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Design for Qualification: A Process for Developing Additive Manufacturing Components for Critical Systems

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Abstract

Additive Manufacturing (AM), and more specifically Powder Bed Fusion, offers design freedom, functional integration, and cost efficient manufacturing of customised products. These design and manufacturing capabilities are relevant for the space industry with its characteristic low production volumes, high-performance products, pursuit for low weight, and a recent need for cost reduction due to increased market competition. At the same time, the space industry is characterised by products in harsh environments without room for failure, nor the possibility to repair broken parts in service. Product qualification is therefore an important part of the product development process in the space industry, with the purpose of showing that the product design and its manufacturing process fulfils the technical requirements. Qualification is a challenge for AM that currently exhibits a sensitivity in part mechanical properties based on geometry and build orientation, as well as a variability in process outcome. As with other manufacturing processes, design engineers have to take process capabilities into account during product design to render a manufacturable product (Design for AM), but also to achieve the right quality and function (Design for Excellence). Apart from manufacturability, product qualification has to be considered early in the product development process of AM parts. Given the lack of understanding of AM process characteristics, design engineers are in need of design supports to facilitate the qualification of critical AM parts. This paper presents a Design for Qualification process model for development of AM components in critical space systems. The model is proposed based on research performed in the space industry with several case companies.

Keywords: Product Development, Design for Additive Manufacturing, Space applications, Qualification

1 Introduction

Additive Manufacturing (AM) is a production technology that has received attention in recent years due to its many advantages. One of these is customised design for small series which is appealing for the space industry, characterized by small volumes and technically sophisticated solutions with high performance (Gibson et al. 2015). Several AM parts have been used successfully in space applications, but it is still rather uncommon due to that AM processes are considered relatively immature. The processes can exhibit a significant variation in process outcome, meaning that it is not sure that two products printed at the same time have the same performance. For a successful implementation of AM in space applications it is important to understand the AM process, how to design for AM to avoid failure, and create systematic methods for design and qualification. Much responsibility lies on design engineers, not only from the functional perspective, but also to make sure that a part is manufacturable, reliable and cost efficient (Bralla, 1999). Design for Manufacturing (DfM) has as its primary objective to ease manufacturing and reduce manufacturing cost. However, there are other factors that are important to consider as well, e.g. function and performance, safety, high quality, and serviceability (Bralla, 1996). These are desirable characteristics of a product, and the design of a product that maximise all of these is referred to as Design for X, X representing each characteristics (ibid.). With the advent of AM technologies and their possibilities and limitations, DfM has evolved into DfAM (Gibson et al., 2015). While the definition of DfAM is ambiguous among researchers (Kumke et al., 2016), its importance in the development of parts for AM is often highlighted due to that process characteristics have to be considered early in the design (Thompson et al., 2016). Typical characteristics are build orientation, support structure and material properties (ibid.). However, DfAM should also be considered in a broader perspective, where the choice of suitable parts and AM processes is included, as well as the consideration for post-AM processing activities, e.g. surface finishing (Kumke et al., 2016). This perspective can be expressed as the need for an 'end-to-end manufacturing process', where early design, material supply, manufacturing, post-processing and qualification are all linked to the production of critical AM parts (Brandão et al., 2017). The aim of this conceptual paper is to present an approach for the design and qualification of critical products for space applications based on previous and current research activities. The AM process considered in this research is metal powder bed fusion (PBF).

2 Qualification of Additive Manufacturing in the Space Industry

The challenge with qualification of critical AM parts has been discussed in previous research contributions (e.g. Gorelik, 2017; Seifi et al., 2016; Taylor et al., 2016). In the development of critical parts for AM, understanding the influence of material properties on part behaviour is crucial. However, AM processes today show intrinsic material characteristics that are challenging for this understanding: (i) anisotropy and location dependent properties, (ii) defects (e.g. pores, inclusions), and (iii) rough surfaces that may impact fatigue life (Seifi et al., 2017). From a part design perspective, the geometry has an impact on these characteristics, especially on microstructure and defect occurrence, due to that the thermal history of built parts varies with the geometry (Murr, 2015; Seifi et al., 2017). Defects and rough surfaces may impose the largest challenge for critical parts since they can overshadow microstructural effects (Lewandowski & Seifi, 2016; Romano et al., 2017), and designing parts for AM with the assumption of a defect free material is probably not realistic (Dordlofva & Törlind, 2017).

