INDICATORS AND DESIGN STRATEGIES FOR DIRECT PART PRODUCTION BY ADDITIVE MANUFACTURING

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Abstract

Additive manufacturing (AM), a layer based material addition technology to create three-dimensional objects directly from a 3D CAD model with little restrictions regarding the shape of the object. Today AM is already a proven technology for direct part production. The challenge is to identify suitable components of a product that will benefit from AM's capabilities. To support the identification of parts this paper presents indicators to parts where a re-design for additive manufacturing will create the most added value. Furthermore the benefits of additive manufacturing are subdivided into process advantages and design advantages. This distinction is fundamental, because it represents a great impact on the development process itself and the design strategy. The advantages, indicators and design strategies are explained and illustrated on two cases.

Keywords: design process, design practice, additive manufacturing, product value, Functional modelling

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1 INTRODUCTION

Additive Manufacturing (AM) is a group of manufacturing technologies which produce three-dimensional objects by adding material, usually in a layer by layer process. The part is produced based on a 3D model which is digitally sliced into layers. (ISO/ASTM 52921: 2013)

Since the beginning of the 1980s Additive Manufacturing evolved from the first processes for the rapid production of prototypes into a number of different processes of which some are capable of direct part production. Today processes like selective laser melting (SLM), selective laser sintering (SLS) and with some limitations fused deposition modelling (FDM) provide a stable manufacturing process to produce parts in end-user quality out of metal or thermoplastics. The material properties of additive manufactured parts often reach or exceed the characteristics of conventional ones. Additive manufacturing processes are technological mature for industrial production and due to a sufficient process stability and a rising competition between service providers (Baldinger 2014) Additive Manufacturing becomes economically feasible for a growing number of industrial and end-user applications. (Gebhard 2011)

Despite the quality of the produced parts and the growing productivity of the equipment it is unlikely for Additive Manufacturing to substitute traditional manufacturing processes in general (Uglow et al. 2013). Instead Additive Manufacturing is already a valuable extension to existing production technologies. The processes have a few distinct characteristics, like the almost unlimited freedom in design, which help to overcome the limitations of conventional processes. At the same time Additive Manufacturing causes higher manufacturing costs compared to conventional processes. The challenge for a designer is to identify parts and assemblies where using the freedom of design create an added value and by this justifying the additional costs of Additive Manufacturing.

2 IDENTIFICATION OF PARTS WITH DESIGN POTENTIAL

Companies continuously work on the design and performance of their products in order to maintain and extend their market position. These activities in research and development are a major factor for success. The objective behind the improvement or optimization may vary. Typical examples are an increase of performance, a better efficiency or the reduction of costs. A company has different options to reach these targets. (Ehrlenspiel et al. 2007)

One possible route to an improved product is a change of production technology. Additive Manufacturing is a young production technology which is deemed to offer new ways in product development. In the last decade the maturity of these processes was largely increased due to research on new materials, development of better equipment and a better understanding of the processes which led to robust and stable processes. Today Additive Manufacturing processes are proven production technologies to produce goods for industrial and end user applications (Uglow et al., 2013). Designers should consider using the advantages of Additive Manufacturing to create an added value for the user of their product.

The advantages of Additive Manufacturing mainly derive from the basic principle of adding material in a cyclic process based on a 3D CAD-model without the need for any tools or fixtures. A literature review reveals a number of different approaches to describe and cluster the potentials of Additive Manufacturing. Based on examples of end products Gebhard (2013) demonstrates the larger freedom in design, which enables the integration of functions and the use of innovative design elements, a simple way of mass customization as well as a way to create novel materials and innovative manufacturing strategies. Wohlers (2013) clusters direct part production into reduction of tooling, agile manufacturing operations, reduction in inventory, decentralized manufacturing, part consolidation, light weighting und lattice structures. He derives these clusters from case studies which also demonstrate that Additive Manufacturing is already able to produce industrial goods. Other publications, like Gausemeier et al. (2012) and Uglow et al. (2013), further distinguish the potential benefits of Additive Manufacturing between different applications or industries.

All of these examples show the broad range of ideas and opportunities to use Additive Manufacturing in direct part production. A designer might feel swamped by the multitude of possibilities and it clearly is difficult for him to use the described cases of successful applications to solve a specific task. This is especially true for the first step on the way towards an additive manufactured part: to select the right part of a specific product to be produced by AM either without any changes or after a re-design.

