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A Design for Qualification Framework for the Development of Additive Manufacturing Components—A Case Study from the Space Industry

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Abstract: Additive Manufacturing (AM) provides several benefits for aerospace companies in terms of efficient and innovative product development. However, due to the general lack of AM process understanding, engineers face many uncertainties related to product qualification during the design of AM components. The aim of this paper is to further the understanding of how to cope with the need to develop process understanding, while at the same time designing products that can be qualified. A qualitative action research study has been performed, using the development of an AM rocket engine turbine demonstrator as a case study. The results show that the qualification approach should be developed for the specific application, dependent on the AM knowledge within the organization. AM knowledge is not only linked to the AM process but to the complete AM process chain. Therefore, it is necessary to consider the manufacturing chain during design and to develop necessary knowledge concurrently with the product in order to define suitable requirements. The paper proposes a Design for Qualification framework, supported by six design tactics. The framework encourages proactive consideration for qualification and the capabilities of the AM process chain, as well as the continuous development of AM knowledge during product development.

Keywords: additive manufacturing; design for additive manufacturing; verification; qualification; design for qualification; space industry

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This paper builds on a demonstrator project described in a conference paper presented at the 70th International Astronautical Congress (IAC), 2019, Washington D.C. [1] and makes new contributions based on additional data.

1. Introduction

Metal Additive Manufacturing (AM) has rapidly increased in popularity for the development and manufacturing of end-use products. However, there are also challenges in ascertaining the quality of products manufactured with AM, especially in applications with strict requirements on performance and reliability [2,3]. Such applications are typical in the space industry where AM is seen as a key manufacturing technology in the future, having the potential to simplify supply chains, reduce lead time and manufacturing cost, as well as increase design flexibility and product performance [4–6]. One example is the European Space Agency (ESA) demonstrator initiative Prometheus; a next generation rocket engine scheduled for start of testing in 2020. Its goal is to have a cost of 10% of the current Ariane 5 engine, partly achieved by the use of AM [7]. In order to achieve such drastic cost reductions for space applications, new industrial system set-ups are needed, combined with extreme design-to-cost, efficient product development and the use of AM [8,9]. Examples of AM space components that have been used in service are brackets for satellite antennas

[10], brackets for spacecraft waveguides [11] and lunar lander engine mounts [12,13]. In general, however, information about the criticality level of AM parts that have been used in service is limited [3] and well-described examples of AM used for critical parts are lacking. Instead, the approach of adopting AM in the aerospace industry has been cautious. Aircraft manufacturers have introduced flying AM parts in limited numbers and only for non-critical applications [14]. In space industry, mainly secondary structures and other non-critical parts have been in focus [15]. In fact, there is an expressed skepticism towards using AM in the near term for critical applications [6,16,17]. Critical parts are those that require the most stringent measures to show proof of function according to a categorization based on the consequences of potential failure (see e.g., Reference [18]). The process of showing that space applications (and processes) meet specified performance, quality and reliability requirements is called qualification [19]. For conventional manufacturing technologies, the knowledge that has been established over decades can be used during product development to ascertain that products can be qualified [20]. For AM, this established knowledge is still missing, making development and qualification of AM parts a major challenge [2,21]. Consequently, to further the adoption of AM in the space industry, organizations need to build understanding about AM processes and how to develop products for AM [6,20]. From this perspective, organizations need to explore what aspects that are most important to understand in terms of qualification of AM components, in order to consider them as early as possible during product development. Furthermore, identification of these aspects is necessary in order to identify what knowledge is available within an organization. This is important both in understanding what knowledge that needs to be developed but also to understand what the organizational capabilities are to choose and design products and define their qualification approach according to these capabilities. Supports that aid design teams in this task are needed, specifically for highlighting the necessity to consider qualification early during AM design [22]. This paper presents a study conducted at a company in the space industry developing an AM rocket engine turbine for demonstration testing. The paper expands on a previous conference paper [1], where the development of a verification approach for the AM turbine is presented. The purpose of this paper is to present a generalized framework for how to develop AM products and their qualification approach, to be used by engineering teams that aim to adopt AM technologies.

One challenge in discussing AM qualification is that it is an ambiguous term where qualification, certification, verification and validation are used in similar contexts by different industrial sectors [23]. For clarification, this paper uses the following terminology [24]:

Validation: process which demonstrates that the product is able to accomplish its intended use in the intended operational environment.

Verification: process which demonstrates through the provision of objective evidence that the product is designed and produced according to its specifications and the agreed deviations and waivers and is free of defects. Verification is a pre-requisite for validation.

Qualification: that part of verification which demonstrates that the product meets specified qualification margins.

Qualification is hence part of the overall verification of the final product [25].

1.1. Challenges with Qualification of Additive Manufacturing Parts

Materials manufactured with AM exhibit intrinsic characteristics that impose challenges for the design and qualification of critical applications. Four main concerns are—(i) defects, (ii) anisotropy, (iii) surface roughness and (iv) similarity between test coupons and actual parts [21]. Adding to the complexity of understanding AM processes is the variation in produced material that can be seen on part-to-part and machine-to-machine basis [2]. These aspects make it challenging to characterize AM processes and to determine material design data. To support the implementation of AM, there is therefore a need for AM standards [21]. However, the characteristics of AM processes and materials and the multitude of available processes makes standardization complex. Especially since standards used for conventional manufacturing processes or materials are not always suitable [26]. The America Makes and ANSI Additive Manufacturing Standardization Collaborative (AMSC) has provided a roadmap for the standardization of AM, including a presentation of current standardization efforts and identified gaps [23]. There is a breath of ongoing activities, including already published standards from Standard Development Organizations (SDOs) used by the space industry (e.g., ASTM and SAE). However, the roadmap highlights that the current number of standards is insufficient and that there is a need to develop new standards applicable throughout the AM process chain. A consequence of the lack of established standards is that, as of today, there are no consensus-based approaches for the qualification of AM processes and parts [23]. In the space industry, NASA has expressed that it cannot wait for SDOs to develop standards for AM due to its ongoing activities to introduce AM in flight applications [27]. Consequently, NASA has developed and published their own document dealing with the manufacturing of spaceflight hardware using AM—the *NASA Marshall Space Flight Center (MSFC) standard for AM hardware manufactured with laser powder bed fusion* (LPBF) [28] and *specification for control and qualification of the LPBF processes* [29]. The document provides a framework of requirements for design evaluation, metallurgical process control, part process control, equipment control and the implementation of a quality management system. However, the document is still not detailed enough for the qualification of AM components and NASA is working on agency-level AM standards for manned and non-manned spaceflight, as well as aeronautics, respectively [27]. These new standards will provide requirements for what needs to be considered for all phases of design, manufacturing and qualification [27].

As a contributor to the AMSC standardization roadmap, the NASA MSFC underlines the task that is put on engineering organizations to establish requirement frameworks concurrently as process understanding evolves. This is a consequence of the rapid adoption of AM that is seen across industries, while process understanding is still being developed [23] (p. 211). Due to the general lack of understanding of AM processes and lack of standards, the approach to qualification of AM parts has so far been on a part-by-part and process basis, relying on both destructive and non-destructive testing (NDT) [21]. Examples of this approach for space applications can be found in literature, for example, References [11,12]. Hence, in order to establish a qualification approach (and AM requirements frameworks), organizations need to build AM understanding concurrently with the development of AM products, based on testing and inspection. However, testing and inspection is also challenged by the lack of aforementioned standards for AM parts.

For critical space applications, parts have to be shown to be fracture tolerant (see e.g., Reference [30]). Consideration for and characterization of defects is consequently important in the design of fracture critical parts. Furthermore, rough AM surfaces can act as micro-notches due to higher stress concentrations at surface features [23], becoming a concern if finishing or machining is not applied. As argued by Gorelik [3], a relevant damage tolerance approach relies on process control and capable NDT methods. However, the aforementioned lack of standards for AM processes and test methods make this challenging and an appropriate approach combining established (traditional) knowledge and available AM knowledge is needed. One NDT method that is frequently mentioned for AM is X-ray Computed Tomography (XCT) for both detecting defects and dimensional control of geometry and surfaces [31]. The achievable resolution of XCT is however still a limitation for larger parts, making it difficult to use for industrial applications since it is dependent on size, thickness and geometrical complexity of the part [21]. This difficulty with inspection will probably require many parts to have multiple NDT methods to give full coverage [21].