In the development of space systems, product requirements are flowed from the system owner to the sub-system supplier (interfaces and function), which have to be fulfilled in accordance with the relevant regulations (Dordlofva, 2018). Specific qualification requirements are imposed on a part depending on its criticality classification, i.e. the consequence of it failing (ECSS, 2017). A possible catastrophic or critical impact (e.g. loss of system or mission) requires that the part is shown to be fracture tolerant, i.e. to withstand local defects without performance degradation below the requirements (ECSS, 2009). Such verification can be either analytical, through testing, or a combination of both (ibid.). The current lack of understanding of AM processes, and processes linked to the manufacturing (e.g. post-processing or inspection), has led to a combination of coupon/part testing and non-destructive testing (NDT) for the verification of AM parts (Seifi et al., 2017). However, test coupons are not certain to represent the behaviour a part, or its microstructure, and it is highlighted that AM test artefacts have to represent the part to be qualified (Gorelik, 2017; Taylor et al., 2016). Furthermore, established NDT methods and standards for AM materials are lacking, and developing such methods for AM is challenging due to part property variation, part geometric complexity, surface roughness, and access to surface or volume inspection (Seifi et al., 2017). Until NDT methods have been developed, testing and inspection of parts will have to be part specific (ibid.). Analytical verification can (and usually does) complement the testing, but it is challenging to know what and how to analyse AM parts (e.g. how to treat defects) (Gorelik, 2017; Seifi et al., 2017). The need for a damage tolerance approach for critical space applications accentuates this need for understanding the 'effect of defect' in AM materials. Process simulation will be valuable in predicting part material properties, but currently such computational tools are rather rudimentary and require further development (Martukanitz et al., 2014).

2.1 Test Artefacts in Additive Manufacturing

For better process understanding, performance evaluation of AM systems is important. In the measurement of manufacturing technology performance, mainly two approaches exist: (1) direct measurement of system components or characteristics, and (2) measurement on manufactured test artefacts (Moylan et al., 2014). Currently, the more suitable approach for AM systems is the use of test artefacts due to difficulties in measuring characteristics of AM processes in-situ (ibid.). Test artefacts have been much used in AM for benchmarking as presented by Rebaioli & Fassi (2017) in an extensive review where they describe over 60 artefacts presented between the years 1991 and 2017. The intent of a test artefact should be to: (i) demonstrate the capabilities and limitations of the machine or process (e.g. smallest feature, surface roughness), (ii) relate build results to AM system errors to enable adaption of process settings to improve the outcome, and (iii) allow for measurement of e.g. geometrical features, internal porosity, or mechanical properties (Moylan et al., 2014). Mahesh (2004) highlights that both *geometrical* and *mechanical* characterisation is important for a complete benchmark of the manufacturing process. The importance of standard test artefacts and measurement methods to facilitate evaluation and comparison of processes has been pointed out by e.g. Mahesh (2004) and Moylan et al. (2014). Currently, such standards do not exist, but are being developed by the joint effort between the ASTM F42 and ISO/TC 261 working groups (ISO/ASTM, 2018).

3 Concurrent Product and Additive Manufacturing Process Development

The need for an 'end-to-end manufacturing process' for critical AM parts as suggested by Brandão et al. (2017), raises the question how the product development process for space applications is impacted (Dordlofva, 2018). The current level of AM process maturity makes 'learning by doing' an inevitable approach, meaning that AM manufacturing engineers and design engineers have to work closely together, i.e. manufacturing process development and DfAM become closely linked (ibid.). A study in the space industry on product development for conventional manufacturing technologies showed that product and manufacturing process qualification are linked together, and that products in the aerospace industry often require a tailored manufacturing process (Dordlofva & Törlind, 2017). Such concurrent development of the part and manufacturing process should be considered in AM as well (Dordlofva, 2018), and can be viewed from two perspectives; (i) to design the part for the process (e.g. design for defects (Seifi et al., 2017)), and (ii) to design/tweak the process for the part (Orme et al., 2017). DfAM is therefore suggested to be an important part of AM qualification, and a refined model of the product development process utilising AM for space applications was presented by Dordlofva (2018), see Figure 1. From a qualification perspective, the dotted box highlights the need for a system-level perspective on part criticality and qualification requirements, but also the importance of a concurrent development of product and AM process.

