mathematical model for evaluating spare parts qualification costs for AM and CM. Through the case studies, the model hopefully makes it clear to the scientific community that neglecting qualification costs is not feasible when assessing the viability of metal AM. At a practical level, the contribution of this thesis is a python script to support managers and practitioners in calculating and comparing qualification costs for AM and CM.

Before concluding, the following weaknesses of the master thesis need to be discussed:

- The limitation of the literature review is the reliance on previously published research. Furthermore, the literature for RQ1 is not solely peer-reviewed journal articles. Hence, the sources used are less trustworthy. Additionally, deciding which qualitative findings to use for the quantitative phase in a mixed-method approach is challenging. However, the focus group meeting mitigated some limitations by contributing to current industry knowledge.

- Another perceived weakness with a literature review, in general, is that they lack an explicit intent to maximize scope or analyze data collected. Therefore, any conclusion they may reach is open to bias from the potential to omit, perhaps inadvertently, significant sections of the literature or by not questioning the validity of statements made (Grant and Booth 2009). Furthermore, authors may only select literature that supports their hypothesis, and this subjective reading prevents study replication by other researchers.

- One weakness is that the qualification model is solely based on the DNV-ST-B203 standard.

Moreover, the standard is mainly focused on the PBF process. Thus, the qualification model may not be applicable in every case. To a certain extent, this problem is mitigated because PBF is the most common metal AM process, and a large portion of the qualification tests are relevant for other metal AM processes (DNV 2020; Gokuldoss et al. 2017). Furthermore, almost all the standards share similar definitions of risk and risk assessment needed to qualify a metal AM process and part, which eases the transition from one standard to another (Malkawi et al. 2021). And lastly, users of the qualification model can decide for themselves the cost of the different tests. If one particular test is not applicable for a given case, the value can be set to zero (see Appendix A).

- Another weakness is related to the model's assumptions, namely that the same qualification tests are used for AM and CM. Consequently, qualification costs for one-off production are the same for both manufacturing technologies. However, according to Fieldmade, this is not necessarily true for every case since qualification for CM is more established and well-defined than for AM. Even though it may be a fair assumption, there needs to be more than just the traditional inspections for more complex metal AM parts in the future (Weaver 2019).
- Finally, omitting the model's cost of producing the test jobs can also be considered a weakness. Essentially, you run almost a full building chamber to print a near-net-shaped sample for testing. This uses a lot of powder and takes a significant amount of time, adding extra cost to the process. Thus, researchers should add the test job production cost to their process costs if they were to include the qualification model for future works.

6 Conclusion

This master thesis proposes an easy-to-use mathematical model for evaluating spare parts qualification costs for AM and CM. The developed model is based on the DNV-ST-B203 qualification standard, and it calculates costs for nine different qualification routes for both manufacturing technologies. The nine options are derived from 3 levels of criticality (i.e., the criticality of an end-use part) and their 3 case scenarios, ranging from best to worst-case. A mixed-method approach was performed using qualitative and quantitative methods to develop the qualification model. The qualitative phase consisted of a literature review and a focus group meeting, which led to the qualification standard and assumptions underlying the model. This was followed by the quantitative phase, i.e., the development of the model itself and its application to two case studies.

The qualification model developed herein represents the main contribution of this master thesis since nothing similar has been done before. In fact, to the best of my knowledge, no tool has been developed so far to support managers and practitioners in evaluating qualification costs for AM and CM. This need was fulfilled by making a python script based on the qualification model.

The following list summarises some additional findings of the present thesis:

- The more parts being manufactured for testing, the more favorable CM is. The #parts parameter in the model only applies to AM because batch testing is inappropriate for this technology. On the other hand, the rest of the model's input parameters are treated similarly for both manufacturing technologies.
- The DNV-ST-B203 qualification standard is, in many cases, too rigid and expensive. This was especially true for criticality 3 in general and the worst-case scenario with criticality 1. In both case studies, the qualification costs were between twofold and tenfold the rest of the production costs for many of the qualification routes. Thus, promising metal AM spare part candidates were not necessarily as promising anymore by applying the qualification model.

Although the DNV-ST-B203 standard might exacerbate realistic qualification costs to a degree, the model still fulfills its objective of developing an easy-to-use mathematical model for evaluating spare parts qualification costs for AM and CM. Through the case studies, the model hopefully makes it clear to the scientific community that neglecting qualification costs is not feasible when assessing the viability of metal AM.