The impact of product geometry on the material microstructure is an inherent characteristic of the AM processes. This is due to that the microstructure is dependent on the thermal environment of the built part, which in turn is influenced by the build set-up [32]. The use of traveler (witness) specimens is a common approach to monitor the quality of a build as a means to identify system drift [12,28,29,33]. However, due to the geometrical dependency on the microstructure, the representativeness of such reference specimens to the properties of a part is not evident and needs careful evaluation and further research [3,21,34]. It is therefore also important to have test specimens that are representative of the actual part, which could for example, be taken from a geometry as similar to the part as possible [35].

In summary, in order to design AM components that can be qualified, consideration has to be taken for the complete AM process chain, including the capabilities of the AM process, post-processes and inspection methods. These capabilities also drive what products and applications that should be pursued, that is, non-critical or critical parts.

1.2. Product Development with Additive Manufacturing

Design for AM (DfAM) is field of research with many contributions in recent years [36–39]. Methods and guidelines have been proposed for different purposes, for example methods to inspire novel designs [39–41], guidelines for manufacturability with specific processes [42–44] or to generally guide in assessing suitable designs [45]. Kumke et al. [36] categorize DfAM research into *DfAM in the strict sense* (concerning the design of the component) and *DfAM in the broad sense* (concerning part and process selection and manufacturability). While *DfAM in the broad sense* includes *DfAM in the strict sense*, it also highlights that there are other considerations that are necessary to ascertain that an AM product can be manufactured. Laverne et al. [39] label this as *Restrictive DfAM* or *Dual DfAM* (in contrast to *Opportunistic DfAM*), highlighting that these approaches to DfAM focus on aspects such as manufacturability and material properties or to utilize the potentials of AM in a realistic manner, respectively. Both *DfAM in the broad sense* and *Restrictive/Dual DfAM* highlights the need to take a broader perspective of Design for AM, than just focusing on the 'free form potentials' of AM. As argued, this perspective is essential in the development of components that need to fulfil strict requirements on qualification. Frameworks for DfAM that includes this perspective have been proposed in for example, References [16,36,46]. These frameworks emphasize the importance of considering for example, mechanical properties and analysis of the AM design. While contributions to the DfAM field highlight the importance of a broad perspective on product development with AM, there is less focus specifically on how to consider aspects related to the qualification of parts in regulated industries.

Different approaches for qualification of AM parts have been proposed elsewhere. Taylor et al. [35] made a comparison of qualification methods for conventional manufacturing processes and concluded that an approach for qualification of AM parts would have to combine the knowledge and methods from the qualification of different manufacturing processes. They propose the use of a building block approach similar to what is used for fiber composites [47] in order to successively build sufficient knowledge based on testing. The building block approach argues for the importance of testing at multiple levels, including test coupons, elements, sub-components, components and full scale, in order to sufficiently understand the performance of the part [35]. Gorelik [3] refers to decades of aviation experience of introducing new materials and processes and concludes that effective risk mitigation can be assured through—(i) manufacturing process control, (ii) an appropriately formulated damage tolerance approach and (iii) capable (material-specific) NDT methods. Portolés et al. [48] propose a generic qualification procedure to be adapted for each combination of AM process, material and part. They point out the importance of raw material control, development of an AM process window and the importance of identifying the key variables impacting the manufacturing. O'Brien [6] proposes an approach (specifically for the space industry) where mission risk and AM maturity are evaluated to define an AM part category, which in turn defines the AM requirements and specifications for the part. Continuous process monitoring and tracking of material properties is essential, especially for low AM maturity. O'Brien further stresses the importance of an AM design that considers the manufacturing chain by, for example, specifying the necessary process controls and controls of the part, including consideration for build orientation and nesting. Proof testing and inspection should be considered necessary when AM maturity is low in order to show that design data are met. Dordlofva and Törlind [20] describes three approaches to consider for qualification of AM parts by studying conventional part and manufacturing process qualification and associated challenges for AM:

1. Use established material design data for a qualified AM process that can be used as reference for any product to be manufactured with the same AM process.
2. Use established material design data for a known material (possibly different from AM) as reference and show that this data can be used as minimum properties for the AM material in the design (e.g. use casting material data as reference).
3. Tailor the manufacturing process according to the requirements of the specific application (similar to composites), which means that AM process parameters are adjusted until the part structural properties are satisfactory.

Approach 1 requires extensive process and material characterization programs. Due to the sensitivity of AM materials to process parameters, machine type, part geometry and the rapid development of AM technologies, this approach is challenging for near term application of AM when process understanding is being built. Approaches 2 and 3 are more suitable in this case since they allow for AM process understanding to evolve while products are developed. However, since they imply that sufficient AM material design data is not available, they rely more on inspection, component testing and continuous process control and recording of material properties (as argued by O'Brien [6]). Both of these approaches are therefore linked to the part-by-part qualification approach previously mentioned.

In summary, while DfAM literature highlights that AM process chain perspectives are needed in the design of AM components, there is lack of descriptions on how to consider qualification of critical aerospace parts in this context. Research also highlight the importance of process and part control, the performance of part testing and establishment of relevant material design data. This process chain perspective is necessary in the development of AM components that requires qualification. To support this perspective, this paper therefore proposes a *Design for Qualification* framework. The key purpose of the framework is to stress the importance of and encourage, consideration for aspects related to qualification in the early phases of product development with AM. Furthermore, since knowledge about AM process capabilities is still constantly evolving, the framework also encourages critical assessment of organizational AM maturity in order to develop products within capabilities but also to develop these capabilities.

1.3. Design for X

Design for Qualification is in essence a question of designing a product for the specific aspect of qualification. In the formulation of the proposed framework, inspiration has therefore been sought from Design for X literature. Design for X are design supports that focus on maximizing a specific 'X aspect' of a product by providing guidance for considerations for that aspect as early as possible [49]. Common methodologies are Design for Manufacturing (DfM), Design for Manufacturing and Assembly (DfMA) or Design for Quality [50]. The importance of Design for Qualification is that it should support engineering teams to *proactively* consider qualification during the development of the AM component [22]. Proactive Design for X supports often use *qualitative guidelines* due to that they are generic, flexible and open for interpretation [49]. This implies that they are adaptable depending on the needs and capabilities of the engineering team. It is common for DfX supports to usually focus on a limited number (7 ± 2) of vital elements at a time [51]. One example of such qualitative guidelines is presented by Alexander and Clarkson [52,53] in their *Design for Validation* model that includes six design tactics. Design for Validation stresses the importance of considering requirements and their verification for both the product and its manufacturing process during design. While being developed for the regulated medical industry, Design for Validation pinpoints the close connection between product and the manufacturing process, where final verification and validation should drive the design of both. Similarly, the Design for Qualification framework presented in this paper stresses that the final qualification should drive the development of both AM products and the AM process chain. In their Design for Validation model, Alexander and Clarkson [52] defines a generic verification V model as illustrated in Figure 1. In its basic form, this can be translated to the design sequence *requirements capture, design and verify*, which is common to most product development models (c.f. [54]). This V model is used for the generalization of the presented framework.

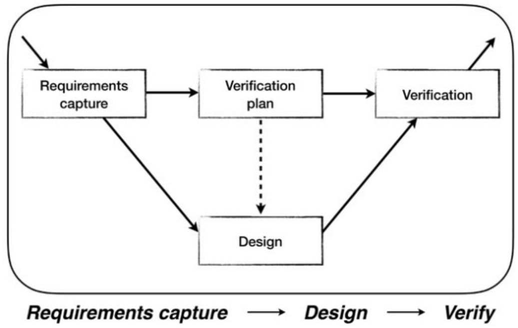

Figure 1. Generic verification V model (inspired by Reference [52]).