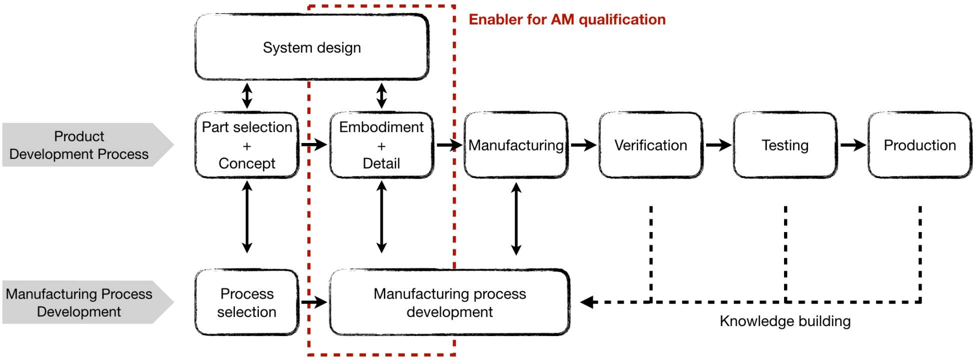

Figure 1. Refined model of the product development process for AM in space applications, utilising concurrent product and manufacturing process development and systems design (Dordlofva, 2018).

It is essential to assess the readiness of the AM process when implementing it as a manufacturing process for critical applications. A successfully used approach within the space industry is the Technology Readiness Level (TRL) scale, where technology maturity is assessed based on testing at increasing levels of difficulty (Mankins, 2009). Similarly, assessment of knowledge maturity during product development can aid design teams to clarify what is known or unknown (uncertain); *"... knowledge maturity is about providing design teams with insights about which areas they have sufficient knowledge and information in, and highlighting the areas where more knowledge and thus work is needed*" (Johansson et al., 2008, p. 4). Knowledge building is therefore also a key component in the model shown in Figure 1.

3.1 Prototyping in Product Development

Rapid prototyping is an early collective term for layer-wise technologies which evolved into AM with their increased use for direct manufacturing (Gibson et al., 2015). Prototypes are used throughout a product development process for four primary purposes; learning, communicating, integrating, and showing functionality at project milestones (Ulrich & Eppinger, 2012). However, despite the frequent use of prototypes, its definition is ambiguous and prototypes can have different purpose or meaning depending on the perspective and prototyping culture of a company (Schrage, 1993). Houde & Hill (1997) argued that *"Prototypes provide the means for examining design problems and evaluating solutions. Selecting the focus of a prototype is the art of identifying the most important open design questions"* (p. 368). A product development approach that can be related to this view can be found in Hartmann (2009) that describes a design process practiced by IDEO (a renowned Palo Alto-based design consultancy). In this process, prototypes are used in a three-stage model, where each stage utilise prototypes for different purposes; to Inspire, Evolve and Validate (see Figure 2).

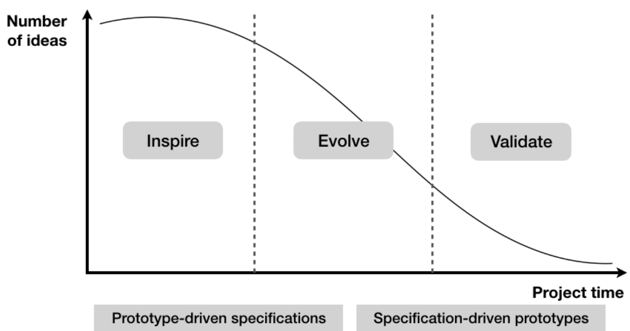

Figure 2. Three-stage model of the prototyping process at IDEO (adapted from Hartmann, 2009, p. 21).

The idea is to start product development with many parallel prototypes to explore different design options, continuing with a smaller number of prototypes to evaluate and evolve specific design questions. In the final stage, more complete prototypes are used to validate the design. The purpose of this process is to facilitate a product development approach where the product specification is driven by prototypes, and where prototypes are later used to validate the product specification (Hartmann, 2009).

4 Method

The work presented in this paper is based on previous descriptive research from three studies including interviews and workshops with three companies in the Swedish space industry (Dordlofva, 2018). The research has largely been based on the DRM framework – Design Research Methodology (Blessing & Chakrabarti, 2009) – where the previous work presented the first two steps in DRM, i.e. research clarification and the first descriptive study. The current paper is an initiation of the next step, the prescriptive phase, that has the purpose of elaborating on an envisioned design support using the knowledge that has been gathered in the previous phases (ibid.). The results from the previous research highlighted the importance of building knowledge for the design and qualification of critical AM parts for space applications. The aim of this paper is to present a model for developing this knowledge through concurrent development of part and AM process to facilitate qualification, a *Design for Qualification* process. A workshop series with three companies from the aerospace industry has been used to introduce and develop the process. Each company has a global presence within the space industry with the number of employees ranging from 1 300 to 18 000. The workshop series includes Swedish subsidiaries that are developing and manufacturing sub-systems for space applications. Within the project, each company is developing a use-case (part) to be manufactured with PBF. While the workshop series has the industrial objective to design each use-case with a PBF process in mind, one of the academic objectives is to develop a process for the qualification of each part. The focus of this paper is to present a first model of this process to be studied further.