This decision is even more difficult for the large number of companies, which have not used Additive Manufacturing yet and therefore have no experience from previous AM projects.

The authors of this paper follow the approach to assist companies during the development of a first additive manufactured part for a serial product in order to build up knowledge and experience. They presented in Leutenecker et al. (2013) and Klahn et al. (2014) a guiding principle for the identification of suitable parts and assemblies in an existing design, as well as during the development of a product from scratch. The identification is done by the designers, because they are the experts for a system and have detailed knowledge on the functions of the components as well as on the challenges of the application. The guiding principle clusters the potential benefits of Additive Manufacturing in four selection criteria oriented on the main objective of the design for Additive Manufacturing: *integrated design*, *individualization*, *lightweight design* and *efficient design*. The goal of the selection criteria is to reduce the multitude of potential benefits to four design goals which are easy to comprehend and memorize.

3 DESIGN STRATEGIES IN ADDITIVE MANUFACTURING

The identified components, whether they are from an existing product or a new development, can use two basic advantages of Additive Manufacturing: large freedom of design and flexible manufacturing direct from CAD without tooling. The large freedom of design originates from the different cost structures of additive and conventional manufacturing. In Additive Manufacturing the production time and costs are mainly determined by part volume and bounding box while the efforts for conventional production technologies, like casting or milling, are also determined by the complexity of a part. In this context Additive Manufacturing offers the design advantage to increase the complexity of a design in order to improve its functionality beyond the limits of conventional manufacturing. The ability to produce a part, whether it's simple or complex, directly from CAD-data is a process advantage of Additive Manufacturing. Without the investment in individual tooling or CAM-programs the production of single parts and small lot sizes by Additive Manufacturing offers a cost and lead time benefit over conventional processes.

The design advantage and the process advantage of Additive Manufacturing are linked to the selection criteria as well as the following design process. Usually the selection criteria *integrated design*, *lightweight design* and *efficient design* are based on the design advantage. Whereas the selection criterion *individualization* mostly utilizes the process advantage of AM. In the following design process the designer has to decide on which advantage he exploits in the detailed part design. A manufacturing driven design strategy uses the process advantage and allows adjusting the production chain to the lot size. A function driven design strategy focuses usage of the product throughout its life time and uses the design advantage of AM. This usually leads to a complex shape and a dedicated AM-design. To clarify the different nature of these strategies and highlight the implications of the choice made both are explained in the following.

3.1 Manufacturing driven design strategy

The manufacturing driven design strategy uses Additive Manufacturing as a production technology. In this strategy the benefits of using Additive Manufacturing are derive from a substitution of manufacturing processes. By using only the process advantages of Additive Manufacturing the designer maintains a conventional design and complies with the design rules of other manufacturing technologies. Rapid Prototyping was the most prominent case of using the process advantages of Additive Manufacturing and still is an important application (Wohlers 2013). A part, designed for conventional production, is manufactured additively for time and cost reasons during the development process. The process advantage of Additive Manufacturing can also be used in series production especially to mass customize a product. Very prominent examples are additive manufactured dental implants (Roland Berger 2013). The shape of the implants was not altered when going from conventional processes to Additive Manufacturing. The dental labs only use the flexibility of the process to produce an individual, freeform object for each patient at lower costs. Another case that benefits from Additive Manufacturing's process advantage is the production of thermoplastic parts. Without the need to invest in an injection molding tool small series for niche markets become economically feasible. Companies can also reduce the risk of the ramp up of a new product. Instead of ordering a mold upfront the product is launched with additive manufactured components. The company can easily adjust the design according to the feedback of the first customers. Once launch is successful and a stable design is reached the production can be scaled up and might be transferred to a mass production process like injection molding. This transfer is only feasible, if the design complies with the design rules of the conventional manufacturing process.

