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Cost Efficient Design and Planning for Additive Manufacturing Technologies

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Abstract

Additive manufacturing offers advantages for the production of a final product. Nowadays still many companies have not integrated this new technology into their product development processes (PDP). This paper will discuss additive manufacturing with regards to the current available PDP's while setting a focus on the economic aspects of the integration. Based on a sample part several tools will be discusses which may be uses in the different phases of product development. These tools aim on the simplification of integrating additive manufacturing technologies into existing PDP's. Included are methods for early and accurate cost estimation as well as product selection processes, best practice templates for creating knowledge and process awareness.

Introduction

Additive manufacturing technologies are more and more in the focus of the industry. Expectations towards the technology are growing permanently as people also speak about a "disruptive technology" [Cl13] or about the "next industrial revolution" [Eco12]. More and more companies try to get in touch wit layer based manufacturing technologies. Still, additive manufacturing technologies have not yet made their way to become a "direct manufacturing" production technology for the use of final products. So far AM-technologies are still mainly applied in the prototyping sector even if the market for AM especially in the metals sector is growing rapidly [Woh15].

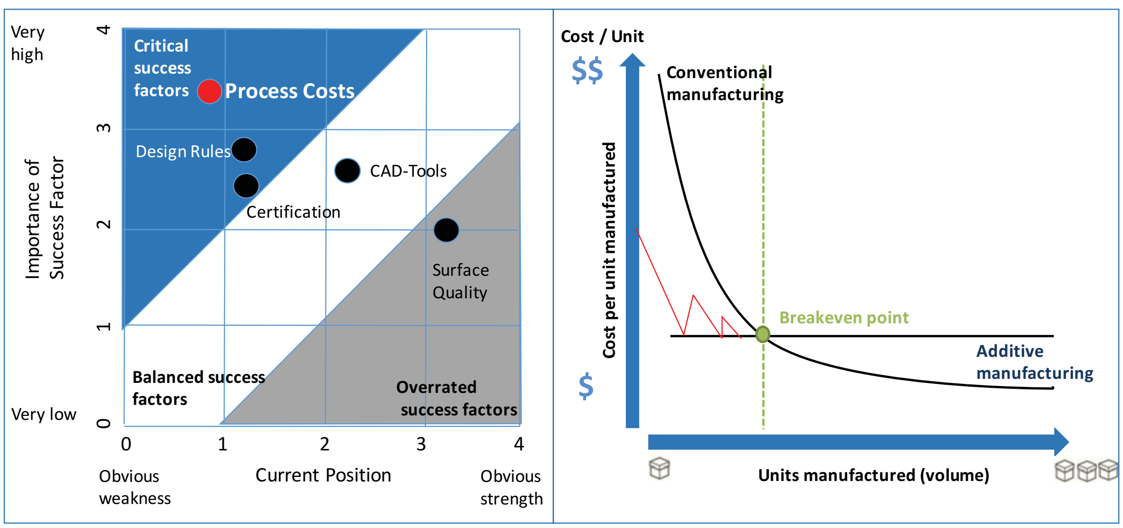


Figure 1: Critical AM Success Factors (left [GEK11]) and comparison of AM with traditional costing curves (right: Deloitte)

The utilization of new technologies like AM is an important aspect in the strategic planning of companies. Often the possible benefits are not meeting the expectations. The expectations of the customers are especially high due to the hype in the media [Gar15]. This effect increases with an increasing complexity of the process and of the structures in the organization. Therefor one should try to overcome the gap between new users of a technology and the according technology. The knowledge about a new technology plays a crucial role in this context. [BHK96]

One of the main critical factors for the hindrance of AM technologies are the process costs itself (compare Figure 1). Additive manufacturing is a highly complex process in itself. During the integration, the whole process chain needs attention concerning the different aspects as it has significant interdependencies [VDI14]. That is also the reason why many designers are not comfortable with the cost estimation for additive manufacturing based processes. Especially in an early phase of product development where knowledge based or systematic approaches are available for traditional technologies, additive manufacturing is lacking behind.

While traditional manufacturing methods exist a long time AM, especially as industrial production technology for end part is comparably young technology. There are a lot of information which exist for traditional manufacturing technologies, but which are not available for AM. This includes aspects like surface finish, tolerances, energy consumption and process speed. Standards, test methods and associated knowledge is still in development and not yet state of the art. [DSK+15]

As aspects like manufacturing speed are some of the main costing influence factors [GRS10]. Estimating the build time is certainly one of the most important factors in costing models because it significantly influences the costs of the build job. Many authors have put some effort into calculating the building time (compare [MeRe1] [GRS10]). Other options for estimating build time include a calculation with the build speed values displayed by the manufacturers. These in general are much slower in reality then the optimum noted in the product documentation. The calculation of additive manufacturing parts in an early stage of product development seems to be troublesome. Especially as AM has a significant impact on the later lifecycle costs [LJM+13] as well as on the different supply chain models of a company [LDK16].

Traditional manufacturing like milling or casting have been on the market long enough to build a vast knowledge about capabilities and limitations. It is easy to design for such a process as vast knowledge is widely available e.g. in several guidebooks. These things are not true for additive manufacturing, even for the current state of the art. In addition, such guides will need some kind of flexibility for expansion due to the rapid evolving nature of the layer based technology. [DSK15]

But not only the AM costs and the design capabilities seem to be a problem. The part selection of part candidates for the technologies has been proven to be a showstopper as well. [LRJ+15] Not all parts are feasible to use with AM which is true for several aspects. On the one hand the current available design rules have shown (compare [Ada15]) are not all geometries suitable or even buildable with AM. On the other hand, AM as true for every other manufacturing technology is not applicable economically for every part. [LRJ+16] While the applicability for highly optimized parts in the aerospace sector has been proven to be beneficial, the technology still has problems with larger numbers of lot sizes e.g. For the automotive industry. [LJM+13]

Costing in Additive Manufacturing

Costs for additive manufacturing are discussed many times in the literature as the technology promises "complexity for free" as one can see in Figure 2. The graphic emphasis is that AM may be rather used for high complex parts then simple geometries as costing advantages might be achieved there. This is supposed to be possible due to the elimination of manufacturing constraints and e.g. to build monolithic structures. This implies cost saving potentials during assembly, and in part management. But not all structures can be manufactured with additive manufacturing [ADA15]. On the other hand high complex statures nowadays still need a lot of post processing and quality assurance costs.

As stated above many aspects depending on knowledge are not entirely known when it comes to the use of the technology. The obvious purchase price of the machine can only be seen as the tip of the iceberg (compare Figure 1Figure 2). Many other costs need to be considered like the buildup of knowledge as well as maintenance and operating costs [LRJ+16]. When deciding to use AM, one should consider these aspects as training, and gathering experience is necessary before starting production. Some Service providers have been building parts for one year before they were comfortable enough to sell parts to the end users. It is a powerful technology which needs to be understood in it's own terms [Zeli13].