5 Design for Qualification

The suggested concurrent development approach for critical AM parts (Figure 1) faces the same challenges as a proper DfX approach; concurrent and simultaneous engineering that requires a team of engineers from multiple disciplines, including design engineers and manufacturing engineers (Bralla, 1996). Due to the current maturity level of AM processes, one approach to qualify AM parts has been to adapt the process to the part requirements (see e.g. Orme et al. 2017). This is similar to the approach used for fibre composites, that (like AM) show material property dependency on part geometry (CMH-17, 2012). While the rapid manufacturing and flexibility of AM processes support such manufacturing process design, a difficulty still lies in the lack of understanding of the process characteristics (Lewandowski & Seifi, 2016), and the impact of these on part design. The proposed DfAM working process builds on this need to continuously build knowledge of the AM process capabilities through ‘learning by doing’, while considering product qualification.

5.1 Process Needs

In preparation for one of the workshops that aim to develop and evaluate the *Design for Qualification* process, the participating companies were asked to: (i) identify their perceived main known uncertainties for manufacturing their use-case with PBF, and (ii) define the main open issues for qualification of the use-case. Table 1 summarise the main findings.

Table 1. Main manufacturing uncertainties and qualification issues specified by the participating companies

Known uncertainties for manufacturing	Open qualification issues
Why and where do pores and other defects occur? What parameters impact the occurrence of defects?	Impact of defects, surface roughness and other material properties on part performance. Handling of variations in material properties.
Is there a variation in material properties? How can repeatability be guaranteed?	Weldability of used material alloys.
What is the achievable surface roughness? What measures have to be taken to get an acceptable surface roughness?	Cleanliness of parts from PBF processes (powder remnants).
What is the geometrical accuracy? What parameters impact the geometrical accuracy?	Capabilities of NDT methods on AM materials.

Although Table 1 lists the challenges independent of company, one finding was that each company had specific challenges for their use-case. Furthermore, when asked separately about the process of qualification, it was also found that each company faced different requirements depending on the type of part (use-case). This is linked to the criticality classification of a part and highlights a need for a qualification process that allows adoption to part specific requirements. The characteristics of AM materials; anisotropy, defects and surface roughness, strengthen this argumentation since they can depend on the part geometry. The proposed process builds on the use of artefacts, and on the basis that artefacts used for testing have to be representative of the manufactured AM part to capture its behaviour (Gorelik, 2017; Taylor et al., 2016). When the participating companies were introduced to the notion of using test artefacts to assess and evaluate uncertainties (unknowns), they identified two objectives with using such parts: (1) test design concepts, and (2) verify the part and AM process. This twofold need has been considered in the development of the proposed design process.

5.2 Process Model Proposal

The core of the proposed process is the need to include qualification into the DfAM process which was highlighted by Dordlofva (2018). The main challenges for such a process were concluded to be: (i) finding the right part design for the AM process, and (ii) defining the right level of requirements for the part. The purpose of the proposed process is therefore to:

A. Continuously build knowledge on AM process capabilities through concurrent engineering between design teams and AM process engineers.
B. Facilitate DfAM through an increased understanding of design possibilities and limitations through iterative feedback from manufactured test artefacts.
C. Incorporate a procedure into the DfAM process to enable the qualification of parts in critical applications through developing the qualification logic with the specific part.

Figure 3 (below) is an evolution of Figure 1 and presents a tentative model of the *Design for Qualification* process intended for the development and qualification of critical AM parts.

