Towards a sustainable and economic selection of part candidates for Additive Manufacturing

Christian Lindemann*, Ulrich Jahnke*, Thomas Reiher*, Rainer Koch*

*Direct Manufacturing Research Center (DMRC) and Chair of Computer Application and Integration in Design and Planning (C.I.K.), The University of Paderborn, Pohlweg 47-49, 33098 Paderborn, Germany

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Abstract

Additive manufacturing has a high potential for improving time and cost efficiency as well as functionality of products in many branches. Today potential users struggle with the integration of this technology in their businesses. The production costs of this technology often seem too high compared to traditionally manufactured parts and many users seem disappointed with the performance of the technology. One of the crucial points for bringing the technology to new users and new industries is the appropriate selection of feasible part candidates. A systematic selection of parts is crucial for the sustainable and successful use and integration of additive manufacturing into existing businesses. The selection needs to be based on technical, economical and strategic aspects. This paper presents a methodology to help end users to find appropriate part candidates, which are capable of bringing AM into their businesses. The concept furthermore includes approaches for redesigning current available parts and helps to estimate the economic implications of the use of the technology.

Introduction

Globalization, high competition and a shift towards buyers market are some of the main challenges today's manufacturing industry is facing. In this modern manufacturing environment effective and flexible manufacturing processes are the foundation of successful everyday business. The demand for innovative, individual and high-quality products increases steadily along with the reluctance to pay high prices for high quality.
Additionally the economic lifespan of these products decreases which leads to the necessity of shorter time-to-market and shorter development cycles. [SBA02] Furthermore the individualization of customer demands increases which leads to an increasing diversity of variants.
One possibility to encounter these developments may be delivered by the production technology additive manufacturing (AM). [LJM+12] AM is becoming more and more attention in recent year and is a fabrication process that is getting increasingly important e.g. for the aviation industry. Several companies and research projects devote themselves to the usage of this manufacturing process and how it can be used for aircraft components. On the one hand, the advantages such as lighter components and thus saving fuel, the reduced material waste and the fact that even complex structures can be built are often highlighted [Shel10]. On the other hand a lack of experience and also high quality expectations make it difficult for AM to be established in the aviation industry. To address this especially the aerospace industry is performing a tremendous amount of research regarding metal processes. Metal systems are becoming more popular, as the sales of metal AM systems increased 75.8% last year according to Wohlers. [Wohl14]

Economic aspects for successful use of AM technology

AM brings in a lot of potentials that needs to be considered for the assessment of an economical use of this technology. Compared to traditional manufacturing AM offers an enormous freedom of design while there is no direct connection between complexity and manufacturing costs. [HHD06] Therefore it is a very interesting technology for branches that can benefit from a design that is more function-orientated than based on the limitations of the manufacturing method. It becomes possible to reduce the complexity of assemblies by combining multiple parts or functionalities in just one part. [GRS10] This is just one opportunity to save costs in the production phase although the production process itself may be more expensive strongly depending on the part. Furthermore it offers more potentials in costs saving as there is no need for tooling and warehousing of production tools. Thus producing parts directly ready for usage can shorten the time-to-market as changes can be applied short-termed. On the other hand AM brings in new limitations so that certain design rules and AM specific aspects need to be considered already in the design phase. Therefore the fulfillment of requirements of a product like stresses and strains, surface quality and dimensional accuracy etc. have to be considered in the very early stages of product development. To consider all these aspects a deep knowledge is needed and it is crucial not to take only the production costs itself into account. Depending on the branch a detailed look at the whole lifecycle of a product is worthwhile like in the aerospace industry. [LJM+12] A load-adapted and optimized design is the basis for a lightweight design that saves costs during the utilization phase by reducing fuel consumption of planes over 30 years. [HPP10] Therefore to manufacture additively can be an economical decision even if the production costs itself seem high due to the production speed.

As current state of the technology comes still along with a lot of limitations AM is not capable and not useful to manufacture all imaginable parts. The building chambers of the manufacturing machines are very limited in size at this time and the possible surface quality and dimensional accuracy has to meet the parts requirements. [Gebh13] At least the economical effort for post processing to achieve the requirements has to be taken into account. In most cases it is not sufficient to look at a part that is manufactured traditionally and to think about a switch to AM. It is more probable to take all the interfaces and functionalities of a part into account and to think about a redesign and how an added value can be achieved considering all the potentials of AM. Thus to use AM with an economical benefit already today a methodology for the selection of most promising part candidates is very needed and the whole lifecycle of products with respect to the potentials of AM has to be taken into consideration.

Introducing a new technology into business

Introducing a new technology into a business is not always easy to manage. AM can be seen as a learning process nowadays more than a "Plug and Play" solution. Conrow says: "*Just like CNC machining, additive manufacturing is a powerful, sophisticated manufacturing resource that has to be understood on its own terms."* [www01] One cannot expect to have ready to build parts right from the beginning. E.g. the service provider "C&A Tool of Churubusco" started selling parts after gathering experience with only sample parts for more than a year before going into manufacturing. [www01]

When deciding for additive manufacturing one should consider these aspects as training and experience gathering is necessary before starting with the production. Beside the problems of the AM technology most companies see big advantages that additive manufacturing offers for their specific branches or businesses. But many of them are skeptic when and in what scope to approach this new technology.