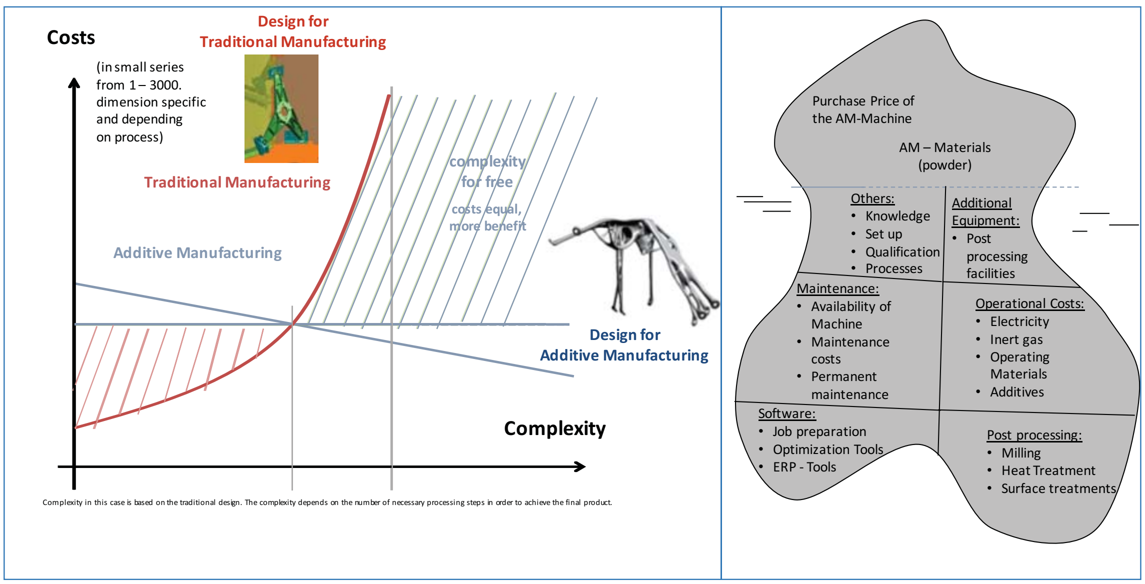


Figure 2: „Complexity for free" (picture left) AM manufacturing costs beyond the surface of the purchasing price (right)

In total the technology has many advantages, which may result in cost reductions in certain areas. The simplification of supply chains, the weight reduction potential and the reduction of part numbers can be named amongst others.

The question arises if additive manufacturing now needs a whole new approach for the cost assessment. In total the advantages which additive manufacturing offers are not completely new for this world. Intelligent product design has always led to cost and time savings during product development. Furthermore, the reduction of part numbers has been achievable in the past as well in other dimensions. Figure 3 shows that a significant time and cost saving potential exists with both, additive and traditional manufacturing technologies.

The cost estimation on the other hand remains similar to the cost estimation in traditional manufacturing. The calculation of machine rate costs for AM-technology still remains the same as for traditional manufacturing technologies. The major problem when estimating production costs therefore is the estimation of the build time [GRS10].

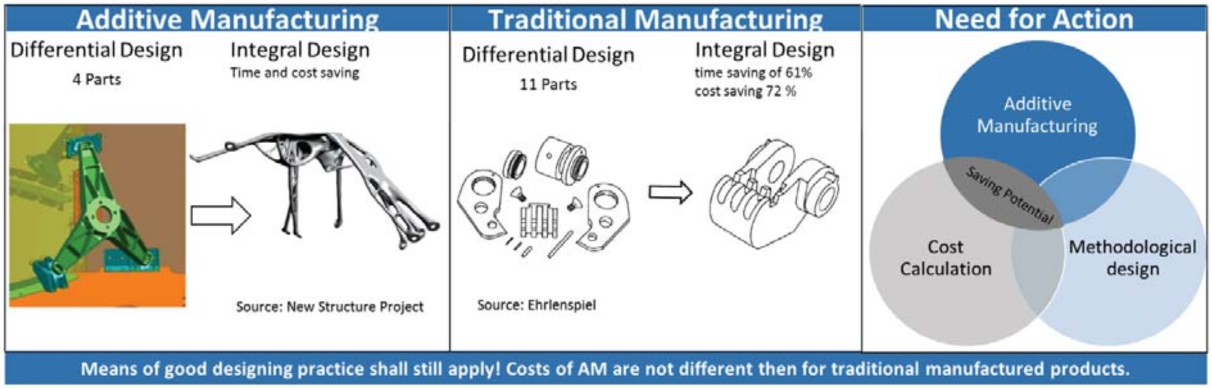


Figure 3: Additive vs. traditional manufacturing

Additive manufacturing can potentially change costs with cost reduction potentials which may go beyond the pure production costs. [LJM+13] Therefore there is the implication that AM cost accounting shall incorporate the Life Cycle Costing (LCC) concept. But this is not only relevant for additive manufacturing. The topic gets more and more attention in companies. The European Union e.g. has recently published the directive 2014/24/EU on public procurement where the recommend the "*cost-effectiveness approach such as life-cycle costing*". The broad application of LCC would as well benefit the implementation of AM in the companies.

Cost efficient design and Planning and the role of the Engineer

"*Cost efficient product concepts, the reduction of the number of parts, manufacturing, material, and assembly cost efficient design of products*" are the foundation for such a product development process [EKL07]. The cost efficiency during the product design is therefore an important aspect of the product development process itself. The thought of cost efficiency is divided into functional and manufacturing oriented efficiency aspects. While functional aspects may include reduction of part numbers and intelligent product design for usage, the manufacturing oriented design aims for manufacturing time and material cost reduction. [NEF12]. The aim is to find an optimal solution for a certain technical problem. This includes the fulfillment of all the technical requirements also with regards to manufacturing, usage and the later product lifecycle. If economical beneficial the solution can be considered optimal [HaBo11].

As indicated by Figure 3, the product designer has a major influence on the outcome of the product development process and respectively the costs. According to Ehrlenspiel [EKL+07] at al. around 70 % of the total product lifecycle costs (LCC) are set and in the development phase while during the start of production only 30% of the total costs have occurred already. [EKL+07] The product designer is responsible for the technical and economic properties of a product. Product development, due to commercial importance needs to be timely efficient in order to achieve good and cost efficient product solutions. The process needs to be flexible, capable of being planned as well as optimized and verified. "Such a procedure, however, cannot be realized if the designers do not have the necessary domain knowledge and cannot work in an efficient way". [PBFG07]

The most important aspects for a sustainable cost management are [PBFG07]:

- Knowledge about processes and respective about the costs
- Interdisciplinary collaboration
- A systematic approach

In summary, the design engineer has a major impact on the total part and lifecycle costs of a product. Nevertheless, he needs to be supported by the allocation of knowledge, a systematic approach in the product development process (PDP) as well as by an interdisciplinary collaboration with other entities in the company.

Need to support (design) engineers

The paper so far has shown that there is a necessity to support the design engineer in order to make sure he can work cost efficient with AM technologies. Missing knowledge and standardization therefore seems to be one of the biggest showstoppers for the technologies. Figure 4 summarizes some interdependencies and requirements of AM technologies and am methodology for a cost efficient design (CED). These are derived from different authors and can be considered generally valid.

Figure 4: Cost-efficient design and Additive manufacturing

In all, this leads to the conclusion that there are certain requirements to be met if one wants to support the designer during the product development in order to achieve a cost efficient utilization of additive manufacturing technologies. The requirements are summarized in Figure 5.

No.	Requirement	Description
1	Effort / Simplicity	The targeted user of this method is the designer. Designers are responsible for a majority of the total part cost but have limited time to deal with the cost optimization.
2	Systematic approach	Cost efficient design requires a systematic approach. The use of AM shall be more in focus of the engineers. The approach has to be implemented in existing PDP processes.
3	Adaptibility	As different braches/companies/products have different requirements and PDP's with regards to their products, it shall be possible to adapt the methodology / tools.
4	Quick cost calculation	The methodology shall be capable of delivering first results in an early phase of product development to select appropriate part candidates.
5	Best Practices	As knowledge about AM product is scarce especially with regards to costs. Existing projects and build up knowledge shall be documented.
6	LCC Costing	The Methodology shall be able to estimate benefits, which go beyond the manufacturing costs as AM has an impact on the whole product creation.
7	Maintenance	The developed methodology shall have a low effort in maintenance. It shall be possible to keep the methodology up to keep up with the technological development of AM.
8	Emphasize AM strength	The methodology shall emphasize the strength of the technology and help the product designers to find economic solutions and appropriate part candidates for AM.