2. Materials and Methods

The research approach used for this paper is collaborative action research [55] where the author followed a product development project at a company in the aerospace industry (GKN Aerospace, Trollhättan, Sweden). The project is developing a sub-system for a rocket engine where AM was chosen as the manufacturing technology. Collaborative action research has a twofold purpose, which is specially to develop new knowledge by the participating researcher(s) but also to develop practical knowing within the organization that is studied [56]. The research is qualitative in nature, where the author participated in project meetings, project reviews, studied project documents and conducted interviews. Several forms of data collection have hence been used in order to provide a detailed account of the research object (i.e., the project) [57], where the studied phenomenon has been the development of the verification approach for the AM components. The collected data is summarized in Table 1.

Table 1. Data collection during the research process.

What	Quantity	Comment
Meeting notes		27 months (September 2017 to November 2019)
Project meetings	22 meetings	General project meetings, design reviews, AM verification meetings
Customer meetings	3 meetings	Design reviews and AM verification meetings
AM supplier meetings	19 meetings	Scheduled 'weekly' meetings
Internal documents	1 document	Summarizing documentation for internal critical design review (CDR).
Un-structured interviews		
At the company (two sites)	6 respondents	Respondents were not directly involved in the development project, providing 'external' views on product development with AM.
AM supplier	1 respondent	AM supplier used by the development project.
Focus groups	2 groups	Group 1: 6 participants (design, material and process engineers) Group 2: 2 participants (engineering organization managers)

The research process has been iterative, where the author initially mainly acted as an observer during the design of the AM components, participating in meetings and following the progress of the design. Consequently, the author was not involved in the design definition of the components but was able to document the design process, including perspectives of the engineers [58]. The active participation of the author was in the formulation of the verification approach, collaborating with the engineering team as the component designs had evolved. This part of the research is presented in the conference paper [1], which *this* paper is an expansion of. After the formulation of the verification approach, a first draft of a generalized framework for development of AM components and their verification approach was developed by the author. The framework was based on the verification approach [1] but for the generalization, inspiration was taken from literature, in particular the work of Alexander and Clarkson [52,53]. Furthermore, two other studies performed by the author contributed to the formulation of the framework. The first study focused on how qualification can be given increased attention during the development of AM components [22]. The findings showed that it would be beneficial to consider qualification as early as possible in order to design components that can be qualified, especially when designing for a new manufacturing process like AM. The second study focused on understanding how engineers can improve how they design components for AM, while at the same time developing an understanding for the AM process [59]. The findings showed that specific uncertainties related to the design and the AM process are beneficially explored, tested and evaluated by using part-specific artefacts. These two studies have contributed to a broader understanding of the studied phenomenon (verification of AM components). The studies are hence referenced in the description of the framework where appropriate. The overall research process is shown in Figure 2 where the time frame for collection of the different data are indicated, as is the completion of the related papers [1,22,59].

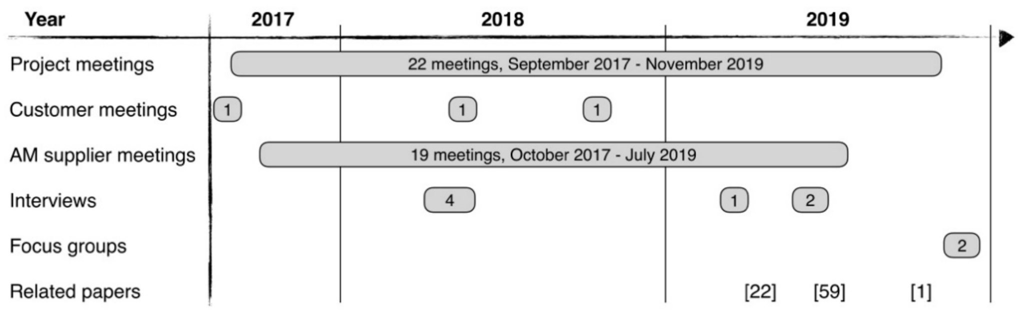

Figure 2. Time frame for the collection of data specified in Table 1. Completion of the related papers [1], [22] and [59] are indicated for reference (note that for Reference [59] submission is indicated).

The first draft of the framework was presented and discussed during two focus groups [60], including engineers from the development project, as well as engineers not directly involved in the project. The focus groups provided an opportunity to 'test' the framework on engineers with experience of product development in the space industry, in order to receive feedback on its possible use. After the focus groups, the body of collected data (Table 1) was analyzed in detail for further elaboration of the framework. The data was analyzed using the approach described by Miles et al. [61]. *Data condensation* and *data display* was done using spreadsheets, where the data was categorized according to the draft framework. *Conclusion drawing* implied iteration between analyzing the displayed data, referring to literature and refining the framework.

3. Results

The results from the study are presented in two sections. The first section presents the case study, describing the development of the AM components and their verification approach. The second section is the analysis of the case study, leading to the formulation of the framework for development of AM products for space applications with particular attention to aspects related to qualification.

3.1. Case Study

The studied development project has the aim of demonstrating a low-cost rocket engine turbine in engine testing. To reach low cost, three design aspects were defined—i) few parts, ii) efficient manufacturing and iii) robust design. AM has the potential of realizing part-integration and increase efficiency in product development and manufacturing. It was therefore in the interest of the company to evaluate, develop and demonstrate the feasibility of using AM in rocket engine turbines. An LPBF EOS M400 was chosen for manufacturing and the material is a Nickel-based alloy. An external supplier was used for the manufacturing.

3.1.1. Design Approach

The use of LPBF enabled the number of turbine parts to be reduced to a minimum (two), a rotor and a manifold, through utilization of the capability to manufacture an integrated manifold and stator (i.e. an enclosed geometry). The turbine parts are presented in Figure 3. A robust design was pursued by defining large tolerances to comply with the LPBF process and to allow as-built surfaces as much as possible (which in turn also reduces cost). The functions of the manifold are to receive and contain the driving gas and to accelerate the gas towards the rotor. Structural functions of the manifold are to be an integrated part of the turbopump, coupling the outlet structure (downstream) and the pump (upstream). The manifold therefore plays an important role in total structural stiffness of the turbopump. The main function of the rotor is to transfer gas energy into pump torque through a shaft.

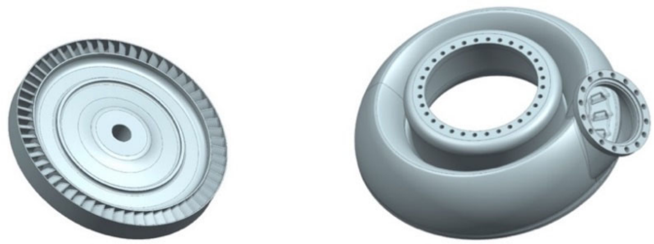

Figure 3. The additive manufacturing (AM) turbine components; rotor (**left**) and manifold (**right**) (courtesy of GKN Aerospace).

