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FULL RESEARCH ARTICLE

Holistic approach for industrializing AM technology: from part selection to test and verification

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Abstract Even in times where additive manufacturing has a peak in media and industry interest, only few companies have already implemented this technology. Many companies struggle with the use of AM even if they have already identified the benefits of this technology for their business. Additional knowledge along the whole product development chain is necessary to succeed in implementing this technology. As all other production technologies, AM has certain strength and weaknesses which affect the suitable part candidates. Redesign or manufacturing approaches of unsuited part candidates are no very likely to be successful. In general, aspects like design rules need to be known along the product development process in order to achieve technology-based benefits during production and post-processing resulting in economic success. This paper will present a holistic approach which will assist the designer during product development and manufacturing based on an example part from the space industry. Then methodology starts with an appropriate part selection as a key parameter for the product development process. Based on the promising part candidates, deductions for the further product development process will be described. This includes approaches for functional integration as well as a methodology for the compilation of part requirements. Those are utilized for a black box methodology, ensuring a time-efficient redesign based on FEA optimization and design rules for additive manufacturing. Best practices for integrating (or in the best case avoiding) traditional technologies are discussed. Based on this, the development of industrialization and test and verification plans for production are shown. This includes the marking of parts for traceability during the whole product lifecycle for quality reasons as well as for product protection. Furthermore, production and production planning are discussed. This is followed by post-processing and testing procedures of the part. The paper will close with a detailed economic view on the topic and some deductions regarding the changes in the supply chain. The methodology itself is discussed and explained on a real sample metal part. The general methodology is discussed on the basis of the space industry but is subject to be adapted to other industries.

Keywords Additive manufacturing · Industrializing · Test and verification · Redesign · Product safety · Supply chain · Costs · Topology optimization

1 Introduction

Additive Manufacturing (AM) is nowadays very popular in the media and of high interest for many companies as it is considered to become a game changer in several industries. The special characteristics of AM, for example the cost-efficient production of complex shaped parts and the on-demand production due to the shortfall of tools, offer a huge potential for reducing costs and becoming more

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efficient [1]. Companies have a lack of experience with this comparably new technology. For a successful integration of AM, it is necessary not only to know about the characteristics and benefits of AM itself. Gaining knowledge about the whole product development and production process from new product concepts to the production itself is crucial. Although AM enables far more complex designs than conventional technology is capable of, there are still some constraints that have to be taken into account. AM-specific design rules have to be followed in order to enable manufacturability and achieve a high part quality. The design is not only relevant for the production but also influencing the costs. Support structure and the orientation within the build chamber are two important cost and quality drivers that the engineer has to be aware of to fully exploit the (cost) potential. It is important to start the AM product development (PDP) process with the right selection of a suitable part for this technology. Several perspectives have to be checked whether it is economical and technical reasonable to apply AM for the particular part. A branch-specific trade-off methodology supports this action. It also has to be taken into account that the AM typical bionic design leads to difficulties during the post-processing. The complex, only functional load-dependent design hampers the machining with conventional technologies and a reference point is often missing to align the parts inside the machines. Such challenges are known already from casting technologies but are even increased for additively produced parts.

It can be observed that each process step during product creation and production is influenced by AM and the arising problems need to be solved or even prevented by using the appropriate tools especially in the early phase of the product development. There are already many isolated applications and a variety of research topics that deal with the above-mentioned problems. Most of them do not offer a holistic approach which takes the whole process into account. This paper intends to provide an overview of the complete process on the basis of a sample part from space application and provides methodologies for the process steps that have to be conducted for a successful AM integration.

2 Part selection

One of the crucial points for the successful use of AM is the selection of part candidates. Before doing so, an organization first needs to decide whether AM might be a production technology feasible for their businesses and if they are willing to use this technology. In this paper, the step for this decision-making process is assumed to be positive. Once this decision has been taken, the application potentials for certain parts can be discussed. Similar to all other manufacturing technologies, AM is not the optimal production method for every part. Thus, a methodological approach is needed to identify specific applications. The appropriate part selection targets to solve three major tasks:

1. finding a part which can be produced by AM (with reasonable technical effort);
2. finding a part which offers an economic benefit; and
3. finding a part which may be used as an end product (cost–benefit/quality control).

Literature and applications have proven that producing parts additively which were not designed for AM is not suitable [1]. Furthermore, the review of “Direct manufacturing Design Rules” has shown that not every geometry can be produced with AM and especially not in a stable and repeatable process [2]. Thus, not every part can be produced by AM with a reasonable technical effort. As, for example, in metal processes, high cross-sectional areas and massive blocks require very deep process knowledge and high effort on support structures to overcome challenges with internal stresses. Therefore, one can easily understand that the economic successful use of the technology is strongly related to the part selection. Furthermore, costs of the AM technology are complex to assess and can hardly be approached by inexperienced users. The advantages of the technology often make it necessary to consider more than just the production costs [3]. Finding a part which may be used as an end product seems to be easy when one has successfully mastered producibility and economic considerations. But for the use as an end product, aspects like availability of material data, possibilities to conduct post-processing steps, or process stability tests play a crucial role.

To check for these above-mentioned aspects, a methodological repeatable approach has been developed that can be applied before starting the product design. This general approach can be split into three phases and is usable for experienced as well as inexperienced AM users [4]. Inexperienced AM users are guided based on a workshop concept.

The central tool in this methodology is called “Trade-off Methodology Matrix” (TOM) and is shown in Fig. 1. In general, it consists of three parts which split into a part definition, a preliminary section, and furthermore a final trade-off section. The part definition contains basic information like a brief description of the function, typical production quantities, production costs, dimensions and mass of the part, as well as the currently used material. Once these data are entered, the user gets a first quote over the rough production costs. For an easy-to-use tool in this early phase, the production costs are calculated based on certain assumptions like depreciation times and a specific demand. Detailed costs can be assessed later in the methodology.