Therefore many companies are approaching this technology on the basis of sample parts from their current product portfolio. Also many research projects, for example the European FP7 project RepAIR[1] and the European Space agency Project "New Structure" are undertaking the same approach in taking existing parts as an example and redesigning them.
One focus that both projects have in common is the fact that the manufactured parts shall be manufactured economically. That means that the parts manufactured with AM shall be cheaper during the product lifecycle for the manufacturing company.
The most important issues when establishing a new fabrication technology is whether it has economic benefits. To ensure this, the value stream and the supply chain of AM must be understood. [KOPT06, p. 7] Regarding e.g. aeronautic components, an optimized design can lead to a severe fuel reduction, especially considering the entire life cycle of an aircraft. These benefits, however, must first be examined and accepted by aircraft manufacturer before AM will replace established processes. So far, a holistic view regarding economic aspects of additive manufactured parts is still subject of research projects. [Brec11]

Importance and process of part selection for AM

Literature has proven that producing parts additively which were designed for traditional manufacturing processes do not suit the technology (e.g. [Zeah06]). Sometimes the restrictions of this technology don't even allow manufacturing a part with AM. When considering "Direct Manufacturing Design Rules" one can clearly see that also this technology has certain restrictions and not every kind of geometry can be manufactured [ZiAd13]. Nowadays many manufacturing companies are not familiar with AM, especially regarding its benefits and limitations. Over the past years the technology has experienced more and more media attention and many companies have become aware of the possibilities this technology may include for their own business. [LJM+13]

One can see that the selection of appropriate parts is crucial for the successful and economical beneficial use of additive manufacturing. Therefore a workshop concept (compare figure 1) for part selection and requirements gathering has been developed, based on [LJM+13], which should minimize the effort for the whole process and ensure a successful part redesign. It aims to help inexperienced users to identify feasible part candidates for AM production. Nevertheless it can be used for experienced users as well when skipping the first steps of the methodology. Assessing appropriate part candidates can be very time consuming as in many cases further information about a part is needed. Therefore this approach tries to reduce the effort for information collection before appropriate parts are selected. The methodology is divided into three main phases. In the following these three phases are described. The single steps in the phases and the different result can be found in figure1.

1. Information Phase → The AM technology is introduced to the AM interested party. The advantages of the technology are shown with the help of product examples, which internalize the advantages of the technology, and current technical application spectrums are presented. Especially technical limitations are explained in detail. The discussion of basic design rules for AM regarding to [ZiAd11][ZiAd13] enables the part designing entity to select proper parts for AM. At the end of this phase the end user shall be able to select a large number of sample parts without further help of AM experts and enter them into a trade-off methodology matrix (TOM). The main goal of

[1] *The RepAIR project receives funding from the European Union Seventh Framework Programme (FP7/2007-2013; Work Progamme 2013, Cooperation, Theme 7 Transport (incl. Aeronautics)) under grant agreement n°605779.*

the information phase is to give the participants a basic understanding of the technology. This is necessary because target group of the workshop are company representatives without knowledge about additive manufacturing. Moreover should the information phase enable the participants to start the internal part screening. This phase can be skipped for more experienced users.

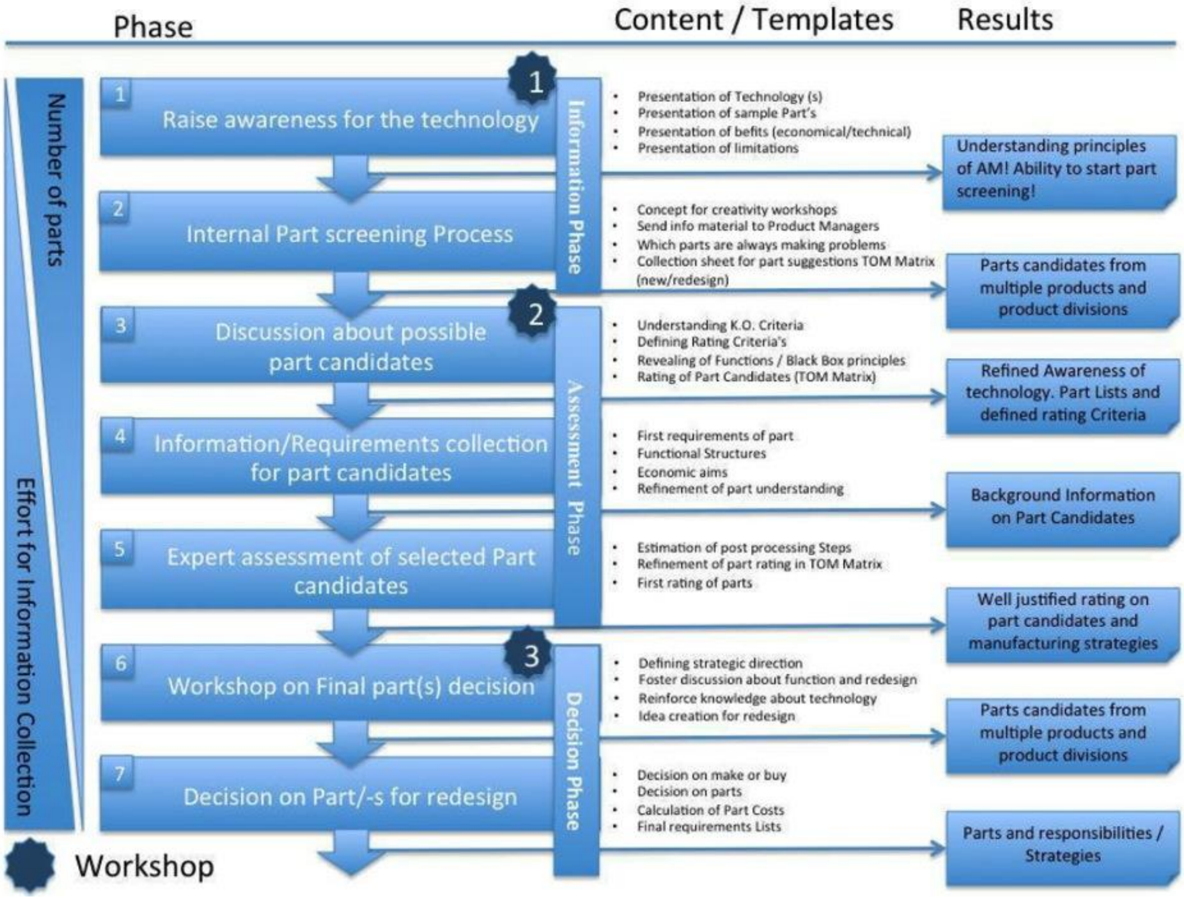

Figure 1: Methodology for part selection

2. Assessment Phase → During this phase the number of collected parts shall be narrowed down in order to reduce the effort of information collection. This screening is concluded by applying a trade-off methodology matrix (TOM). The first segment of this matrix can adapted to the special needs of an industry (e.g. space parts). The parts will be ranked according to assessments of AM experts and part owners. The result of the matrix's assessment presents a first choice of suitable parts for AM.

