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Method for Function-Based Identification of Potential AM Components in Conventional Product Architectures

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Abstract

The implementation of additive manufacturing enables the the re-thinking of a product towards function-oriented design. This study proposes a method, which uses a set of rules and indicators to implement functional integration, part consolidation, part separation and on-demand manufacturing onto a conventional prodcut architecture to restructure it into an AM-oriented product architecture. The feasibility of the method is demonstrated on an assembly from the field of high temperature applications.

Keywords: product architecture, additive manufacturing, part consolidation, laser beam melting identification method, value-driven design

1. Introduction

Additive Manufacturing (AM) refers to a set of technologies used to produce physical objects from computer aided design (CAD) data by adding layers of material. While the design of conventionally manufactured parts is often limited in terms of geometrical complexity, AM opens the possibility for designing highly complex, lightweight, and customized products with improved features such as internal cooling structures, among others.

When implemented correctly AM can also potentially reduce inventory levels by manufacturing products on-demand and thereby simplifying the supply chain, as well as decreasing time-to-market and reducing assembly effort. Despite the design freedoms offered by AM, a successful industrial implementation of this technology remains to be a challenge. Since not all parts are technically possible or economically profitable to manufacture additively, a key success factor is properly identifying suitable parts out of a company's product portfolio. A growing number of tools and identification methods are found in literature that deal with this issue. Many of these methods focus on a geometry-oriented part identification (Lindemann et al. 2015; Klahn et al. 2014; Knofius et al. 2016; Klahn et al. 2020; Leutenecker-Twelsiek 2019a), while only few studies have addressed the possibility to identify potential part candidates based on their functions (Richter 2020; Reichwein et al. 2021).

This study proposes a combined function and component-oriented heuristic approach to restructure a conventional product architecture towards AM and thereby identify potential AM candidates. Therefore, geometrical and cost related data as well as part manufacturing information are retrieved from CAD/PLM and ERP tools, as well as specification sheets including functional product descriptions. AM Candidates are split into function and part candidates for which one or more AM drivers or value-added potentials may apply. This study focuses on the following AM drivers: integrated design, performance-oriented design and on-demand manufacturing to support service scenarios. Furthermore, this paper intends to emphasize the use of product architecture as an enabler towards functionality-based AM product re-development.

2. State of the art

Ulrich defines the product architecture as: "the scheme by which the function of a product is allocated to physical components" (Ulrich 1995). Krause et al. 2021 suggest that the product architecture consists of a product structure, being the physical structure of a product, a function structure, meaning a solution-neutral, functional description of a product, and the mapping of functional elements to physical components (Krause et al. 2021).

Schuh et al. distinguishes between two types of product architectures: modular and integral architectures (Schuh et al. 2012). A modular architecture is characterized by a one-to-one mapping of functional element to a physical counterpart. On the other hand, an integral architecture is characterized by having several functions being fulfilled by one component (Schuh et al. 2012; Ulrich 1995). Thus, it becomes evident how the design of a product architecture has an impact on the approach taken in the product development process (Krause et al., 2021). For example, companies aiming to reduce part count while maintaining the same functional scope may follow an integral design approach (Krause et al. 2021; Ziebart 2012). In contrast, differential design refers to the principle of decomposing a component or a product into several new components while maintaining the same functional scope (Krause et al. 2021). For example, companies aiming to improve product characteristics may decompose a component into newly designed components made out of requirement-specific materials (Inkermann et al. 2019; Krause et al. 2021). Further design approaches such as modular design will not be discussed in this paper.