To aid design engineers find the right part design and define the right requirements for the part, inspiration is taken from the IDEO design process (Figure 2). By using artefacts (prototypes), the engineers can explore uncertainties that are identified during the design process by testing concepts using the actual AM process. The process model distinguishes between three types of artefacts: *design*, *qualification* and *standard test* artefacts. The design and qualification artefacts correspond to the identified need to test design solutions and to verify part performance respectively. A standard test artefact is seen as necessary for process benchmarking and process verification, but its development is outside the scope of this research (see section 2.1). The purpose of the artefacts changes as the product design evolves and the engineers identify new uncertainties. In the first phase of the process, the **design artefacts** should be viewed as ‘concept artefacts’ where the purpose is to explore early design and AM process uncertainties. Examples could be limitation in manufacturing overhang features without support structure, or impact of a feature orientation on surface roughness. This way, the capabilities of the AM process should drive the design to aid the engineers find a suitable AM design. During the ‘Embodiment + Detail’ phase (in DfAM these are merged since a distinction between the two cannot be made (Kumke et al., 2016)), a transition to specification-driven artefacts is made once sufficient knowledge has been gathered and the part specification starts to drive the design. Fewer but more elaborate ‘embodiment artefacts’ are built to evaluate design solutions, and ultimately specify the product requirements. An example could be a section of the complete intended product (including several of the already tested features) to test the capability of the process to build it in one piece, possibly in different directions on the build plate. A restriction that may occur when using metal PBF is the cost of producing a multitude of artefacts. However, **standard test artefacts** should also aid in understanding the *fundamental* process capabilities. The distinction between the design artefacts and a standard test artefact is that the design artefacts are used for testing product specific design solutions that are not covered by the features on a standard geometry. Standard test artefacts should also facilitate the discussion with manufacturing engineers (or supplier) to assess the suitability and capability of the AM process (Moylan et al., 2014). Also illustrated in Figure 3 is the use of standard artefacts for periodical process quality control in production.

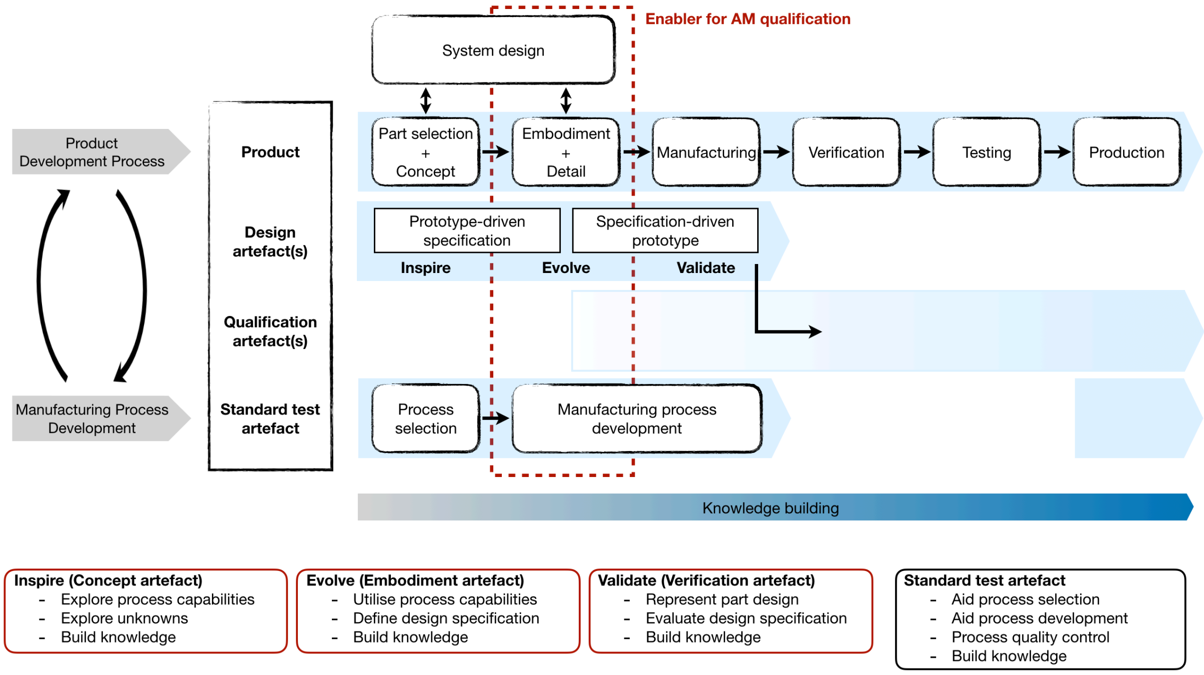

Figure 3. A tentative model of the Design for Qualification process intended to facilitate the development and qualification of AM parts for critical space applications.