3. Decision Phase → The decision phase aims at finding the part(s) that represent the biggest benefit for specific AM adapted redesign. The end user needs higher effort on collecting and documenting the part requirements, this is achieved by completing the "InformationForms" (compare section "Methodology for redesign of parts and the gathering of requirements"). The more detailed information enables, also on basis of the Trade-off methodology matrix, to draw a well-justified selection of the part to choose for a promising redesign regarding AM. This phase incorporates economic aspects of part manufacturing.

Trade-off Methodology Matrix

The Trade-off Methodology (TOM) matrix is one of the key aspects of the part selection process. The purpose of the TOM matrix (compare figure 2) is a screening of parts and whether the additive manufacturing of those parts enables benefits. In the top section of the matrix the individual parts for consideration are described. Typical used information are a brief description of the function, typical production quantities, production costs, dimensions, the mass of the part as well as the currently used material. Furthermore a first estimation of how many parts can be placed on an AM Building platform is calculated based on the bounding box dimensions of the part. The description is completed with a picture of the part candidate. All these are basic information that can be used for the part assessment and a rough economical analysis later on.

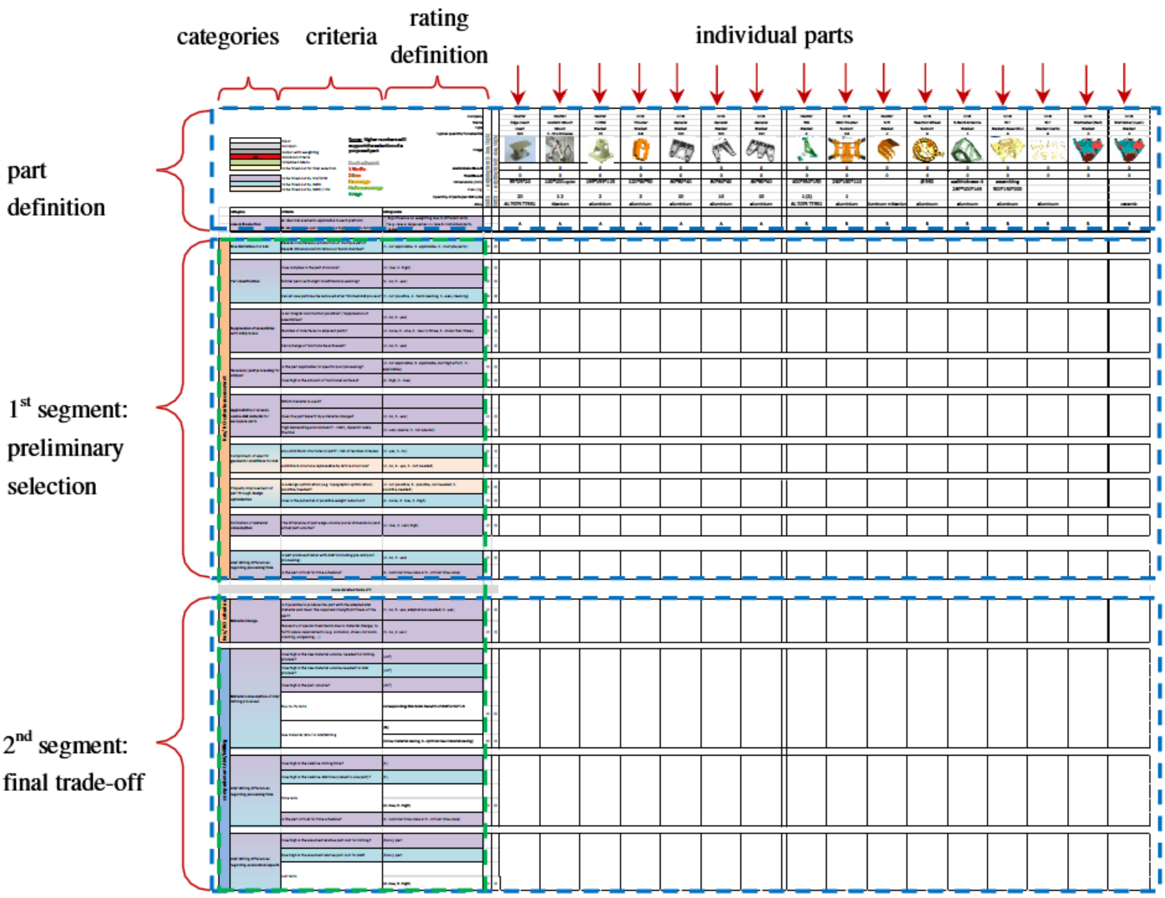

Figure 2: Trade-off Methodology Matrix (TOM)

The first section of the TOM Matrix is supposed to be filled at the beginning of the assessment phase. Criteria, definitions and ratings can be defined according to different branches and industries or the different strategies of the companies. Every section is structured into different main categories that include several sub criteria. These sub criteria can be rated similar as in 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 criteria, one can see that this aspect is more important for the aerospace industry or race car applications then for medical components.

This section will discuss the different categories and criteria of the first segment in the TOM Matrix based on examples from the space sector aiming at the use of metal materials.

Size limitations: The build chamber size of AM machines significantly limits the different fields of application. Common building chamber sizes are 250x250x300 mm e.g. for metal processes. Larger machines do exist and can be taken into account as well like the SLM 500 HL with a maximum build chamber size of 500x280x325 mm [Wohl14]. Nevertheless the availability of manufacturing equipment in house or at the targeted service providers needs to be taken into account.

Part classification: This category aims at defining the part in regards to complexity. Therefore three sub criteria were defined. The first question aims at the complexity of the manufacturing of the considered part. Complexity of the part hereby is mainly defined on how complex the part is to manufacture. Parts with a high buy to fly ratio for example are usually very complex to manufacture. Complexity can be seen as a benefit for the use of AM [Geb13]. The second criteria rate how many similar parts are available in a company. Does this part represent a typical problem in a company? Redesigning a part for AM which might be slightly adapted und used for other products will be more economical and more beneficial for a company.