3.2 Function driven design strategy

The function driven design strategy exploits the characteristics of AM to improve the functions of a product. Using the full potential of Additive Manufacturing‘s freedom in design usually rules out the transfer to conventional manufacturing without a major adjustment of the design. Therefore it is essential to have a solid business case for a purely additive design of a serial product. The decision for manufacturing an end product additively should be made at the beginning of the development process. At this point in time only few limitations are defined and the design can follow the function of the part. So now it is possible to realize complex geometries to approximate the design on a specification e.g. results from CFD or topology simulations. The resulting design often contains complex internal structures or integrated joints impossible to manufacture conventionally. An example for such a design is the medical device for shockwave therapy which was presented in Klahn et al. (2014). Handling properties, assembly and shockwave generation were largely improved by using the freedom in design offered by Additive Manufacturing.

4 CASE STUDIES

Two case studies are described in the following to illustrate the different nature of the process and design advantages. The first case presents an add-on for whiteboard marker which is conventionally designed and benefits from the process advantages of Additive Manufacturing. The second case study describes the re-design of a jigsaw base which uses the design advantages.

4.1 Case on manufacturing driven design strategy

The case of the Memox add-on for whiteboard marker illustrates the process advantages of AM. The purpose of the add-on is to place a board marker on a whiteboard directly and easily. The solution provided by the Memox is a little add-on for the cap of the marker that places a magnet to the tip of the cap. The basic requirement of the product development process was to safely attach the pen to the board and to be easily adaptable to any commercially available board marker. During the development of the add-on a Fused Deposition Modeling (FDM) printer was used for short iterations. A lot of different designs with variations of magnets and shapes where created for handling tests. For the first customer acceptance test in an office, a small series of 50 pieces were produced by Selective Laser Sintering of PA12. The initial design is depicted in figure 2.

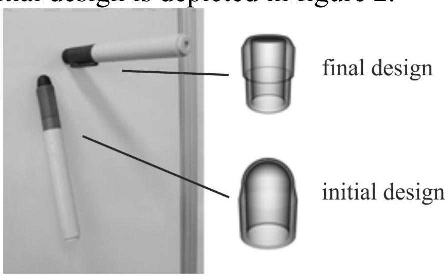

Figure 2. Board marker cap-design after customer feedback (top) initial design (bottom)

Selective Laser Sintering was chosen because the robustness of FDM prototypes was only sufficient for the development phase and injection molding involves high tooling costs. In this case the customer acceptance test showed a good handling and usage of the add-on, but there is a shorter usage life of the marker. The writing performance of the marker deteriorated quicker than usually observed on this product. The improper storage of the markers on the whiteboard was identified as the root cause. Due to the hemispherical shape of the initial design the tip of the markers points upwards and this leads to premature drying out. This was remedied by a change of cap and magnet geometry. The final design of the add-on cap ensures a horizontal position of the marker. Both the hemispherical initial design of the

cap and the final design are shown in figure 2 together with the resulting orientation of the marker on a whiteboard.
The rapid iteration in the design and the first customer acceptance test allowed a short development time and a robust design at the start of series production. For the successful launch of the product into the market a rapid availability of the product is important. Finding the right manufacturing technology for a quick ramp-up of this innovative product was the next step. A direct comparison shows significant difference in costs. To create reliable date on manufacturing costs different companies were asked for a quotation to produce a pilot series of given numbers of caps in less than 3 month. The offers are summarized in Table 1. The add-on caps are 20 mm high with a maximum diameter of 15 mm, with a volume of 1480 mm^3. An AM service provider offered to produce the add-on caps in SLS. Two prototype tooling companies (1) and (2) offered small series injection molding, with a delivery time of three weeks. These three companies offered only the production and delivery of the caps. The forth company is a mold manufacturer for series production and offered an injection molding tool made from tooling steel and also to produce the parts. Due to the higher complexity of an injection molding tool for series production a delivery time of 3 months is expected.

Table 1. Direct cost of different manufacturing processes to produce a pilot series

number of units	direct cost per unit [€]			
	AM Service Provider SLS	Prototype tooling (1) injection molding	Prototype tooling (2) injection molding	Series tooling injection molding
25	6.88	107.83	194.56	-
100	6.60	33.33	54.88	-
1 000	1.04	4.98	5.97	19.10
10 000	1.00	1.41	1.00	2.24
100 000	1.00	1.08	0.52	0.74

Figure 3 shows clearly that in the presented case for the production of up to 10,000 units AM is more favorable than injection molding. At higher batch sizes the investment in tooling pays off and conventional injection molding is more favorable in costs.

