APPROACH TO CONSIDER RAPID MANUFACTURING IN THE EARLY PHASES OF PRODUCT DEVELOPMENT

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Abstract

Additive Manufacturing technologies are becoming more and more economical. In some cases – due to the possible complexity of geometry – they can be competitive to conventional manufacturing. But nowadays, Rapid Manufacturing is mostly not included in the decision for the manufacturing technology because of a lack of knowledge on the part of designers. In order to consider Rapid Manufacturing as an alternative, a step-by-step decision-making process with evolving parameters is proposed in this approach. Here, the consideration of Rapid Manufacturing, as well as Conventional Manufacturing technologies, can be included in the assessment. The proposed step-by-step procedure with hierarchically structured characteristics for the product and the manufacturing processes should ensure that decisions are supported in the early phases of product development as well as in the later phases. By using the suggested procedure, it is possible to take full advantage of the potential of Rapid Manufacturing in the early phases of the product development process. In this stage, the potential can be classified as the highest, because of the high level of design freedom.

Keywords: Early design phases, Decision making, Design process, Rapid Manufacturing, Additive Manufacturing

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Please cite this paper as:
Surnames, Initials: *Title of paper*. In: Proceedings of the 20th International Conference on Engineering Design (ICED15), Vol. nn: Title of Volume, Milan, Italy, 27.-30.07.2015

1 INTRODUCTION

Additive Manufacturing technologies produce solid parts layer by layer. In the past, these parts were mostly used as prototypes (Rapid Prototyping). In contrast to this, Rapid Manufacturing or Direct Manufacturing means that parts are produced as end products, thus the product requirements are more rigorous then for prototypes (Borille und Gomes, 2011). An end product is defined as a marketable product with a lot size starting from one (VDI 3404).
An improvement in the quality of additive-manufactured parts in the last years makes Rapid Manufacturing more and more competitive compared to conventional manufacturing technologies (Gibson et al., 2010). In addition to this fact, manufacturing processes are becoming more stable and reproducible (Gebhardt, 2013). The first rapid-manufactured products are already on the market, like some special drills with cutting inserts developed by Mapal (Mapal, 2014). Like in this example, where the cooling channels could be better integrated into the drill, the advantages of Rapid Manufacturing are justified by the freedom of design and the possible shapes.
Wohlers Report (Wohlers, 2001, 2010) gives an annual overview of how companies are using Additive Manufacturing techniques. As seen in Figure 1, the use of Additive Manufacturing has changed in the last few years. In 2001, Rapid Manufacturing was not explicitly listed, but formed part of the 4% ‘Others’ category, whereas in 2010, 15% of all products were end products (Wohlers, 2001, 2010).