Kumke underlines that product architectures should be designed for AM, which means considering both restrictive and opportunistic criteria, in order to fully exploit its benefits (Kumke 2018). Wagner proposes a product development approach based on a design pattern matrix. This approach focuses on functional integration by developing unbiased functional carrier variants in regards of manufacturing technology (Wagner 2018). Richter presents an approach for product architecture design (PAD) to exploit AM potentials and inspire designers to develop AM-oriented product concepts (Richter 2020). Steffan et al. 2020 present a procedure to systematically consider AM potentials on functional level in early product design phases (Steffan et al. 2020). Reichwein et al., 2021 propose a criteria-based method, which intends to adapt product architectures towards AM by subsequently consolidating and separating components (Reichwein et al., 2021). Other methods, such as proposed by Lachmayer, rely on geometric aspects of parts, such as surface and volume potential (related to part complexity) for AM-potential identification (Lachmayer und Lippert 2020)

Many current industrial applications for AM were subject to a substantial redesign before proven additive manufacturing (Kumke 2018; Klahn et al. 2014). Thus, a decisive step for successful integration of AM in industrial products is the identification and selection of proper candidates for AM. Lindemann et al. propose a methodology for part selection consisting of an information and an assessment phase. In the information phase, novice AM users are provided with an overview of advantages and limitations of AM to inspire them through the screening process resulting in a list of potential part candidates. Then, the part candidates are assessed and selected by experienced AM users using the "Trade-off Methodology (TOM) Matrix" (Lindemann et al. 2015). Leutenecker-Twelsiek proposes a method which consists of a computer-aided pre-selection, a manual identification conducted by AM experts and a subsequent candidate assessment (Leutenecker-Twelsiek 2019a). The manual identification is based on mapping potentials of AM to its corresponding indicators. In this case, indicators are primarily geometrical characteristics that are found in parts which have already been successfully converted to AM. Klahn et al. propose a method which combines AM potentials with design strategies (minor or major changes) to identify and select the right parts for specific AM applications (Klahn et al. 2020). Parts with minor design changes are identified in an automatized process and parts with major design changes are identified manually based on the experience and judgement of AM experts.

Several studies have highlighted the effect of using AM in spare parts management (Knofius et al. 2016; Ley et al. 2017b; Fontana et al. 2018). Knofius et al. propose a weighted ranking method to identify part candidates using restrictive and opportunistic spare part attributes (Knofius et al. 2016). Ley et al. propose an identification algorithm consisting of a sequential multi-step filter system. The filter system removes standard, easy-to-manufacture parts as well as technically and economically unsuitable parts out of the candidate list (Ley et al. 2017b). The remaining spare parts represent the

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potential candidates for AM. Fontana et al. identify spare parts for AM by comparing the total costs divided by the volume of conventionally manufactured spare parts, to the price per volume of material, in this case polymer powder, to manufacture additively (Fontana et al. 2018).

Several researchers have focused on identifying parts for a single AM potential such as part-count reduction (Yang et al. 2019; Yang et al. 2018; Nie et al. 2020; Kim und Moon 2020). Yang et al. developed an automated method, which incorporates the concept of modularization by grouping parts into modules and checking each module for consolidation feasibility based on a set of automated rules (Yang et al. 2019). In further work, Yang et al. generalized this approach by proposing an automated method for AM part identification exploring multiple AM potentials and presenting an insight on which of the AM potentials may be added to a product (Yang et al. 2020).

Table 1. Overview part identification methods

	Criteria		Generally applicable?		Required AM knowledge		Method implementation		Adressed AM Potentials	
	Opportunistic	Restrictive	Yes	No	Novice	Skilled	Manual	Automated	Single	Multiple
Fontana et al. (2017)	✓	✓		✓		✓	✓			✓
Klahn et al. (2020)	✓	✓	✓			✓	✓	✓		✓
Knofius et al. (2016)	✓	✓		✓	✓		✓			✓
Leutenecker-Twelsiek (2019)	✓	✓	✓			✓	✓			✓
Ley et al. (2017)	✓	✓		✓		✓		✓		✓
Lindemann et al. (2015)	✓	✓	✓		✓	✓	✓			✓
Nie et al. (2020)	✓		✓		✓			✓	✓	
Yang and Zhao (2018)	✓		✓		✓			✓	✓	
Yang et al. (2019)	✓		✓		✓			✓	✓	
Yang et al. (2020)	✓		✓		✓			✓		✓

