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Conception of a design catalogue for the development of functionalities with additive manufacturing

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Abstract

A key factor for exploiting the potential of additive manufacturing technologies is the full utilisation of the available geometrical freedom of design. Common solutions for design problems can be conceived in a new way using this freedom of design and the integration of functions and the use of a product can thereby be increased. One problem in the utilisation of additive manufacturing technologies is the lack of knowledge on the part of designers about the possibilities they provide. In order to give designers the ability to utilise these technologies in a more efficient way, possible good solutions for repetitively occurring design challenges should be provided to lead to an optimised design for additive manufacturing. This information can be provided in the form of a design catalogue. In this paper, the concept of a design catalogue for additive manufacturing technologies for several functions that can be fulfilled by technical systems is presented. In order to ensure high usability of the catalogue, the concept is based on a common definition of standard functions of technical systems. The main research question that recurs throughout the paper can be formulated as follows: "How should a function-oriented design catalogue for additive manufacturing technologies be structured in order to support designers in utilising the potential of the available freedom of design?" An additional challenge of the use of additive manufacturing technologies is their large number and consequently the mapping of possibilities provided by additive manufacturing technologies to the various processes. For this reason, the catalogue includes the information regardless of whether the function-orientated solutions are suitable for a special manufacturing process or not. The realisation of the design is supported by further information about restrictions that have to be respected. This information is additionally included in the catalogue. For a better understanding, some of the contained design solutions for the catalogue are shown in comparison to conventional design solutions.

Keywords: Additive Manufacturing, design catalogue, function driven design

1. Introduction

Additive manufacturing (AM) technologies are becoming more and more stable and reproducible (Gebhardt, 2013). An improvement in the quality of additive-manufactured parts over the last years has increased their competitiveness with regard to conventional manufacturing technologies (Gibson, Rosen, & Stucker, 2010). Therefore, they can even be used for the production of end products. End products are marketable products with a lot size starting from one (VDI 3404). For the purpose of the production of end products, AM technologies also have to prove economical compared to conventional manufacturing technologies. The costs of AM almost only correlate with the required build volume for the product and not with its shape. In contrast to production using conventional manufacturing technologies, the costs of AM do not increase to a great extent with the complexity of the product (Zäh, 2006).

By utilising the high freedom of design provided by AM technologies, the required build volume and subsequently the costs of production can be reduced. In addition to this, other advantages of the products can be achieved with a design for AM, such as a lightweight design of the product or a reduction of necessary assembly steps (Wohlers, 2014). With AM, the functionality of a product can be improved beyond the limits of conventional manufacturing by taking advantage of increasing the complexity of its design (Leutenecker, Klahn, & Meboldt, 2015). A design for AM leads to a high integration of functions, which comes with part integration. It is unlikely that AM technologies will replace conventional technologies in general, but they can be considered as an extension of the available technologies. To summarise, with an adjusted design for AM, the technologies in question are becoming more competitive compared to conventional manufacturing technologies in terms of costs, and the products can provide some additional advantages.

2. Problem statement and goals

During product development, according to guideline (VDI 2221), the definition of a product becomes more specific. The most freedom of design is left in the early phases of the product development where the working principles of the product are not yet determined. Until now, the freedom of design provided has basically not been exhausted by designers (Gebhardt, 2013). The reason for this is that they are not trained to design for AM. In order to utilise the full potential of the freedom of design of AM, the designers have to be supported in these early phases where the potential is still available.

New products or products redesigned for AM have to fulfil the same functions as conventionally manufactured products. However, as shown before, the available geometrical freedom of design has to be utilised to create a crucial advantage compared to conventional production. This means that the desired functions have to be fulfilled in a different way for a design for AM. As an example, joints can be integrated with AM in a part so that an assembly becomes unnecessary. In a conventional design, the same degree of freedom would have been solved by using a pin connection between two assembled parts.

According to Klahn, Leutenecker, & Meboldt (2015), the decision for the use of AM as the only production technology at the beginning of a product development process allows full utilisation of the design advantages of AM. In order to achieve the goal of developing additive-manufacturing-compliant products, designers should be supported in the early phases of product development. The "search for solution principles and their combinations" in guideline (VDI 2221) describes the step where working principles to fulfil the desired functions within the product are determined. The input in this step is the desired functions and their structures. The output is the principle solution to fulfil them. Subsequently, the functions of the product can be divided into sub-functions for which sub-solutions have to be found. Here, "the search for solution principles depends initially on the degree of novelty of the task and on the state of knowledge of the designer" (VDI 2221).