Figure 5: Requirements for a methodology for cost efficient design and planning (CED)

There exists different Product development processes in the literature as well as in the different companies. These product development processes need to build the foundation for a cost efficient design methodologies. In general product development processes are split in different phases of the development and shall guide the engineer trough the PDP process. These methodologies commonly propose tools to execute in the different phases. As this work understands itself as a guideline for implement cost efficient design measures for am in different entities a simple model will be used here.

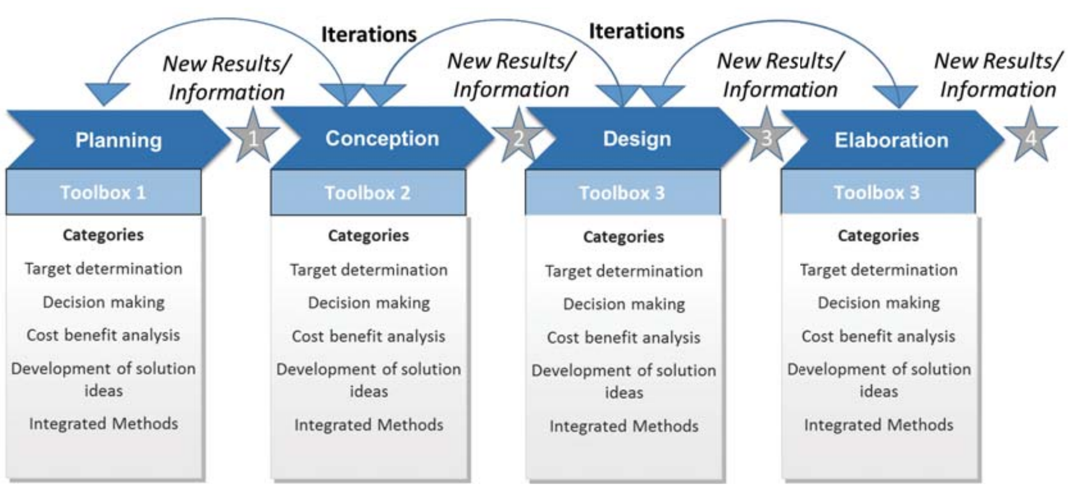


Figure 6: Simplified model for a PDP compare [VDI2221][PBFG07]

This model therefore may be adapted to other PDP's (as demonstrated later in the paper). Therefor a simplified PDP development will be considered which is split in the phases seen in Figure 6. Most of the common models could be categorized in such different phases in the process which may interact in some way through iterations. After the finalization of a phase, decisions are taken and new information is available. This is then available for the tools from the toolboxes of the different phases.

In general such a PDP provides tools and splits them in methods, e.g. for target determination, development of solution ideas, cost and benefit analysis or in evaluation procedures and decision methodologies (compare [VDI2221]). This differentiation also shows how diverse the tasks for an engineer are and that a wide knowledge about the field of application is necessary. The following section will discuss several tools which may fit in the different Toolboxes of our sample PDP (SPDP).

New /adapted Tools for AM in the PDP

This section will discuss briefly different tools which were developed to be implemented in a PDP with regards to enable a cost efficient design approach under the current (technological) circumstances. The different sections will discuss in which phases these tools can be used and for what purpose. The tools have been designed to fit the different available information in the different design phases. Later on these measures will be implemented into a sample product development process. All tools were developed according the nominated requirements regarding a methodology for CED.

Strategic measures

The economic analysis of the additive manufacturing technology can be split up in a strategic and an operative aspect. The strategic question one needs to ask is if the AM technology might be an attractive addition in accordance to the overall production portfolio. On the opposite side the operational questions (which this paper focusses on), rather deal with the determination of the product (-ion) costs. [Geb13] With regards to the strategic aspects a couple of literature models have been developed (e.g. Siegwart and Singer (compare [Geb13]), but most of them do only focus on the implementation of prototyping aspects. If additive manufacturing technologies are not attractive for a company (yet), then one does not need to bother with the implementation of CED in the PDP.

Figure 7: Indication if AM is beneficial

One needs to keep in mind that additive manufacturing is more then only the production of parts. It can be a game changer in product design, value chains and business model [GRS10]. Keeping that in mind, the uncertainty if and especially when to invest, is crucial and needs to be well thought. While standard accounting methods like the return on invest calculations may be performed there are several other aspects to consider. In total one can sum up that if one can get a pretty good feeling on the suitability of AM if one can answer most of the questions in Figure 7 with yes.

The tool may be used in or before the planning phase and is therefore just at the boundary of this project. Similar approaches can be found e.g. in [woh15]. In this area still some research is necessary.

Quick Cost Calculation

Quick cost calculation is a term which is called design accompanying calculation and not clearly defined. While the DIN 32990 part 1 defines it as a "temporal and/or functional simplified calculation" while the VDI guideline 2235 "Economical decisions during design engineering process - Methods and Equipment". Association of German engineers" anticipates the use of certain costing functions. In general these may be distinguished in expert estimations, similarity calculation, analytical or statistical costing functions. I general they are simplified with regards the time and or objective [Fi08]. Many costing models have been developed for AM with the major one being Hopkins et al. and Ruffo et al. [RTH06] While each model has its distinct strength the main problem is to determine the build speed in an early phase of development. There have been many authors dealing with this topic as well [MeRe10][Bau12][GRS10][BVB11]. Most of these models are very sophisticated with regards to the determination, but most of them are specialized and have deviation with regards to the real build times. This work will present an analytical methodology to estimate part costs for non am experts in an early phase. The results get more accurate during the PDP as further details about the final design are available and before dedicated software will estimate the exact build times for a product.

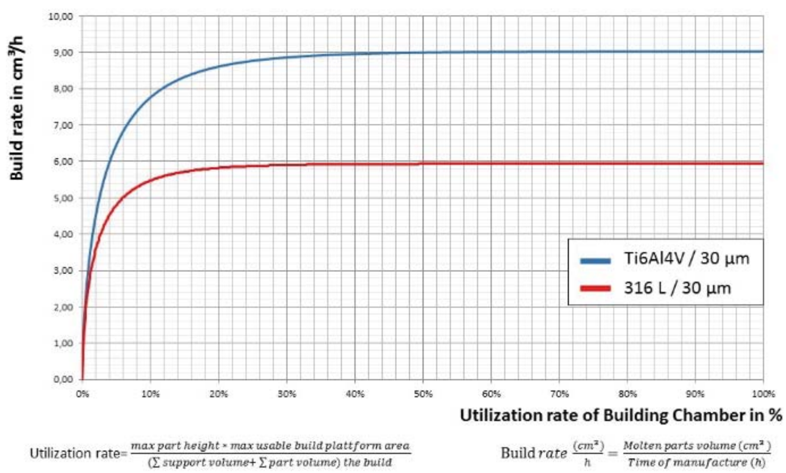


Figure 8: Build speed curve

In general, AM is a process with many influencing factors with regards to the build time and respective the build speed[1]. [LRJ+16][GRS10] Some of them which are machine dependent and others which are dependent on the part and its requirements. Figure 8 shows a casual interdependency between build speed and the utilization rate of the building chamber based on a certain older machine material combination. The diagram was developed using the test platform displayed in Figure 9, and shows that there is a significant interdependency between the utilization rate of the build chamber and the overall build speed of the machine. A second curve exists which defines the influence of the support structures. Therefor the only two aspects necessary are the parts volume and the utilization rate of a building chamber in order to achieve accurate results. The methodology can serve in many functions.

[1] Build speed is defined in the section "Excurse: Build speed, quick calculation and productivity"

It can help giving a first quote to a customer or estimate if a part shall be produced in house or at the premises of a service provider. The build of the platform allows maintenance of the curves as they can be determined for new machines and materials. It is cost efficient as the platform was designed for a small build time on the machine. It can serve in the detailed LCC costing framework as build time engine.