Table 1 summarizes and compares the identification approaches mentioned above based on candidacy criteria, general applicability, required AM knowledge, implementation and AM potentials addressed. Most of the studies follow a generalized approach considering mainly opportunistic criteria yet focusing mainly on part-related attributes. An automated approach to reduce bias and increase industrial applicability is covered by about half of the evaluated studies from Table 1. Furthermore, combined part and function-oriented approaches to identify potential part candidates for AM is rarely found in literature (Richter et al. 2016). The topic of designing or adapting product architectures to AM has been only recently become subject of research and addresses PA design from a purely component viewpoint (Richter 2020). Based on the above, this study proposes a method which applies AM potentials on a conventional product architecture with the purpose of restructuring it towards an AM-oriented product architecture. Also, both restrictive and opportunistic aspects will be considered and the method is targeted towards both novice and expert users. By means of this, both parts and functions, which could potentially benefit of a product or assembly redesign for AM, are identified. In an additional step, component re-design is usually necessary. However, this is outside the scope of the present study.

3. Part identification method

3.1. Framework and target

The presented method uses a set of rules and transformation indicators to restructure a product architecture towards AM and thereby identify part candidates. The method should be applied on a small group or a particular of products/assembly as it is not automated. It is targeted towards non-AM expert designers or engineers in companies who are willing to consider Laser Beam Melting (LBM). Basic AM knowledge and an understanding of the assembly or product in consideration is required. Main aim of the method is to provide a structured approach on part consolidation and functional integration by LBM in product architectures defined by conventional machining. A comparison of different manufacturing techniques as well of finding parts for hybrid manufacturing is outside the scope of this paper.

Figure 1 shows the proposed workflow for an AM conception process for existing products, particularly for adaption scenarios. The current scope is enclosed by the dotted line, parting from an existing product architecture.

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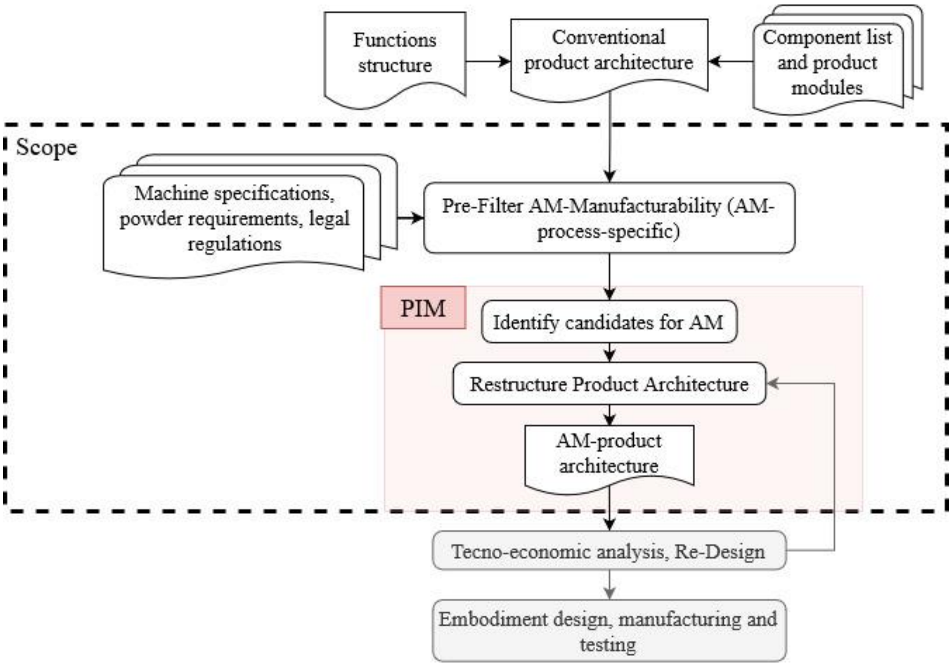

Figure 1. AM Conception workflow to be applied on existing products or assemblies

The conventional product architecture (Conventional-PA) must be at hand previous to applying the current method. Then, potentially unsuitable components for manufacturability with LBM are filtered out (see Section 3.2). The part identification method (PIM), described as well in the following Section 3.2 is applied on the remaining parts.