Once a product specification is close to completion, verification of the design and the manufacturing process is essential to identify any remaining issues. Dordlofva & Törlind (2017) describes this process for aerospace products manufactured using conventional manufacturing processes, that (like AM) produce hidden defects such as porosities (e.g. welding). Such a verification process relies on the use of complete parts or purposely built specimens to establish the amount, size and location of defects that may occur in order to design the part accordingly. Specimens are usually built in parallel with the part, or as ‘hang-on bars’ on the part. Destructive and non-destructive testing is then used to evaluate the design and manufacturing process outcome. For sensitive processes where material properties are dependent on the part geometry (e.g. castings), 'hang-on bars' and parallel-built specimens are used to evaluate the bulk material. Defects on the other hand depend on location in the geometry, and a sacrificial part is therefore often needed to get a representative evaluation. 'Verification artefacts' are proposed to be developed as the final design artefact in this tentative process model. These artefacts should be representative of critical features of the product, and should allow for the application of chosen verification methods, both destructive and non-destructive. The purpose is to limit the need for sacrificial products during design verification, and to use the 'verification artefacts' as **qualification artefacts** in the qualification process. Developing these artefacts concurrently in the product development process allows to establish a qualification logic for the product with the product itself.

5.3 Initial Process Introduction

This section describes an example of the use of **design artefacts** in the early phases of the product development process. A five step approach is suggested to define the artefact design: (1) **Identify** design and manufacturing uncertainties, (2) **Extract** design features that need verification, (3) **Design artefact** for testing according to verification needs, (4) **Print artefact** with AM process(es), and (5) **Evaluate** process outcome. Figure 4 shows an example of a 'concept artefact' that was designed by one participating company. The use-case product of the company requires a design with a continuous overhang with limited possibility to remove support structure.

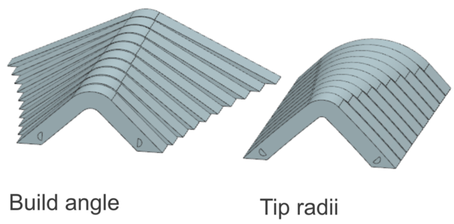

Figure 4. Model of design artefacts developed by one company to evaluate the need for support structure.

A general design rule that is often cited for laser-based PBF processes is that features with an angle of 45 degrees or more relative to the build plate can usually be built without support structure (e.g. Moylan et al., 2014). For the use-case developed by the company, the artefacts pictured in Figure 4 served the purpose to challenge this design rule due to the need to explore the actual limitations of the used laser PBF process, including angles below 45 degrees. The results after printing the artefact showed that angles below 45 degrees were in fact possible to build given the used geometry. This indicates that it is not straightforward to set generalised design rules, and that what is feasible depends on the overall design. In order to further understand the limitations and expand the design alternatives, artefacts with increasing top radius (right in Figure 4) was also included. Furthermore, all artefacts were printed in different directions relative to the powder recoater to evaluate its interaction with the parts being printed. The results from the printing gave the design engineers valuable knowledge to further develop the product, utilising what was learnt from the artefacts.

6 Concluding Discussion and Future Research

The use of AM in critical space applications is challenging due to limited knowledge and understanding of AM processes and materials. AM materials show geometry dependent properties, and the current lack of established test methods for AM parts makes it necessary to have part specific qualification. While process simulation could aid in understanding geometry impact on material properties, such tools are still on a rudimentary level. In the near term, systematic means to understand AM processes through 'learning by doing' will therefore be important to build and capture knowledge. Previous research (Dordlofva, 2018) identified the need to include qualification early in the product development process, and to build AM process understanding through concurrent development of part and AM process. Such an approach should also aid design engineers to find the right AM design and the right product requirements. This paper has presented a tentative model for a *Design for Qualification* process that utilise two different artefacts – the *design artefact* and the *qualification artefact.* The design artefact is used to explore possible design solutions and understand process capabilities that are used to define the product specification. The product specification is then used to define the qualification artefact that should represent critical features of the product that needs verification. By using knowledge that has been built during the concurrent development of product and AM process, a qualification logic can be developed with the product, initiated already in the 'Embodiment + Detail' phase. Since the qualification logic is developed with the product, appropriate test methods suitable for the part can also be identified. The qualification artefact is distinguished from a *standard test artefact* (Moylan et al., 2014) which is intended to test and develop AM process capabilities, and for continuous AM process quality assurance during production. A five-step approach has been suggested to aid the development of a design artefact (Identify, Extract, Design, Print, Evaluate), and an example of a design artefact was provided. The use of such an artefact showed potential for understanding AM process limitations and to provide valuable insights for design engineers. The *Design for Qualification* process that has been described is a tentative model. Future activities will focus on testing the model with the companies involved in the research project to evaluate its validity, and to develop it further.

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