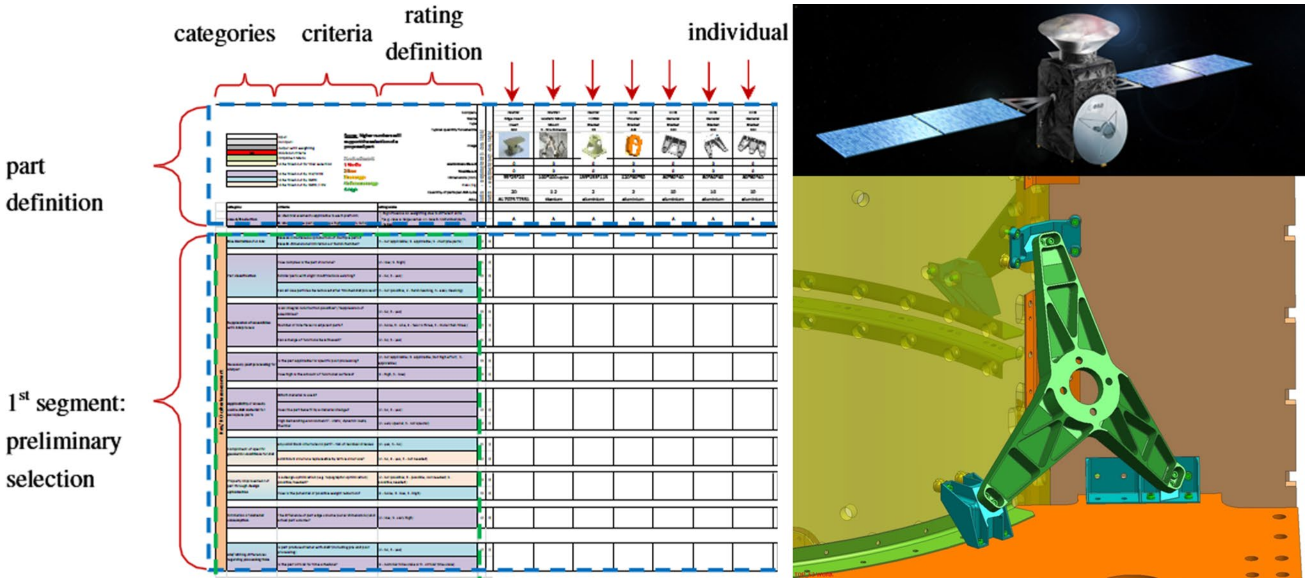


Fig. 1 *Left* excerpt of Trade-off Methodology Matrix (TOM), *right* ExoMars satellite. (Source: ESA), RW-*Bracket*

The first segment of the TOM aims at inexperienced users and marks some k.o. criteria in order to have an easy part assessment, while the second segment focuses on more experienced users. The assessment is based on different criteria, definitions, and ratings which can be defined according to different branches and industries or the different strategies and requirements of the companies. Every section is structured into different main categories that include several sub-criteria (e.g., “Compliment of specific geometric conditions for AM”). These sub-criteria can be rated similar to a value benefit analysis. Through a change of ratings or through an adaption of sub-categories, the matrix may be adapted to several different applications. Taking “possible weight savings” as one example criterion, one can see that this aspect is more important for the aerospace industry or race car applications than for medical components. The third segment is the final trade-off which requires very detailed information on the part and includes a much more detailed cost analysis to finally decide if a part should be manufactured additively or not.

One example for the right selection of part with the help of the TOM matrix is shown in Fig. 1. The considered part is a Reaction Wheel-Bracket (RW-Bracket) which is used to mount a reaction wheel in a telecommunication satellite. This assembly is used four times per satellite to control the orientation of a satellite in space. This part was selected mainly due to a good feasibility rating for AM in criteria like supposed weight reduction possibility, potential for monolithic design and consequent interface reductions, low amount of solid block structures hampering additive manufacturing, and a high buy-to-fly ratio, requiring a high milling effort and thereby causing a lot of waste. As shown in Fig. 2, there is the main bracket shown in green and the additional smaller brackets. Both of the orange brackets may be integrated to save milling effort and weight.

3 Redesign

Now that a suitable part has been selected, it has to be checked how a redesign can increase the benefit of AM. Conventionally designed parts are often hardly producible by additive manufacturing as those designs often do not follow indispensable additive manufacturing design

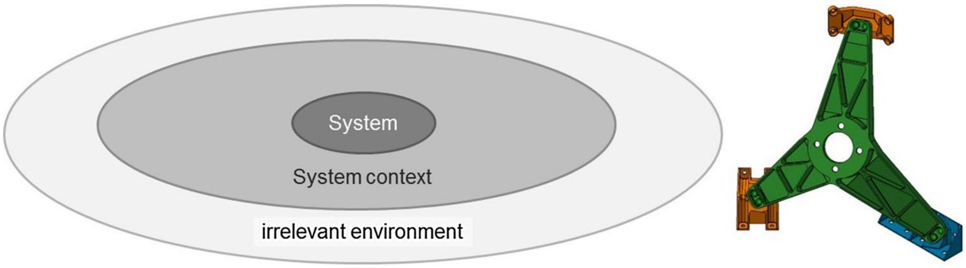


Fig. 2 Definition of system context [4], RW-*Bracket* (*green*) with integrable small *brackets* (*orange*) and without integrable *bracket* (*blue*). (Color figure online)

rules [2] to ensure a reliable manufacturing of high-quality parts. For example, huge material accumulations with large areas in one layer lead to high residual stresses and thereby can lead to a distortion of the part and have to be avoided [2]. Furthermore, a conventional design cannot exploit the advantages of AM. By use of AM, highly complex designs are possible to create without increasing costs [5]. This should be utilized to design parts getting the most benefit out of the used material by avoiding unused material only due to manufacturing constraints. In general, a part benefits from a redesign.

Different approaches exist for designing parts for additive manufacturing while optimizing the geometry according to the specific advantages and restrictions of the process. One way to achieve a conventional solid design into a manufacturable lightweight one is to replace the solid material with very small unit cells or lattice structures. These structures are supposed to save a significant amount of material and thereby weight, costs, and waste while providing nearly the same part properties, as dispensable material is saved while the remaining material is used best [6, 7].

A holistic approach needs to reconsider the overall design or even the part itself including its environment and assembly. The most comprehensive methodology is to start the redesign by scrutinizing the system context and to search for function integrations and monolithic design capabilities. Best results for using the advantages of AM can be achieved by avoiding conventional constraints of designs and manufacturing. Therefore, the system (part) has to be considered including its system context (assembly) and detached from the irrelevant environment as shown in Fig. 2. The irrelevant environment represents all surrounding parts that cannot be integrated. For the considered sample part "RW-Bracket," this might be the satellite's primary structure as it is made from huge carbon fiber-reinforced plastic panels (CFRP-Panels). At the current state of the art, they cannot be integrated into the part in one manufacturing process [4].

Figure 3 sums up this consideration including the RW-Bracket for example. The bars at the left show the applicability of AM technology in contrast to the optimization potential of the technology. They indicate a contradiction between each other as the applicability is the largest for the smallest and easiest part, while the general optimization potential is the largest for the overall system.

As mentioned in the part selection, there is the possibility of integrating two of the smaller brackets. Figure 2 shows the main part (green) and two smaller brackets marked in orange. These are only used for mounting the green one and thereby can be integrated from functional view. The third, blue one is used for other purposes as well and thereby must not be integrated.

Furthermore, neither the Reaction Wheel itself nor the total satellite system can be integrated into the RW-Bracket. Therefore, the RW-Bracket is defined as the system, the orange brackets as the integrable system context, and the blue bracket as well as the Reaction Wheel and the CFRP-panels as the irrelevant environment.