Suppression of assemblies: One of the many advantages of the AM technology is the possibility of functional integration into single piece assemblies [GRS10]. Therefore this category is subdivided in criteria for the specifications of number of external interfaces, the options of suppression of assemblies and the merge of part functions. If parts are assembled to other adjacent parts due to milling constraints, a suppression of assemblies can be possible and achievable with AM. Many interfaces may lead to function integration or an integral design. Space parts may benefit from integral design due to the significant reduction of required parts and a reduction of assembly time. AM could enable the function integration such as integrated heat insulation, a high flexibility or integrated joints as well.

category	**criteria**
Suppression of assemblies with AM process	Is an integral design possible? / Suppression of assemblies?
	Number of interfaces to adjacent parts?
	Can a merge of functions be achieved?

Figure 3: Category "Suppression of assemblies"

Necessary post processing for AM part: Additive manufactured parts can only achieve certain surface qualities and therefore often need post processing for different reasons [GRS10]. As this fact is one disadvantage of the technology some post processing steps like heat treatments or surface finishing are necessary. This category is subdivided in the part applicability for post processing and asks the amount of functional surfaces. There might be a need in post processing as well if many support structures are used.

Applicability of already used AM material for aerospace parts: This category shall help to find appropriate material. Nowadays not all information are available for all materials. Therefore one should focus on materials that are already used in the industry or for that public material data is available. This may be tests like fatigue resistance (compere e.g. [LTR+13]) for TiAl6V4 that are necessary but would have to be performed costly for other materials. Therefore the sub-criteria in this section ask for current materials and the possibility of a material change. Furthermore the materials environment and the different load cases are considered here in order to be able to identify possible materials for a redesign if a material change seems to be necessary or beneficiary.

Compliment of specific geometric conditions for AM: This category aims on making sure that the part candidates can be manufactured with the AM technology. As stated out before the use of Design Rules is important to achieve the desired results with the AM technology. Therefore some questions have been derived from the Direct Manufacturing Design Rules developed at the DMRC (compare to [ZA11][ZA13]). Aspects considered are large solid block structures in a part as these structures are hardly to be manufactured because of the risk of residual stresses. If this applies the manufacturability could be achieved by the use of lattice structures.

Property improvement of part by design optimization: This category aims to identify the optimization potential of a part by the use of enhanced design possibilities by AM. These rating proposals and definitions exist for all the other categories as well in order to achieve repeatable results and to help the end users with the rating.

category	**criteria**	**A**	**B**
Property improvement of part through **design optimization**	Is a design optimization (e.g. topographic optimization) possible / needed?	3	3
	How is the potential of possible weight reduction?	3	3

	design optimization	**weight reduction**
	design optimization due to AM manufacturing process (e. g. topographic optimization)	based on past experience of AM experts, a first, rough estimation of the possible weight reduction / safety factors need to be considered
1	-	-
2	part already optimal designed for loads	none
3	design optimization possible but not needed, because the effort for design change does not justify the possible gain / e.g. for Case A parts	<10 % weight reduction compared to original design
4	potential for design optimization possible and also required	11-20 % weight reduction compared to original design
5	big potential for design optimization possible and strongly required / e.g. mainly for Case B parts	>20 % weight reduction compared to original design

Figure 4: Category and criteria for property improvement

Material consumption: AM can significantly help to reduce scrap as the only wasted material is the material of support structures in metal processes. With an intelligent product design even these can be mainly avoided. Therefore the criteria are the difference of the part edge volume (outer dimensions/bounding box) and the actual part volume. This is similar to the term of "buy to fly ratio" which is frequently used in the aerospace sector.

Processing time: The processing time criterion aims on estimating processing times regarding the traditional manufacturing. Long traditional manufacturing times are in favor for the use of the AM technology. The second criterion is the question if the part maybe time critical for the entire product development process. These are parts, which mainly depend on the design of other parts, which needs to be finished before. These parts are often in the need of fast development and the adaption to small or high complex building spaces.

After the finalization of the rankings for the first parts of the first segment, which can mainly be filled by non AM experts, a certain rating for each part will appear in the TOM matrix. The results of the highest ranked parts will be discussed with AM experts and the total List will be narrowed down to a maximum of 3 different part candidates. Only these part candidates will be regarded in the second section of the matrix. The commitment on these three part candidates will be the end of the assessment phase. AM experts will mainly perform the second section. The second section consists of the following categories.

<u>Material change:</u> In this category the part is rated regarding the possibilities to produce the part with the adapted AM material and meet the required strength/stiffness of the part. Furthermore an estimation of necessary post processing steps will be rated. In the space case this means the necessity of special treatments due to material change, to fulfil space requirements (e.g. corrosion, stress corrosion cracking, outgassing, ...).

<u>Material consumption:</u> In this category the needed raw material volume for AM and milling as well as the part volume have to be entered. This results in the calculation of the buy-to-fly ratio and a ration for raw material. A high buy-to-fly ratio is a strong point for AM because with AM the buy- to-fly ratio can be reduced drastically as only little support material is needed for manufacturing that is not included in the end part. This can lead to massive cost reduction. An estimation for the need for the use and the amount of the support material is performed.

<u>Processing time:</u> In this category the time for milling and AM process has to be estimated. This includes the lead, process and post processing time. For AM the process time needs to be scaled down to one piece. These values will then be compared and result in scores for the parts.

<u>Economic Aspects:</u> Here the category assumed relative part costs for AM and milling are compared. This results in the calculation of a cost ratio.

After the finalization of the second segment a rating for the last three part candidates will appear. Special information collection sheets (described in the next segment) for part requirements have to be filled out by the part owners and sent to the AM experts. This will help the AM experts in a final part assessment and with the later redesign of the parts. The final decision for a part redesign will be taken in a last discussion with the AM experts and the part owners before the redesign process begins.