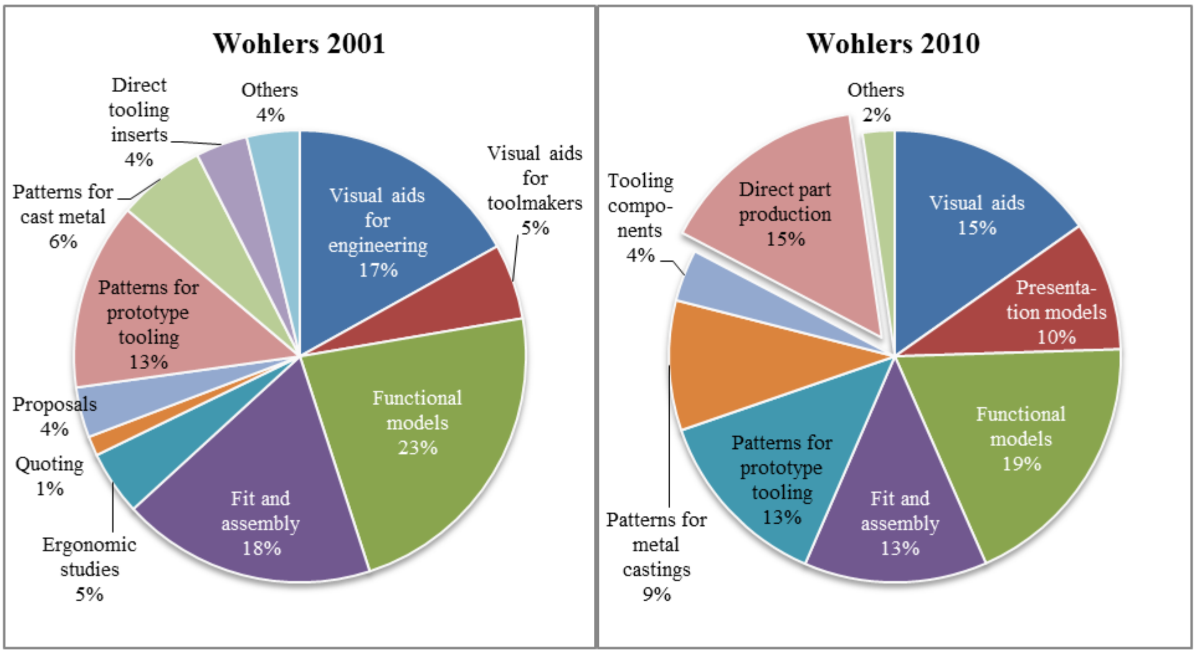

Figure 1. Use of Additive Manufacturing in 2001 and 2010 (Wohlers, 2001, 2010)

The development of the use of Additive Manufacturing shows that the technology provides the potential for directly producing end products, and its use for this application is increasing. A detailed analysis of the current manufacturing cost and an evaluation of expected improvements by Roland Berger Strategy Consultants in 2013 reveals a cost reduction potential of about 60% in the next 5 years and another 30% within the next 10 years (Langefeld, 2013). According to Hopkinson et al. (2006), Rapid Manufacturing displays many of the clear symptoms of a technology that can be described as disruptive. This means that Rapid Manufacturing will become more and more competitive to conventional manufacturing in future.
One of the major benefits of Additive Manufacturing is that it is possible to produce virtually any complexity of geometry at no extra cost. However, conventional manufacturing techniques show a direct correlation between the cost of a component and its design (Hopkinson et al., 2006).
The relationship between the complexity of geometry and the manufacturing costs is shown as an example in Figure 2.
Above a critical level of complexity of a product, as in many bionic structures or in parts with an optimised topology, Rapid Manufacturing can be cheaper than conventional techniques. Above a

certain level of complexity, the parts are not producible by conventional techniques any more. On the other hand, conventional manufacturing techniques are more economical in the case of products with lower complexity. Thus it does not make any sense to produce e.g. a simple plate using additive technology.

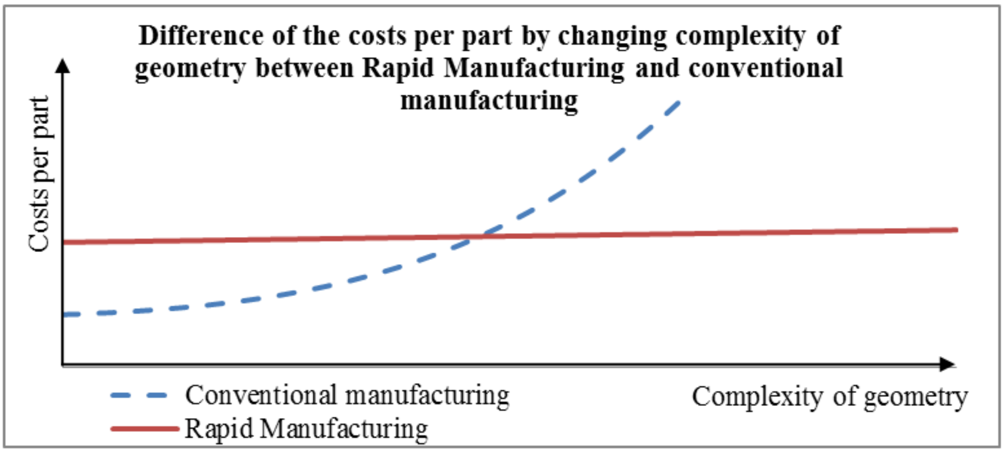

Figure 2. Difference of the costs per part by changing complexity of geometry between Rapid Manufacturing and conventional manufacturing adapted from (Hopkinson et al., 2006)