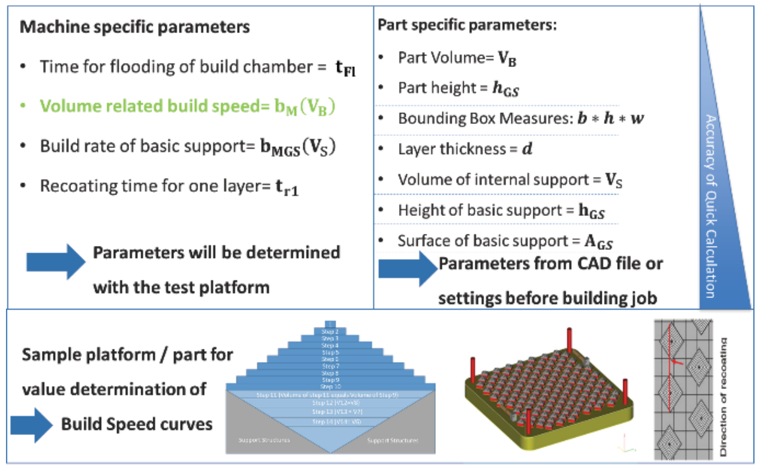


Figure 9: Influence factors

<u>Part- / Process- selection</u>

One of the key factors fur the success of additive manufacturing is the selection of appropriate part candidates. If possible part selection shall be systematic and repeatable. [LRJ+15] Despite the almost unlimited shapes AM can generate, not all technologies can be manufacture with AM technologies as proven by the so far published design rules (e.g. [Ada15]). Which comes to the conclusion the part selection tool needs to screen the candidates with regards to manufacturability, economic success and the ability to produce an end use part [LRJ+16]. In the literature the approach is generally to find a manufacturing technology for a part, rather then finding a part for a manufacturing technology. With regards to this aspect, Westkämper et. al. [WeWa10] propose to evaluate criteria for the choice of manufacturing technology with regards to Product/-Process-/Economical/-as well as environmental and social criteria.

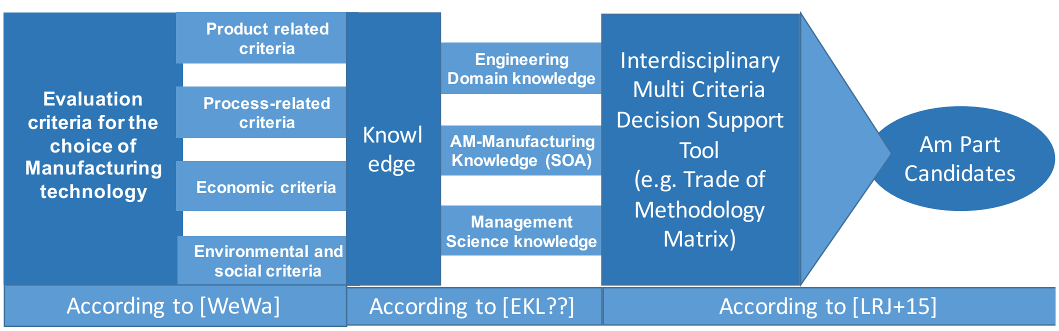
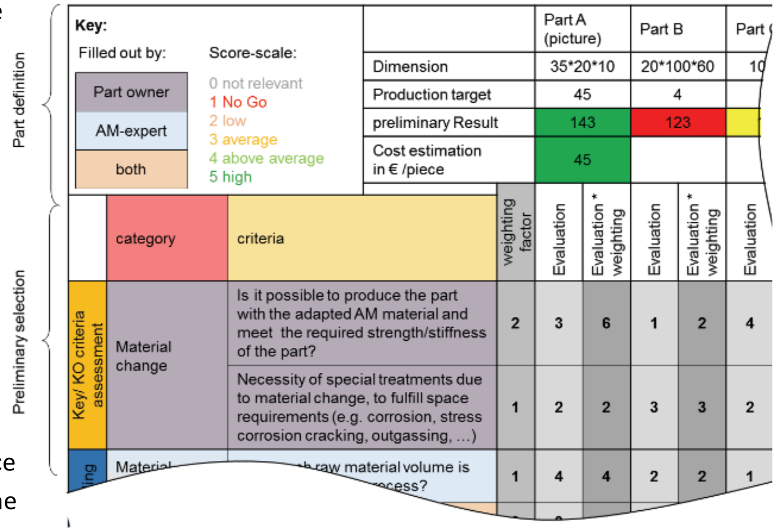


Figure 10: From manufacturing technology selection to part selection for technology

To evaluate these criteria knowledge is necessary in order to be able to rate these criteria. In general, one needs knowledge about costing structure and the possibility to influence LCC costs, about the later product and its requirements and as well especially about the manufacturing process. As this knowledge is not always available, an interdisciplinary multi criteria decision support tool was developed to support the design engineers (compare [LRJ+15]). This tool has selected important questions from the different criteria and build multi criteria decision tool which can be used by non AM experts in addition to AM experts. Once first information about the part is collected, the integrated quick calculation measures will give a rough first estimation on the part costs and allow a comparison to traditional manufacturing.

Other economic factors are integrated with regards to a benefit analysis in the multi criteria decision support. In general, such an approach needs to be adapted to certain

Industries or application fields. E.g. the benefits and requirements of an airplane are different to these of a tractor. Therefore, the section with regards to management science knowledge and especially to the engineering domain knowledge need to be adapted for each company/application field. The Area of AM-manufacturing knowledge on the other hand is more subject to technological development.

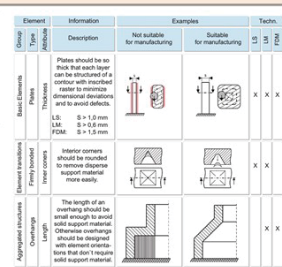


Key: Filled out by: Part owner / AM-expert / both	Score-scale: 0 not relevant, 1 No Go, 2 low, 3 average, 4 above average, 5 high			Part A (picture)		Part B		Part (
		Dimension		35*20*10		20*100*60		10
		Production target		45		4		
		preliminary Result		143		123		
		Cost estimation in € /piece		45				
category		criteria	weighting factor	Evaluation	Evaluation * weighting	Evaluation	Evaluation * weighting	Evaluation
Key/ KO criteria assessment	Material change	Is it possible to produce the part with the adapted AM material and meet the required strength/stiffness of the part?	2	3	6	1	2	4
		Necessity of special treatments due to material change, to fulfill space requirements (e.g. corrosion, stress corrosion cracking, outgassing, …)	1	2	2	3	3	2
ing	Materi…	…h raw material volume is …cess?	1	4	4	2	2	1

Figure 11: Excerpt of the general TOM framework

category	criteria	A
Conformity of specific **geometric conditions** for AM	any solid block structures in part? - risk of residual stresses	1
	solid block structure replaceable by lattice structure?	2

	block structures	Block structures replaceable by lattice structures
	solid block structures induce a risk of residual stresses (e.g. horizontal faces bigger than 40x40 mm² hardly possible for some steels, aluminium more possible)	Wall-thickness > 3 mm
1	-	-
2	large portion of block structures / >30%	no lattice structure possible
3	mainly block structures / 10-30%	-
4	hardly block structures / <10%	replacement with lattice structure possible
5	no block structures strength/ stiffness/ lower CTE mismatch/ ...	no replacement needed



Source: Adam, Zimmer; Project Direct Manufacturing Design Rules; DMRC Annual Report 2012, Direct Manufacturing Design Rules, Adam

Figure 12: Excerpt from a sample Trade of Methodology Matrix [LRJ+15]

An example from the TOM aiming on checking the manufacturability (AM-Process knowledge) can be seen in Figure 12 .As AM is not capable of building massive structures such geometries are not possible to be built in metals. If such areas exist in a part, these may be replaced by lattice structures. The general approach is described in more detail by Lindemann et. al. 2015. The methodology may be used in different phases of the PDP-process. It main aims in general are:

1. Finding a part which can be produced by AM (technically)
2. Finding a part which offers an economic benefit (rating against other variants)
3. Finding a part which may be used as an end product (cost-benefit / quality control)

In the planning phase it may help determining AM suitable product ideas. In the design phase it may help to compare solution variants. In total it is a good tool to give the designer confidence during the whole PDP process. If the usage is recommended in a PDP, AM is one possible solution the engineer needs to think of. The right part selection makes the difference between an efficient or an effective AM design process.