Methodology for redesign of parts and the gathering of requirements

After the part selection has been performed successful one has to start with the redesign. Therefore this methodology proposes to use a black box principle as seen in figure 6. The considered part or system is broken down to its main functions in order to enhance the possible design freedom. This shall help to increase the opportunity to make use of the AM advantages. In many cases the part candidate is only a small part of the entire system and not a whole product. Therefore the interplay between the different sub systems of the whole product needs to be considered. This consideration can help to make use of the functional integration of parts.

In order to define interfaces and perform a redesign, which tries to incorporate several parts into a one-piece assembly, all systems and parts are broken down with the black box principles. With the help of the “true function” of single parts and the whole system, the interfaces between the different parts shall be kept to a minimum. Interfaces shall be designed when possible with low requirements on accuracy as this will raise the need for post processing of the additive manufactured components.

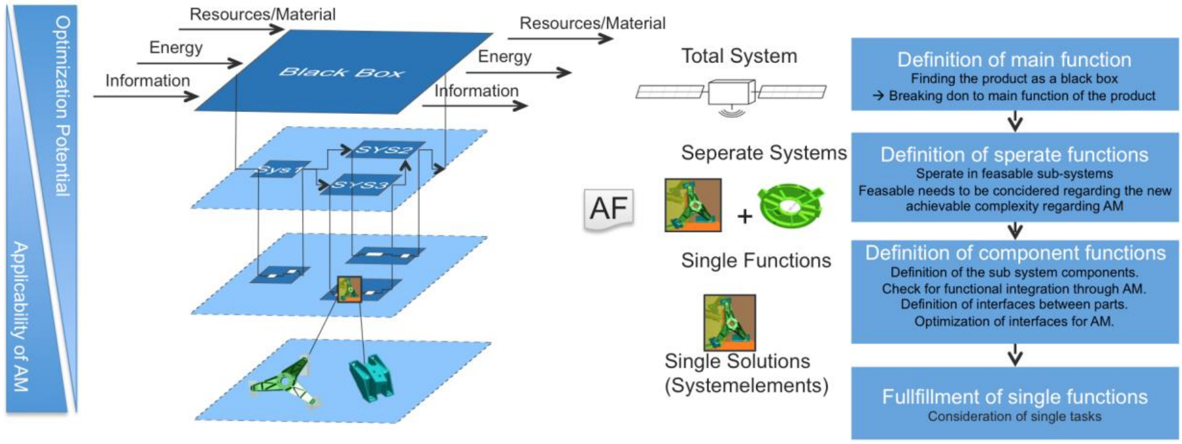

Figure 5: Principle of Black Box Systems for redesigning AM Parts e.g. satellite structures (based on [PaBe07])

The part foreseen for a redesign is defined as the “system” or “key part” (KP) (compare figure 6). Parts, which interact with the key part and parts, which may be integrated in the design process, are defined as “system context” or “adjacent part” (AP). The rest of the system is not relevant for the redesign process and therefore called irrelevant environment. In order to perform a redesign, which suits the whole black box principle, the different part requirements are needed. Therefore certain information collection sheets have been developed for the key parts and for the adjacent parts.

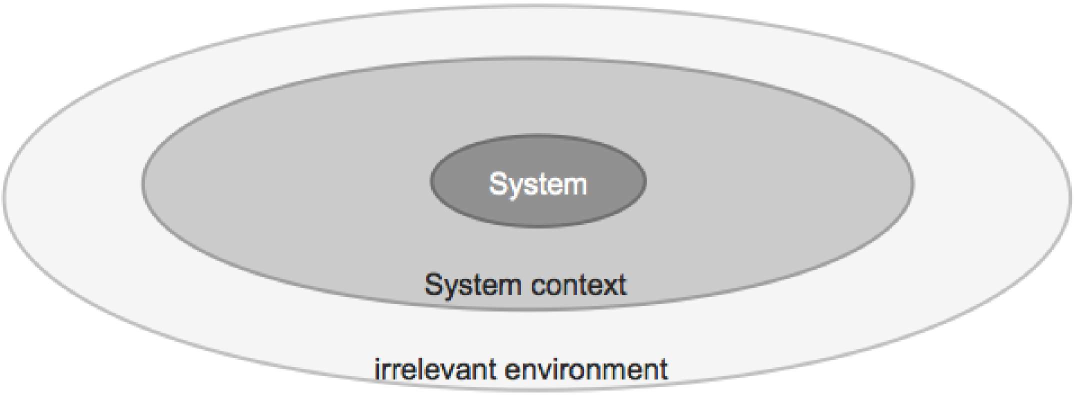

Figure 6: Defining systems and gathering requirements (according to [PoRu11])

The used template for a key part is shown in 7. The template does not only ask for the requirements and properties of a single part but for the function of the complete assembly by use of different related forms for the key part, adjacent parts and the assembly itself. Different information about purpose, environment, and connection to other parts are used to create a comprehensive picture of the considered part and its assembly. The gathered information ensures that the person preforming a redesign has all necessary information in order to make use of the AM advantages during the design process.

This example shall be demonstrated with the help of a Satellite system. The key part has been defined using the example of a structural satellite part. The considered part is a Reaction-

Wheel-Bracket (RW-Bracket), which is mounted to the reaction wheel. This flywheel mass is used four times per satellite to control the orientation of a satellite in space.
Thinking in these levels offers the opportunity of new solutions. For example further improvements may be achieved by integrating the bottommost parts, RW-bracket and RW-bracket connectors into one single piece assembly. For conventional manufacturing this is not possible due to manufacturing and economic restriction restrictions.