Rapid Manufacturing directly produces components from a three-dimensional, computer-aided design without the need for tools, and allows the production of more than one part at a time in the same process (Ruffo et al., 2006). Because there are no further preparatory steps needed, the advantages of Rapid Manufacturing are especially high in the production of smaller lot sizes. Here, the share of the costs for the tools and the work preparation for conventional techniques is particularly high.
The relationship between the costs per part and the lot size is demonstrated in Figure 3. The costs per part for Rapid Manufacturing are nearly constant and the lot size does not show a high influence on these costs. However, the costs per part of conventional manufacturing decrease with the number of parts. If the part is producible in both ways and its complexity is above a critical level of complexity, Rapid Manufacturing is more economical until the break-even-point. With a larger number of parts, conventional manufacturing should be preferred. The second line for Rapid Manufacturing and a design for function shows that the costs per part can be reduced if the design is optimised for Additive Manufacturing. That means that the break-even point is at a larger lot size. A second line for conventional manufacturing is missing, because in this case, the parts cannot be produced using these techniques. A change of the complexity of the geometry within the limits of conventional manufacturing, as described in Figure 2, would cause a vertical movement of the curve for conventional manufacturing.

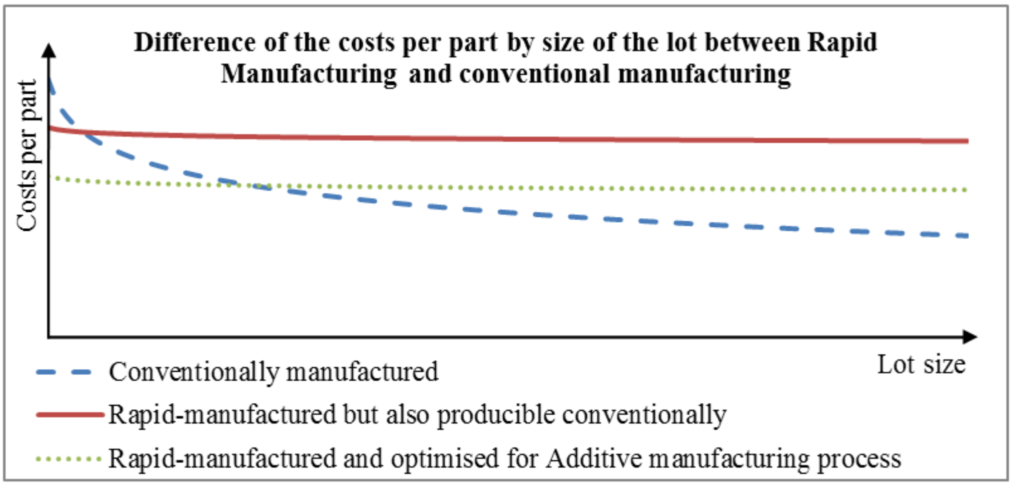

Figure 3. Difference of the costs per part by size of the lot between Rapid Manufacturing and conventional manufacturing adapted from (Ruffo et al., 2006)

2 PROBLEM STATEMENT AND GOALS

The main advantages of Additive Manufacturing technologies are related to the ability to build geometrically complex shapes without tooling and with high process automation (Borille und Gomes, 2011). But nowadays, they do not achieve the same surface qualities and tolerances of form and dimension as conventional production processes such as milling. Therefore, if Conventional Manufacturing techniques of a component are merely substituted by an additive procedure, it will not create the desired results, plus it will be much more expensive. But there is often a way to fulfil the same function as the conventional part with a part that was especially designed for Additive Manufacturing. This is because additive technologies offer the designer the possibility of improving part functionality using more complex shapes (Borille und Gomes, 2011). If the design also uses the possibilities of component integration, it is possible to reduce the costs for additive-manufactured parts. In some cases, if a product is strictly designed for Rapid Manufacturing from the very beginning, it can even become the more economical design. In order to realise these benefits, it is necessary to think and design in a different way in the early phases of the product development process; namely by considering the given possibilities of shapes and integration of function provided by Additive Manufacturing technologies.