For an additive-manufacturing-compliant redesign of a product as well as for a new product, the possible solutions are most likely unknown. In relation to this, possible solutions should be provided for designers to lead them to a compliant design for AM. The possible solution principles should be structured in a way that provides easy access to the desired solution. An often used, and therefore proven, method to structure such design solutions is a design catalogue.

The structure used within a design catalogue should take into account that the information which is available at this stage of product development is limited to the product's desired functions. Regarding this, and to make the design catalogue applicable to various design tasks, it should be structured based on generally valid functions. "When classifying characteristics it is best to choose generally valid functions, which help to elicit the most product-independent solutions" (Pahl et al., 2007).

In order to present a tool that serves the need for support in the early phases of product development, the main research question that recurs through this paper can be formulated as follows: "How should a function-oriented design catalogue for AM technologies be structured in order to support designers in utilising the potential of the available freedom of design?"

3. Definition of generally valid functions

As mentioned previously, the functions of a product can be divided into sub-functions. In order to define generally valid functions, they have to be of such a level of granularity that they cannot be divided any more. Generally valid functions therefore have to be sub-functions. They represent a high level of abstraction and are of a lower complexity than the overall function of the product (Pahl et al., 2007).

Table 1 gives an overview of the most common definitions of generally valid functions. It shows the terms used by Krumhauer (1974), Claussen & Rodenacker (1998), Roth (2000a), Koller & Kastrup (1994), Heinrich (1968) and Waldvogel, (1969). As can be seen, the range of the number of defined, non-divisible, generally valid functions varies from three to more than ten. The definitions of Heinrich (1968) and Waldvogel (1969) do not perceptibly enlarge the spectrum of used terms and they are not as common as (Roth, 2000a), for example. The definitions of Krumhauer (1974), Claussen & Rodenacker (1998), Roth (2000a) and Koller & Kastrup (1994) are more common in product development and are also mentioned in (Pahl et al., 2007), for example. Therefore, they are discussed in more detail in this section.

All of the discussed definitions of generally valid functions have in common that they are based on the three conversions which are realised by technical systems that exist (Pahl et al., 2007):

- Energy: mechanical, thermal, electrical, chemical, optical, nuclear…, also force, current, heat…
- Material: gas, liquid, solid, dust …, also raw material, test sample, workpiece …, end product, component…
- Signals: magnitude, display, control impulse, data, information…

Table 1. Terms used in different definitions of generally valid functions, adapted to (Krumhauer, 1974)

Krumhauer	Claussen & Rodenacker	Roth	Koller & Kastrup			Heinrich	Waldvogel
Energy Material Information	**Energy**	**Energy Material Informa-tion**	**Energy**	**Material**	**Data**	**Energy Material Informa-tion**	**Several**
Change	Block	Change	Change	Change	Connect	Supply	Transfer
Increase	Link	Transform	Enlarge	Enlarge	Reproduce	Transmit	Create
Reduce	Channel	Connect	Reduce	Reduce	Channel	Transform	Change
Link		Channel	Change direction	Channel	Transcode	Convert	Maintain
Split		Store	Channel	Isolate	Store	Store	Separate
Channel			Isolate	Join		Transfer	Merge
Block			Accumulate	Dissociate			Combine
Store			Divide	Mix			
			Mix	Separate			
			Separate	Accumulate			
				Divide			

In (Krumhauer, 1974), general functions for possible use with a computer application during the conceptual design phase have been developed. In this case, changes of type, magnitude, number, place and time between the input and output of a technical system have been considered. Pahl et al. (2007) assign generally valid functions to the defined functions of Krumhauer (1974). The assignment is shown in Table 2.

Table 2. Generally valid functions according to Krumhauer and the assigned functions of Pahl et. al.

Characteristic	Functions according to Krumhauer	Assigned functions according to Pahl et. al.
Type	Change	Change
Magnitude	Increase Reduce	Vary
Number	Link Split	Connect
Place	Channel Block	Channel
Time	Store	Store

In (Claussen & Rodenacker, 1998), the definition of generally valid functions contains just three of them. The differentiation of the functions is blocking, linking and channelling of energy. The general validity is discussed for the flow of different forms of energy through technical systems. The context of the technically used view of the flow of signals and material is not covered in this definition.