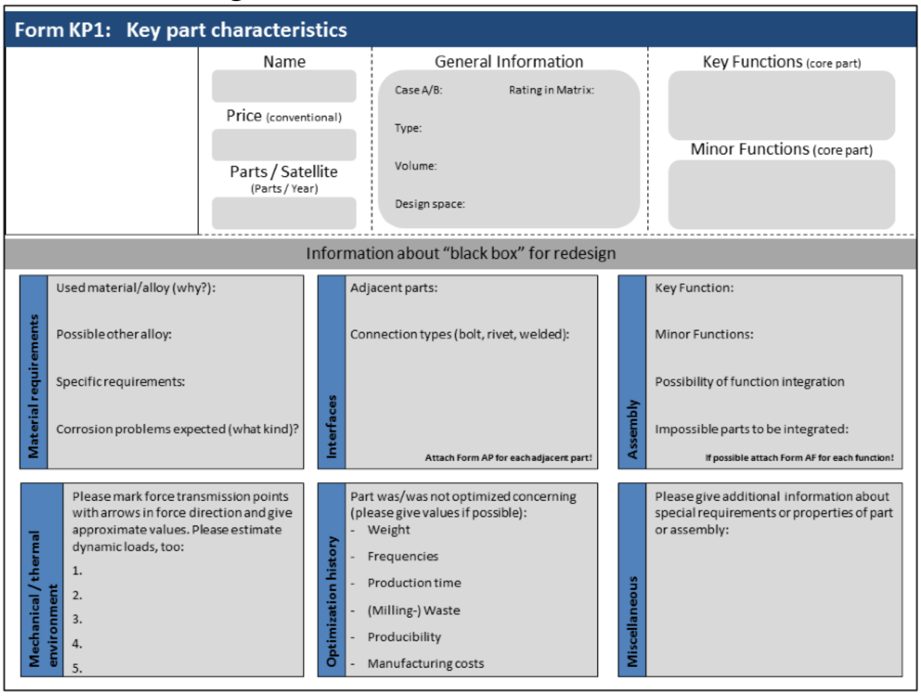
Form KP1: Key part characteristics
Name
Price (conventional)
Parts / Satellite (Parts / Year)
General Information
Case A/B:
Rating in Matrix:
Type:
Volume:
Design space:
Key Functions (core part)
Minor Functions (core part)
Information about "black box" for redesign
Material requirements
Used material/alloy (why?):
Possible other alloy:
Specific requirements:
Corrosion problems expected (what kind)?
Interfaces
Adjacent parts:
Connection types (bolt, rivet, welded):
Attach Form AP for each adjacent part!
Assembly
Key Function:
Minor Functions:
Possibility of function integration
Impossible parts to be integrated:
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:
1.
2.
3.
4.
5.
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:

Figure 7: Template for key parts

Once the requirements are selected there are several different approaches to redesign an AM part. For structural parts e.g. a topology optimization (TO) is one possibility to gather optimal structures for a lightweight and thus economic design. In TO the maximum usable measurements of the part in order with no interfering with other parts is defined as the design space. By the use of Finite Element Analysis (FEA) methods the material, which is not carrying loads, is reduced in an iterative process. As a result the material is reduced down to a minimum regarding the assumed load cases and by this an optimal lightweight design is supposed to be achieved.
In general this design could not be manufactured with traditional methods due to undercuts and complex shape of struts, which may appear in the design. For achieving feasible results for conventional machining, the programs offer different manufacturing constraints. As an example it is possible to optimize the shape of the part so that the accessibility for a cutter head is given from only one or two sides. These constraints lead to a less-optimal design from a mechanical point of view. This is shown in figure eight. The red version shows the milling design while the green version shows the same connection able to withstand the same loads with less material. Accessibility for the cutter and a clarified design easy to mill is needed. Thus a big, wide design is chosen while the TO design is able to lead the forces very direct on the shortest way. This results in a significant weight reduction of the TO parts, compared to the milling optimized parts.

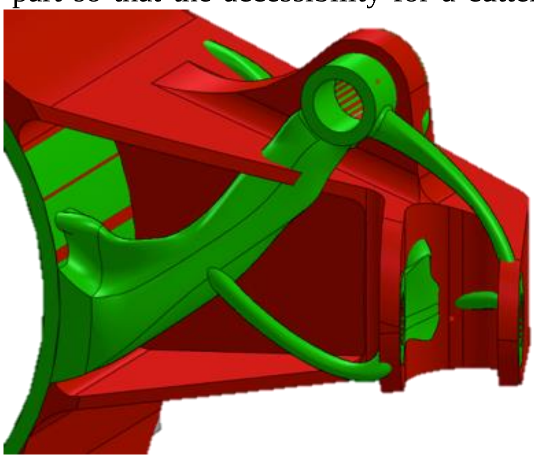
Figure 8: Differences in milling- and AM-design

For AM the manufacturing constraints of the TO algorithm are expendable and there is no need for hampering the optimization algorithm in finding the most lightweight design.
Though there are some limitations in AM one has to keep in mind. As an example this might be the maximum material conglomeration due to possible internal stresses as in wall thicknesses. These information is have been published in specific AM-design rules. [ZA11], [ZA13] By this the algorithm has to be forced to select small struts and appropriate thin plates instead of clear defined solid material. This counteracts most of the conventional optimization aims. To gain best designs there is a need for special algorithm extensions calculating these structures.

The AM design freedom can be used by renouncing the existing manufacturing constraints, to enable the optimization algorithm to position the material in the best way. This leads to very complex and optimal shapes with less material for withstanding the loads. For manufacturing these shapes need to be redesigned in a CAD-tool. Four different design approaches have been tested. They shall be demonstrated with the help of the following part: An upright of a Formula Student racing car as this is very similar to aerospace parts due to its high buy-to-fly ratio. This part is used in the suspension to connect the cars whisbones to the wheels. Similar to structural parts of spacecrafts, aircrafts and many other products where lightweight design is desired, this sample part is loaded with different forces in various loadcases and only small displacements are allowed. By this a high complex design with bionical struts and complex shapes appears to achieve best weight reduction with respect to the constraints.