The research for this paper has shown that presently, there is no method which supports designers in the decision for the manufacturing technology – including Rapid Manufacturing processes – through the whole product development process according to (VDI 2221). Recently, Rapid Manufacturing technologies were not used (Gebhardt, 2013), because most designers still do not really know about the possibilities they offer, such as facts about achievable densities or possible geometries (Marquardt, 2014). So, at present, there is in fact no design for Rapid Manufacturing in most companies. That means that Rapid Manufacturing nowadays is only considered as a manufacturing choice if Conventional Manufacturing is not possible. Often, this observation is just made in the late stages of the product development process. So, because of the lack of knowledge about Rapid Manufacturing, the possibilities for geometric complexity offered are not used and development time is wasted.

To avoid this extra development effort and use the options of complex geometries, the possibility of using Rapid Manufacturing should be considered as early as possible in the product development process. Therefore, it is necessary to support designers with a method that helps to consider the possibility of Rapid Manufacturing in the early stages of the product development process. Because of the many different manufacturing processes, and regarding the high uncertainties of the early stages of the product development process, the decision for the appropriate manufacturing technology cannot be made in one step. The method should therefore not only support designers in the early phases of product development, but up until the point where development ends and production begins. To not create an extra tool purely for Rapid Manufacturing and to make objective decisions, the method should also include the choice for conventional manufacturing technologies.

The core of this paper comprises an approach to support designers by proposing a decision scheme which becomes more and more detailed during the product development process. According to this scheme, the choice for the manufacturing technology should be made step-by-step, including Rapid Manufacturing as well as conventional manufacturing.

The overall research question that leads through this paper is: *"How does the concept of a decision process for manufacturing technology have to be structured to include the choice for Rapid Manufacturing from the early stages of the product development process?"*

2.1 Focus of the paper

The focus of this paper is a step-by-step choice of the manufacturing technology according to the increasing product knowledge during the product development process. Therefore, the decision of the most suitable manufacturing technology becomes more and more concrete within the product development process. The consideration of the use of Rapid Manufacturing for creation of end-use parts instead of conventional manufacturing technologies is addressed in particular.

Despite several steps of a stage-gate-process according to Cooper (2011) in innovation management, the steps for the manufacturing choice are not linked to a fixed time. The method proposed in this paper is not meant to force decisions and to create extra gates in the product development process, but to support designers in the decision for a certain manufacturing technology depending on the actual product knowledge.

The approach of a step-by-step decision for the manufacturing technology is especially suitable for the development of new products, but it can also be used to rethink an existing product.

3 STATE OF THE ART

In this section, existing decision-making methods used in the context of Rapid Manufacturing are described.

3.1 Decision making in the context of Additive Manufacturing

It is not the focus of this contribution to specify the decision-making method which should be used during the process of selecting a manufacturing technology. Generally, it can be used in nearly every conceivable procedure.

In the past years, several decision-making methods for the selection of Additive Manufacturing systems have been developed. Some of them are even computer-based. The early approaches for decision-making systems mostly did not consider additive technologies as competition for conventional manufacturing; rather, they tried to support the selection of Rapid Prototyping technologies or Additive Manufacturing technologies to create tools (Rapid Tooling) (Ghazy, 2012). However, some of the newer methods include the manufacturing of end-use parts. Ghazy (2012) gives a good overview of the existing methods.

One of the first methods including Rapid Manufacturing was proposed by Bernard et al. (2003). They discussed a knowledge-based environment dedicated to the choice of rapid product development processes. That means that they considered the integration of CAD or reverse engineering alongside the manufacturing technology. The discussed system – called ACPIR – is based on rules established by experts. However, the system cannot be changed by the user and only supports the selection within Rapid Manufacturing.

The RP selector developed by ivf (2005) and a selector for Rapid Manufacturing technologies developed by the Georgia Institute of Technology, the main concepts of which can be found in (Gibson et al., 2010), were developed in 2005. They both support the decision between different Rapid Manufacturing technologies and provide information about materials, but do not include conventional manufacturing.

Mahesh et al. (2005) address an integrated Rapid Prototyping decision-making system (IRPDMS) based on fuzzy decisions and benchmarking for selecting appropriate Rapid Prototyping and Manufacturing processes. It provides decision support for five Additive Manufacturing technologies while interacting with a benchmark database.