To be able to take this decision, a profound knowledge of the part is needed. Therefore, detailed information on function, loading conditions, constraints, frequency requirements, and available design space is needed to start an appropriate redesign. Forms providing well-thought questions help gather this information fast and easily. They have to be targeted on key part characteristics, adjacent parts that may be integrated, and assembly characteristics. One of the key part characteristics

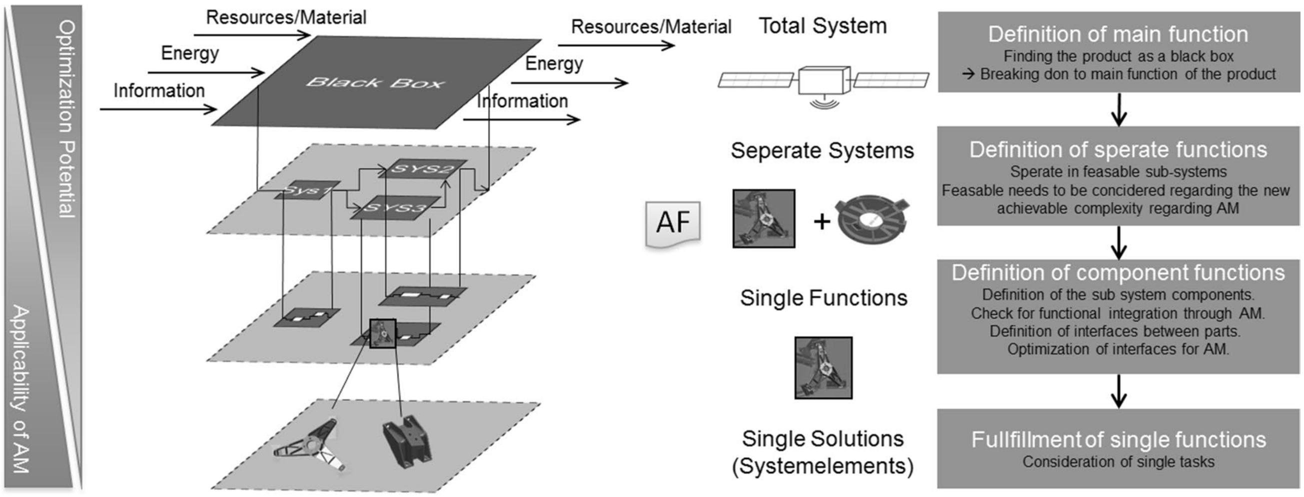


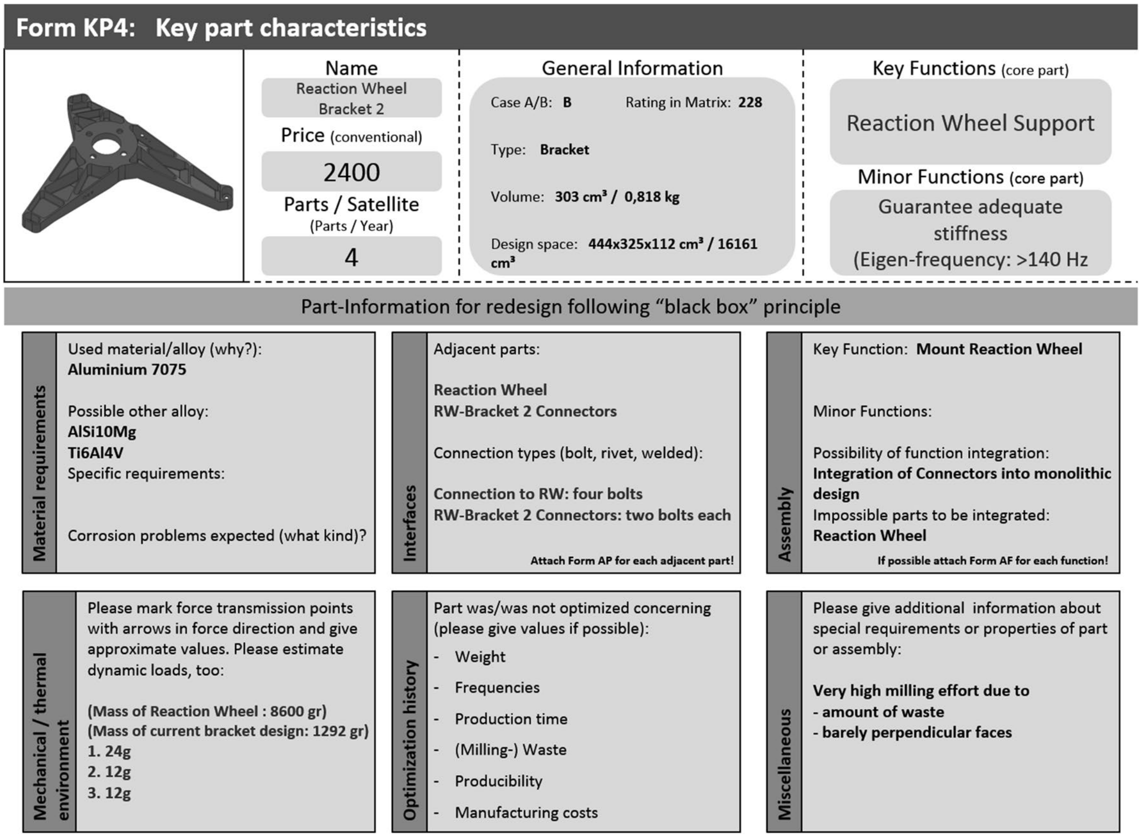
Fig. 3 Optimization potential and applicability of AM for *Black Box* redesign [4]

InfoForm is shown in Fig. 4, already filled with information for the RW-Bracket.

Based on the filled InfoForms, the part can be redesigned. Especially for structural parts like the considered one, an FE-based topology optimization is a powerful tool to distribute the lowest needed material in a design space for fulfilling all requirements like stiffness in case of displacements and eigenfrequencies. Figure 5 shows the optimization and design process of the Bracket. First, the complete available space around the bracket is divided into design space where material is allowed and the optimization algorithm can replace the material and non-design space where the material has to be kept whether it is mechanically loaded or not, like interfaces. These non-design spaces are used to apply all mechanical loads and supports. The first "optimization" picture shows the first result where the overall material is reduced to a much lower volume but not to the final result, to reduce computation effort. The final optimization result is shown with a selected density threshold. Hereby the best volume distribution is shown to fulfill all requirements regarding maximum displacement of the mounting point and the eigenfrequencies.

Due to geometrical mistakes in the results and imperfections regarding insufficient design space and coarse meshing, it is not reasonable to manufacture the results directly but to revise and smoothen them [8]. Due to the inherent geometrical coarseness of polygon models, especially of topology optimization results with eventually very huge elements, a transition is needed. Figure 5 shows the overall process including the translation into voxel-based model that is very easy to adjust. The final design with smoothed surfaces and perfect smooth radii without high stress risings can be transferred back into a NURBS-based model. This model can be intersected with the original CAD model to ensure the right position and size of parametric elements like screw-holes and interfaces [9] with conventionally built parametric CAD models and assemblies.