Due to the complex geometries and large size of the components (~40 cm diameter), manufacturability was a key concern during the design process. Build chamber size, use of support structure, recoater interaction and surface roughness were limitations to be considered, as was to optimize use of material to reduce cost. The build chamber size naturally put a restriction on the maximum diameter of the parts. Support structure was not allowed internally in the manifold due to no possibility for removal. This impacted the geometry of the manifold which had to be designed to be self-supporting, while the internal surface roughness could not be too rough due to structural integrity and gas flow properties. Material use became a task of balancing the need to fulfil structural requirements, without excessively thick walls. The enclosed manifold also challenged inspection capabilities and surface treatment of internal surfaces. Several uncertainties related to capabilities of the LPBF process, inspection methods and post-processing were consequently identified. Specific 'design artefacts' were designed to be representative of the part in order to evaluate these uncertainties coupled to the component geometries. Figure 4 shows examples of design artefacts used to evaluate the capability of the LPBF process to build manifold roof geometries without support structure. In total, 33 samples of the design artefacts in Figure 4 were printed to evaluate impact of build orientation on manufacturability (especially recoater interaction), as well as design concepts and limits for self-supporting roofs. In particular, the resulting internal surface roughness of the artefacts was an important factor for the final definition of the roof geometry. In general, design artefacts were used iteratively during the design process, which allowed the definition of the component geometries and understanding of post-process capabilities. Further information about the process of working with design artefacts can be found in Dordlofva & Törlind's research [59]. Close collaboration with the AM supplier turned out to be essential during this iterative design process where the supplier's process expertise aided in identifying what uncertainties to evaluate and how to solve specific manufacturing-related issues. The large parts implied that designing the parts to constrain stresses became a key aspect. To reduce cost and due to lack of suitable and developed surface finishing processes, the choice was to only perform local surface finishing in sensitive areas.

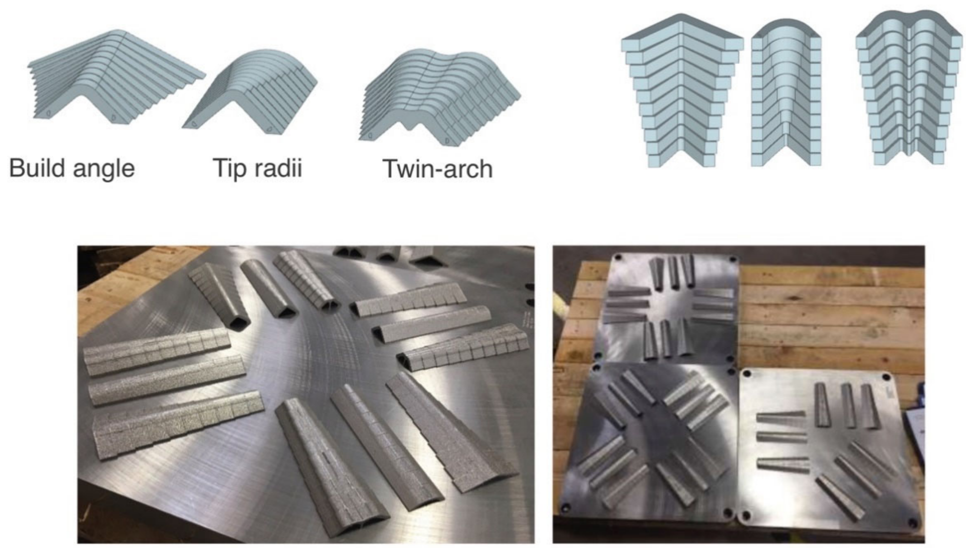

Figure 4. Example of design artefacts used to evaluate the capability of the laser powder bed fusion (LPBF) process to build the unsupported roof of the manifold. Specifically, impact of build orientation on manufacturability and design concepts and limits of the self-supporting roof were studied (courtesy of GKN Aerospace).

3.1.2. Verification Approach

A key challenge was the development of a verification approach in order to approve the turbine for engine testing. Both components are classified as engine critical parts and structural integrity was therefore of highest importance. The verification approach described here (and in Reference [1]) therefore concerns *structural integrity*. Verification of requirements related to, for example, aerodynamic performance is necessary as well but was not part of this study. The verification approach was developed concurrently with the turbine components, as more knowledge about the manufacturing process was gained. The overall objective of the verification approach was to successively reduce the risk for failure due to AM process-related uncertainties through the different phases of the turbine development and manufacturing by:

1. Use of relevant and conservative material data.
2. Use of additional safety margins in analysis due to AM-related uncertainties.
3. Assuring a stable AM process through process control and use of extensive inspection of each manufactured hardware, as well as destructive and non-destructive testing of components and travelers.

The approach is represented by three pillars—*Material data*, *Analysis* and *Hardware* as illustrated in Figure 5.

3.1.2.1. Material Data

Due to a lack of sufficient AM material data, other relevant material data had to be identified for design. By comparing available (limited) AM material data with material data for traditional manufacturing processes, initial conservative assumptions were made to define material design data (i.e. using casting and forging). In order to verify the assumptions and use of non-AM data for design, AM material testing was conducted during the turbine development. While the material testing was not sufficient to provide design data, the test results showed that the assumptions made were indeed conservative (see Reference [1] for details on material correlation). The material data from testing was compiled for future use.

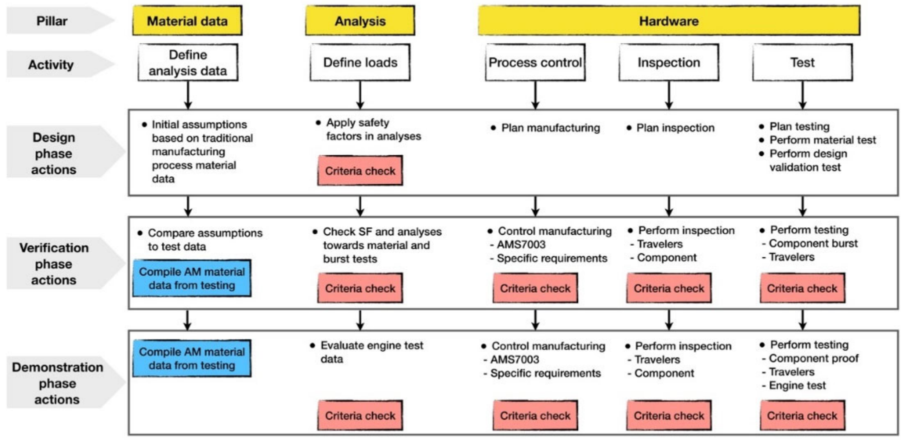

Figure 5. Pillars of the verification approach for the AM turbine (courtesy of GKN Aerospace).

3.1.2.2. Analysis

For the analytical verification, the definition of anticipated load conditions for the turbine components is the initial step. The loads were provided through customer specifications that were updated during development and update of load requirements was therefore a continuous activity to ascertain that relevant loads were used for analysis. To account for uncertainties in AM material properties and as-built surface roughness, AM safety factors (SF) were applied in the analysis for each uncertainty respectively. These AM SF were additional to those SF required by design specifications. A criteria check was made to ascertain that the turbine functional requirements were met (with a conservative margin) for the material data assumptions and applied SF. The actions were iterative until all criteria were fulfilled. As with the assumptions on material data, the applied SF were compared to AM material testing, verifying their relevance (see Reference [1] for details).

3.1.2.3. Hardware

Verification related to the manufactured hardware was based on three activities—process control, inspection and testing. Each of these activities are crucial for assuring the quality of the manufacturing and the integrity of the manufactured part. During the design of the turbine components, the actions to be performed within each activity were defined, evaluated and applied. For example, available and relevant process standards and specifications were identified, evaluated and used based on their assessed maturity. Table 2 shows what actions that were applied for each of the activities. It should be stressed that the activities were iterative and the actions evolved as more knowledge about the AM process and the part was gained during the design phase. For example, different post-processing and inspection methods were evaluated in parallel using design artefacts as presented in Section 3.1.1.

Table 2. Activities related to hardware verification and applied actions.

Process control	Inspection	Testing
• Use AMS7003 for process control (with additional requirements) • Use NADCAP certified AM supplier • Use travelers • Apply heat-treatments incl. HIP • Machine interfaces • Manual removal of support structure and polishing of corresponding surfaces	• Optical and CMM measurement • FPI on both machined and as-built surfaces • X-ray of material (limitations for thick sections) • Visual inspection (limitations for internal surfaces on manifold) • XCT on travelers	• AM material testing • Component testing (burst and proof) • Microstructure evaluation and tensile testing of travelers

Due to the high loads that the turbine components are exposed to during operation, the failure mode which by all means shall be avoided is burst as this kind of failure has large consequences. A crucial action was therefore to perform experimental verification of adequate safety margins on complete parts (burst tests on both rotor and manifold). The results from burst tests quantified the accuracy of the safety margins from predictions, including the method and modelling for stress computation, the failure criterion and the material data applicability. Figure 6 shows the manufactured burst rotor and manifold. The results from burst testing showed good agreement with the analytical predictions for both components and also that failure occurred in predicted areas (see Reference [1] for details on burst testing). Both tests therefore provided valuable data and are an important step in the verification of the AM turbine components. Final validation of the AM turbine will be engine testing (planned to start in 2020) of two turbines. Manufacturing and verification of the engine hardware follows the same approach as described above, with proof testing included as the component test before acceptance for engine test.