Within the part identification method, at least one AM-oriented PA - that is, a restructured PA containing AM-candidates- can be created based on the potential part candidates for AM. A technical and/or economic assessment, as well as re-designing the parts for manufacturability, Life-cycle-analysis and testing are generally the next step after AM-candidate parts are identified (Bracken et al. 2020), (Reiher et al. 2017). These steps, however, are not part of the scope of the current paper. Potentially, the proposed AM-oriented PA can and should be further updated based on the outcomes of the redesign and assessment processes.

3.2. Pre-filter and part identification method (PIM)

The proposed pre-filter based on restrictive criteria for manufacturability under LBM (Ley et al. 2017b; Yang et al. 2019) is designed to reduce the workload for the PIM by excluding candidates based on clear lack of economic viability or manufacturability. The filter criteria are arranged hierarchically by economic viability and LBM-manufacturability and are applied sequentially as follows:

1. Filter out standard parts and machine elements (Ley et al. 2017b; Yang et al. 2020)
2. Filter out easy-to-manufacture components via conventional manufacturing (Ley et al. 2017a)
3. Filter out materials unavailable as metal powder for LBM (Ley et al. 2017b)
4. Filter out components larger than build volume allowance (Ley et al. 2017b)
5. Filter out components with local or international legal restrictions on manufacturing (Ley et al. 2017b)

Manufacturing filter criteria (3, 4, and 5) are subject to the state of technical development with regard to machine technologies and material development for AM (Ley et al. 2018; Yang et al. 2020). Hence, a backlog is proposed for components that don't match either current material availability, machine build volume restrictions and/or legal restrictions, since these aspects are likely to undergo further development within the growing market of AM technologies. In terms of build dimensions, AM redesign may differ from the original design in terms of volume and size, making the component dimension constraint different than originally believed (Page et al. 2019). In addition, part separation to solve the build dimension restriction has also been explored in literature (Reichwein et al. 2021). Parts for which legal restrictions prevent manufacturing-in-house (Criterion 5) should either be categorized as potentially unsuitable, e.g., in case of export restrictions

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(Ley et al. 2018) or sent to the backlog, e.g., in case a patent expires. Backlog components may be analysed for LBM-suitability in near or further future.

The filtering process is followed by the actual part identification method (PIM). Parts are identified based on indicators shown in Figure 2. These are derived from the Conventional-PA, ERP/PLM systems and from CAD model data found in parts which have already been manufactured additively (based on Leutenecker-Twelsiek 2019a). The indicators are divided into three value categories, which give an insight of the value that could potentially be added to the product with AM. AM features a large number of value-added categories in the fields of design, geometry complexity, supply chain and performance enhancement (Yang et al. 2020; Leutenecker-Twelsiek 2019b; Page et al. 2019; Kumke 2018). This study focuses on three main value-added categories: integrated design, performance-oriented design and on-demand manufacturing as depicted in Figure 3. Integrated and performance-oriented design relate to both adaption scenarios, meaning cases where parts can be fabricated additively without major design changes, and new development scenarios. On-demand-manufacturing can also be applied in a service scenario. Value categories are not exclusive, meaning indicators could appear in more than one value category.

Regarding integrated design, the PIM distinguishes between candidates for functional integration and candidates for part consolidation. Starting off with functional integration, the user should scan the Conventional-PA and search for springy, shock absorbing or mechanical damping functions (Page et al. 2019). Next, cooling functions (Leutenecker-Twelsiek 2019b) and parts with a 1:1 functional relation (Yang et al. 2019), meaning parts in a product which have a high functional dependency or whose functions are exclusively related to another part shall be identified. After the first scan, the user CAD model data shall be examined looking for cooled parts, statically connected elements, parts with a high number of blind plugs to close channel holes as well as parts subject to high temperature loads (Leutenecker-Twelsiek 2019b). One of the potentials of AM towards functional integration are parts with complex inner structures, which could be added to the inner contour of a part to ensure proper cooling (Page et al. 2019).