Black Box - Methodology

The methodology of reducing a product depending its functions with regards to the in- and output in the categories Material/Information/energy is not new. The approach has been described in depth in [PBFG07][EKL07]. But with regards to the current application of Am it has three major implications especially when talking about re-design of existing parts.

1. Tracing the original requirements (finding the purpose of the product)
2. Defining the design space for the redesign (integration of parts/functions)
3. Identifying interfaces to other systems (quality of interfaces / post processing)

Parts designed for traditional process do in general not suit the cost efficient AM process. Therefore, most parts need to undergo a redesign phase. In order to find the original requirements which have not been affected by the manufacturing restrictions it is recommended to refer to the redesign candidate as a block/ a system in the black box. This will help to dig for the part requirements. The active dealing with the classification of the part in a system or a wider context will help to figure out if an integration of functions or an integration of parts is possible. Defining the interfaces between the redesign system and the original will help to save costs for the later post processing as the surface quality of AM shall be considered.

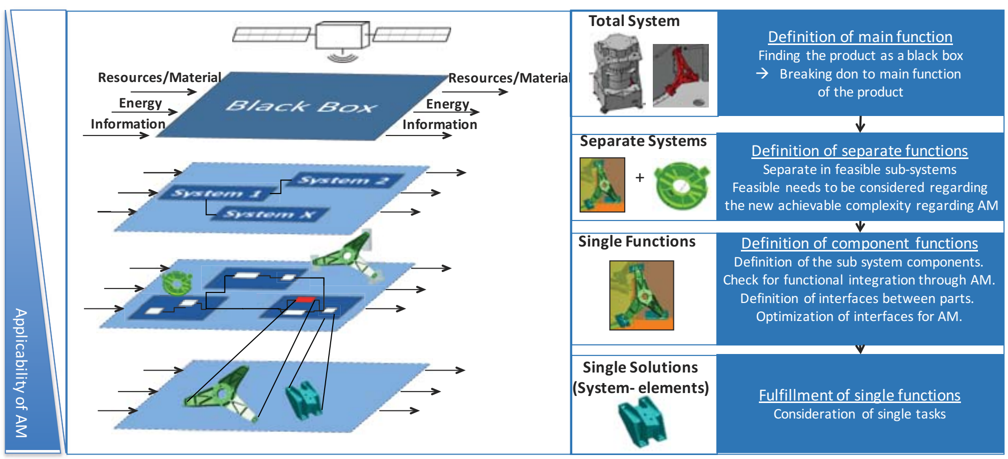


Figure 13: Black Box Methodology - Example of a Satellite part

The tool will mainly be used in the conception and the design phase in order to elaborate the possibilities of functional integration or at the beginning of the PDP to repatriate requirements. It shall help to reduce the overall number of parts as well as the later post processing costs.

Lifecycle Costing-Framework

To understand the full costing impact costs of AM, one needs to understand the whole process chain. Deciding to use this technology nowadays often means a trade-off between production costs and added value. The approach of lifecycle thus delivers an appropriate framework. Lifecycle costs consider more than just the production or self-costs (producers' view) or the purchase price (customers' view). Costs occur during the whole lifecycle of a product. In many cases customers do not necessarily consider this aspect. A customer sees the purchase price as the main criteria, but there are many other aspects where costs occur, for example, during the usage of the product [EKL07].

Additive manufactured parts can provide benefits that can affect the lifecycle costs of a product, they are usually lighter and can provide increased value for the customer. During the whole lifecycle, products generate costs that users are often not aware of. Usually only the acquisition price is what customers take into account when they are about to buy a product. Several other costs arise during usage and removal. The production and acquisition costs are usually only a small amount of the costs that are generated during a product's life. The lifecycle costs cover all expenditures during the different phases of the lifecycle, from the perspective of the manufacturer and user.

One methodology for lifecycle costing that can be easily adapted to the needs of AM is the 'DIN EN 60300-3-3 Dependability management – Application guide – Life cycle costing' as already described in [LJM+13]. In general, it splits the costs into six different processes that need to be considered. While the model in general has a sequential approach, it is has been split into three different phases and in total seven processes (compare Figure 14). The seventh phase deals dedicated with the advantages of Am like intangible assets or cost benefit analysis. Furthermore, the possibilities of AM for product piracy prevention are considered (compare [JLM+13]. It distinguishes between production costs, which in the early phase of product development are the main point of discussion; continues with self-costs, which include the design process; and finally ends with the lifecycle costs in phase three.

Figure 14 can be understood as a model for comparing production alternatives. It describes a general approach to justify AM part costs compared with traditional methods. The first step is always to start by estimating the production costs in an early phase of product development. This phase is in general very particular dependent on the peculiarities of the used AM process, as each process has slight differences important to the cost estimation. Much AM-dependent knowledge is necessary to accurately calculate part costs. These calculations need to be adapted as the product design process evolves and more part details become fixed. If after this phase AM is still a production alternative, the self-costs need to be considered next. These include all costs occurring on the producer's side. The model highlights the costs for 'concept and definition' as well as for 'design and development'. The self-costs and the production costs need to be updated during the product development process as the final part evolves. In this phase, AM may play out its advantages according to prototyping and testing; much time can be saved through the use of 'final' prototypes. While during this phase most of the other costs are influenced and fixed, the impact of this phase is often underestimated. Shorter development cycles may be a major benefit if product designers are used to AM and its design rules. Since the later product characteristics are set in this phase, the lifecycle costs are set as well. Intelligent product design with the use of design catalogues helps to reduce lifecycle costs.

Considering all lifecycle-based costs can be time-consuming. And again, if AM is still a production alternative after consideration of the self-costs, the later 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 changer for supply chains and business models. As one needs to think about customer benefits as well; it is strongly recommended to discuss the costs and benefits during this phase with different roles in an interdisciplinary team (e.g., engineering, marketing, sales).

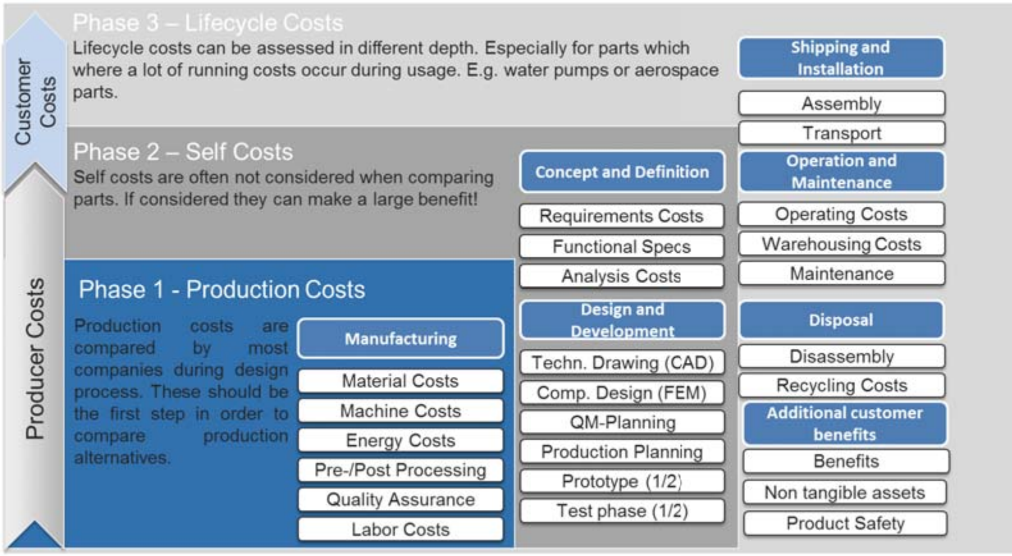


Figure 14: [DIN05][EKL07][LRJ+16]

For all phases dedicated lists for cost saving potentials are provided as discussed in Figure 19. The tool can be used in different detail grades. The setup offers only to compare differences which are to expect between production alternatives up to a sophisticated lifecycle costing. If the engineer has found the justification for a part, he shall end the methodology and leave it to cost accounting departments. The model may be used for planning, design and post calculation purposes. The next section will detail Phase 1 of this model.