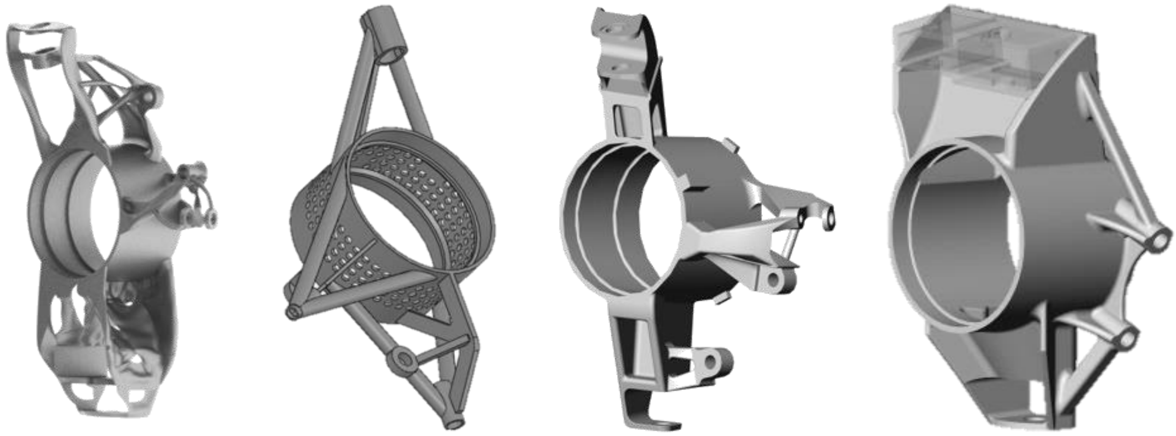

Figure 9: Overview of different approaches for designing an optimized structural AM-part

The following design approaches have been tested (figure 8 from left to right):

1. CAD remodeling of TO results:
   Freeform surfaces are used to reproduce the calculated shapes as exact as possible.
   This leads to a high complex and a very lightweight design. A big disadvantage is the very high amount of work due to modeling the complex structures with common CAD tools and features. The data quality is not sufficient for preprocessing due to not connected surfaces resulting in non-detection of volumes.

2. Use of design rules without TO:
   The upright was redesigned with a wire frame model and an FEA analysis without TO but with regard to the design rules developed at DMRC [ZiAd14]. This leads to design suitable for AM production in case of e.g. wall thicknesses and support structures. The design is not optimal with regards to topology optimization. The result is highly dependent on the used engineering sense and the experience of the designer. Data quality is very good because of the possibility to use standard CAD features.

3. Use of TO and standard CAD features:
   The TO results are used to create a design set up by standard CAD features like linear extrusions. This leads to good data quality but non-optimal design because some high complex shapes are not existing but clearly defined volumes. Due to disuse of design rules the manufacturability is not optimal. E.g. some parts of the support structure may not removable. The part is not optimized regarding the reduction of needed support structures.

4. Use of TO, standard CAD features and design rules:
   As in approach No. 3 the TO results are reproduced using standard CAD features but with regard to the Direct Manufacturing Design Rules. This leads to non TO-optimal results too, as some complex shapes cannot be used in the design. Nevertheless the manufacturability for AM is optimal due to the reduction of support structures and optimal geometries preventing deviations in tolerances due to inner tensions.

The different approaches show following benefits of designing structural components for AM:

- Already highly optimized parts can benefit of AM by further weight reductions.
  First approaches with the upright led to weight reduction of 40% from 515g to 305g. [LJM+13]
- Weight and costs can be saved as the first approach led to a cost reduction of 60% mainly because of material costs. [LJM+13]
- AM offers new design elements like "lattice structures" and by this helps to find optimal designs
- Approach three allows better designs while using AM without leaving the "comfort zone" of experienced engineers
- New design elements and staying in "comfort zone" of traditional manufacturing is not compatible to each other!

Depending on the needed requirements and on the AM experience of the designers all of these four design concepts have strengths and weaknesses. The designer needs to decide for one of these approaches based on the actual needs of the parts. In general the use of the Direct Manufacturing design rules has proven to simplify the production with common AM production systems. The recommendation by the authors is the use of alternative four if AM and TO knowledge is spread with the designers. Furthermore there are drawbacks hampering the use of TO for AM based on different problems:

- The direct use of TO results is not possible due to unusable surfaces and possibility of interrupted struts
- No consideration of AM design rules in TO
- Standard CAD tools hamper with the design of sufficiently complex shapes
  ➔ Linear extrusions do not match the complex shapes.
  ➔ Freeform surfaces produce data with bad quality

The shown drawbacks for an efficient redesign process to use TO for AM can be encountered by one of the following suggestions:

- Development of new CAD features with more easier freeform surface processing
- Better TO algorithms with suitable manufacturing constraints for AM

Applying product protection means to Products

Using the methodology described above can help to identify suitable part candidates to prevent product piracy by the use of additive manufacturing as well. Therefore different criteria need to be considered focusing more on the specific application of preventing product piracy that will be described in the following. In the project "prevention of product piracy" within the technology network "intelligent technical systems Ostwestfalen Lippe" (it's OWL) this specific view on the potential economical impacts of additive manufacturing is analyzed. Consequences of product piracy have been shown in the latest study of the German Engineering Federation (VDMA). 337 companies have been questioned, more than 50% larger than 250 employees and more than 25% larger than 1000 employees. 71% of these companies are affected by product piracy with a total economical damage of 7,9 billion EUR by a total turnover of 205,8 billion EUR. Their losses in sales of original product equal about 38.000 employments. As the study shows that in most cases (71%) the acquisition of data needed for imitating the original products has been performed by reverse engineering (industrial spying: 15%), Additive Manufacturing may help to complicate this kind of data gathering. [VDMA14]

The reverse engineering process is divided in eight phases according to the literature: Preparation, prescreening, disassembly, establishment of functionality, performance benchmark, material determination, extraction of geometry, identification of manufacturing method and data verification. [Guil11][Wang11] Especially the phases in the middle of the whole process can be impeded by technological measures that become possible by the use of additive manufacturing. As mentioned above the freedom of design, the possible integration of functions and the economical individualization of products are potentials of additive manufacturing. The potentials will be no more discussed as a lot of protective measures like the increase of geometric complexity with internal structures, black box design etc. become applicable on roughly all levels of intervention against product piracy. [JLM+13] The most crucial point is to identify the most promising part candidate to be protected. In addition the trade-off methodology and the according decision matrix further and/or different criteria become more important. Focusing on the main aim of protection it is essential to identify the part that is most crucial for the functionality of a system / assembled product. Therefore each part of a system has to be analyzed and its importance for the functionality of the system or a functional subsystem has to be assessed. Once the most important part has been identified and has been assessed as producible additively during the trade-off methodology the selection of a suitable measure has to follow. This selection strongly depends on the chosen part and its requirements, geometry and possibilities for a redesign. The more the measure complicated a certain phase of the reverse engineering process the higher the protection will be.