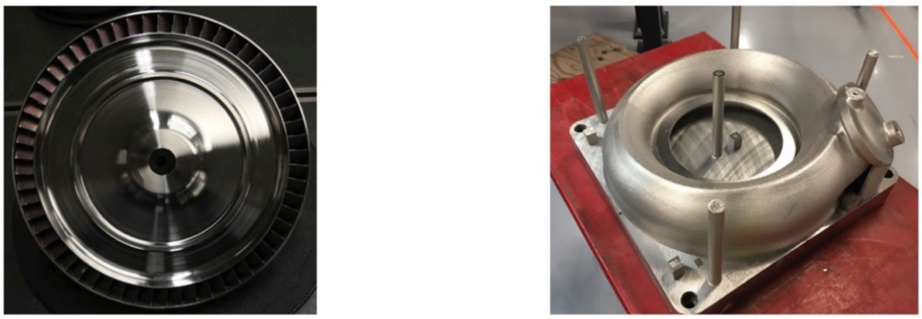

Figure 6. Burst rotor and manifold manufactured with LPBF. The manifold build plate includes travelers for tensile and microstructural evaluation. Note the 'lid' on the manifold inlet which was added to be able to perform the burst testing, utilizing the flexibility of the LPBF process (courtesy of GKN Aerospace).

By focusing on understanding the specific challenges with the turbine (e.g. manufacturability and structural integrity), in combination with general AM-related challenges (e.g. impact of surface roughness, methods for inspection and surface finishing), the development of the turbine demonstrator allowed the building of knowledge about the possibilities and limitations of using AM in critical space components. Since knowledge-building is essential for AM development, a key factor in the verification approach was continuous record-keeping of test results for statistics and for correlation of analysis.

3.2. Proposal for Tactics to Design for Qualification

This paper proposes a framework with the purpose of stressing the importance of *proactive* consideration for qualification during product development of AM products. Based on the case study and analysis of the collected additional data (Table 1), six qualitative design tactics are formulated for the structure of the framework. Qualitative tactics are chosen since they leave room for adaptability and interpretation [49], depending on the needs of the company, the AM knowledge within the company and the product application. Furthermore, qualitative design supports are more useful in the early phases of design when the purpose is to make *proactive* design decisions [49]. To generalize the framework, the generic verification V model (Figure 1) is used to define the tactics according to the *requirements capture, design and verify* sequence as presented in Figure 7. The framework should support the identification of requirements, the design of a part that can be verified, specifying AM process verification and performing the relevant verification activities. Ultimately, enabling product and process qualification. The formulation of each design tactic follows.

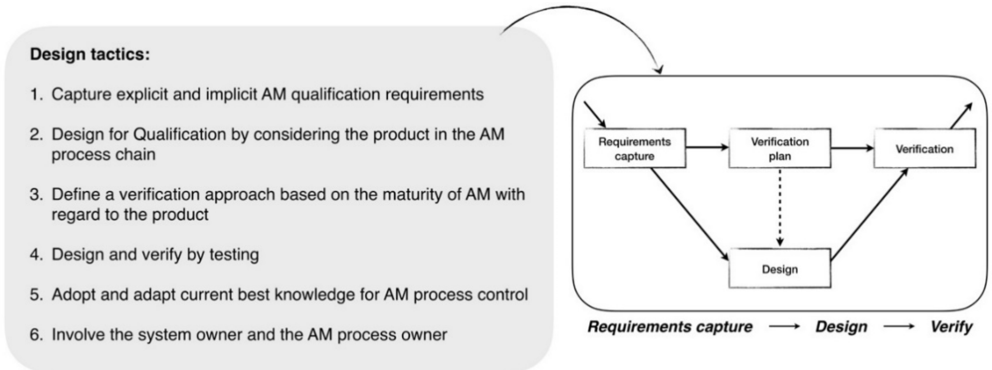

Figure 7. The six design tactics formulated based on the study with the purpose of facilitating and encouraging proactive consideration for qualification during product development with AM. The tactics are mapped onto the *requirements capture, design and verify* sequence to generalize a Design for Qualification framework.

3.2.1. Tactic 1: Capture Explicit and Implicit AM Qualification Requirements

While there was no formal requirement on *qualification* for the turbine (being a demonstrator), both external and internal reviews defined verification requirements according to design specifications for *product development*. With the purpose being *demonstration* and maturing of the LPBF technology in turbine applications, this may to some extent be counterproductive. This highlights an important aspect that, due to the many uncertainties related to the AM process, companies may tend to fall back on what is known and perform reviews thereafter to 'be on the safe side.' For example, a demonstrator, the accepted risk should be assessed and clearly defined to foster the purpose of furthering the understanding AM. The same can be translated to product development. To develop a relevant and realistic qualification approach, requirements need to be clearly defined in order to be able to consider them as early as possible.

In systems engineering, requirements are often communicated through specifications for, for example, interfaces, function, performance and so forth. However, there are also *implicit* requirements that impact design and qualification. In a recent study on how qualification is considered during product development in space industry [22], ten *qualification drivers* were presented that drive the requirements set on the product qualification. Both *explicit* and *implicit* requirements were identified to be driven by these qualification drivers. For example, the cost of qualification is an important aspect in the space industry currently seeing a pressure to decrease cost [22]. In this industry, qualification is often part of the overall product development cost funded by the customer [22]. For a company (i.e. a sub-system supplier), there might be a strategic importance in developing AM knowledge, which for example was one reason why LPBF was chosen for the turbine manufacturing in the case study. Consequently, it should be assessed whether a more expensive qualification approach could be accepted by a company for, say, the first AM products to be developed. This would possibly imply additional cost for the company but could be necessary in order to build understanding about the AM process. Such implicit requirements are crucial when development teams are defining a qualification approach, to make sure that it is anchored in expectations from both external and internal stake holders.

In summary, in order to develop a relevant and realistic qualification approach, both explicit and implicit requirements that impact qualification should be assessed and defined as detailed as possible early in the concept phase.

3.2.2. Tactic 2: Design for Qualification by Considering the Product in the AM Process Chain

Manufacturability was given much attention during the development of the turbine and was assured during design by successively evaluating AM process capabilities coupled to the geometry (e.g. recoater interaction, need for support structure, build chamber size). Furthermore, due to lack of established inspection methods for AM products, it was early identified that several methods would be needed. Still, there were difficulties in making a complete inspection of the parts due to their complex design (e.g., thick sections or internal surfaces). For a demonstrator hardware, this can be accepted through for example, risk analysis and risk mitigation by conservative design. For production hardware, the possibility to sufficiently inspect the part has to be included when making design decisions. Design for Inspection is hence one example of a crucial approach when developing AM components. Other considerations are for example what post-process that are feasible (Design for Post-processing), if the part can be successfully removed from the build plate, if powder can be removed or how a part can be verified through testing (Design for Testing). For example, in terms of testing, the turbine development team utilized the flexibility of the LPBF process to tweak the AM designs in order to manufacture suitable hardware for burst testing, without impacting the overall design (see Figure 6). Furthermore, due to a general uncertainty in AM materials characteristics and AM process stability, the design approach for the turbine included conservative design margins for structural integrity, implying a consideration for how optimized the parts were allowed to be in terms of weight. During one of the interviews the respondent expressed that if there is risk of certain defect sizes to go un-detected, the priority should be to make parts thicker rather than pursuing light-weight too much.