Costing Framework

As already mentioned in the quick calculation segment, an overall costing framework is required in order to successfully approach part costs. In [LJM+12] a costing framework was proposed which was based on Ruffo et. al. and extended by a time driven activity costing approach. As discussed in [JTP00], process modelling and activity based costing can provide good and especially useful cost information for product designers. The categorization of activities in bigger groups and the attachment of cost information has proven to help designers get the right costing information and to utilize them appropriate. The costing framework itself is designed according to [JTP00] into different details grades. So for a first glance it may be very simple, but allows to go deeper in later phases of the product development.

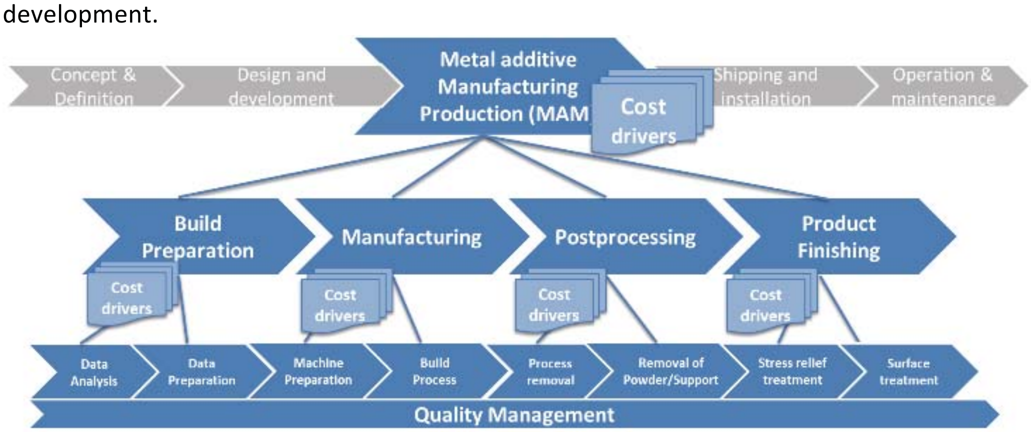


Figure 15: Process model for production

This methodology enables a company to adapt different process changes in the company. And add or remove processes adjacent to AM like different post processing steps or similar. With regards to find the peculiarities of the different AM process, the procedures from the transformation from a CAD to an STL file till the product finishing have been modeled with business process modeling. Especially focus was taken with regards to the peculiarities of the AM processes and the different roles involved in the product creation process. With this knowledge the exact costing framework can be build and enriched with the build time estimation from the quick calculation guide.

<table>
<tr><th colspan="10">AM User-Input (Selective Lasermelting SLM)</th></tr>
<tr><td rowspan="2">Machine</td><td rowspan="2">Select a Machine</td><td rowspan="2">Price [€]</td><td colspan="3">Building Space</td><td colspan="4" rowspan="2"></td></tr>
<tr><td>X-Axis [mm]</td><td>Y-Axis [mm]</td><td>Y-Axis [mm]</td></tr>
<tr><td>Material</td><td>Material</td><td>Mass Density [kg/dm3]</td><td>Price [€/kg]</td><td></td><td>Quantity of Powder of Production Target (all Build Jobs) [kg]</td><td>Quantity of Powder of Production Target (one Build Jobs)[kg]</td><td>Used Powder for Production Target [kg]</td><td colspan="2">Used Powder for Support (Ground-Structusupport, Specimen) [kg]</td></tr>
<tr><td rowspan="3">Workpiece</td><td colspan="6">Data Buildung-Parts</td><td colspan="3">Estimation Data Building-Parts</td></tr>
<tr><td colspan="3">Bounding Box Sizes</td><td rowspan="2">Bounding Box Volume [cm³]</td><td rowspan="2">Real Building Volume (from STL-File) [cm3]</td><td rowspan="2">Weight [Workpiece] [kg/stück]</td><td rowspan="2">Support in % to Volume of workpiece</td><td colspan="2" rowspan="2">Support in % to Volume of workpiece</td></tr>
<tr><td>X-Axis [mm]</td><td>Y-Axis [mm]</td><td>Z-Axis [mm]</td></tr>
<tr><td rowspan="2">Workpiece / user information</td><td colspan="5">Buildjob-Data</td><td colspan="4">Übergabe zur Kalkulation</td></tr>
<tr><td>Production Target [pcs]</td><td>Maximum Number of Workpiece per Build</td><td>Number of Workpieces placed per Build Job</td><td>Calculated Build Jobs [pcs]</td><td>Volume Support one Workpiece [cm³]</td><td>Volume of one Workpiece [cm³]</td><td>Total Volume of P.T. Groundsupport+ Specimen [cm³]</td><td colspan="2">Total Volume P.T. (incl. Ground & Stucturesupport & Specimen) [cm3]</td></tr>
<tr><td rowspan="2">Complexity / Optional Post-Processing</td><td colspan="2">Complexity Factor</td><td>Preparation</td><td colspan="4">Post-Processing (optional)</td><td colspan="2">Build Speed Rate [cm³/h]</td></tr>
<tr><td>Preparation</td><td>Postprocessing</td><td>slicing/positioning/ machine preparation [h/production target]</td><td>Hipping [€/Stück]</td><td>Stress relief heat treatmant? [h/stück]</td><td>Sand blasting? [€/Stück]</td><td>Anodizing? [€/Stück]</td><td>Estimated</td><td>Actual</td></tr>
</table>

Legend:
- User Input
- Deposited informaton
- calculated

Figure 16: Sample from the costing framework

Therefore the methodology can be adapted to special needs of companies and branches and technologies (e.g. SLM,FDM,LS) while the core of the framework stays identical as most AM technologies have similar processes in some way. The costing framework can be used accompanying the product development phases from the planning phase till the post calculation. Therefore it can help to document exciting product design approaches.

Knowledge Base

Knowledge has shown to be one of the key factors for the implementation of additive manufacturing. It is necessary to perform different tasks in the product creation process. As the literature [VDI2222] [EKL07][PBFG07][VDI2235] discusses, different kind of knowledge catalogues can be used in different places of the product design. Some quick calculation measures are based on knowledge and experience as well as design catalogues. Missing comfort of the engineers and missing design rules e.g. are even today not easy to access if available. As already discussed, standards are not widely available and part properties depend strongly on the parameters there is a strong need to document lessons learned and internal capabilities and experiences. Therefore the usage of design catalogues in different phases is to be encouraged. This will include Design Rules (compare [Ada15]), solution principles, mechanical properties or catalogues for a cost efficient design. While all of the need to be utilized in the PDD the section will discuss a catalogue for cost efficient design.