The assembly as shown in Fig. 6 with one large part (green) and three smaller ones (orange and blue) was reduced to two parts as the blue one is not allowed to be integrated. As a result, the weight was lowered by 60% from 1114 to 456 g, while the stiffness was even increased as seen from the maximum displacement lowered by 37% from 0.076 to 0.048 mm and an increased 1st eigenfrequency of 20% from 180 to 216 Hz. Additionally, the buy-to-fly ratio, as an indicator for waste production, was lowered by 97% from around 50–1.5.



Form KP4: Key part characteristics

Name
Reaction Wheel Bracket 2
Price (conventional)
2400
Parts / Satellite (Parts / Year)
4

General Information
Case A/B: **B**
Rating in Matrix: **228**
Type: **Bracket**
Volume: **303 cm^3 / 0,818 kg**
Design space: **444x325x112 cm^3 / 16161 cm^3**

Key Functions (core part)
Reaction Wheel Support
Minor Functions (core part)
Guarantee adequate stiffness (Eigen-frequency: >140 Hz

Part-Information for redesign following "black box" principle

Material requirements
Used material/alloy (why?):
Aluminium 7075
Possible other alloy:
AlSi10Mg
Ti6Al4V
Specific requirements:
Corrosion problems expected (what kind)?

Interfaces
Adjacent parts:
Reaction Wheel
RW-Bracket 2 Connectors
Connection types (bolt, rivet, welded):
Connection to RW: four bolts
RW-Bracket 2 Connectors: two bolts each
Attach Form AP for each adjacent part!

Assembly
Key Function: **Mount Reaction Wheel**
Minor Functions:
Possibility of function integration:
Integration of Connectors into monolithic design
Impossible parts to be integrated:
Reaction Wheel
If possible attach Form AF for each function!

Mechanical / thermal environment
Please mark force transmission points with arrows in force direction and give approximate values. Please estimate dynamic loads, too:
(Mass of Reaction Wheel : 8600 gr)
(Mass of current bracket design: 1292 gr)
1. 24g
2. 12g
3. 12g

Optimization history
Part was/was not optimized concerning (please give values if possible):
- Weight
- Frequencies
- Production time
- (Milling-) Waste
- Producibility
- Manufacturing costs

Miscellaneous
Please give additional information about special requirements or properties of part or assembly:
Very high milling effort due to
- amount of waste
- barely perpendicular faces

Fig. 4 InfoForm for the key part RW-*Bracket*

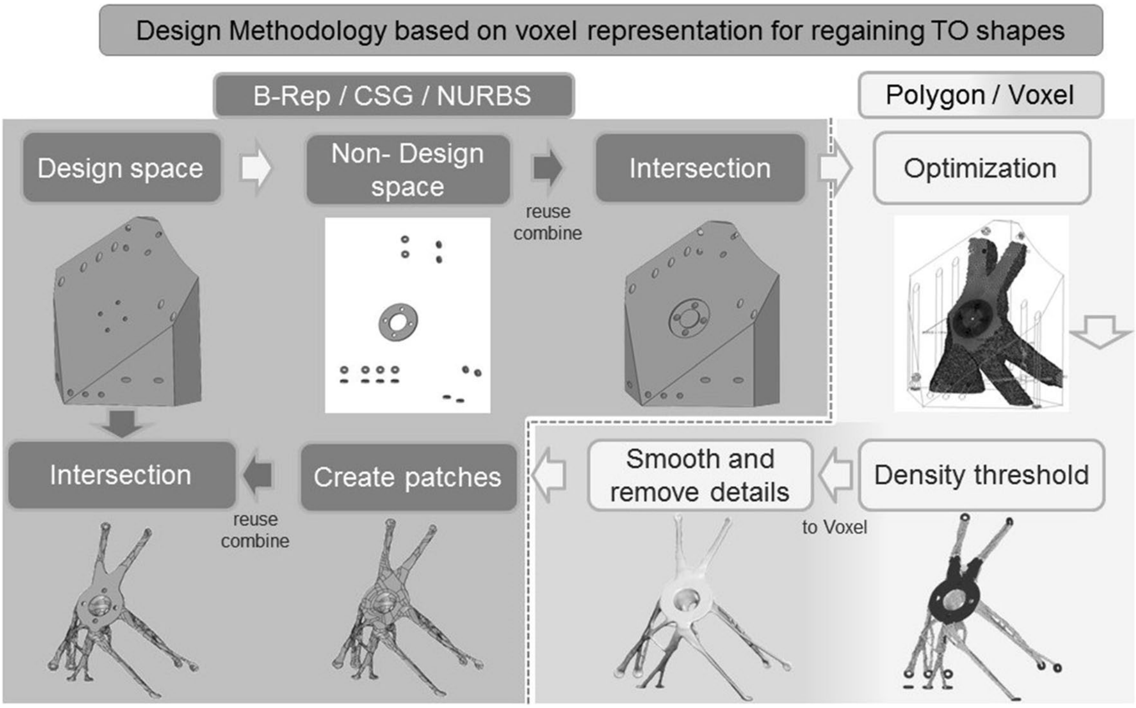


Fig. 5 Design methodology based on voxel representation for regaining [8]

Based on the outcomes of the project: Direct Manufacturing of Structure Elements for Next Generation Platform. Funded by ESA under Artes 5.1 Contract No.: 400107892

Fig. 6 Results of design optimization

These improvements could mainly be achieved due to the dispensation of the beforehand required isolated milling of the small brackets. By omitting these brackets and the high design freedom, the force flux can be led directly to the mounting points and thereby use least material.

4 Manufacturing strategy

The redesign of the selected part led to a design supposed to be optimal to fulfill the requirements gathered in the InfoForms and the TOM. During the redesign, a special emphasis on manufacturability was placed. For subsequent manufacturing of the part, some AM-specific details have to be considered in order to achieve a high part quality. These are considered when setting up the manufacturing strategy.

The manufacturing strategy needs to be taken into account during the design process already and can be an iterative process. The manufacturing strategy aims at repeatable manufacturability on part quality as well as on the economic use of the technology. Some of these factors which influence the build results are shown in Fig. 7. For successful manufacturing, predefined maintenance steps have to be defined and followed to make sure that the machine is in a well-kept condition such as a clean build chamber and appropriate filter condition. Furthermore, the digital data have to be prepared thoroughly. This includes bug fixes and proper positioning in the build chamber with enough support structure to