The development of an AI-based Rapid Manufacturing Advice System by Munguía et al. (2010) assesses the possibility of Rapid Manufacturing instead of conventional manufacturing. This is done by means of a computer-aided system, intended to guide the designer in the selection of optimum production parameters, according to general product requirements. As it is focused on the early stages, it addresses a lot of the aforementioned problems. The main difference to this approach is that the evolution of product knowledge is not considered within the procedure. For this purpose, the system works with pre-defined necessary input parameters (Munguía et al., 2010) of just one level of detail.

Ghazy (2012) developed a computer-based system (AMDSS) to support the decision between different Additive Manufacturing technologies. The decision process consists of several steps. In the first step, possible processes to produce the part are filtered by requirements like size, quantity, surface finish, minimum wall thickness and accuracy level. The second step is a material filtering step. Its output is possible materials which can fulfil the requirements within the filtered processes. The next step is the decision between the suitable processes and materials. It starts with the weighting of nine criteria: strength, hardness, heat deflection temperature, density, dielectric strength, modulus, wall thickness, accuracy and surface finish. So it includes not only the Additive Manufacturing process, but also finishing options. Based on the weighting, the process and materials are ranked.

Most of the listed methods cover the decision between different Rapid Manufacturing technologies, even if they are not focused on Rapid Manufacturing. The main difference to the approach of this paper is that they do not contain an iterative thinking process according to the increasing product knowledge in the product development process.

4 APPROACH FOR AN EVOLUTIONARY SELECTION OF THE MANUFACTURING PROCESS

This section, describes the steps of an evolving decision for the manufacturing process. That means that the number of possible manufacturing technologies will be reduced during the development process.

4.1 Steps of the decision for the manufacturing technology in the product development process

In order to use the full potential of Rapid Manufacturing, the potential of the technology should be considered as early as possible in the product development process. As shown in Figure 4, according to Krause (2007), product knowledge increases within the product development process, whereas the freedom of design decreases. Especially in the early phases of product development, for example – according to (Pahl et al., 2007) – in the planning and task clarification and the phase of conceptual design, the freedom of design is very high. This provides high potential for a design for Rapid Manufacturing.

However, the product knowledge is still low at this time, and the final decision for the used technology cannot be made. In this case, the designers come to a decision in different steps related to the product knowledge. Figure 4 shows three example steps of decision making in the product development process. As indicated, the decision is not bound to a fixed point in time in product development.

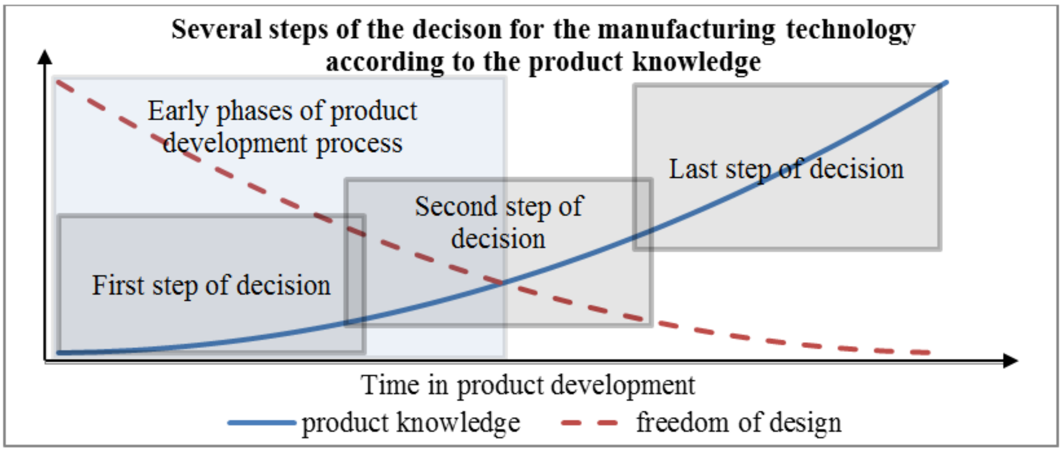

Figure 4. Several steps of the decision for the manufacturing technology in accordance with the product knowledge adapted from (Krause, 2007)

The different steps for the decision for the manufacturing technology with regard to the increasing product knowledge become more concrete during the product development process. This means that the requirements that are interlinked between the product and its manufacturing technology can be described more and more accurately. The comparison of the parameters is demonstrated in Figure 5 for two different steps of the decision for the manufacturing technology. As shown, the information that can be called upon for the decision increases between the several steps.