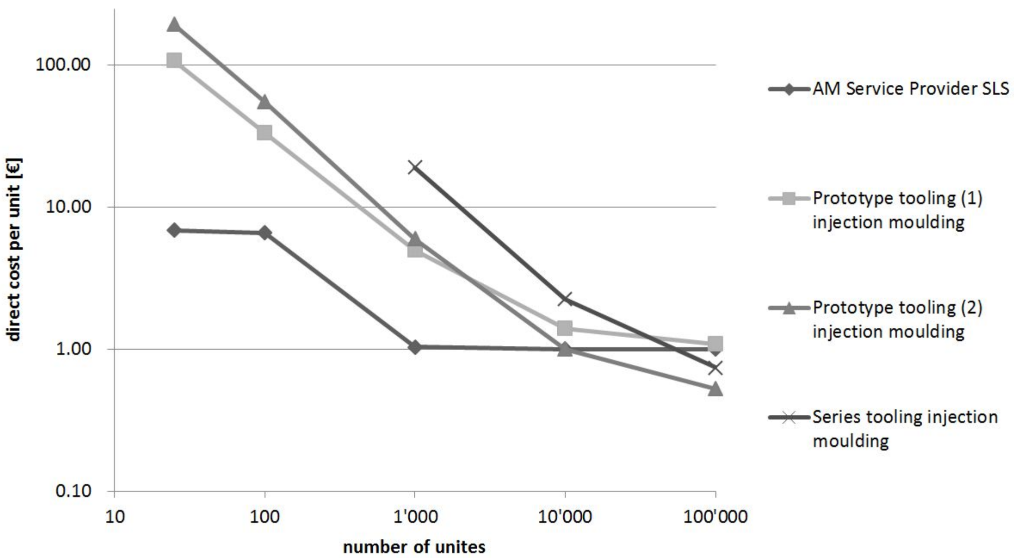

Figure 3. Direct costs per unite as a function of lot size

This Case highlights the importance of distinguishing between process and design advantages of Additive Manufacturing, because they are linked to the choice of design strategy. The design of the add-on caps complies with the rules of conventional manufacturing methods in particular the ones for injection molding. Due to this it is now possible to change the production process for mass production

of the Memox add-ons for board markers. The downside of the manufacturing driven design strategy is that the use of Additive Manufacturing does not create any added value to the user, because of the conventional part geometry.
Finally, it should be noted that this case clearly shows that AM can be used not only in product development and testing. Especially for the launch of a product its high flexibility and cost advantages for smaller quantities make Additive Manufacturing a suitable method for the series production. When a transfer to conventional manufacturing is planned at a later stage, it is important follow conventional design rules.

4.2 Case on function driven design strategy

Deciding at the beginning of a development process to use Additive Manufacturing as the only production technology allows a function driven design and full use of the design advantage of AM. The following showcase of an optimized jigsaw base illustrates this approach. An initial analysis of the sawing process revealed that the sawdust blower device of a commercially available jigsaw provides a clear view of the cutting line. The installed saw dust extraction, however significantly reduces the sawdust transport and thus contaminates the work piece with a considerable amount of sawdust. One reason for this is the positioning of the openings of blower and extractor the evaluated jigsaw model. Both are located in the body of the jigsaw, behind the jigsaw blade and well above the work piece. Due to this positioning the air flows of the blower and the extractors neutralize each other.
The goal of the redesign was to relocate or redirect both the sawdust blower and the dust extraction from the jigsaw body into the base. As an additional function a switch for the dust blower should also be implemented in the jigsaw base. The air comes from the body of the jigsaw and is either directed to the cutting area or vented at the side of the base.
A first simple test with this arrangement showed a significant reduction in pollution on the work piece. Based on these test results, the positioning of the ducts in the redesign of the new jigsaw base was carried out which can be seen in figure 4(a). By positioning the sawdust blower directly opposite of the extraction both act in the same direction. The flow of air transports the sawdust into the extraction and the performance of the system is improved.