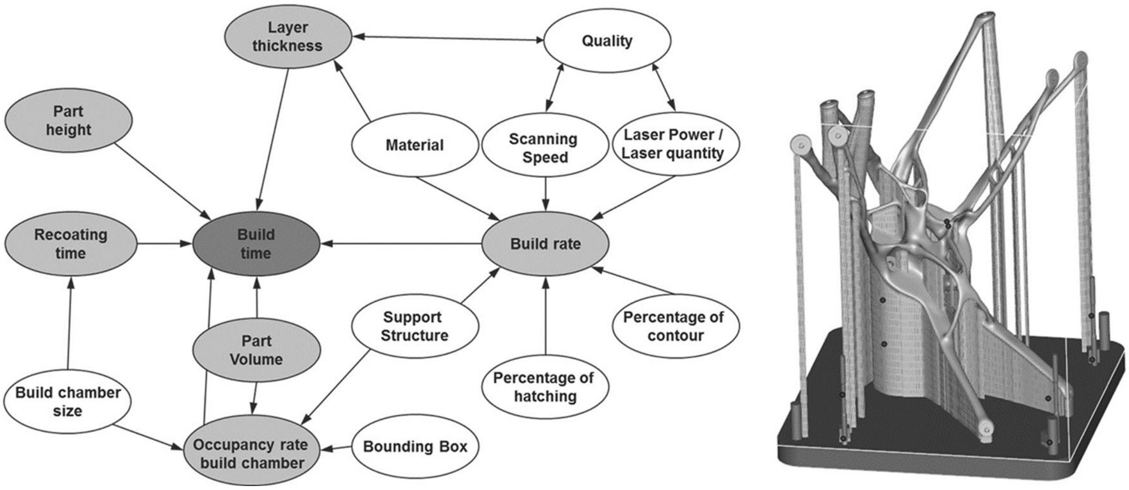


Fig. 7 *Left* important aspects influencing the manufacturing strategy; *right* positioning in build chamber and support structure of sample part including test specimens

ensure a safe build process, preferably located at surfaces which need to be post-processed anyway.

The RW-Bracket is positioned in a 45° polar angle to the build platform and nearly in the middle of the build chamber. Furthermore, the part is aligned 45° to the coater. The orientation of 45° to build platform is chosen to reduce support structures and thermally induced stresses. The slower the volume growth, the lesser the induced stresses and by that less warpage occurs. This improves the part quality but decreases the build speed. Furthermore, the alignment to the coater is important as otherwise the already solidified material can lead to too high resistance to the coater and so cause a stop of the build process as the control software assumes that the part is distorted.

The required support structures affect the build time, the total material usage, and the effort for post-processing. By reducing the amount of support, the needed build time is reduced and the post-processing effort decreases as less material has to be removed. While the support decreases the part surface quality increases as the contact points generally will need post-processing. On the other hand, insufficient support structure may lead to a failed build job or a distorted part and so it might be better to use more support and post-processing effort.

Different temperature conditions in the machine have some impact on the resulting material properties that has to be considered especially if no heat treatment is planned in post-processing. A higher pre-heating of the build plate may reduce internal stresses and thereby foster a safer build job and a high part quality.

5 Quality management

Quality management is a vital part of the additive manufacturing process. In general, the tests that need to be performed can be split up into three different phases.

5.1 Fundamental testing (fixed and part-independent)

Fundamental testing builds the basis for the use of the AM Technology. Its aim is to understand material and process characteristics. These tests are mainly performed for unknown material, new or changed process parameters, or changed subsequent processes like heat treatment. In this fundamental testing, all tests with regard to material-specific, essential behavior are performed as needed to qualify the overall manufacturing process. Depending on the part or process requirements, they can include general tensile tests, SCC testing, crack growth behavior, or fatigue testing. Furthermore, the composition and the dryness of the used powder need to be assessed.

5.2 Process stability testing (fixed and part-independent)

Process stability testing is one of the major aspects when focussing on industrializing the AM technology. Once the parameters of the process have been determined in step one, they are subject to be frozen. This starts with the treatment and test of the bulk material and includes standard operating procedures for operating the AM machines. Furthermore, each build job shall contain witness samples to test the overall process performance. These test specimens shall at least include mechanical tests for tensile strength and density but can as well be enhanced by tests to investigate the microstructure of the materials. These tests shall ensure to find out if changes in the process stability occur and give the opportunity to intervene. Figure 8 shows an example for several test specimen for the build platform of a bracket. In the future, inline process technologies may simplify the actions on process stability testing.

5.3 Technology readiness testing (TRT) (part-specific testing)

The technology readiness testing is completely based on the part requirements and is done on the basis of the actual part. This includes certain non-destructive tests as CT scans, dimensional tolerances, surface quality, and mechanical testing at qualification or acceptance loads. As tests like CT scans may come to their boundaries with very complex geometries, one has to consider the need and feasibility of these tests during the design phase. This phase is comparable with machine capability testing known from traditional manufacturing technologies.

For the RW-bracket quality management issues have already been considered during the part selection. Therefore, specific fundamental testing had been performed already for the possible material and therefore led to a more time- and cost-efficient design. In addition, as induced by the application, crack growth tests had been performed with regard to the fundamental testing aspects. This enabled a reliable redesign of the bracket. Furthermore, different test specimens (compare example of Fig. 8) had been defined to be built in every build job to be able to react to deviations in the process. In general, the designer needs to take quality control aspects into account when choosing a part and the according design based on the part requirements. If, e.g., a CT scan is demanded, the part design needs to be adapted accordingly. As the RW-Bracket is a very huge part, a CT scan of the overall part is only possible with a low resolution for geometry comparison as shown in Fig. 9. A fine-resolution scan with regard to internal material properties like pore size and distribution is only made from crucial areas with critical stress risings like the mounting points. One example is shown in Fig. 10, where a relative density of 99.63% is determined.

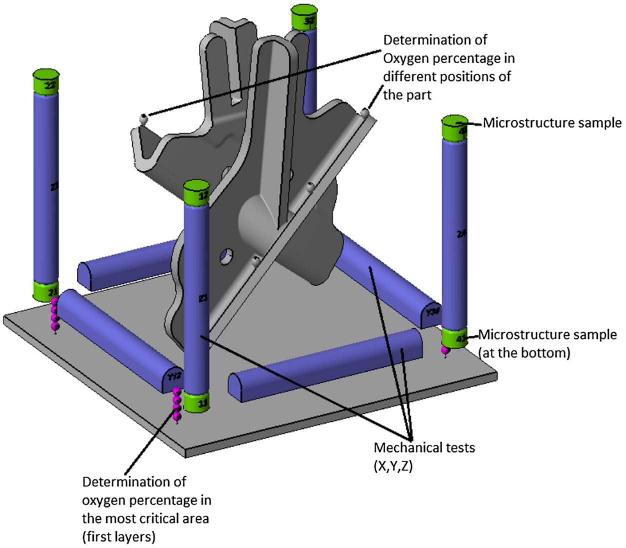


Fig. 8 Build platform containing several specimen for quality assurance. By courtesy of project “RepAIR”

In some branches, the documentation of test results is very important with respect to legal requirements. A very practical way to gather the results and therefore the evidence of legally required tests accessible is to use a database and reference markings directly produced on or under the parts’ surface as described in the next section ‘Marking.’ Furthermore, a continuous long-term improvement process is realizable by adding markings that are traceable during the product lifecycle.