Part consolidation refers to the act of integrating multiple parts in a product (Kim et al. 2019). In this field, the user should scan the Conventional-PA and search for parts which perform the same function (sub- or main function), as well as parts belonging to the same module (Yang et al. 2019) and evaluate them towards part consolidation. An assessment towards part consolidation would include ensuring there is no significant difference in terms of maintenance frequency between the consolidated parts, as well as ensuring that consolidated parts do not block assembly access (Page et al. 2019). The assessment could result in the consolidation of two or more parts in a product or even the reconceptualization of a module from several parts to one.

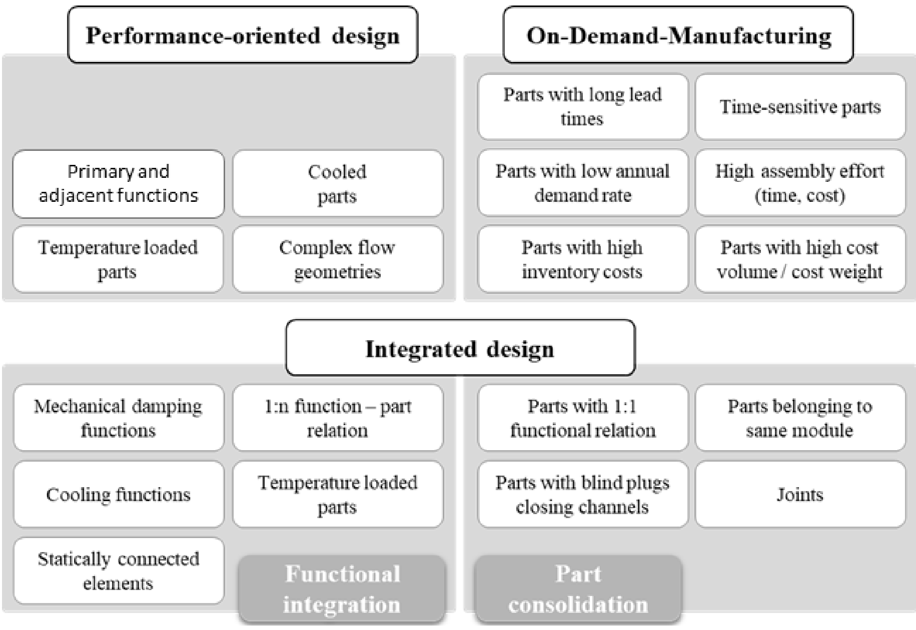

Figure 2. LBM-specific indicators for part identification method

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Performance-oriented design refers to an approach by which a product is designed towards enhancing its performance (Leutenecker-Twelsiek 2019a; Kumke 2018). Starting off with the Conventional-PA, parts fulfilling both primary and adjacent functions shall be searched for. Primary functions cover functions which directly affect the flow-dynamics performance of a product, whereas adjacent functions might be fixing, sealing or other mechanical functions. In this case, the identified part could potentially be decomposed into two, following the concept of differential design (see Section 2). One rather simplified part shall cover adjacent functions and the remaining part can be redesigned with AM towards performance enhancement. Furthermore, based on CAD model data, the user should check for temperature loaded parts, cooled parts, and parts with complex flow geometries (Leutenecker-Twelsiek 2019b). Parts for which these indicators apply could profit from a redesign towards heat-exchange efficiency and should be further evaluated.

Candidates for on-demand manufacturing are identified based on data retrievable from ERP tools or internal documents. Parts that should be considered as candidates are those with long lead times (Diegel et al. 2019), low annual demand rate (Frandsen et al. 2020), time-critical parts (Frandsen et al. 2020), parts required in remote locations (Yang et al. 2019) as well as parts with high inventory costs (Page et al. 2019). In addition, parts which involve a high assembly effort (Kruse und Reiher, T., Koch, R. 2017) as well as parts with a high cost volume/weight, meaning parts for which total costs divided by its volume/weight is higher than the negotiated price per volume of powder material for LBM (Fontana et al. 2018), should be further evaluated.