It is worth noting that the results achieved are only valid under the following assumptions: the same qualification tests are used for AM and CM, and one testing facility can do all of them. Besides, it is important to remember that the proposed model only studies qualification costs. For instance, the cost of producing test jobs is omitted from the model.

Therefore, future developments of this research could include the test job production cost in the qualification model. However, I recommend implementing the qualification model to a production or supply chain cost model instead. This way, it is possible to include the test job production cost where they belong, namely in the process costs. It is also advisable to look into digital qualification because, as this master thesis has demonstrated, there is a need to implement faster and cheaper qualification methods for metal AM. Without it, CM will likely continue overshadowing metal AM, even in the spare parts industry.

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Appendix

A Qualification cost - Python script

```python
import math
##### Input from user #####

i = input("Please enter manufacturing technology (AM or CM):\n")

if i == "AM" or i == "am":
    i = 1
    parts = input("Please enter the number of parts being produced:\n")
    parts = int(parts)
    buildJobs = input("Please enter the number of parts per build job:\n")
    buildJobs = int(buildJobs)
    if parts == buildJobs:
        parts = 1
    elif buildJobs > parts:
        parts = 1
    elif parts > buildJobs:
        parts = math.ceil(parts/buildJobs)
elif i == "CM" or i == "cm":
    i = 2
    parts = input("Please enter the number of parts being produced:\n")
    parts = int(parts)

j = input("Please enter criticality of part (1,2 or 3):\n")
j = int(j)

k = input("Please enter case scenario:\n Type 1 for best-case (BPQ and PQ already done).\
          \n Type 2 for medium-case (PQ already done).\n Type 3 for worst-case (nothing is pre-qualified).\n")
k = int(k)

##### Transportation and inspection costs - Change values if necessary (set zero if not applicable) #####

uT  = 20               # Unitary cost of transportation of one part/test job to and from testing facility
Ten = 35               # Cost of tensile testing
Imp = 65               # Cost of impact testing
Mic = 85               # Cost of microstructural assessment
Har = 150              # Cost of hardness testing
Por = 75               # Cost of porosity testing
Che = 70               # Cost of chemical testing
Vis = 10               # Cost of visual testing
Sur = 15               # Cost of surface NDT
Vol = 150              # Cost of volumetric NDT
Dim = 50               # Cost of dimensional check

##### Calculation of qualification costs #####

# Defining variables:
QC_ijk = 0; BPQ_k = 0; PQ_jk = 0; PT_j = 0; parts_ij = 0; uT_jk = 0

# BPQ cost:
if k == 3:
    BPQ_k = 12*Ten + 3*Imp + Har + Mic + Por + Che
else:
    BPQ_k = 0

# PQ cost:
if j == 3 and (k == 2 or k == 3):
    PQ_jk = Ten + Imp + Mic + Har + Por + Vis + Sur + Vol + Dim
```

```
else:
    PQ_jk = 0

# PT cost:
if j == 3:
    PT_j = Ten + Imp + Mic + Har + Por + Vis + Sur + Vol + Dim
elif j == 2:
    PT_j = Ten + Imp + Vis + Sur + Vol + Dim
else:
    PT_j = 0

# Accounting for how parts_ij changes
if i == 1 and (j == 2 or j == 3):
    parts_ij = parts
elif j == 1 or i == 2:
    parts_ij = 1

# uT_jk cost:
if j == 3 and k == 3:
    uT_jk = uT*(parts_ij + 2)
elif (j == 3 and k == 2) or (j == 2 and k == 3):
    uT_jk = uT*(parts_ij + 1)
elif (j == 3 and k == 1) or (j == 2 and (k == 1 or k == 2)):
    uT_jk = uT * parts_ij
elif j == 1 and k == 3:
    uT_jk = uT
elif j == 1 and (k == 1 or k == 2):
    uT_jk = 0

# Total qualification costs:
QC_ijk = BPQ_k + PQ_jk + PT_j * parts_ij + uT_jk

print("\nQualifiication cost =", QC_ijk)
```