The essence of this tactic is that the capability to verify an AM product has to be considered early in the development process in order to design products so that they can be verified and ultimately qualified. This capability is governed by the organizational maturity of the complete AM process chain, including designing products for AM, controlling the AM process and manufacturing parts, post-processing, inspection and testing. The product is in this context important since there is a coupling between geometry and the capabilities of the AM process chain. While AM provides potential for innovative design solutions, some solutions might not be possible to verify, making qualification impossible. One interview respondent stressed that there is a difference between design rules indicating for example what angles can be built without support structure and design guidelines that help to design for the process. This design tactic emphasizes the importance of the latter and that it is important to develop such guidelines. It is stressed that other performance requirements need consideration from the verification perspective as well, for example how surface roughness will impact requirements related to aerodynamic performance.

In summary, to Design for Qualification implies to consider the whole AM process chain, its verification and its needs and capabilities for verifying the product design.

The verification approach developed in the case study divides verification into design verification through analysis (represented by the pillars *Material data* and *Analysis*) and verification of the hardware through process control, inspection and testing (represented by the pillar *Hardware*). Each of these has to be included when defining the verification plan. For the definition of relevant design tactics, a distinction is made between i) analytical verification of design, ii) verification of the manufactured product and iii) verification of the process (i.e. process control). Consequently, three design tactics are proposed related to verification.

3.2.3. Tactic 3: Define a Verification Approach based on the Maturity of AM with Regard to the Product

For the analytical design verification, a key challenge for new manufacturing processes is to define relevant material design data. The case study approach was to assess the maturity of internal AM material data, concluding that it was not sufficient to be used as design data. Material design data was instead used from conventional materials, assuming (and showing through test) that AM material properties are better, with the addition of AM SF. Furthermore, component burst testing was used to verify the analysis. This conservative approach was deemed necessary due to uncertainties in AM material characteristics, uncertainties in AM process stability and the criticality categorization of the parts (engine critical parts). The objective should be to find a balance between conservatism and weight (low weight being a design driver for space components), while being able to successfully verify the design within the acceptable risk. The choice of material design data approach for analytical verification should therefore be based on maturity of material data, part criticality and risk analysis. The product and its application are therefore central. Whether the intention is to perform testing or if it is production for flight, should dictate what requirements that can be accepted as one project member expressed it. This connects back to the first design tactic, stressing the need to define what requirements that are acceptable and what the expectations are. Naturally, the lower the maturity of AM, the less critical applications should be considered for AM, especially for flight.

One characteristic of AM that impact the choice of verification approach is the dependency between material properties and part design. As one AM material specialist expressed during an interview, the moment the geometry is changed, the thermal history in the build process changes, potentially impacting the material properties. The general perception when discussing this issue during interviews, was that verification (and qualification) of AM parts will have to be part-specific in the near term. Each part (or product) has its specific requirements with regard to, for example, static and dynamic loads, the possibility to machine or not machine surfaces or being easy or difficult to inspect. Consequently, AM process capabilities should be evaluated successively by designing, manufacturing and testing different parts, building process understanding along the way. In the longer term, this could possibly lead to verification approaches based on families of parts and in the even longer term, based on the AM process.

In summary, the verification approach should depend on the product, its application and the organizational maturity of the AM process (including the whole manufacturing chain). AM maturity should be evolved based on product applications, using their specific requirements to acquire the necessary understanding. This third design tactic is therefore closely connected to the fourth design tactic.

3.2.4. Tactic 4: Design and Verify by Testing

A consequence of that AM processes are relatively immature is that engineering teams need to develop AM process understanding as products are developed (as exemplified in the case study). In a recent paper [59], the value of using purposely designed test artefacts to evaluate AM uncertainties related to manufacturability, post-process capabilities and material properties was studied. It was shown that the strength of using purposely designed test artefacts is that they are representative of the product being designed and part-specific uncertainties can therefore be evaluated. The dependency between an AM product's geometry and its mechanical properties further stresses the need to perform part-representative testing. In the turbine case study, design artefacts were utilized for design concept verification, post-process and inspection method evaluation, as well as component and process verification (burst tests). The latter was considered a necessary part of the verification due to the lack of previous process verification of the AM machine and lack of sufficient understanding of AM material characteristics. Furthermore, testing through inspection methods was also deemed necessary to reduce risk of failure through defects. This multitude of testing approaches allowed correlation with analysis, providing confidence in the analytical verification and verified the manufacturability of the part. It should be stressed that the final verification that a product can be built with the specific AM process is not achieved until the complete part has been manufactured. However, the use of design artefacts allows successive assurance of manufacturability in small steps, limiting the need for manufacturing full-scale parts early on. Put differently, the rapid manufacturing that characterize AM allows more testing to be performed on part-representative artefacts but it is also necessary to identify what is most important to test [59]. From a production perspective, the verification approach could include periodical cut-ups (as is often the case with castings) or proof-testing for the acceptance of each hardware (as planned for the turbine).

In summary, the purpose of this design tactic is to encourage evaluation of process- and part-specific uncertainties by using the AM process, to evaluate methods for post-processing and inspection and to use adequate inspection and testing procedures to verify the process and product.

The iterative nature of this tactic allows continuous development of the verification plan by revisiting the requirements, the design and the verification approach as testing is conducted and evaluated.

3.2.5. Tactic 5: Adopt and Adapt Current Best Knowledge for AM Process Control

Product qualification and process qualification are two different activities, although sometimes linked to each other. A standard process (e.g. milling) is usually qualified independent of any products it will be used on. However, for critical processes where product material properties are process-sensitive (e.g. casting or AM), process qualification is usually also product dependent [20]. It is out of scope of this paper to contribute to the field of AM *process qualification* since control and development of the process has not been studied in particular. However, since the requirements on process qualification has to be defined by the design organization, this tactic has the purpose of providing a suggestion for how to specify these requirements by reflecting on the case study. In the case study, two measures were taken in order to control the process. First, a Nadcap certified supplier with a proven record of using AM for product manufacturing was used. This made it possible to utilize their process knowledge and internal quality systems. Second, the AMS7003 standard for LPBF process [62] was used to specify requirements towards the supplier. Due to identified gaps in the applied process standard, additional product- and company-specific requirements were included. This way, current best knowledge on process control was adopted but also adapted to meet the requirements of the turbine verification.

Standardization of AM processes and any processes to be included in the AM process chain is an important step towards the widespread implementation of AM [21]. Still, organizations tend to developed their own standards and/or specifications (see e.g., References [28,29]). However, it can be difficult to define for example a material specification without a specific application. Specifications are therefore often developed for a product, implying that they include company Intellectual Property (IP). So, while there is need for company specific specifications, general AM standards are needed for the industry to agree on acceptable measures for process control, that is 'what needs to be done.' For example, AM machine suppliers continuously update machine software or additional machines are introduced into workshops to increase capacity. Standards should support how to handle such situations to avoid that different companies (e.g. a customer and a supplier) have different views on what the correct measures are.

In summary, while there is need for companies to develop AM process specifications that are suitable for specific applications, general AM standards are needed for a consensus-based view on AM process control. This tactic therefore encourages to contribute to standards development by adopting and adapting standards that are available, according to the specific needs of the design organization.

3.2.6. Tactic 6: Involve the System Owner and the AM Process Owner

The last design tactic 'supports' each of the previous design tactics. In the case study, close collaboration with both the system owner and the AM process owner was necessary during the development of the product, the process understanding and the verification approach.

As is typical in systems engineering, the system owner (customer) defined the requirements of the product (system needs), what design specifications to use, aided in requirements interpretation and performed design reviews. For example, while verification requirements are specified in the used design specifications, the interpretation and applicability of these requirements were discussed. Furthermore, as the verification approach for the turbine evolved, it was discussed with the system owner to comply with their expectations. An example of this for a flight hardware would be that if the verification approach would rely on designing a conservative and 'heavy' AM turbine in order to have margin for significant AM-induced defects, the result might be a turbine not fit for the system. In particular, it was noted that close dialogue was necessary when interface requirements changed since many specific design choices were made to comply with the LPBF process and new interface requirements challenged these choices. It is evident that especially design tactic 1 and 6 are closely connected.