Eventually, candidates are individually analysed towards suitability for integrated design, potential for performance enhancement and opportunity of on-demand manufacturing in an iterative process. This analysis yields possible new product structures and component constitution for an AM-PA. Following steps require printability assessment using methods from section 2. This could lead to restructuring the AM-PA in an iterative process.

4. Application and results

The PIM was applied on a gas turbine pilot nozzle assembly, as the one shown schematically in Figure 3. Generally, products from this field must be stable, resistant, and reliable at high temperatures and through temperature changes. Therefore, these products could benefit from some of the possibilities AM has to offer, such as economic and resource-saving fabricability of materials with improved thermomechanical properties as well as optimised internal cooling structures, which are not manufacturable with conventional manufacturing processes. Prior to this study an expert team identified two possible candidates for LBM within the evaluated assembly.

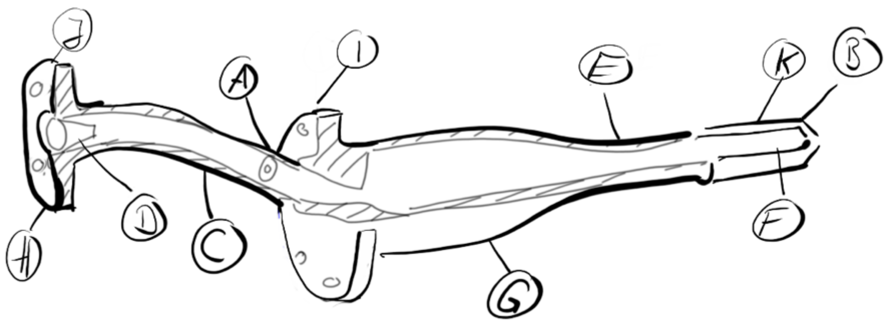

Figure 3. Gas turbine pilot nozzle assembly with components marked A to K

The present analysed assembly is subject to high temperature and pressure levels under operation conditions. Its main function is to conduct and distribute a fluid mix evenly and under specific conditions (temperature, pressure, velocity, etc.) into a combustor assembly. Since no Product Architecture was originally available for the assembly, the first step entails the development of a reverse engineered Conventional-PA using *METUS* Software[1], as shown in Figure 4. The Conventional-PA was developed based on information provided by the manufacturer regarding the

[1] https://www.id-consult.com/methode-und-technologie/metus-software.html

assembly and its functions. The physical structure consists of eleven parts (A to K), three modules (A to C) and one assembly. Accordingly, the function structure is divided into seventeen sub functions, two main functions and a total function.

In the next step, assembly parts were filtered according to the filtering process described in Section 3.3. Filtered-out parts are either considered potentially unsuitable or sent to backlog accordingly. In Figure 5, rejected parts are marked a dark blue colour. As a result of the filtering process, six parts (components B, E-I) are passed to the PIM.

Part B fulfils three functions, which are: protect component F against corrosion, relief stress and cool part F. Therefore, part B has a 1:1 functional relation to part F, which means the possibility of functional integration of these components with AM should be considered. Since Part K serves only for the physical connection between B and F, it would disappear as its function would no longer be required in this case. Parts E and G share the same functions, which are: conduct fluid and ensure proper fluid behaviour. In addition, both parts are positioned adjacent to each other. Therefore, these parts should be considered potential candidates for part consolidation. Since Part H includes both flow relevant functions as well as mechanical functions, meaning functions from different functional areas, it should be considered a candidate for performance-oriented design. Part H could be separated into two adjacent parts following the concept of differential design (see Section 2). One part could focus on fulfilling the mechanical functions and another part could be designed to improve flow behaviour with AM. On-demand manufacturing yields a high cost-weight ratio of 4 for components B, E-H (see Figure 4). Part I does not fit to any of the indicators or heuristic rules proposed in Section 3.3 and should therefore be sent into the backlog.