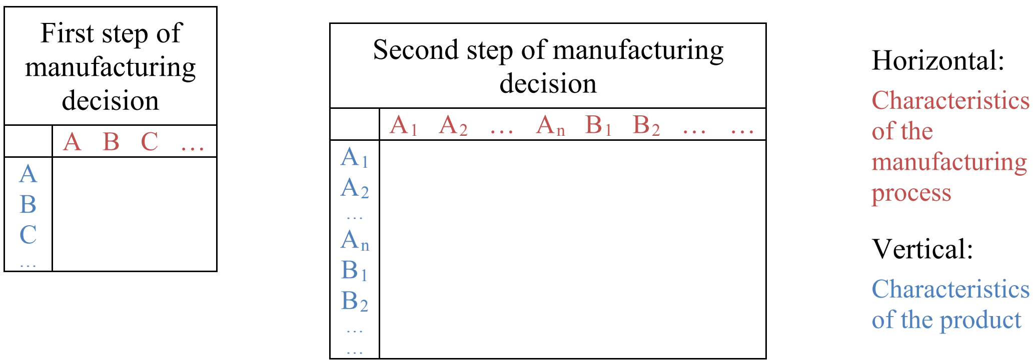

Figure 5. Different steps of the decision for manufacturing technology with increasing product knowledge

4.2 Definition of hierarchically structured characteristics

In order to match the product requirements and the achievable characteristics of production technology in different phases of the product development process, it is necessary to cluster both in a hierarchical structure. Here, the structure is the same for the product and for the manufacturing processes. Figure 6 represents the general hierarchical structure of characteristics that can be defined to enable the decision for the most suitable manufacturing process. The specific structures for manufacturing processes and products are discussed in the following sections. In the structure of Figure 6, the details of the characteristics increase from general characteristics to specific characteristics. As can be seen, for example, characteristic A includes the sub-characteristics A_1 until A_n , whereas the sub-characteristic A_1 again includes the more detailed characteristics A_{11} until A_{1n}. The definition of the characteristics and the levels of detail are not generally covered in this paper. This means that the level shown in Figure 6 is not binding, so it can also be appropriate to define four levels of detail for characteristic B, for example.

Kerbrat et al. (2010), for example, define three categories of parameters to estimate manufacturing complexity for machining and Additive Manufacturing. In the proposed scheme, these three categories (geometric parameters, material information and technical specifications) could be seen as the characteristics B_1, B_2 and B_3. Furthermore, they divide the technical specification (B_3) into dimensional tolerance, geometrical tolerance, location tolerance and surface finish. This means that they are the sub-characteristics B_{31} to B_{34}. Used as an example for filling the scheme in this case, characteristic B could here be technical requirements, whereas characteristic A could be the manufacturing time per part with the sub-characteristics A_1 as time for preparation and A_2 as time of manufacturing process per part.

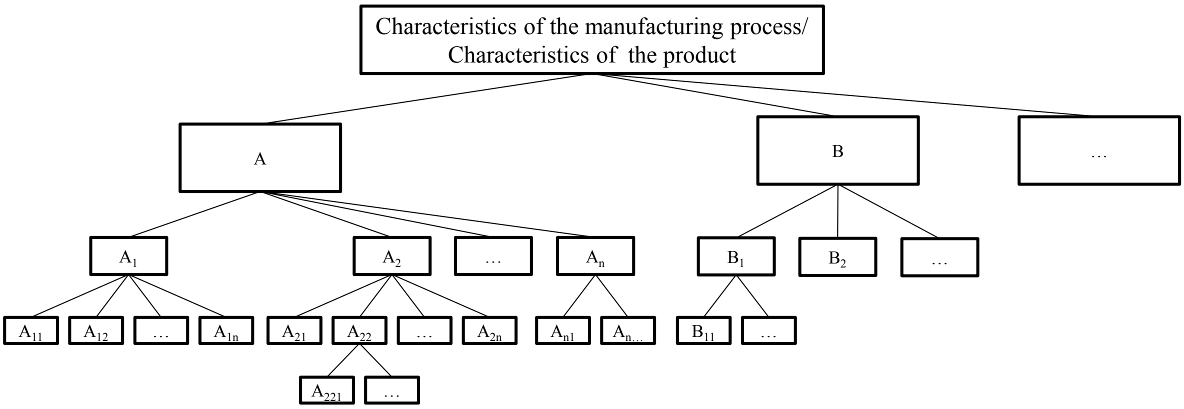

Figure 6. Hierarchical structure of characteristics of the product or the manufacturing process