With regard to manufacturability, the experience of the supplier (AM process owner) proved essential. The supplier was able to provide feedback on design concepts, propose changes and support in the design and evaluation of the design artefacts. For example, recoater interaction was not first considered by the design team but early seen as a challenge by the supplier. The design artefacts in Figure 4 were therefore used to evaluate the impact of recoater interaction as well as the capability to build an unsupported roof. Another example is the use of support structure. While it is often a 'rule of thumb' to minimize support structure when designing for LPBF, the supplier raised the concern of building such large parts with too few support structures due to thermal stresses. Instead, the experience of the supplier aided in adding the proper amount of support structure to constrain the stresses (although this proved challenging and was also a trial and error task). Consequently, design tactic 2 and 4 are closely connected to design tactic 6.

In summary, the last design tactic is an encouragement to include both the system owner (customer) and the AM process owner (internal or external) across the design tactics (and the framework). Their knowledge and expertise should be utilized to facilitate—proper definition of requirements, a suitable design of the product according to manufacturing process chain capabilities and relevant verification activities.

4. Discussion

The turbine components in the case study are *demonstrator* hardware, which implies that the applied verification activities should be sufficient to approve use in testing conditions. Product development of *flight* hardware need to adhere to more stringent *qualification* requirements [25]. The use of AM in regulated industries is characterized by conservatism, a necessity since early failures of critical AM parts could delay its implementation in aerospace [3,6]. The design of AM products and the approach for their verification therefore need to be based on substantiated decisions. The case study shows an example of how a verification approach was defined during product development as more knowledge about the AM process and the product was gained. This approach is by nature prone to be the case for AM as a new technology and as argued by for example, NASA MSFC, a necessary approach in developing requirements for AM [23] (p. 211). The proposed design tactics communicates this task that is put on design organizations, promoting a cautious but exploratory, approach to product development with AM and the definition of verification requirements. Figure 8 illustrates the design tactics in the *requirements capture, design and verify* sequence, formulating a Design for Qualification framework.

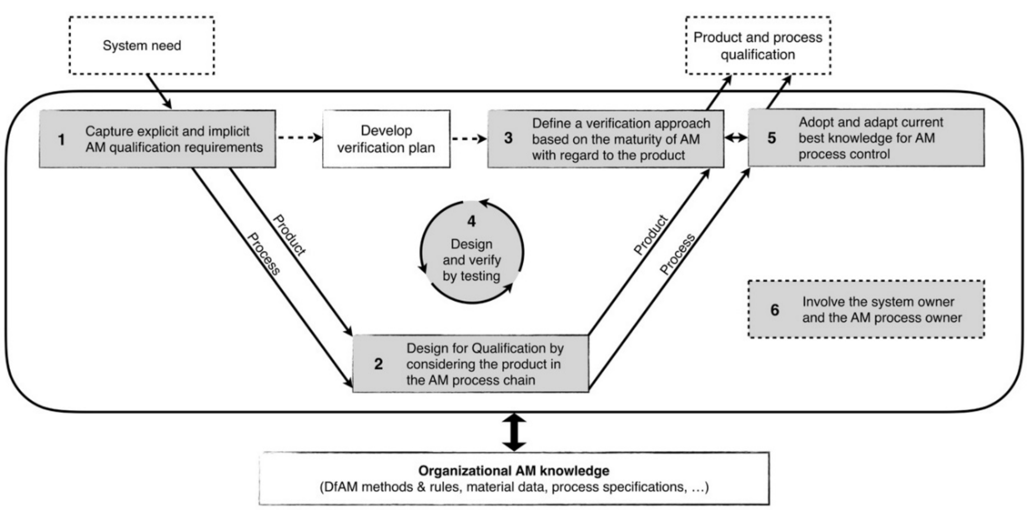

Figure 8. The Design for Qualification framework and the six design tactics. The framework is structured according the generic V model for verification, where each of the design tactics provide a direction for how to utilize the *requirements capture, design and verify* sequence in order to consider qualification aspects related to AM during product development, that is to Design for Qualification.

At the bottom of Figure 8, organizational AM knowledge is connected to the framework. The double-headed arrow illustrates that available AM knowledge determines the preconditions for applying the framework but also the encouragement to develop AM knowledge during a development project. Hence, the framework encourages the continuous assessment and building of AM knowledge. Its primary intention is to be used by engineers in the space industry (and aerospace in general) that follow strict procedures during product development. Each of the framework's phases and their association to the design tactics are discussed next.

4.1. Requirements Capture Phase (Tactic 1 and 6)

As illustrated in Figure 8, the development of a verification plan is an essential activity in order to provide input to the design process to make sure that products can be verified (and ultimately qualified). A design team should therefore strive towards defining the verification activities as clearly as possible early in the design process [52,53]. This implies a front-loaded design process, where particular attention should be on defining the conditions that apply for a specific AM product. Although design requirements tend to change during system development [63], the expectations related to qualification should be defined early on, both from the system owner and the design organization (design tactic 1). The V model was chosen as the structure of the framework inspired by Alexander & Clarkson [52] but also due to its resemblance to the Vee model of systems engineering [64]. By using the *requirements capture, design and verify* sequence, the importance of proper requirements definition is highlighted and it is presented in a structure familiar to organizations involved in the engineering of space systems [25].

The difficulty with defining verification requirements for AM is that there are several uncertainties due to lack of knowledge concerning AM process capabilities, repeatability, part material properties and suitable post-process and inspection methods [2,21]. A consequence is therefore that companies might need to question if current requirement specifications need to be adapted/changed for AM. This was brought up during one of the focus groups used to evaluate the framework. While there is need to make sure that AM products are designed not to fail, current requirement specifications might imply design requirements that are not suitable for the constantly evolving AM processes. For example, Taylor et al. [35] argue that at the current maturity of AM processes, the use of traditional test matrices to develop statistically based AM material design data could be questioned in the near term. Instead they propose to perform reduced material testing for initial sizing of the part and then to perform part-specific material property testing. In systems engineering, the best knowledge about the system lies with the system owner, who therefore can foresee the consequences of a potential failure [3]. This knowledge should be utilized in the proper identification, questioning and definition of requirements for AM components (design tactic 1 and 6). This exemplifies the general support of design tactic 6 and in Figure 8 it is therefore placed off-set with dotted lines to represent its intended use across the overall framework.

4.2. Design Phase (Tactic 2, 4 and 6)

Current research argue that multiple inspection methods and component testing will probably be necessary in the near term for the qualification of AM components and that this is the practiced approach by organizations introducing AM [6,17,21]. For space applications in particular, Design for Inspection and Design for Testing has been highlighted as important [6]. This was also the approach in the case study. Based on these insights, the framework encourages the early consideration for inspection and testing and how such activities should be utilized in the product verification. This implies that components need to be designed according to the capabilities of these processes and any other processes that will be used in the manufacturing chain, for example post-processing (design tactic 2 and 6). This is an example of *Restrictive* or *Dual DfAM* [39] or *DfAM in the broad sense* [36], with specific attention on enabling qualification. It is therefore stressed that, in relation to DfAM literature, the proposed framework highlights considerations related to the *qualification* of AM parts, that is to *Design for Qualification*. As such, it is complementary to other DfAM methods and guidelines that are available or being developed by design organizations or academia. Their simultaneous use and exploration are encouraged by the double-headed arrow connecting current AM knowledge with the framework in Figure 8. However, designing for the AM process chain is still hampered by that the understanding of the AM process chain is developing [6]. For example, post-process and inspection methods for AM are still being developed, as are their standards [23]. Again, this shows the responsibility put on design organizations to develop an understanding for the complete AM process chain, concurrently with the development of products. To foster such understanding, representative testing is crucial (design tactic 4 and 6), since representativeness between test artefacts and products is a key issue for AM, especially in determining mechanical properties [3,21,35]. The iterative process of applying design tactic 4 is illustrated in Figure 8 by its placement in the middle of the *requirements capture, design and verify* sequence.