An example for product protection due to the use of additive manufacturing is shown in Figure . A manufacturer of water pumps faced a lot of imitations on the market and thought about counteracting measures. As described above the starting point was the identification of the most crucial part in this product needed to fulfill the functionality. The wheel shown in the figure has been selected as it is necessary to generate an air-water-mixture that is the main function of the pump. The part shown on the left was the original and often and very easily copied part. The measure that has been chosen was to increase the complexity to make the reverse engineering process more complicated. Therefore the part has been redesigned within the consortium of the Direct Manufacturing Research Center (DMRC[2]).

[2] *The DMRC is a research institute combining academia and industrial partners. The main aim is the development of a robust and repeatable direct manufacturing process. Source: www.dmrc.de*

Source: Author, ATI Aquaristik, [GGL12, Page 60]

Figure 10: Example for protection against product piracy by additive manufacturing

The whole pump became five times more efficient because of this new design and its enlarged surface. This new design is just producible additively with a very deep knowledge needed to set up all the machine parameters to achieve the required stiffness and quality. The level of protection is based exactly on this knowledge needed for the manufacturing process. Therefore the use of additive manufacturing brings a protection against product piracy as well as an added value in terms of an increased efficiency of this product based on the well-selected crucial part.

Summary and outlook

This paper has stated out the importance of an appropriate part selection for additive manufacturing. The developed methodology is easily adaptable to the knowledge of the user and the special needs of different industries and branches. The methodology has proven applicability in several research[3] and industry projects in aerospace applications. Independent part selections from experts analyzed within a research project had a large overlap with the results of the TOM matrix in different trials.
It allows companies with only basic AM knowledge to start a part screening for applicable AM candidates in their own company with a reasonable effort. These part candidates can then be discussed with AM experts in order to find the right candidates, which allow companies an economical use of the AM technology. The methodology allows the application of measures against product piracy if needed. The included cost calculation module based on [LJM+12] and [LJM+13] allows a first estimation of production cost in a very early design phase without transforming CAD models into STL files and without buying expensive software tools.
The black box principle in the redesign process helps to identify the main functions of the products targeted and the relevant environment, so one can benefit from the various advantages and the design freedom that AM hast to offer. The TOM Matrix and the part information forms help to ask the right questions and to reduce the effort for requirements collection. Focusing on parts suitable for AM identified with the help of the TOM also helps saving money as no effort is spent on parts which are not suitable or not promising for the use of additive manufacturing.
By different redesign methods either the benefits of AM with regard to lightweight design or the manufacturability stand in the focus. New CAD-features or topology optimization constraints have to be developed to enable an efficient redesign of structural parts with use of

[3] *E.g. "RepAir - Future RepAIR and Maintenance for Aerospace industry" as well as in the Project "NewStructure: Direct Manufacturing of Structure Elements for the next generation Platform"*

AM. In general some key aspects for cost efficient AM production could be derived from the experiences made during several redesign approaches.

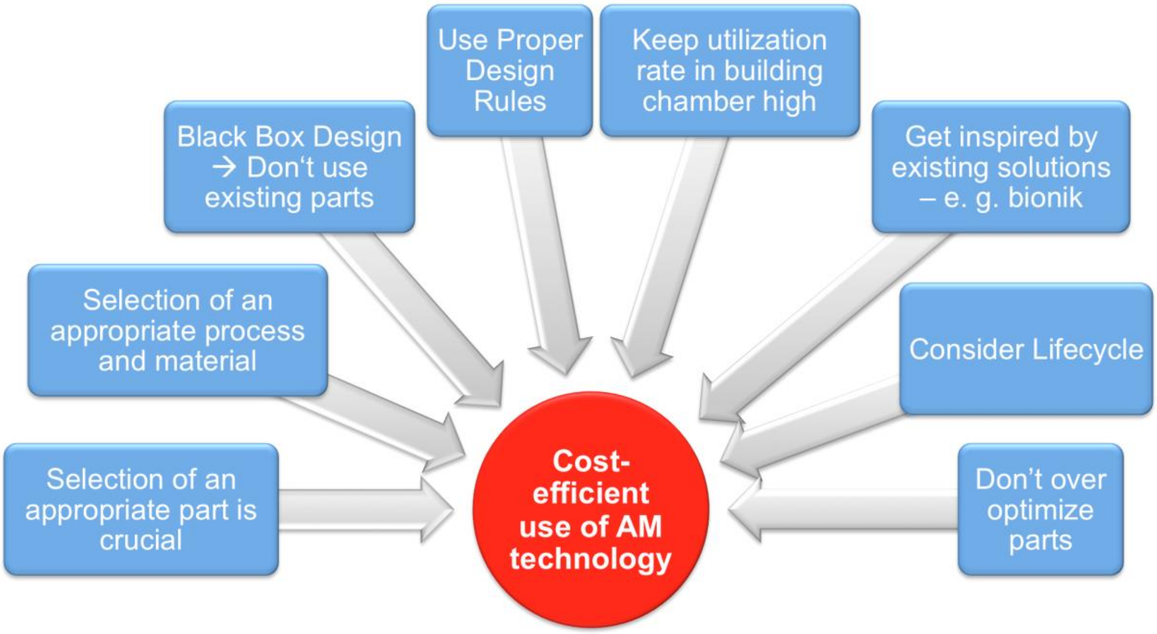

Figure 11: Key Factors for successful use of AM technology

During further use of the part selection methodology the different templates, which were developed, will be refined. While using the methodology all the gathered data can be stored and lead to a large part database showing different steps of development in redesigning AM parts. Furthermore the achieved benefits and problems can be stored and lead to interesting case studies or further input for product examples in the information phase. All parts will be investigated in particular for their economical feasibility. Successful redesign case studies will help to encourage further companies to get in touch with the AM technology. In the future the economic section will be enhanced by the lifecycle costing model of [LJM+13] in order to achieve more better economic justification for the use of AM parts.

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