To avoid an imbalance between the different characteristics at the same level of detail, the weighting, which is linked to the number of different characteristics in Figure 6, must be kept in mind during the selection of the manufacturing technology. This can be achieved by first defining a weighting for each characteristic, as in the case of the utility analysis according to (Zangemeister, 1970). It can alternatively be achieved approximately when only characteristics of the same level of detail are weighted against each other and the number of sub-characteristics of each level is nearly the same. The procedure in this case is imprecise, but it can be appropriate for the first steps of the decision, where the product knowledge is low and the provided information is vague.

It would also be possible to merely define different levels of detail without any relationship between them. That means that, for example, characteristic A does not contain any sub-characteristics any more, and it only exists in one level of detail. The consequence would be that the different levels of detail are not comparable any more due to the weighting. That is why a hierarchical structure is preferred in this work.

Because the hierarchical structure includes the manufacturing as well as the product, they are summarised as the technical characteristics.

4.3 Characteristics of the manufacturing process

As the knowledge of the achievable characteristics of the manufacturing technologies either exists in the own company or can be obtained by producers of the manufacturing systems or suppliers, it is possible to fill the hierarchical structure from Figure 6 with conceivable manufacturing processes.
Bearing in mind that the manufacturing technologies in a company are limited, meaning that not every conceivable technology is available, it is not necessary to fill the proposed scheme with the characteristics of every possible manufacturing process until the last stage. For the first qualitative decisions, it is appropriate to only characterise the existing manufacturing processes in the company and of its suppliers, plus the Rapid Manufacturing. To open the mind to other possibilities, the first level of every main group of manufacturing processes should be filled.
Afterwards, this set of characteristics of the manufacturing processes can be compared with the required characteristics of the product. Table 1 demonstrates how characteristics of several levels of detail can be structured to make the decisions for possible suitable manufacturing technologies during product development, using different kinds of characteristics, depending on the level of detail.

Table 1. Characteristics of several levels of detail for different manufacturing technologies

First level of detail								
Characteristics		Casting			Rapid Manufacturing			…
A	Technical possibilities	+			0			
B	Manufacturing time per part	0			+			
C	Costs per part	+			-			
…	…							
Second level of detail								
Characteristics		Sand casting	Chill casting	…	Laser sintering	Selective laser melting	…	
A_1	Achievable surface characteristics	0	0		0	0		
A_2	Max. volume per part	+	0		-	-		
A_3	Possible geometrical complexity	0	0		+	+		
…								
B_1	Setup time per part	-	-		+	+		
B_2	Cycle time per part	+	+		-	-		
…								
Third level of detail								
A_{11}	Achievable surface roughness R_a in µm	6,3	12,5		12,5	12,5		
…	…							

4.4 Characteristics of the product

The different hierarchical levels of the characteristics in Figure 6 represent the increasing knowledge during the product development process. This means that – as shown in Figure 7 – the knowledge about the characteristics of the product increases through its development, so the manufacturing process at the beginning of the development of a new product cannot be finally defined. In the course of the development, the knowledge increases and the required characteristics of the different levels of detail can be filled. The point in time where the knowledge of the specific product characteristics exists is indicated in Figure 7 by the letters on the graph. The collection of characteristics of the product is the same as for a manufacturing technology in Table 1.