B Case A - Python code

```
from sympy import symbols, solve, lambdify
import matplotlib.pyplot as plt
import numpy as np

def QualificationCost(i,j,k):
    i = i
    j = j
    k = k
    parts = symbols("N")
    uT  = 20             # Unitary cost of transportation of one part/test job to and from testing facility
    Ten = 35             # Cost of tensile testing
    Imp = 65             # Cost of impact testing
    Mic = 85             # Cost of microstructural assessment
    Har = 150            # Cost of hardness testing
    Por = 75             # Cost of porosity testing
    Che = 70             # Cost of chemical testing
    Vis = 10             # Cost of visual testing
    Sur = 15             # Cost of surface NDT
    Vol = 150            # Cost of volumetric NDT
    Dim = 50             # Cost of dimensional check

    QC_ijk = 0; BPQ_k = 0; PQ_jk = 0; PT_j = 0; parts_ij = 0; uT_jk = 0

    # BPQ cost:
    if k == 3:
        BPQ_k = 12*Ten + 3*Imp + Har + Mic + Por + Che
    else:
        BPQ_k = 0

    # PQ cost:
    if j == 3 and (k == 2 or k == 3):
        PQ_jk = Ten + Imp + Mic + Har + Por + Vis + Sur + Vol + Dim
    else:
        PQ_jk = 0

    # PT cost:
    if j == 3:
        PT_j = Ten + Imp + Mic + Har + Por + Vis + Sur + Vol + Dim
    elif j == 2:
        PT_j = Ten + Imp + Vis + Sur + Vol + Dim
    else:
        PT_j = 0

    # Accounting for how parts_ij changes
    if i == 1 and (j == 2 or j == 3):
        parts_ij = parts
    elif j == 1 or i == 2:
        parts_ij = 1

    # uT_jk cost:
    if j == 3 and k == 3:
        uT_jk = uT*(parts_ij + 2)
    elif (j == 3 and k == 2) or (j == 2 and k == 3):
        uT_jk = uT*(parts_ij + 1)
    elif (j == 3 and k == 1) or (j == 2 and (k == 1 or k == 2)):
        uT_jk = uT * parts_ij
    elif j == 1 and k == 3:
        uT_jk = uT
    elif j == 1 and (k == 1 or k == 2):
        uT_jk = 0
```

```
    # Total qualification costs:
    QC_ijk = BPQ_k + PQ_jk + PT_j * parts_ij + uT_jk
    return QC_ijk

# Criticality 3
print("Criticality 3")
for k in range(1,4):
    print("Case",k)
    N = symbols("N")
    AM_Q = QualificationCost(1,3,k)
    CM_Q = QualificationCost(2,3,k)
    AM_T = 560.55 + AM_Q
    CM_T = 22.68 + 22366/N + CM_Q

    Breakeven = solve(AM_T - CM_T)
    Breakeven = Breakeven[1]
    print("Breakeven point:",Breakeven)

    AM_T = lambdify(N,AM_T)
    CM_T = lambdify(N,CM_T)

    N = np.linspace(1,15,100)
    plt.plot(N,AM_T(N),label="AM")
    plt.plot(N,CM_T(N),label="CM")
    plt.xlabel("Production Volume (N)")
    plt.ylabel("Total cost per Assembly ($)")
    plt.ylim([0, 10000])
    plt.legend()
    plt.show()

    AM = np.array([560.55, AM_T(Breakeven)-560.55])