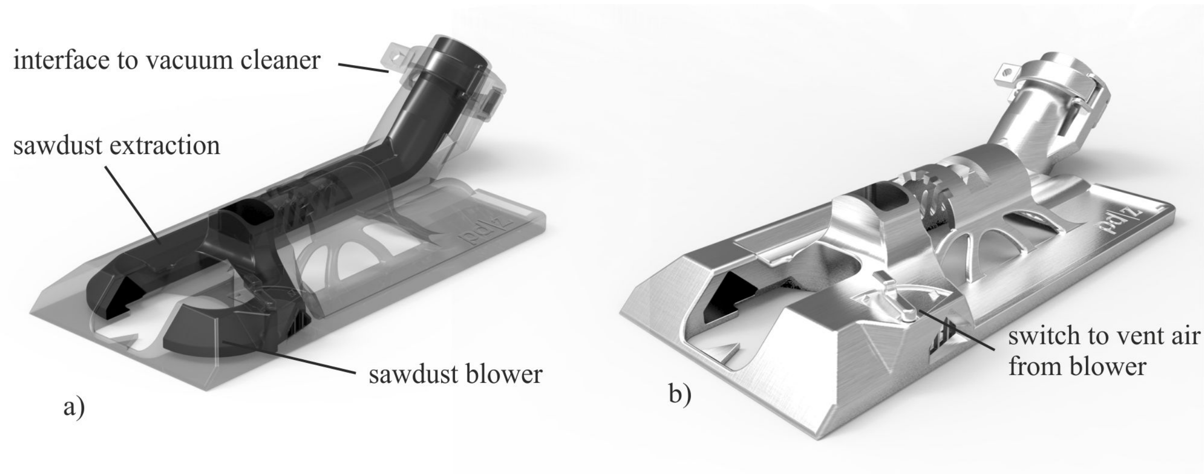

Figure 4. New jigsaw base a) internal duct design, b) CAD-model of final design

In the AM-process of Selective Laser Melting (SLM) all overhanging structures above a certain angle require support structures. The ducts are designed with triangular cross-section to reduce support structures and to avoid a costly removal of these structures during post processing. The integrated switch in the channel of the dust blower also needs support. Both the lever on the outside and the internal gate valve are overhanging structures that require support during the manufacturing process. In order to allow a free movement of the switch, a downward tapering is added to lever and gate. Thus, only a minimal linear support structure is required, which is broken away at the first actuating. The remaining supports at the lever can be removed easily. To remove the remnants of the support structure in the duct, a shear edge has been integrated into the component as seen in figure 5. This allows the shearing of the support structure from the gate valve at the first full opening of the gate. After the design of the jigsaw base for the process of SLM a prototype is produced in SLS to test the performance of the saw dust removal. A direct comparison with dust blower and extraction shows that over 95% of the sawdust on the work piece surface is removed by the optimized jigsaw base compared to the conventional base.

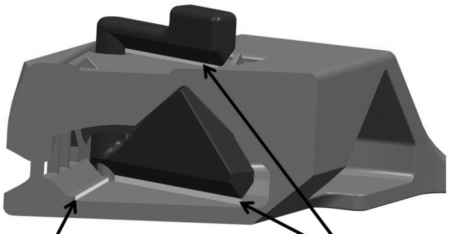

Figure 5. Sawdust blower shift detail

The case of the optimized jigsaw base clearly shows that the decision for Additive Manufacturing, and against the option to change back to conventional manufacturing, has considerable impact on the design of the product. Deciding to use the design advantages of AM allows a radical focus on the function, in the presented case on the optimal transportation of sawdust. A striking feature of the design of the jigsaw base is the circumvention of AM's process restrictions by design. Especially in the metal processing of SLM there are design rules (Kranz 2015, Adam 2014). A designer is strongly advised to comply with these rules to ensure a stable and cost efficient manufacturing process.
Designing the jigsaw base with a clear focus on the functions of the sawdust removal led to a design, which can only be manufactured by Additive Manufacturing. A simple change of the production method is therefore not possible. A re-design for conventional manufacturing is not impossible, but will lead to loss in performance and requires dividing the base into several subparts. This might be necessary, if the presented showcase is to be industrialized since the usual jigsaw production is above hundred thousand units per year.

5 IMPLEMENTATION AND FEEDBACK FROM INDUSTRY

The four selection criteria presented in section 2 and the design strategies were taught in trainings and at public events. They were presented together with industrial case studies to demonstrate the application of the criteria in the selection process and to give the audience an inspiration for designing a successful additive manufactured part in their company.