4.3. Verification Phase (Tactic 3, 4 and 5)

The framework encourages that in the development of a verification approach, an assessment has to be made of the organizational maturity of the AM process chain with regard to the product application to ascertain that they are compliant (design tactic 3). By assessing the current AM knowledge, identifying gaps and exploring the AM process chain through a practice-oriented 'learning by doing' approach (design tactic 4), the design team in the case study was successively able to define a verification approach suitable for the demonstrator turbine. Risk analysis and risk mitigation through a conservative design verification approach were key aspects in this specific case. O'Brien [6] suggests that an AM risk classification should be made where the mission risk class, the part's criticality and the available material design data shall define the requirements set on the AM verification and the suitability of using AM for a specific application. Similarly, current and future NASA standards use risk classification to define requirements on AM parts dependent on consequence of failure, structural demand and AM risk [27–29] The development and inclusion of an AM risk classification system to be part of the framework is seen as a future need to further support engineering teams in defining a suitable balance between conservatism and utilization of AM potentials.

With regard to process control, the framework encourages the adoption and adaption of standards that are available for AM processes as a step in the general development of AM standards (design tactic 5). Similarly, NASA aims to encourage the use of industry standards when applicable in its future agency-level standards for AM. However, they will also provide guidance for the development of specific process specifications as needed [27]. Another consideration that has to be made in this regard, is to identify what customers are expecting in terms of process control (again stressing the importance of design tactic 1 and 6). For example, ESA is developing an ECSS standard for AM to be applicable for ESA missions . Hence, guidance will be available for companies supplying AM components for ESA missions on what process controls that are necessary for AM components to be acceptable by ESA. AM process modelling tools and process in-situ inspection are suggested to be an important part of future process development and control [17]. Although promising, these tools are still in their infancy and require further development and demonstration [65,66]. Future qualification approaches could hence have increased dependence of process modelling and in-situ inspection, which is not contradicted by the Design for Qualification framework. On the contrary, the framework and design tactics should support engineering teams to approach development of products and AM understanding in a systematic manner. The design tactics are qualitative and there is room for interpretation and adaptation to suit the application being developed and the AM knowledge within the design organization. As this knowledge increases, the tactics should evolve, accounting for new tools and methods.

4.4. Limitations and Future Work

The framework and design tactics in Figure 8 are initial proposals based on the presented case study. A limitation of this initial framework is that it is currently at a rather high level of abstraction. Such 'high-level' models are usually difficult for companies to adapt due to lack of guidance on how they will actually aid in improving the design process [67]. The design tactics are a first measure to 'decompose' the framework into tangible design-related concepts, particularly dealing with the issue of designing AM products that can be qualified. While qualitative tactics were chosen for their adaptability and flexibility [49], they might be perceived as diffuse. For the tactics to be useful and in the end used by engineering teams, they need further elaboration. Boothroyd [68] argues that for design guides to be used, they need to support systematic evaluation that allow engineers to make decisions, otherwise they simply do not help. This was also expressed during the focus groups, where it was suggested that the framework would benefit from allowing engineers to easily assess where the most prioritized knowledge gaps are. It is therefore suggested that each design tactic should be further elaborated to include guidelines that support its practical implementation. As an example, Figure 9 proposes how design tactic 2 could be decomposed into a set of guidelines. Proper design of an AM product for space applications should for example include Design for Inspection, Design for Post-processing and Design for Testing. Each of these would be a specific guideline, supported by for example, a design practice template that provides further instructions for the engineers. In Figure 9, Design for Inspection is taken as an example, where the design practice template includes specific questions for the engineers to address during product development. To support these questions, possible inspection methods are listed, indicating what the current experience within the design organization is with regard to each. The example in Figure 9 should provide inspiration for further research on how the Design for Qualification framework can be developed to support companies in their pursuit of increasing their AM knowledge.

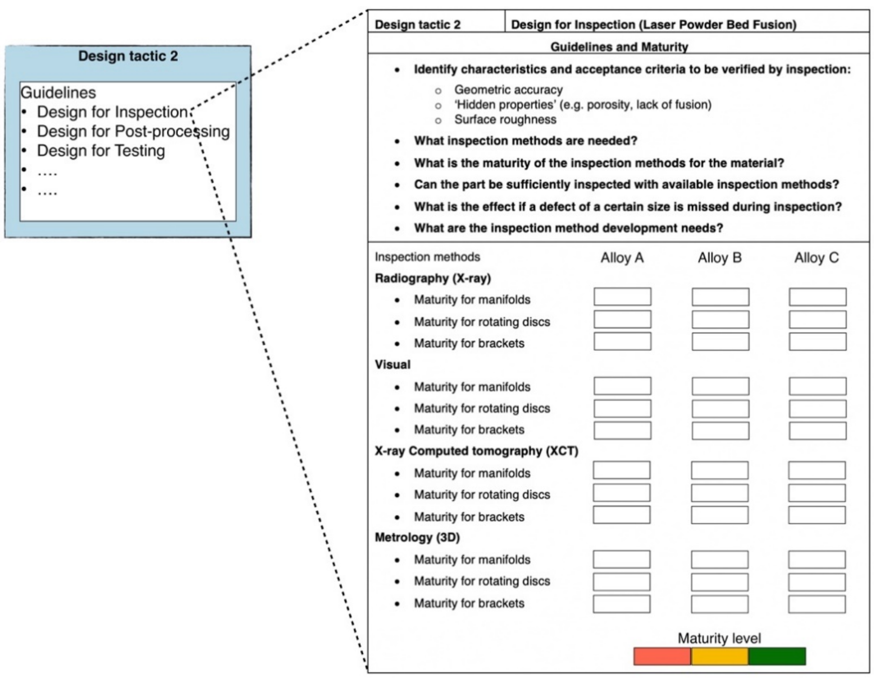

Figure 9. Example of guidelines to be defined for each design tactic. In this case, tactic 2 'Design for Qualification by considering the product in the AM process chain' is shown.

This study has focused on an approach for the verification of structural integrity since this is a main concern for fatigue-sensitive and critical AM parts. The Design for Qualification framework is however generic and applicable for other performance requirements that need to be verified for qualification, for example, aerodynamic performance. Future research should therefore apply the framework and tactics on requirements verification in general for further development and evaluation. Future development of the framework would also be to define its role in distinctive product development phases (e.g. concept design and detail design) in order to better support engineering teams in what activities to focus on in which phase. Another limitation of this study is that the framework has not been validated through implementation in a development project (although it is based on empirical data on how a product development project was carried out). Further research on how the framework is implemented would therefore be a solid contribution to the research field, especially in terms of improvements that are needed based on insights from such implementation.

5. Conclusions

Qualification of products that are manufactured with AM is challenging in regulated industries such as the space industry. Cautious implementation of new technologies is needed to ascertain that products function as intended and do not fail during launch or while in orbit. Design organizations developing AM components for space systems therefore need systematic procedures that aid in defining requirements and products that are suitable based on available AM knowledge. This paper has proposed a *Design for Qualification* framework that highlights that AM is in fact a chain of manufacturing processes for which products needs to designed and which needs to be understood. Proper consideration for the capabilities of the AM process chain is a prerequisite for enabling product qualification. The framework provides a direction for engineering teams to plan and execute their design process, highlighting critical aspects in the *requirements capture, design and verify* sequence of AM product development. The first main contribution of this paper is the description of a case study on how a company develops AM process understanding and products concurrently in order to define a verification approach. Based on this case study, the second main contribution is the Design for Qualification framework including six design tactics for how to consider qualification during product design for AM to expand current literature on product development with AM.

Author Contributions: The author designed the study, collected and analyzed the data and wrote the paper. All authors have read and agreed to the published version of the manuscript.

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