    mylabels = ["Production cost", "Qualification cost"]
    plt.pie(AM,startangle=90,autopct='%1.1f%%')
    plt.legend(labels = mylabels,loc="upper left")
    plt.show()

    CM = np.array([CM_T(Breakeven)-CM_Q, CM_Q])
    mylabels = ["Production cost", "Qualification cost"]
    plt.pie(CM,startangle=90,autopct='%1.1f%%')
    plt.legend(labels = mylabels,loc="upper left")
    plt.show()
    print("\n")

# Criticality 2
print("Criticality 2")
for k in range(1,4):
    print("Case",k)
    N = symbols("N")
    AM_Q = QualificationCost(1,2,k)
    CM_Q = QualificationCost(2,2,k)
    AM_T = 560.55 + AM_Q
    CM_T = 22.68 + 22366/N + CM_Q

    Breakeven = solve(AM_T - CM_T)
    Breakeven = Breakeven[1]
    print("Breakeven point:",Breakeven)

    AM_T = lambdify(N,AM_T)
    CM_T = lambdify(N,CM_T)
    N = np.linspace(1,15,100)
    plt.plot(N,AM_T(N),label="AM")
```

```python
    plt.plot(N,CM_T(N),label="CM")
    plt.xlabel("Production Volume (N)")
    plt.ylabel("Total cost per Assembly ($)")
    plt.ylim([0, 10000])
    plt.legend()
    plt.show()

    AM = np.array([560.55, AM_T(Breakeven)-560.55])
    mylabels = ["Production cost", "Qualification cost"]
    plt.pie(AM,startangle=90,autopct='%1.1f%%')
    plt.legend(labels = mylabels,loc="upper left")
    plt.show()

    CM = np.array([CM_T(Breakeven)-CM_Q, CM_Q])
    mylabels = ["Production cost", "Qualification cost"]
    plt.pie(CM,startangle=90,autopct='%1.1f%%')
    plt.legend(labels = mylabels,loc="upper left")
    plt.show()
    print("\n")

# Criticality 1
print("Criticality 1")
for k in range (1,4):
    print("Case",k)
    N = symbols("N")
    AM_Q = QualificationCost(1,1,k)
    CM_Q = QualificationCost(2,1,k)
    AM_T = 560.55 + AM_Q
    CM_T = 22.68 + 22366/N + CM_Q

    Breakeven = solve(AM_T - CM_T)
    Breakeven = Breakeven[0]
    print("Breakeven point:",Breakeven)

    CM_T = lambdify(N,CM_T)
    N = np.linspace(1,100,100)
    plt.axhline(y=AM_T,color = "C0",label="AM")
    plt.plot(N,CM_T(N),color = "C1",label="CM")
    plt.xlabel("Production Volume (N)")
    plt.ylabel("Total cost per Assembly ($)")
    plt.ylim([0, 5000])
    plt.legend()
    plt.show()

    if AM_Q == 0:
        AM = np.array([560.55])
    else:
        AM = np.array([560.55, AM_Q])
    mylabels = ["Production cost", "Qualification cost"]
    plt.pie(AM,startangle=90,autopct='%1.1f%%')
    plt.legend(labels = mylabels,loc="upper left")
    plt.show()

    if CM_Q == 0:
        CM = np.array([CM_T(Breakeven)])
    else:
        CM = np.array([CM_T(Breakeven)-CM_Q, CM_Q])
    mylabels = ["Production cost", "Qualification cost"]
    plt.pie(CM,startangle=90,autopct='%1.1f%%')
    plt.legend(labels = mylabels,loc="upper left")
    plt.show()
    print("\n")
```