6 Marking

Traceability of parts manufactured additively is one major requirement for a broad application of AM even in industries that are not focusing on products with critical functionality. Markings can be divided by their purpose and precision. For internal quality matters, product-markings like numbering, bar- or QR-codes known from traditional products are sufficient. Ensuring that each code is used only once, at least internally, this kind of marking supports quality documentation. Either relevant information like positioning and orientation within the building chamber can be encrypted in the marking directly or the more convenient way is to use the marking as a reference to the part-specific set in a database.

Thus, it becomes possible to trace back from a part’s marking to process data and quality assurance documentation stored in a database. The complexity of markings’ pattern is not depending on the complexity of data to be traceable when using it as a reference. Otherwise, when the pattern becomes more complex, more data need to be stored directly encrypted in the marking. Aiming at traceability over the whole product lifecycle, e.g., for long-term continuous improvement process or to avoid product liability in case of product piracy, marking has to be confidently unique and inimitable [10].

By the use of AM, both kinds of markings can be implemented in products without increasing production costs. Marking each part manually increases the effort during the

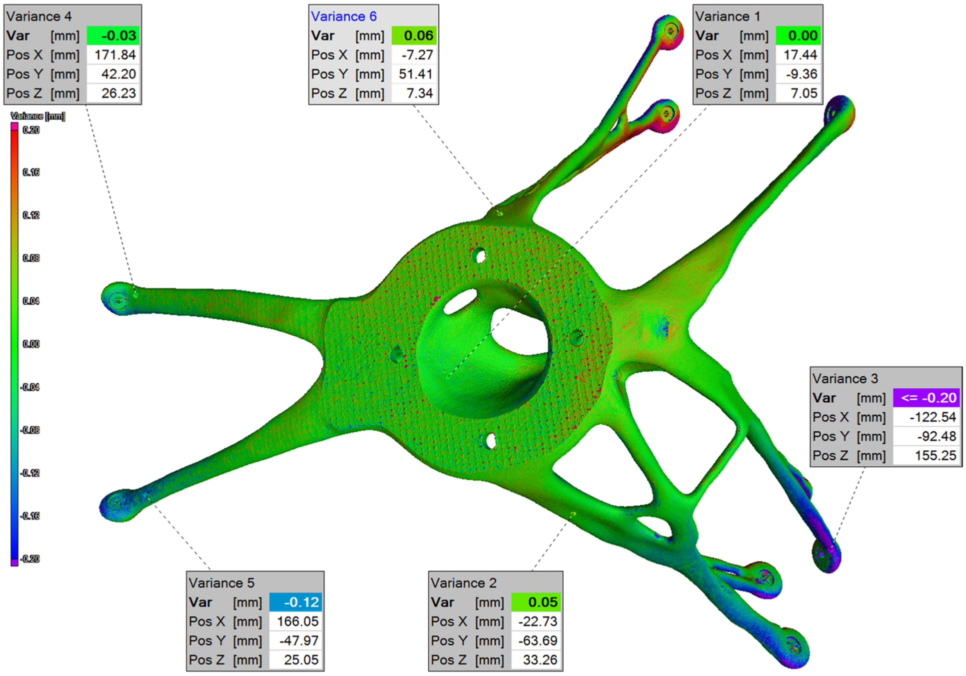


Fig. 9 Comparison of built RW-*Bracket* to nominal CAD from CT fast scan. By courtesy of GE Sensing and Inspection Technologies GmbH

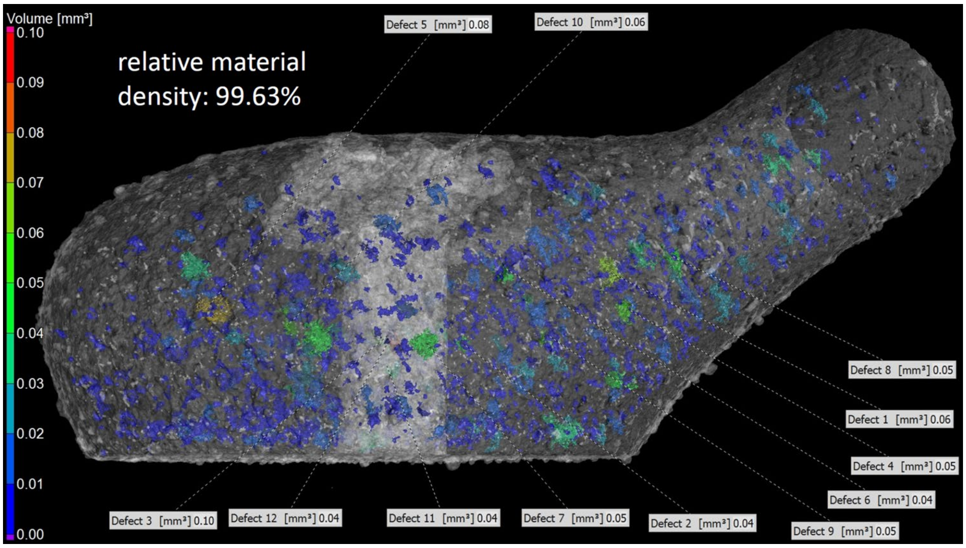
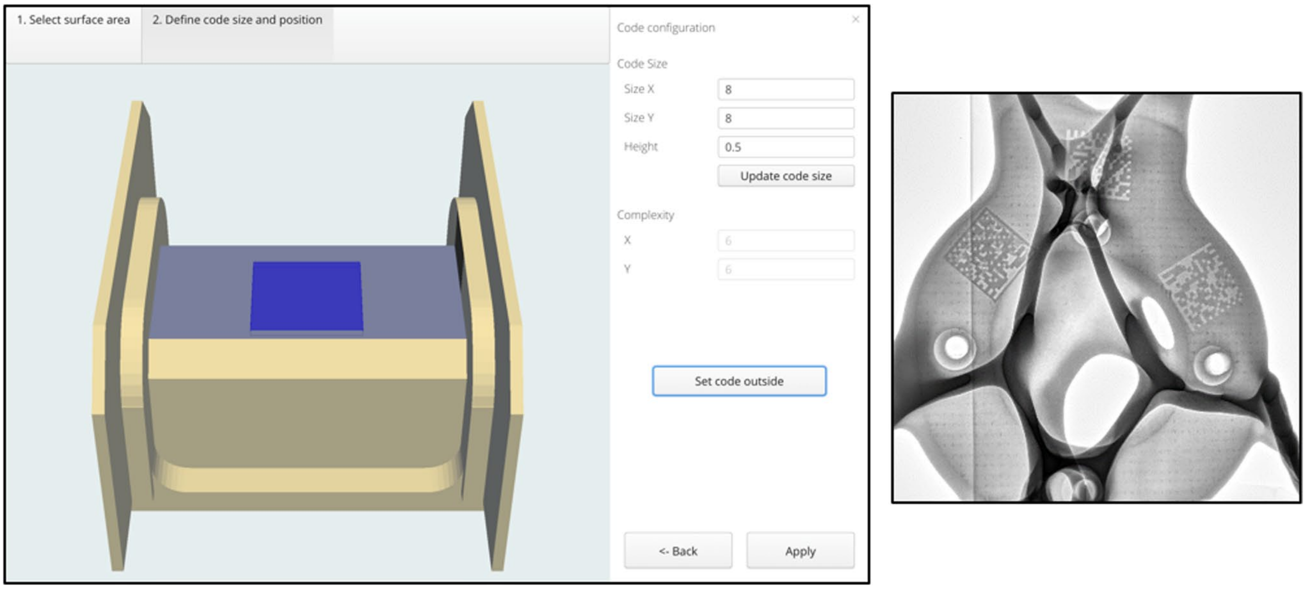