Figure 4 shows the results after applying the PIM. As stated before, unsuitable components are marked in dark blue while those sent to backlog are marked in light grey. The remaining parts and functions represent the potential candidates for AM. In total, five out of eleven parts could be identified, rather than only two prior to this study. The candidates were highlighted according to the corresponding value category (see Figure 4). Parts and functions marked in light blue represent candidates for functional integration, light orange stands for part consolidation and yellow for performance-oriented design.

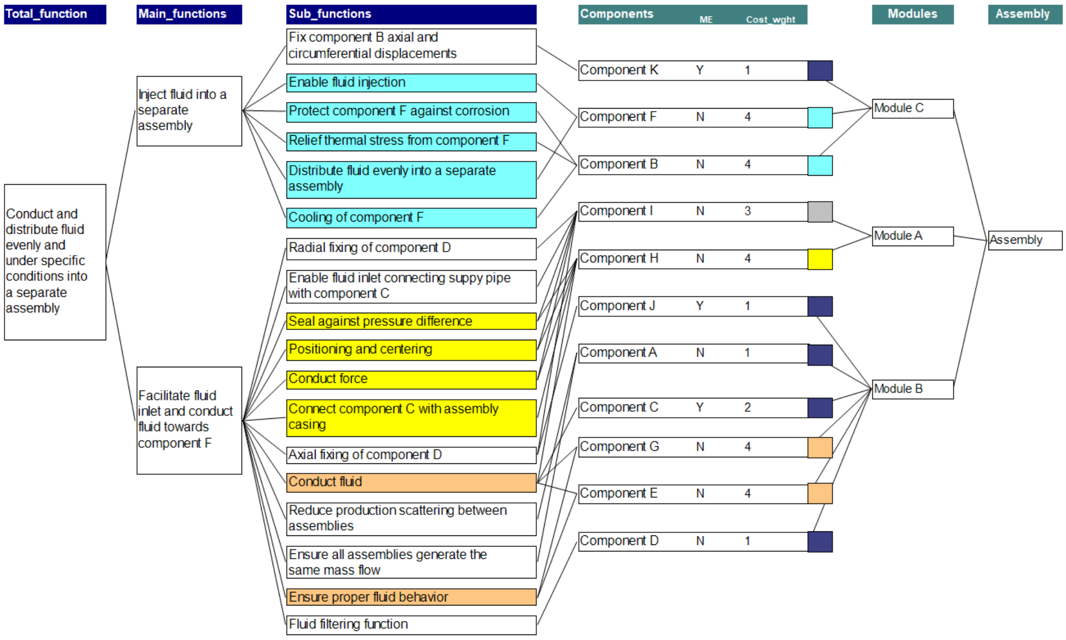

Figure 4. Conventional-PA of gas turbine assembly after applying the part identification method. Components attributes are assessed as "machine element (ME)" and "cost weight "

Figure 5 depicts the derived AM-oriented PA. The newly developed parts, including the suggested manufacturing process (AM/CM) are highlighted in corresponding colours. The proposed product structure consists of nine parts and fifteen sub-functions. The functions of Parts B and F were integrated with AM into one sole part, part M in module C. Part K is no longer required. In addition, parts E and G were

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consolidated to form part L in module B. Part H and its corresponding flow relevant and mechanical functions were separated into two adjacent parts: part N (AM) and part O (CM). Respectively, flow relevant (primary) and mechanical (adjacent) function correspondency are divided into modules A and B.