Roth (2000a) defines five operations by which the status of the three general factors of design thinking, energy, material and signals can be varied. The five operations are changing, transforming, connecting, channelling and storing. Channelling and transforming are summed up as transferring.

- Changing refers to the type of one of the three factors energy, material and signal.
- Transforming refers to the magnitude of a factor. A transformation often implies channelling.
- Connecting can be differentiated into four possibilities which arise from the combination of a difference in direction and the type of flow of a general factor of design thinking.
- Channelling refers to the place of one of the three factors.
- The function of storing refers to the inclusion, the temporary storage and the exclusion of energy, material and signals.

Koller & Kastrup (1994) assign different definitions of general operations for energy-transforming technical artefacts, material-transforming technical artefacts and data-transforming technical artefacts. Here, some of the definition terms used have an opposite meaning. In Table 1, only the specific operations for energy, material and data are shown. In addition to these operations, “Energy and Material”, “Material and Data” and “Energy and Data” can be combined and separated within the definition.

4. Generally valid functions for the development of functionalities with additive manufacturing

As shown in section 3, there are already existing definitions of generally valid functions in literature. In this section, the use of the given definitions for the task of a design catalogue for the development of functionalities with AM is discussed and an appropriate definition is presented.

The structure of the generally valid functions used should be comprehensible. That means it should be based on common terms which are used by designers in daily work. Additionally, the definition of the structure should be clear and precise, so the overlaps in the use of the defined terms should be as small as possible. Considering the fact that AM-compliant solutions for design problems often include not only one of the generally valid functions, but more of them according to the type of definition, the definition used should not be differentiated in too many of them. The fact that overlaps in the understanding of the definition cannot be ruled out underlines this approach. For instance, if a designer is confronted with a definition of twelve generally valid functions but he cannot differentiate between them in practice, the number of effectively used different functions will be under twelve.

Claussen & Rodenacker (1998) do not include the consideration of the conversion of material and signals. As additive-manufactured parts can fulfil functions that can include a flow of material, for example, the definition is not appropriate for a design catalogue for the development of functionalities with AM.

Koller & Kastrup (1994) have the most differentiating definition of the authors presented. This high level of differentiation could cause the effect that accuracy in the assignment of functions and their additive-manufactured solutions could be fabricated, which is not possible in reality. A varying number of definitions of the functions for energy, material and data makes a design catalogue for inexperienced designers difficult to utilise. Therefore, the definition of Koller & Kastrup (1994) is not appropriate for the development of a design catalogue for AM.

Krumhauer (1974) and Roth (2000a) have a lot in common in their definitions. Both fulfil the requirements of a definition of generally valid functions for a design catalogue for AM-compliant solutions. Their single functions are defined in consideration of an independency of each other. As a consequence, it is assumed that the wording is intuitively comprehensible for designers.

The definition of Krumhauer (1974) is developed and used in the context of a computer application, whereas the functions of Roth (2000a) are especially defined for the design process and are proven in this context. Due to this fact, the design catalogue presented in this paper is based on the definition of Roth (2000a).

5. Structure of design catalogues

"Design catalogues are collections of known and proven solutions of design problems" (Pahl et al., 2007). As shown in Figure 1, design catalogues consist of classifying criteria, solutions, solution characteristics and remarks.

Classifying Criteria			Solutions			Solution characteristics					Remarks		
1	2	3	1	2	No.	1	2	3	4	5	1	2	3
					1								
					2								
					3								
					4								
					5								
					6								
					7								

Figure 1. Design catalogue with one-dimensional classifying criteria, adapted to (Roth, 2000b)

The classifying criteria represent the aspects for categorising the content of the design catalogue and thereby determine the structure of the catalogue. The ease with which catalogues can be utilised is mainly influenced by these criteria. (Pahl et al., 2007; Roth, 2000b)

The solution column contains the possible solutions for a design problem and is therefore the main part of the design catalogue. Solutions can be represented by sketches, illustrations, drawings and with physical equations, depending on the level of abstraction. (Pahl et al., 2007)

The column for the solution characteristics shows the characteristics of the solutions and is therefore important for choosing the suitable solution.