C Case B - Python code

```python
import matplotlib.pyplot as plt
import numpy as np

def QualificationCost(i,j,k,parts):
    i = i
    j = j
    k = k
    parts = parts
    uT  = 20              # Unitary cost of transportation of one part/test job to and from testing facility
    Ten = 35              # Cost of tensile testing
    Imp = 65              # Cost of impact testing
    Mic = 85              # Cost of microstructural assessment
    Har = 150             # Cost of hardness testing
    Por = 75              # Cost of porosity testing
    Che = 70              # Cost of chemical testing
    Vis = 10              # Cost of visual testing
    Sur = 15              # Cost of surface NDT
    Vol = 150             # Cost of volumetric NDT
    Dim = 50              # Cost of dimensional check

    QC_ijk = 0; BPQ_k = 0; PQ_jk = 0; PT_j = 0; parts_ij = 0; uT_jk = 0

    # BPQ cost:
    if k == 3:
        BPQ_k = 12*Ten + 3*Imp + Har + Mic + Por + Che
    else:
        BPQ_k = 0

    # PQ cost:
    if j == 3 and (k == 2 or k == 3):
        PQ_jk = Ten + Imp + Mic + Har + Por + Vis + Sur + Vol + Dim
    else:
        PQ_jk = 0

    # PT cost:
    if j == 3:
        PT_j = Ten + Imp + Mic + Har + Por + Vis + Sur + Vol + Dim
    elif j == 2:
        PT_j = Ten + Imp + Vis + Sur + Vol + Dim
    else:
        PT_j = 0

    # Accounting for how parts_ij changes
    if i == 1 and (j == 2 or j == 3):
        parts_ij = parts
    elif j == 1 or i == 2:
        parts_ij = 1

    # uT_jk cost:
    if j == 3 and k == 3:
        uT_jk = uT*(parts_ij + 2)
    elif (j == 3 and k == 2) or (j == 2 and k == 3):
        uT_jk = uT*(parts_ij + 1)
    elif (j == 3 and k == 1) or (j == 2 and (k == 1 or k == 2)):
        uT_jk = uT * parts_ij
    elif j == 1 and k == 3:
        uT_jk = uT
    elif j == 1 and (k == 1 or k == 2):
        uT_jk = 0
```

```
    # Total qualification costs:
    QC_ijk = BPQ_k + PQ_jk + PT_j * parts_ij + uT_jk
    return QC_ijk

# Criticality 1 - Dental prostheses
# Scrap fraction 0.05
mat = 16*1.07
pre = 14*1.07
prod = 31*1.07
post = (12-10)*1.07   # Subtracting the cost of visual testing/dimensional check from post-process costs
QC = []
for k in range(1,4):
    QC.append(QualificationCost(1,1,k,1))

case = ["Best-case","Medium-case","Worst-case"]
material = np.array([mat,mat,mat])
preprocess = np.array([pre,pre,pre])
SLM = np.array([prod,prod,prod])
postprocess = np.array([sum(value) for value in zip([post,post,post],QC)])
ind = [x for x, _ in enumerate(case)]

plt.bar(ind, postprocess, label='Post-process', color='yellow',edgecolor = 'black',
↪   bottom=SLM+preprocess+material)
plt.bar(ind, SLM, label='SLM process', color='yellowgreen',edgecolor = 'black', bottom=preprocess+material)
plt.bar(ind, preprocess, label='Pre-process', color='deepskyblue',edgecolor = 'black', bottom=material)
plt.bar(ind, material, label='Material', color='navy',edgecolor = 'black')
plt.xticks(ind, case)
plt.ylabel("Cost ($)")
plt.xlabel("Scrap fraction = 0.05")
plt.legend(loc="upper left")
plt.title("Criticality 1 - Dental prostheses")
plt.ylim([0, 130])
plt.show()

# Criticality 1 - Dental prostheses
# Scrap fraction 0.1
mat = 17*1.07
pre = 15*1.07
prod = 32*1.07
post = (13-10)*1.07   # Subtracting the cost of visual testing/dimensional check from post-process costs
QC = []
for k in range(1,4):
    QC.append(QualificationCost(1,1,k,1))

case = ["Best-case","Medium-case","Worst-case"]
material = np.array([mat,mat,mat])
preprocess = np.array([pre,pre,pre])
SLM = np.array([prod,prod,prod])
postprocess = np.array([sum(value) for value in zip([post,post,post],QC)])
ind = [x for x, _ in enumerate(case)]

plt.bar(ind, postprocess, label='Post-process', color='yellow',edgecolor = 'black',
↪   bottom=SLM+preprocess+material)
plt.bar(ind, SLM, label='SLM process', color='yellowgreen',edgecolor = 'black', bottom=preprocess+material)
plt.bar(ind, preprocess, label='Pre-process', color='deepskyblue',edgecolor = 'black', bottom=material)
plt.bar(ind, material, label='Material', color='navy',edgecolor = 'black')
plt.xticks(ind, case)