While in traditional manufacturing things like handbooks, costs for similar products and guidelines for cost efficient are widely accessible and available, the implementation of a knowledge management tool for AM is proposed. An excerpt of such a catalogue can be seen in Figure 17. It gives advice on

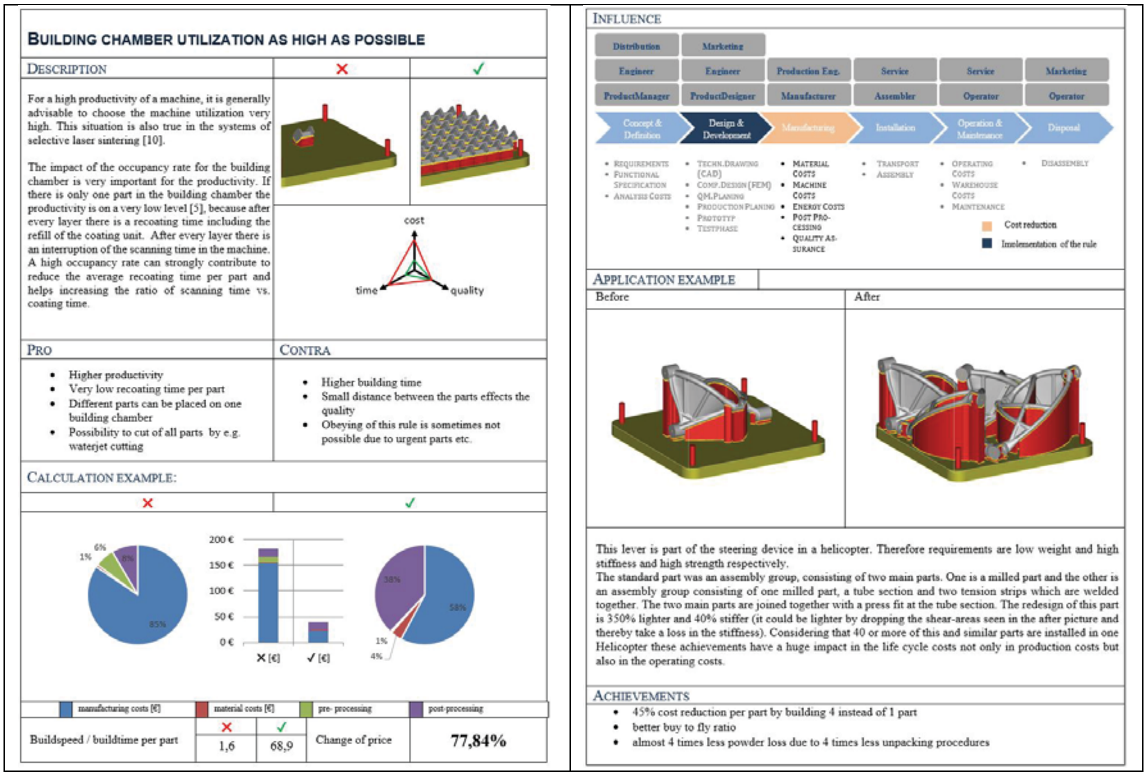


Figure 17: Excerpt of a catalogue for cost efficient design – Build chamber utilization (compare section quick calculation)

cost efficient designing based on examples for a good and a bad product design. All rules are demonstrated with a part which is used is an edge insert used in a satellite which is manufactured with sophisticated milling operations. The Rules are discussed with regards to pros and cons and a costing comparison of the good and the bad example is given in order to get an idea about the costing impact of a certain rule. Furthermore the catalogue displays in which phase of the PDP a certain rule finds application, and where the later costing impact will occur, and which stakeholders are affected in the process. The catalogue closes with a section about an example from a "real part", ideally from a company where this ruled helped to increase cost effectiveness.

The knowledge based catalogue may serve as well in different phases of the PDP. At first it may help to educate new design engineers with regards to the use of the technology. The product examples may help in the conception and design phase. Furthermore best practices and lessons learned with regards to costs and manufacturing may be stored there and help further product developments again. If applied constantly it will also give a basis for similarity based quick calculation measures. The catalogue is understood as a living document which may be updated with current product examples or new research implications. Section may be enhanced by material properties and build speed curves.

Future prediction – Cost Roadmapping for AM

Technology road mapping aims at achieving short or long term product development goals with specific technology solutions. [GB97] These roadmaps can help to find the right timing for the development of new products or the application of an emerging technology. Combining technology roadmaps with costing frameworks allows to estimate costs for a defined product in a certain point in the future. On the one hand promising part candidates can be checked for production costs in the future. On the other hand, companies might be able to define their entry points into a technology. The roadmap shown in Figure 18 is an excerpt of a technology roadmap for powder bed fusion metal technology. Different measures like the buildup rates and the build chamber Volumes are important input factors for the costing model/framework. The combination of road mapping and costing models

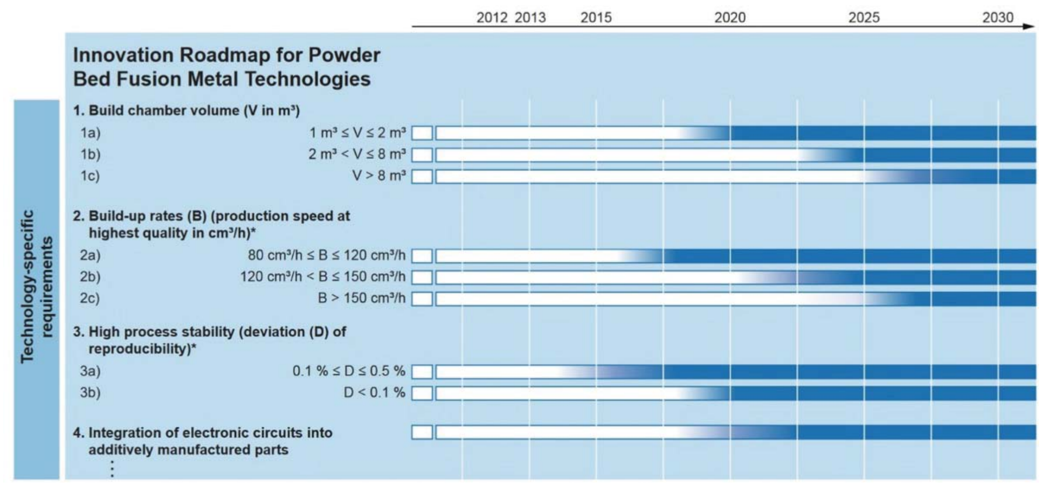


Figure 18: Future estimated developments of Powder bed fusion metal technology [GEKW13]

May be useful to find the dipping point for the entry point in the AM technology. This is different for each and every company. GE for example found its point already in 2013 [woh15] while for other industries this point may still be in the future. The tool can be mainly utilized in the planning phase.

Integration in existing Product Development processes

As Pahl et. Al and Ehrlenspiel et. al. have described, cost efficient design methodologies needs to be embedded into a systematic approach. In general the develped tools and methodologies may be integarted into every design methodology. As an example, we will discuss the integration into a PDP by the example of the Guideline VDI 2221 "Systematic approach to the development and design of technical systems and products". It states the applicability for the branches of mechanical, precision, control, software, and process engineering and cosisits of seven differnet iterative tasks, or the four diffrenet phases planing/conception/Design/and elaboration. [PBFG07]

The VDI 2221 is commonly spread around Germany as the association of German engineers has developed it. It has been improved for over 60 years now with its beginning in 1954 based on the work of Kesselring. To empahzize the importance of the continious cost calculation the VDI 2235 „Economical decisions during design engineering process - Methods and Equipment" and parts of the DIN EN Guideline "Dependability management - Part 3-3: Application guide - Life cycle costing" have been compiled to one flowchart (compare Figure 19). In general the approach now emphasises the need for a calculation accompanying calcultion with regards to the recommendadtion to use a short calculation process. [EKL07] The chart now emphasises that it is not only important tu currently elaborate on the requirements but as well to perform regular cost checks to be avle to come to economicaly based decisions. The blue boxes in the chart describe AM specific adaptions to the currrent process. These may be areas where knowledge needs to be build or where one needs to treat the technology with special care.