Fig. 10 High-resolution scan of Region of Interest (ROI) for density measurement. By courtesy of GE Sensing and Inspection Technologies GmbH. (Color figure online)

design phase enormously and cannot ensure the uniqueness of each marking not even for internal usage. Therefore, a software solution has been developed at Paderborn University aiming at the reduction of effort for implementing individual markings so that designers do not need to mark manually (see Fig. 11, left). Different options have been considered: On the one hand, the marking of a single part with a unique number or code for internal usage is possible. On the other hand, a batch marking for a couple of parts is possible for series production. This is based on a defined pattern and continuous or random but unique numbering or coding. For both options, a pattern for an authentication code can be added to ensure traceability over product lifecycle. Furthermore, users of this software can define and position the pattern in various dimensions nearly unrestricted in size to achieve most feasible compatibility with the part's design. As AM features the production of internal structures, a placement on or under the parts surface is possible as well (see Fig. 11, right). Thus, users can decide if the marking should be directly visible for customers or should be hidden at first glance.

Figure 12 shows one example for marking generated by the software solution based on the STL-file of the RW-Bracket.

As this kind of individualization does not increase production costs and the effort for integration of markings is


1. Select surface area
2. Define code size and position

Code configuration

Code Size
Size X: 8
Size Y: 8
Height: 0.5

Complexity
X: 6
Y: 6

Fig. 11 Screenshot of marking software for defining area of QR-Code (*left*) and CT scan of markings (*right*)

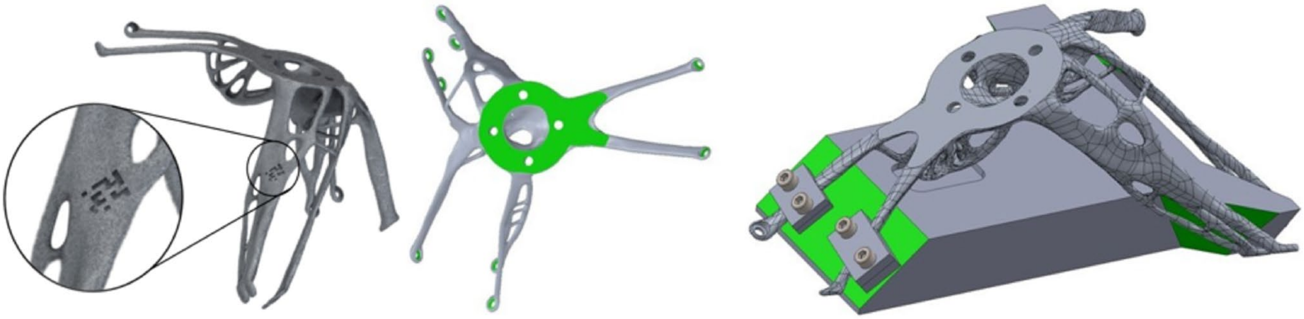


Fig. 12 *Left* generated marking visible on parts' surface; *middle* post-processing surfaces; *right* milling jig

minimized by software in particular for high batch production, product marking should be an obligatory process step.

7 Post-processing

Post-processing is a factor which is often underestimated while talking about AM. Post-processing costs can be a main part of the total part costs [3]. Therefore, the designer needs to think about post-processing aspects in the original design phase. These aspects include the removal of support, heat treatments, and adjustments of surface quality. If one can already foresee that a milling process will be necessary, milling jigs and clamping positions need to be considered. In cases where a high-dimensional accuracy is required, an offset of the surface is needed. The near-net shape geometries shall be avoided in these places as they can be a barrier for the traditional tools (e.g., drilling in a non-centric hole).

Part design with AM is always a trade-off between functional optimization, cost-efficient design, and manufacturability. For the RW-Bracket, the functional (lightweight) design was in the center of attention. Still only few surfaces needed post-processing and sophisticated milling jigs were directly considered during the design phase and produced with AM as well (Fig. 12). For less sophisticated applications, less weight—but higher manufacturing—and post-processing-optimized brackets may be economical and more interesting.

8 Economic evaluation

As true for all other manufacturing technologies, the designer has a high impact on the final part costs and therefore the economic success of an AM part. A change of the build direction, for example, can double the part price due to increased supports and decreased build speed (compare Fig. 7 right). Each of the above-mentioned steps has a high impact on the later part costs.

AM nowadays is still considered as an expensive process and therefore needs to justify its use against traditional manufacturing methods. An AM production with concurrent redesign and post-processing is only reasonable when the costs can compete with traditional manufacturing technologies, or if AM offers some major functional benefits that cannot be achieved in any other way. Therefore, one has to keep in mind that the comparison should not be limited to the production costs. A more holistic view is needed as AM generates benefits in different areas which have to be assessed and compared as well. Many aspects cannot be generalized and need to be evaluated based on the current part and its requirements [3]. The designer has to be aware of the different influence factors on the total costs his decisions affect [11]. Most of these are shown in Fig. 13.

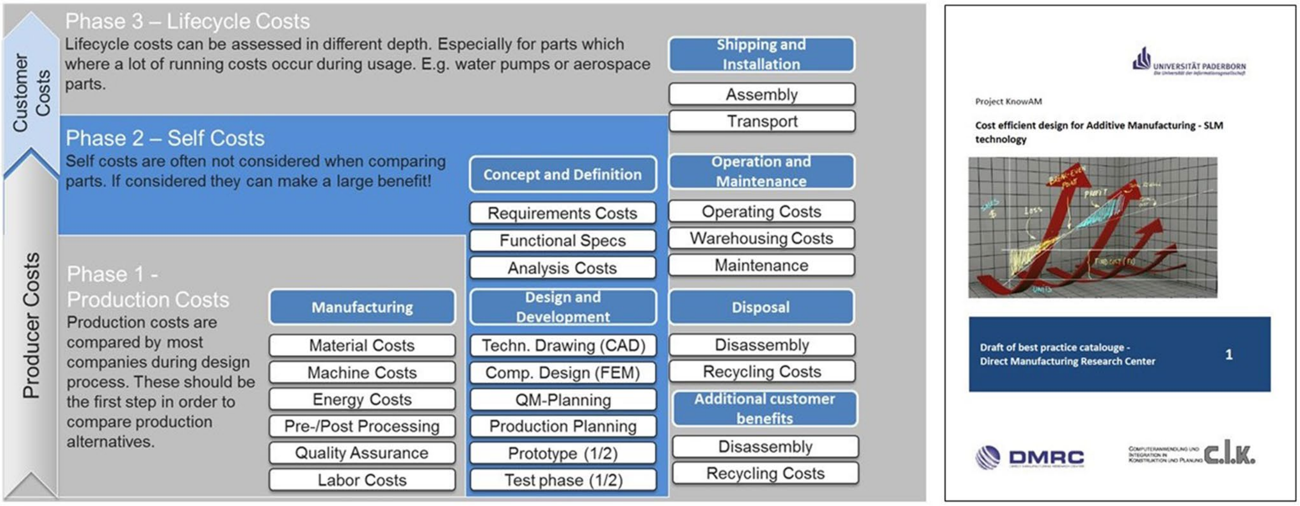
It describes a general approach for the justification of the AM part costs compared to traditional methods. It starts with the estimation of the production costs, which in case of the RW-Bracket have been estimated first during part selection. In a second phase, the self-costs of the product need to be considered. These include all costs occurring at the producer's side. If further justification for the use of AM is needed, the lifecycle costs need to be considered. These play a special role as AM enables the production of parts with special benefits (increased efficiency, less assembly, etc.) and can be a game change for supply chains and business models. A special costing tool has been developed to justify AM part costs against traditional ones [3].