plt.ylabel("Cost ($)")
plt.xlabel("Scrap fraction = 0.1")
plt.legend(loc="upper left")
plt.title("Criticality 1 - Dental prostheses")
plt.ylim([0, 130])
```

```
plt.show()

# Criticality 1 - Dental prostheses
# Scrap fraction 0.2
mat = 19*1.07
pre = 17*1.07
prod = 37*1.07
post = (15-10)*1.07   # Subtracting the cost of visual testing/dimensional check from post-process costs
QC = []
for k in range(1,4):
    QC.append(QualificationCost(1,1,k,1))

case = ["Best-case","Medium-case","Worst-case"]
material = np.array([mat,mat,mat])
preprocess = np.array([pre,pre,pre])
SLM = np.array([prod,prod,prod])
postprocess = np.array([sum(value) for value in zip([post,post,post],QC)])
ind = [x for x, _ in enumerate(case)]

plt.bar(ind, postprocess, label='Post-process', color='yellow',edgecolor = 'black',
↪   bottom=SLM+preprocess+material)
plt.bar(ind, SLM, label='SLM process', color='yellowgreen',edgecolor = 'black', bottom=preprocess+material)
plt.bar(ind, preprocess, label='Pre-process', color='deepskyblue',edgecolor = 'black', bottom=material)
plt.bar(ind, material, label='Material', color='navy',edgecolor = 'black')
plt.xticks(ind, case)
plt.ylabel("Cost ($)")
plt.xlabel("Scrap fraction = 0.2")
plt.legend(loc="upper left")
plt.title("Criticality 1 - Dental prostheses")
plt.ylim([0, 130])
plt.show()

# Criticality 2 - Machinery component
# Scrap fraction 0.05
mat = 30*1.07
pre = 29*1.07
prod = 230*1.07
post = (59-50)*1.07   # Subtracting the cost of visual testing/dimensional check from post-process costs
QC = []
for k in range(1,4):
    QC.append(QualificationCost(1,2,k,1))

case = ["Best-case","Medium-case","Worst-case"]
material = np.array([mat,mat,mat])
preprocess = np.array([pre,pre,pre])
SLM = np.array([prod,prod,prod])
postprocess = np.array([sum(value) for value in zip([post,post,post],QC)])
ind = [x for x, _ in enumerate(case)]

plt.bar(ind, postprocess, label='Post-process', color='yellow',edgecolor = 'black',
↪   bottom=SLM+preprocess+material)
plt.bar(ind, SLM, label='SLM process', color='yellowgreen',edgecolor = 'black', bottom=preprocess+material)
plt.bar(ind, preprocess, label='Pre-process', color='deepskyblue',edgecolor = 'black', bottom=material)
plt.bar(ind, material, label='Material', color='navy',edgecolor = 'black')
plt.xticks(ind, case)
plt.ylabel("Cost ($)")
plt.xlabel("Scrap fraction = 0.05")
plt.legend(loc="upper left")
plt.title("Criticality 2 - Machinery component")
plt.show()

# Criticality 2 - Machinery component
```

```python
# Scrap fraction 0.2
mat = 36*1.07
pre = 34*1.07
prod = 273*1.07
post = (70-50)*1.07   # Subtracting the cost of visual testing/dimensional check from post-process costs
QC = []
for k in range(1,4):
    QC.append(QualificationCost(1,2,k,1))

case = ["Best-case","Medium-case","Worst-case"]
material = np.array([mat,mat,mat])
preprocess = np.array([pre,pre,pre])
SLM = np.array([prod,prod,prod])
postprocess = np.array([sum(value) for value in zip([post,post,post],QC)])
ind = [x for x, _ in enumerate(case)]

plt.bar(ind, postprocess, label='Post-process', color='yellow',edgecolor = 'black',
↪   bottom=SLM+preprocess+material)
plt.bar(ind, SLM, label='SLM process', color='yellowgreen',edgecolor = 'black', bottom=preprocess+material)
plt.bar(ind, preprocess, label='Pre-process', color='deepskyblue',edgecolor = 'black', bottom=material)
plt.bar(ind, material, label='Material', color='navy',edgecolor = 'black')
plt.xticks(ind, case)
plt.ylabel("Cost ($)")
plt.xlabel("Scrap fraction = 0.2")
plt.legend(loc="upper left")
plt.title("Criticality 2 - Machinery component")
plt.show()

# Criticality 2 - Machinery component
# Scrap fraction 0.4
mat = 48*1.07
pre = 45*1.07
prod = 234*1.07
post = (93-50)*1.07   # Subtracting the cost of visual testing/dimensional check from post-process costs
QC = []
for k in range(1,4):
    QC.append(QualificationCost(1,2,k,1))

case = ["Best-case","Medium-case","Worst-case"]
material = np.array([mat,mat,mat])
preprocess = np.array([pre,pre,pre])
SLM = np.array([prod,prod,prod])
postprocess = np.array([sum(value) for value in zip([post,post,post],QC)])