5.1 Selection criteria

The selection criteria proved to be useful in a number of industrial and academic projects. A very positive feedback was given by development projects that started from scratch or targeted a specific challenge in a given design. In these projects the selection criteria led the designers to parts and assemblies where a change to Additive Manufacturing gives additional freedom in design to tackle the challenges. In these scenarios the number of parts in scope is limited and the people involved in the development project are familiar with the design, therefore a manual selection process was applied.
In other projects the task was to screen the whole product portfolio of a small or medium sized company. More people were involved in these projects and the number of parts in scope was higher. To cope with a screening process of this scale the task was handed down to the departments to reduce the scope for each group involved in the project. Each department received a presentation with instructions on Additive Manufacturing and the use of the selection criteria and a template to describe the identified parts. The template summarized the profile of each part and contained basic data like part dimensions, material and lot size plus a description of the expected benefits from changing the production to Additive Manufacturing. A group of Additive Manufacturing experts evaluated the profiles and categorized them in three groups:

- a design for Additive Manufacturing will bring a benefit,
- risks and expected benefits of Additive Manufacturing require a closer evaluation, and

- the part can’t be manufacture by AM in the near future because of dimensions, costs or other restrictions.

A fourth category of parts with no expected benefits was void after the evaluation. A key message of the training was to focus on possible improvements of the performance and the empty category shows clearly that this message was received by the audience.

The experience gained from the screening projects shows clearly that the selection criteria are well suited for small and medium project where the focus is on solving a problem with the advantages of Additive Manufacturing. The second described project is of a different type because of its size and also because the focus shifts towards finding problems for a given solution. Here the quality of the results depends too much on having dedicated persons throughout the company. To improve the screening process the search has to become more systematic and the criteria need to be more detailed.

This is done by adding indicators to support a systematic screening process performed by a small, dedicated team. Indicators can either be used to highlight suitable parts or exclude parts which don’t match the capabilities of Additive Manufacturing. With basic information on size, material and number of parts per year it is easy to exclude parts which are technically or economically not feasible to become an additive manufactured part in a serial product. These indicators are called negative indicators. It is necessary to document the reasons behind each negative indicator so they can be revisited as the Additive Manufacturing processes and equipment evolve. For example there has been an enormous development in recent year regarding building chamber size, build rate and it is expected to continue (Wohlers 2013, Gausemeier 2013).

Positive indicators can also be derived from the basic data that can be found in databases. A positive indicator is a production process that involves drilling many holes of different size and plugs on the bill of material. Based on these indicators it can be assumed that the part has a complex internal channel. Replacing the current combination of drilled holes, sharp edges and dead ends with a smooth freeform channel that is adapted to the requirements of the fluid flow will reduce the pressure loss in the part and increase the performance of the product. This matches the selection criteria of efficient design. Another positive indicator are joined parts from the same material. Probably this design was chosen because of some limitations in conventional manufacturing. By replacing the assembly with a single additive manufactured part it is possible to save production steps and assembly lead time. This corresponds with the selection criteria of integrated design.

The information behind some indicators is directly available in an Enterprise-Resource-Planning (ERP) database. Size, volume, material and required number of parts are easily accessible. Some indicators, like the efficient use of semi-finished material (e.g. buy to fly ration) or the bounding box, probably require some effort to interpret the ERP data. Others are not directly available from the ERP system. The ERP might show that topology optimizations, FEM or CFD simulations were performed, but the detailed results are usually not stored in a format that automatically provides information on how close the part is to the optimum shape. Nevertheless the fact that a simulation was performed indicates that there are important requirements on the part and it needs to be checked, if the performance can be increased by using the freedom of design offered by Additive Manufacturing.

A general characteristic of these indicators is that they only point to a possible application for Additive Manufacturing without providing a quantitative score. The evaluation of the indicated part or assembly remains currently with a skilled professional. He will assess the potential of Additive Manufacturing with respect to the application and the user’s requirements.

5.2 Design strategies

The parts and components identified by the selection criteria a handed over to the design departments. The designers have to choose a design strategy and follow this strategy in the detailed design. From our academic and industrial projects we gained valuable feedback on this part of the development process too.