Additional comments or the origin of the solution can be found in the column for the remarks.

Design catalogues can be realised with one- or multi-dimensional classifying criteria. Figure 1 shows a catalogue with one-dimensional criteria and Figure 2 with two-dimensional criteria. Two-dimensional classifying criteria are used to represent the content of a design catalogue compactly, but it is therefore not possible to present the solution characteristics in the same table. The characteristics merge into the classifying criteria and the access to the catalogue occurs using these. The solutions are located in the fields of the matrix. Three-dimensional design catalogues consist of several two-dimensional catalogues. For every classifying criterion of the third dimension, one two-dimensional catalogue exists. (Roth, 2000b)

Classifying criteria and characteristics	I								
II	No.	1	2	3	4	5	6	7	8
	1								
	2								
	3			Solutions					
	4								
	5								
	6								

Figure 2. Design catalogue with two-dimensional classifying criteria, adapted to (Roth, 2000b)

According to (VDI 2222), design catalogues have to fulfil several criteria to be as generally valid and versatile in their application as possible:

- They should enable fast access to information and convenient use – and provide validity for a large number of users.
- They should be adapted to the design process, consistent within themselves and with other design catalogues, and bring a level of completeness within the given limits.
- They should be expandable, changeable in their details and have an evident structure.

6. Design catalogue for additive-manufacturing-compliant solutions

As pointed out in section 2, a design catalogue for AM-compliant solutions for repetitively occurring design challenges should be based on generally valid functions. An appropriate definition of these functions was discussed in section 4. The classifying criteria of the design catalogue in this paper are therefore specified by the definition of generally valid functions according to Roth (2000a). In Figure 3, the concept of a design catalogue based on these classifying criteria for AM-compliant solutions of design tasks is shown.

As Figure 3 shows, conventional design solutions are included in the column of solution characteristics alongside the AM-compliant solutions, which are the only part of the solution column. This is suitable for an easy understanding of the additive-manufactured solution because the conventional solution will be known by designers in most cases.

<table>
<tr><th colspan="2">Classifying Criteria</th><th colspan="2">Solutions</th><th colspan="8">Solution characteristics</th><th></th><th>Remarks</th></tr>
<tr><td colspan="2" rowspan="3">Functions</td><td colspan="2" rowspan="3">AM-compliant design</td><td rowspan="3">Conventional design</td><td rowspan="3">Functioning of the AM solution</td><td colspan="6">Possible processes</td><td rowspan="3">Additional explanations</td><td rowspan="3">Origins and comments</td></tr>
<tr><td colspan="2">LS</td><td colspan="2">FDM</td><td colspan="2">…</td></tr>
<tr><td>Manufac-turability</td><td>Expla-nation</td><td>Manufac-turability</td><td>Expla-nation</td><td>…</td><td>…</td></tr>
<tr><td>1</td><td>2</td><td>3</td><td>No</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td><td>12</td><td>13</td></tr>
<tr><td rowspan="5">Energy</td><td>Change</td><td></td><td>1</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Transform</td><td></td><td>2</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Connect</td><td></td><td>3</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Channel</td><td></td><td>4</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Store</td><td></td><td>5</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Material</td><td>Change</td><td></td><td>6</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>…</td><td></td><td>…</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Signals</td><td>…</td><td></td><td>…</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

Figure 3. Concept for a design catalogue for additive-manufacturing-compliant solutions

Due to the fact that there is a wide variety of available AM technologies, the practicability of the solution with a specific technology should be included in the design catalogue. Therefore, the presented concept of a design catalogue includes this information in the solution characteristics. The mapping of a specific AM technology and the function that should be realised could also be presented with a two-dimensional design catalogue by adopting the different technologies in the classifying criteria. Regarding the fact that design catalogues with one-dimensional classifying criteria give a better overview of their content as a whole, this option is chosen to simplify the utilisation for designers. In Figure 3, the mapping of AM-compliant designs for a generally valid function to the specific technologies is shown by way of an example for the presented concept for selective laser sintering (LS) and fused deposition modelling (FDM). Alongside the information about the manufacturability of the solution, process-specific explanations of the reasons for it and comments on the circumstances should be included in the catalogue. This gives designers the opportunity to conduct proper design or to find alternative solutions.