ind = [x for x, _ in enumerate(case)]

plt.bar(ind, postprocess, label='Post-process', color='yellow',edgecolor = 'black',
↪   bottom=SLM+preprocess+material)
plt.bar(ind, SLM, label='SLM process', color='yellowgreen',edgecolor = 'black', bottom=preprocess+material)
plt.bar(ind, preprocess, label='Pre-process', color='deepskyblue',edgecolor = 'black', bottom=material)
plt.bar(ind, material, label='Material', color='navy',edgecolor = 'black')
plt.xticks(ind, case)
plt.ylabel("Cost ($)")
plt.xlabel("Scrap fraction = 0.4")
plt.legend(loc="upper left")
plt.title("Criticality 2 - Machinery component")
plt.show()

# Criticality 3 - Aerospace bracket
# Scrap fraction 0.05
mat = 11*1.07
pre = 56*1.07
prod = 638*1.07
```

```
post = (65-50)*1.07    # Subtracting the cost of visual testing/dimensional check from post-process costs
QC = []
for k in range(1,4):
    QC.append(QualificationCost(1,3,k,1))

case = ["Best-case","Medium-case","Worst-case"]
material = np.array([mat,mat,mat])
preprocess = np.array([pre,pre,pre])
SLM = np.array([prod,prod,prod])
postprocess = np.array([sum(value) for value in zip([post,post,post],QC)])
ind = [x for x, _ in enumerate(case)]

plt.bar(ind, postprocess, label='Post-process', color='yellow',edgecolor = 'black',
↪   bottom=SLM+preprocess+material)
plt.bar(ind, SLM, label='SLM process', color='yellowgreen',edgecolor = 'black', bottom=preprocess+material)
plt.bar(ind, preprocess, label='Pre-process', color='deepskyblue',edgecolor = 'black', bottom=material)
plt.bar(ind, material, label='Material', color='navy',edgecolor = 'black')
plt.xticks(ind, case)
plt.ylabel("Cost ($)")
plt.xlabel("Scrap fraction = 0.05")
plt.legend(loc="upper left")
plt.title("Criticality 3 - Aerospace bracket")
plt.show()

# Criticality 3 - Aerospace bracket
# Scrap fraction 0.2
mat = 14*1.07
pre = 67*1.07
prod = 757*1.07
post = (77-50)*1.07    # Subtracting the cost of visual testing/dimensional check from post-process costs
QC = []
for k in range(1,4):
    QC.append(QualificationCost(1,3,k,1))

case = ["Best-case","Medium-case","Worst-case"]
material = np.array([mat,mat,mat])
preprocess = np.array([pre,pre,pre])
SLM = np.array([prod,prod,prod])
postprocess = np.array([sum(value) for value in zip([post,post,post],QC)])
ind = [x for x, _ in enumerate(case)]

plt.bar(ind, postprocess, label='Post-process', color='yellow',edgecolor = 'black',
↪   bottom=SLM+preprocess+material)
plt.bar(ind, SLM, label='SLM process', color='yellowgreen',edgecolor = 'black', bottom=preprocess+material)
plt.bar(ind, preprocess, label='Pre-process', color='deepskyblue',edgecolor = 'black', bottom=material)
plt.bar(ind, material, label='Material', color='navy',edgecolor = 'black')
plt.xticks(ind, case)
plt.ylabel("Cost ($)")
plt.xlabel("Scrap fraction = 0.2")
plt.legend(loc="upper left")
plt.title("Criticality 3 - Aerospace bracket")
plt.show()

# Criticality 3 - Aerospace bracket
# Scrap fraction 0.4
mat = 18*1.07
pre = 89*1.07
prod = 1009*1.07
post = (103-50)*1.07    # Subtracting the cost of visual testing/dimensional check from post-process costs
QC = []
for k in range(1,4):
    QC.append(QualificationCost(1,3,k,1))
```

```
case = ["Best-case","Medium-case","Worst-case"]
material = np.array([mat,mat,mat])
preprocess = np.array([pre,pre,pre])
SLM = np.array([prod,prod,prod])
postprocess = np.array([sum(value) for value in zip([post,post,post],QC)])
ind = [x for x, _ in enumerate(case)]

plt.bar(ind, postprocess, label='Post-process', color='yellow',edgecolor = 'black',
↪  bottom=SLM+preprocess+material)
plt.bar(ind, SLM, label='SLM process', color='yellowgreen',edgecolor = 'black', bottom=preprocess+material)
plt.bar(ind, preprocess, label='Pre-process', color='deepskyblue',edgecolor = 'black', bottom=material)
plt.bar(ind, material, label='Material', color='navy',edgecolor = 'black')
plt.xticks(ind, case)
plt.ylabel("Cost ($)")
plt.xlabel("Scrap fraction = 0.4")
plt.legend(loc="upper left")
plt.title("Criticality 3 - Aerospace bracket")
plt.show()
```

NTNU

Norwegian University of
Science and Technology