Designers are trained in Design for Manufacturing and they are very good in identifying and removing cost drivers of conventional processes in a design. The resulting parts can be manufactured cost efficiently in reasonable lead time using conventional processes. One of the main cost drivers in conventional processes is the complexity of the part’s shape. Additive Manufacturing offers complexity for free and the consequence is a significant change to design paradigms (Emmelmann et al. 2013; Campbell et al. 2013; Campbell et al. 2011). The designers often require guidance during the

first designs for Additive Manufacturing to challenge conventional design rules, e.g. holes are not drilled anymore, and therefore there is no need for them to be circular and straight.
Choosing between conventional and additive manufacturing is a decision at a high level of uncertainty. The designer is already experienced in designing parts for conventional processes and companies have a solid knowledgebase on the properties of such a part. Regarding an additive manufactured alternative this knowledge is missing in most companies.
In the manufacturing driven design strategy the design of the part can be manufactured additively as well as conventionally. There are probably only minor differences between the conventional and the AM version of a design. Therefore a designer is able to estimate the properties of the part and the resulting behavior in the application based on his experience in conventional designs. The uncertainty in the decision results mainly from the unknown cost structure of Additive Manufacturing.
Following a function driven design strategy implies a radical, function-oriented design which is usually not feasible to manufacture conventionally. Without experience in designing for Additive Manufacturing a designer has difficulties to quantify the expected part's volume bounding box and shape. These properties are usually needed to estimate the manufacturing costs. It is even more difficult to estimate the expected benefits of an AM-Design. The benefits not only consist of the direct benefits of a cheaper or faster production. The largest gains are usually achieved from indirect benefits during the lifetime of a product, e.g. from less weight or a higher efficiency.

6 CONCLUSION

The continuous development of Additive Manufacturing processes keeps extending capabilities and reduces manufacturing costs. Additive manufacturing becomes an established manufacturing process for serial products in a growing number of industrial sectors. Although it is unlikely to substitute conventional manufacturing in general, AM's unique characteristics are a valuable contribution to the portfolio of production technologies.
Currently the integration of Additive Manufacturing into industrial processes, on the shop floor as well as in product development, is only at the beginning. One of the challenges is industries' lack of knowledge and experience. Companies are interested in these new manufacturing processes, but finding the right applications is an issue for them. To support designers in this process the authors developed selection criteria. Those proved to be very useful to small teams, but for an extensive search for components that would benefit from a re-design for Additive Manufacturing the criteria are not specific enough. In this paper the concept of selection criteria was extended by indicators for a systematic screening of a given set of components. The indicators either rule out items which can't be produced by Additive Manufacturing or indicate a potential benefit of Additive Manufacturing. Some indicators are derived from data usually stored in an ERP system to enable an automatized pre-selection. Others are ambiguous and require an application expert to interpret. He will also assess the potential benefits of a re-design and do the final selection.
Once a component is selected for Additive Manufacturing the designer has to choose a design strategy. His options are to use either the process advantages in a manufacturing driven design strategy or the design advantages in a function driven design strategy. This is an important decision, because each path has also disadvantages. In a manufacturing driven strategy Additive Manufacturing is primarily used as a manufacturing technology with cost benefits at complex shapes and small lot sizes. Once the situation of the product changes, e.g. the product is established in the market and sales increase, the production can easily be transferred to a conventional process.
In a function driven strategy the designer neglects all conventional design rules and designs the part only according to the requirements of the application and the AM process. The resulting design can only be produced by Additive Manufacturing and a change of production requires a complete re-design. The benefit of this design strategy is a much better performance of the product in terms of weight, efficiency and the numbers of parts in the assembly. Both approaches were demonstrated by cases.
The chosen design strategy has also implications on the selection process. Selecting a component to be designed using the process advantages is easier, because the business case requires only cost estimations of the production processes. A business case for a design which uses the design advantages of Additive Manufacturing has to take into account, that the shape and performance of the

product will change a lot during the development process. This makes the upfront estimation of the production costs and the improved performance difficult.

The presented selection criteria and indicators will provide a proper guidance for companies to make the decision for Additive Manufacturing in their serial products. The awareness for the two very different design strategies to use the advantages of Additive Manufacturing will help them to make informed decisions on the route of the development process.

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