Furthermore, fields for the description of the functioning of the AM-compliant solutions, for additional explanations and the column for remarks are included in the catalogue. By means of the included numbers, every field of the catalogue can be explicitly labelled.

7. Example for the content of the catalogue

Figure 4 shows a sample extract from a design catalogue for AM-compliant solutions of functions. An AM-compliant realisation of the function of the storage of energy, for instance, would be to substitute the common solution of using coil springs with the use of several rings connected with bars at a defined number of points, as shown in solution No. 13 in Figure 4. Using this design, the stiffness of the spring can be increased even if the Young’s modulus of the available material is relatively low. By using this design, the spring can consist of the same material as the other functional parts of the product and can therefore be produced directly as an integrated part.

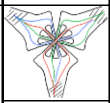
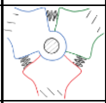
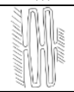
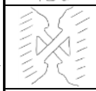
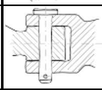
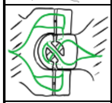
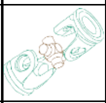
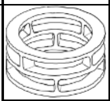
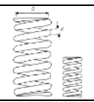
Classifying Criteria		Solutions		Solution characteristics							Remarks
Functions		AM-compliant design		Conventional design	Functioning of the AM solution	possible processes: LS		possible processes: FDM		Additional explanations	Origins and comments
						Manufac-turability	Explana-tion	Manufac-turability	Explana-tion		
1	2	3	No.	4	5	6	7	8	9	10	11
Energy	...		...								
	Connect		5		- Relative rotations of the sections with one rotational degree of freedom are possible	+		0	Support structures are necessary	- Forces and torques can be transferred between the different sections - The connections go through the centre of the sections - The connections are placed on different levels	
		...	...								
	Channel		8		- Different stiffnesses for each direction of translation and rotation	+		+	No support structures when produ-ced lying	- Two parts can be joined together - The two parts can be slightly pulled apart - Rotation is basically limited only to folding of the two parts	
			9		- Limitation to one rotational degree of freedom	+		+		- Limitations to the maximum angel can be integrated - Stiffness and strength can be variated by the number of leaf springs - The leaf springs should be rounded	
			10		- Small angular misali-gnment can be com-pensated for with consecutive arran-ged spring joints	+		0	Support structures are necessary	- Limitations to the maximum angel can be integrated - Stiffness and strength can be variated by the number of leaf springs - The leaf springs should be rounded	
		...	...								
	Store		13		- The segments of the spring are subjec-ted to bending - Stiffness of springs can be increased	+		0	Support structures are necessary	- The spring should be integrated in the part - Variation of the number of layers is possible - Variations of the number of contacts between the layers - Connections between the layers should be rounded - Several concentric springs are possible	
		...	...								
...	...		...								

Figure 4. Extract from a sample design catalogue for AM-compliant solutions

8. Discussion

In this paper, a concept for a design catalogue for the development of functionalities with AM is presented based on the need to support designers in the design for AM. The concept is based on a literature review of design catalogues and possible classifying criteria, which are adapted in the context of AM. The filling of the presented catalogue and the access to it work well with the currently included information as in the example shown in section 7. According to the range of the catalogue and the number of included manufacturing technologies, it could be appropriate in future to convert the structure of the catalogue into two-dimensional classifying criteria or to adjust the solution characteristics. A critical point in filling the catalogue is the different level of detail of the AM-compliant solutions, because there is a wide range of possible applications for these manufacturing technologies. In order to keep the registered solutions consistent, their inclusion of more than one of the defined generally valid functions always has to be examined. Nevertheless, for the task of supporting designers in utilising the potential of the available freedom of design, it is appropriate to gather more solutions, rather than fewer. Small inconsistencies within the solutions are therefore not avoidable.

9. Conclusion and outlook

The presented concept for a design catalogue for the development of functionalities by means of AM is structured according to criteria which provide the ability to organise suitable solutions in a clearly arranged way. The definition of the classifying criteria has been chosen with regard to a general validity and easy access to the solutions.
In future work, the presented catalogue has to be filled with more solutions and the classification used for the classifying criteria has to be proven in practical applications. For better applicability and faster access, the catalogue should be implemented as a computer application.

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