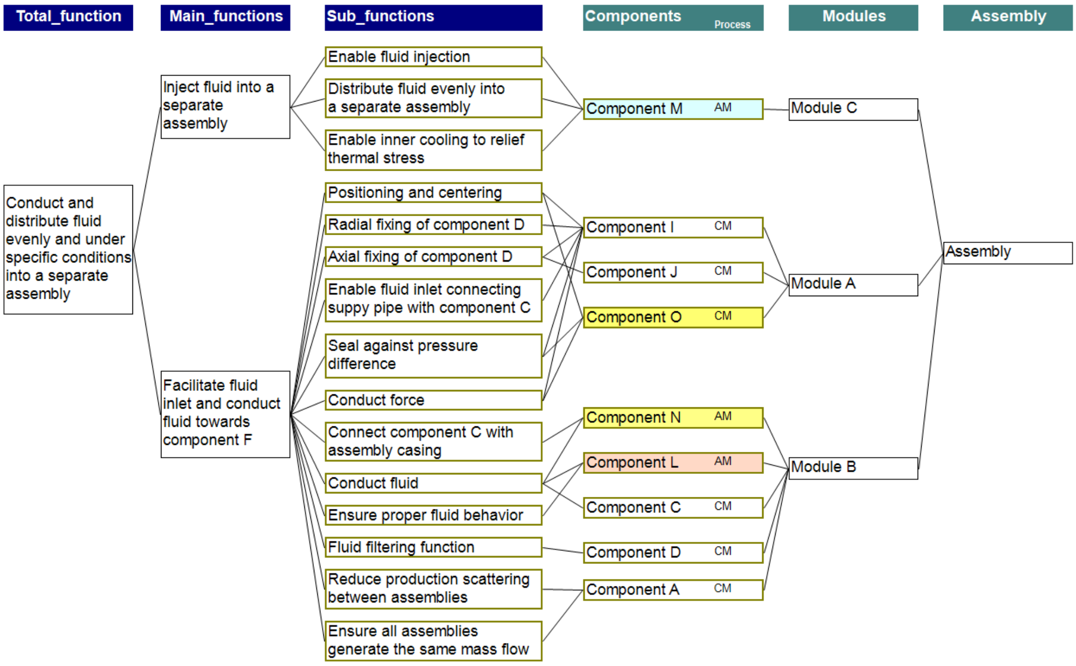

Figure 5. AM-oriented PA of gas turbine assembly

The AM-oriented PA entails only 8 components, as opposed to 11 since the PIM yielded, for the most part, candidates for integrated design.

5. Conclusion and outlook

In this study a new method is proposed to transform a product architecture of a product originally purely driven by conventional manufacturing, towards an AM-oriented product architecture. Based on a product architecture, an appropriate understanding of the interactions between the parts of a product can be understood, both in physical and functional matter, which is key in properly identifying potential candidates suitable for AM. Restructuring the product architecture takes place by using a combined function and component-oriented approach.

The proposed Part Identification Method (PIM) was applied successfully to a gas turbine pilot nozzle assembly. As a result, a restructured AM-oriented product architecture was obtained, whereby five out of eleven parts were identified as potential candidates for AM and recommended for redesign, resulting in a reconfigured product architecture towards application of LBM.

Prior the current approach, only two parts were identified as a potential candidate for AM by AM experts. This demonstrates the potential of product architectures in the identification of potential parts for AM especially if significant redesign for AM is necessary. The presented method emphasises the opportunistic perspective, while applying a restrictive approach to filter out non-suitable parts at an early stage, and bases on product- rather than AM-knowledge.

However, given the sample size, the method should be applied on further assemblies to prove its applicability, particularly on complex assemblies with a higher number of components. Furthermore, the general applicability of the method should be tested on use cases involving other AM processes besides LBM. In addition, future work should look into implementing this method on products from other industries for which AM is conceivable, besides high temperature applications. Moreover, both the processes of creating a conventional product architecture based on PLM data and its adaption towards an AM-oriented product architecture should be at least partly automatized.

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Author contributions

Veronica Molina: methodology, supervision, validation, writing – review, editing and visualization, project administration; Luis Reyes: investigation, methodology, writing – original draft; Sebastian Werner: conceptualization, supervision, validation, writing – review, editing and visualization, project administration; Dietmar Göhlich: resources, writing - review and editing, project administration, funding acquisition

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