In the case of the RW-bracket, the significant weight reduction was a reason enough for the justification of the AM production process as weight savings are a major benefit for space applications. While the pure production costs have been significantly lower compared to the traditional bracket, post-processing and quality costs had a major impact on the final part costs. In total, for the estimated production target, the use of AM technologies has proven to be cheaper for the considered part and therefore validated the results of the TOM matrix.

The documentation of best practices regarding cost-efficient part optimization (compare Fig. 13) is currently under development. The catalogue explains rules for cost-efficient design, gives real part examples, and indicates which rules have influences on which phases in the product development process as well as in the later lifecycle phases of the part. These best practices which shall be documented by all AM users may help inexperienced designers significantly in the product development process.

9 Supply chain aspects

For a holistic cost and benefit analysis, further aspects like supply chains and spare part availability may play an important role as well. Depending on the product type and the supply chain requirements, there are mainly two approaches that have to be considered. The lean approach is characterized by efficient processes and consequently by the elimination of waste, for example by a reduction of failures during both the manufacturing process and the overall order and shipping process. This also includes decreased shipping and wrapping. In general, it is aimed



Lifecycle costs can be assessed in different depth. Especially for parts which where a lot of running costs occur during usage. E.g. water pumps or aerospace parts.

Self costs are often not considered when comparing parts. If considered they can make a large benefit!

Production costs are compared by most companies during design process. These should be the first step in order to compare production alternatives.

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Fig. 13 *Left* approach for costing evaluation; *right* cost-efficient design catalogue to get to more efficient processes. This is most suitable for functional products with a predictable demand.

The other approach is the agile one. The main goal here is to reduce the lead time in order to offer a flexible production with the ability of a fast reconfiguration and a high availability to be able to react to a short-term, volatile demand. This is often the problem for innovative products so consequently the agile approach is applied in this case [12, 13].

AM combines the two approaches being a lean manufacturing technology and offering a high flexibility due to the fact that no shaping tools are required. Warehousing and shipping of finished and semi-finished products can be significantly reduced as only raw material needs to be stored. As it is able to produce even complex products within one manufacturing step, it can reduce the amount of parts that have to be transported. Only post-processing for reaching the final state has to be scheduled. This reduces the inventory and work in progress and thus reduces the capital lockup. Because AM does not require any tools, it does not need any set-up time which is an elementary aspect of a lean supply chain as the instant production leads to efficient processes.

For the application, it can be chosen between a centralized AM production and a distributed one. The nowadays high acquisition price for the manufacturing machines makes the centralized one currently more suitable [12]. Additionally, post-processing and finishing effort have to be considered so that further machinery needs to be available. The low build-up rates lead to longer manufacturing times so that a buffer in terms of low quantity inventory is usually required. The small number of suitable parts is not able to utilize the higher quantity of machines that is available for the distributed approach. But it still guarantees almost full workload for the few centralized ones. The distributed approach cuts down costs on shipping as the machines are directly located at the point of use. Therefore, the acquisition price has to be decreased and a higher quantity of suitable AM parts is required to increase the demand for the machines; a higher accuracy leads to less finishing so that less equipment is necessary for the post-processing of parts. The local production at the point of use significantly reduces the warehousing effort and lowers the logistic costs [12]. For the RW-Bracket, this implies an on-demand and just-in-time production at the point of assembly. The delivery time and costs can be reduced and the overall lead time can be shortened. This is especially important as the paper's sample part is one of the last parts that is developed within a satellite design process but one of the first ones that needs to be installed. Here, a fast, flexible, and local production is advantageous.

10 Summary and outlook

The paper has shown that product development for additive manufacturing nowadays is still a very complex but promising task. There are several process steps that have to be conducted and adapted to the specifics of additive manufacturing. While the best solution is to start with a completely new part design to fully exploit the AM potentials, this is often too difficult for the traditional technology-driven companies. Thus, parts have to be identified that suit the special characteristics of the new technology. The presented methodology to select part candidates is based on k.o. criteria to exclude a major share of all available parts. The remaining ones are checked further for technical feasibility and economic reasonability. Afterwards, the part usually has to be redesigned to increase the benefit of an AM production. On a system level, it is analyzed whether a function integration can be achieved and a topology optimization leads to the optimal material structure for the given design space and defined load cases. Benefits like weight reductions and increased part performance are the result. At this point, several parameters are defined that influence the costs and quality of the future product and carefully have to be balanced. In this process, AM-specific design rules and best practices for cost-efficient design have to be taken into account to guarantee the manufacturability and to decrease the post-processing effort and the costs.

For the production itself, the appropriate material and machine conditions have to be ensured. A quality management specification is the key to get to a stable and reliable production process. It assures the durability and qualification of parts, which often requires non-destructive testing of the produced parts. It has to be combined with the documentation of the results and embedded in a long-term improvement process to enhance product and process over time. This can be supported by permanently marking each part to be able to identify it during its complete lifetime. It simplifies the quality assurance as every part can be assigned to a production batch and the corresponding documentation of process parameters. AM can be used to mark parts without increasing the production costs. A software solution has been developed to automatically conduct this process step.

The production phase is followed by post-processing of the part. The costs to do so can be a main part of the total part costs and should not be disregarded. The required effort is primarily fixed in the design phase and also depends on the application. To still be competitive to conventional manufacturing technologies, a thorough economic evaluation has to be conducted beforehand. This does not only comprise the actual production and post-processing costs but also benefits in different areas. AM can significantly lower the lifecycle costs as well as facilitate supply chain benefits. In general, the designer has a considerable impact on the later part costs and needs to know the influence of factors on the total costs. This is why companies have to use a holistic approach while integrating and applying additive manufacturing into their product and technology range. They have to strive for a comprehensive procedure to successfully exploit all potential that AM offers [14].

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