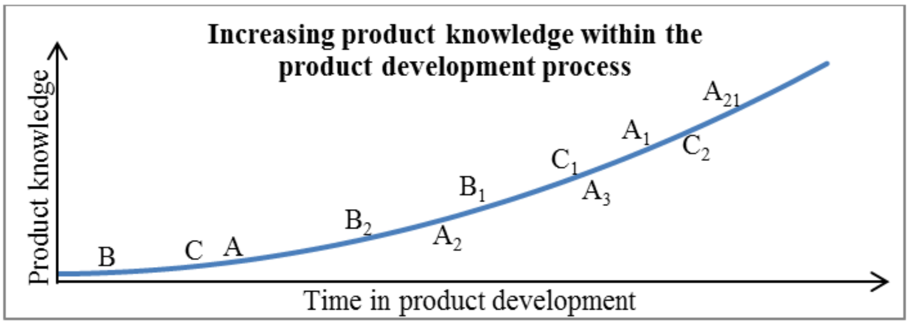

Figure 7. Increasing product knowledge within the product development process adapted from (Krause, 2007)

4.5 Approach for the estimation of the characteristics

As the knowledge about the product increases within the product development process, it is not possible to make definite statements about its characteristics for the different levels of detail. Because the parameters of the manufacturing technology influence each other and the level of influence depends on the design of the manufactured product, the manufacturing characteristics also contain an inaccuracy until the final design. In addition to this fact, a product is not made using one single manufacturing technology in most cases, but rather using several sequential processes.

However, this approach is meant to support the designer in the decision for the manufacturing technology and should be seen as a guideline; it should not exclude possible processes even if it is not certain that they are not capable of creating the desired results. Ashby (2005) proposes a comparable way of thinking in the selection of the manufacturing technology by considering all processes as possible until they are shown to be otherwise.

To achieve the goal of including possible manufacturing technologies as long as possible through several steps of a decision, the characteristics of the manufacturing process, as well as the desired characteristics of the product, should be estimated conservatively. This means that the achievable characteristics of the manufacturing processes should be considered as the best possible results. In case of Rapid Manufacturing, for example, the possibility of polishing should be included in the achievable process characteristics. For the product characteristics, the estimation is more difficult because of the uncertainty. But to get conservative values, it is appropriate to estimate the requirements of the characteristics on the lower side.

If, for example, the first and second steps of a manufacturing decision within the product development process are conducted by using checklists with exclusion criteria after the second step, all possible manufacturing technologies should remain conceivable. The final decision between the remaining technologies, for example, can be made by means of Analytic Hierarchy Process (AHP) to get the best suitable manufacturing technology. By estimating the characteristics conservatively, designers retain the freedom of design for as long as possible and the fact that products are produced in several process steps can be also considered.

Finally, it should be noted that the decision for the used manufacturing technology should always be made by the designer. The proposed scheme cannot cover all possible reasons that have influence on the decision of manufacturing and cannot replace the experience possessed by a human designer.

5 DISCUSSION

In this paper, an approach for a step-by-step decision for the manufacturing technology has been made. Here, the potential of Rapid Manufacturing can be considered from the beginning of the early phases of product development. The proposed scheme of hierarchical structured characteristics for the manufacturing technology and the product is therefore presented in a generic way. This means that it is not restricted to a pre-defined set of characteristics. On the one hand, this provides the ability to adapt the scheme to almost every conceivable manufacturing environment. On the other hand, it is more difficult to understand the purpose of the proposed scheme, as well as its application needs an extensive consultation of possible characteristics. Because a preferred decision-making method is not specified in this approach, some points regarding the use of the characteristics could not be discussed. For example, the height and direction of optimal characteristics depend on the valuation method used. So, depending on the valuation, it can be necessary to formulate the characteristics in a certain way so that higher estimations are always better. Another critical point with regard to the characteristics is the fact that in most decision-making methods, the compared parameters should be independent of each other. To develop a set of criteria that contributes to this fact necessitates a lot of effort. Keeping the overall aim in mind, to enable the designer to make suitable decisions for the manufacturing technology including Rapid Manufacturing, further steps are described in the following section.

6 CONCLUSION AND OUTLOOK

The proposed scheme of hierarchically structured characteristics of the product and the manufacturing process in general provides the ability to include new technologies in the decision for the manufacturing technologies in the early phases of the product development process. This means that, especially for Rapid Manufacturing, its potential to fulfil the same function in another way is considered early enough to design directly for Rapid Manufacturing. In future work, one or more definitions of the technical characteristics have to be defined. Based on these definitions, suitable decision-making methods can be chosen and the combinations must be evaluated. Furthermore, a recommendation for the timing of the decision steps within the product development process should be formulated to contribute to the conception of a guideline for this approach.

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