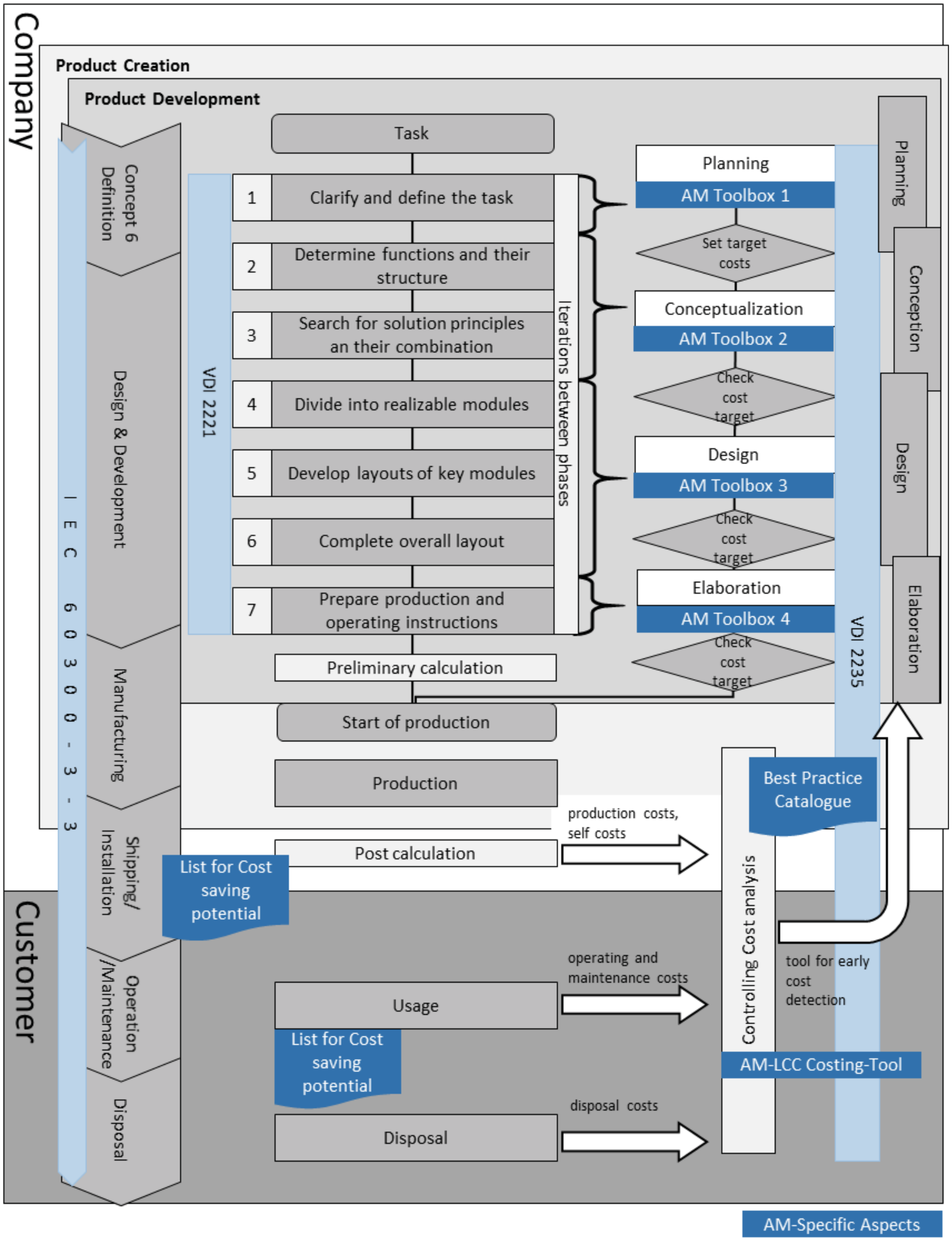


Figure 19: Example of a costing oriented approach and integration of toll for the use of AM [VDI2221][VDI2235][DIN05]

Figure 20 shows a detailed excerpt from the methodology adapted to an am development process. Especially listed are the AM requirements in the phase as well as special cost implications/cost saving potential. This itself will help the designer to keep track of the important influencing factors and to conduct a cost efficient design process without even performing the recommended cost calculations along the PDP. The toolboxes contain furthermore the standards tools applicable for a certain phase used for traditional manufacturing as the have proven applicability over the last decades.

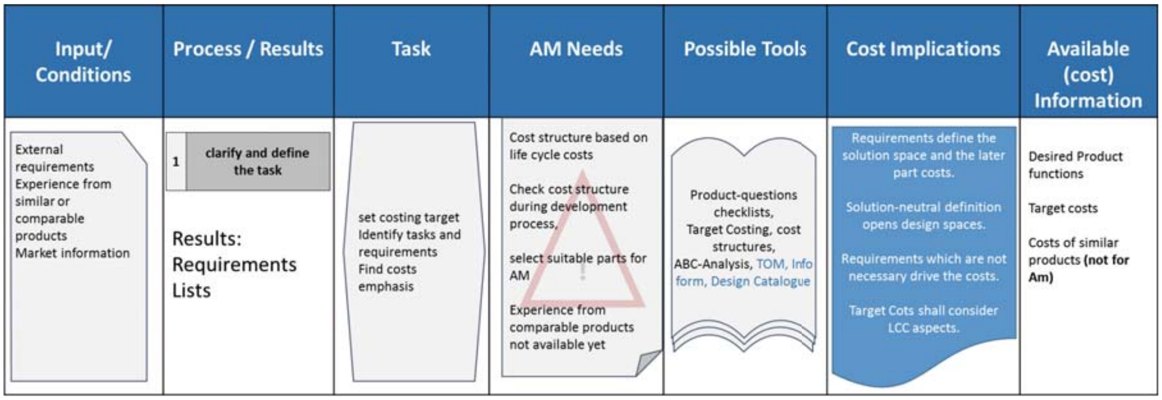


Figure 20: Deatilled view on phase 1 of the VDI 2221 with special attention to the AM technologies and cost implications

Summarized one can say that it is important to integrate time stamps for cost checks in the PDP and to make the designer aware of the choices he has. Some tools can be made mandatory in product development process. Giving more comfort to the engineers with processes tools and design catalogues will boost confidence, increase creativity and lead to a wider and especially cost efficient approach of AM.

Summary and outlook

The biggest problem about bringing additive manufacturing into the companies is not the cost accounting for manufacturing. But the general lack of knowledge about the processes and furthermore not many companies have incorporated the lifecycle costing approach. Until the designers will gather experience they'll need the specific knowledge about the AM processes. This it will already lead to lower overall production costs while using the technology.

The paper has proven the need of the integration of AM-specific Tools in the product development process in order to help the engineers achieving cost efficient design. While the tools themselves have been proven to be useful help for the designers one can assume the toolbox concept for the different phases will help to realize a cost efficient design approach. While the toolbox may not be complete, many of these tools can/shall be adapted especially to companies needs and to specific process parameters applied. The proposed methodology has been applied to the example of selective laser melting process and in adaption to the VDI 2221. The applicability in general is given to the different AM technologies as well as to different product development processes. Maintenance of the methodology is necessary and should be carried out at least once a year. In total the methodology shall help the engineers to get convenient with Additive Manufacturing technologies and help them to justify the use of the technology. The proposed calculation methods do even allow to have a peak in the future of manufacturing in order to asses part costs in the future. In total these toolboxes are not complete yet as there will be more possibilities to support the design engineers with appropriate tools. These may range from Software Tools like FE-optimization models to Standards, complete material handbooks or dedicated supply chain tools. Furthermore, the tools are seen as living entities which need adoption and development over time. While the developed tools cannot be incorporated one on one the methodology behind the creation of these tools and the positioning in the development process shall help companies to utilize AM technologies.

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