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INFLUENCES OF ADDITIVE MANUFACTURING ON DESIGN PROCESSES FOR CUSTOMISED PRODUCTS

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1. Introduction

Manufacturing companies are confronted with the demand for customised products to fulfil individual customer desires [Piller 2006]. The resulting external product variety leads to higher internal variety and thus to process complexity and rising complexity costs [Krause et al. 2014]. The impact of additive manufacturing (AM) on customization is often mentioned in literature, but has not been sufficiently analysed for the implications of AM for design processes. This paper presents the range of product design processes for different levels of customization through AM utilisation, from elaborated individualisation processes to specific product adaptation.

1.1 Research object: additive manufacturing and its consideration in product design

The integration of flexible production systems advances the production of individualised products [Blecker et al. 2004]. Additive manufacturing technologies, as a collective term for layer manufacturing methods, enable tool-less production [Gebhardt 2012]. The main reasons for the use of these flexible production technologies are user-fit requirements, improved functionality to realise complex forms (e.g. in lightweight design), parts consolidation to reduce part numbers, and aesthetics [Campbell et al. 2012]. The object of this paper is the application of AM for customised design of products and the consideration of AM in product design.

1.2 Problem description and research aims

Previous investigations show that AM has a big impact on the production of individualised products and that it influences the design process [Reeves et al. 2011], [Gibson et al. 2015], [Ko et al. 2015]. Despite the capabilities of AM, there is still a lack of accepted methods in design for AM [Rosen et al. 2015] and its potential remains unexploited, particularly in custom part production [Wohlers 2014]. Ko et al. explain that the advances of AM require new design approaches to exploit the advantages of design freedom [Ko et al. 2015].
This paper aims to contribute the design of individualised products and to answer the following research question: Which processes can result in design through the use of AM for customization? Section 2 presents approaches of customization and the background of AM technologies. The research method is described in Section 3, followed by an analysis of the current processes for customization through AM. Section 5 presents the process range of individualised product design using AM and their implications. The approach is presented using an application from the medical industry and the results are discussed in Section 6.

2. State of the art

2.1 Customised product design

Today, customers demand specific product designs that best fit their individual desires. At the same time, products have to be produced with the least possible cost and effort to be competitive with other companies' products. Since this paper focuses on design processes, an overview of existing production processes is presented below, as well as the implications of customised design for production.

2.1.1 Degrees of customization

The first term that referred to the issue was (mass) customization. According to Pine, customers' individual needs and wishes can be satisfied through customised product design at low prices [Pine 1993]. Mass customization becomes a corporate concept for the production of products that meet various demands of individual consumers using flexible processes and organisational structures, independent of the offered number of options [Piller 2006]. Therefore, any form of adaptation and configuration of a product to customer demands is called customization. As a result, products or product families come with different degrees of customization [Krause et al. 2014].

Due to new findings in the research field of mass customization as well as new technologies, e.g. AM, higher degrees of customization can be achieved at reasonable costs. To differentiate from existing approaches, two additional terms were introduced to the issue of customization: individualisation and personalisation. Tseng and Hu derived customer participation as a precondition for personalisation, which they understand as proactive customer involvement through co-design and as an enhancement of mass customization [Tseng and Hu 2014]. The following definitions of customization and individualisation are applied in this work: Customization is any adaptation to fit the needs of a customer or a group of customers; individualisation (Tseng and Hu call it personalisation) is more precise and focuses on one specific customer. This means that customization is the generic term and individualisation is the special case.

2.1.2 Production processes in customization

Various approaches for the customization process have been developed (examples of an overview are [Piller 2006], [Abdelkafi 2008]). In round terms, the degree of customization increases with early initial involvement of the customer (decoupling point). A higher degree of customization has a negative effect on delivery time and efficiency. Abdelkafi identifies three positions of the decoupling point, each of which leads to different production environments: Make-to-Stock environment (customization can be realised by the customer or the retail store), Assemble-to-Order environment (the customer chooses product configurations), and Make-To-Order environment (the production of individual orders) [Abdelkafi 2008]. The customization process is also influenced by the frequency of product individualisation: In a “usual case” other customers could have the same customization goal, in contrast to an “isolated case”, where other users may not have this request [Baumberger et al. 2003]. Production for individualisation can be divided into two subsystems: the non-order-related production and the customer-task-oriented production, whereby components or modules are fabricated with direct connection to the individualisation [Piller 2006]. Flexible production technologies are expedient for customer-task-oriented production to offer high performance, geometric complexity and customer-specific adaptation during production. However, flexible manufacturing influences also the production planning because the structure complexity of scheduling function increases [Blecker et al. 2004].

2.2 Additive manufacturing technologies

Additive manufacturing is the collective term for layer manufacturing methods, such as powder sintering, stereolithography and polyjet modelling. Tooling has been eliminated in AM, which enables production directly from CAD data. Manufacturing costs are dissociated from total number of parts (approximated in Figure 1). Parts with high geometric complexity in smaller volumes are very suitable for AM [Hopkinson and Dickens 2001]. In addition to common rapid prototyping, AM is applied with increasing frequency to the direct manufacturing of end-use parts, becoming a production capable technology [Gibson et al. 2015]. The main reasons for using AM are parts consolidation due to high geometrical freedom (e.g. inner structures, undercuts, and freeform surfaces) and the resulting integration of functions. It also enables improvement in product performance, as well as integration of user-dependent, personalised features and aesthetic designs [Campbell et al. 2012].

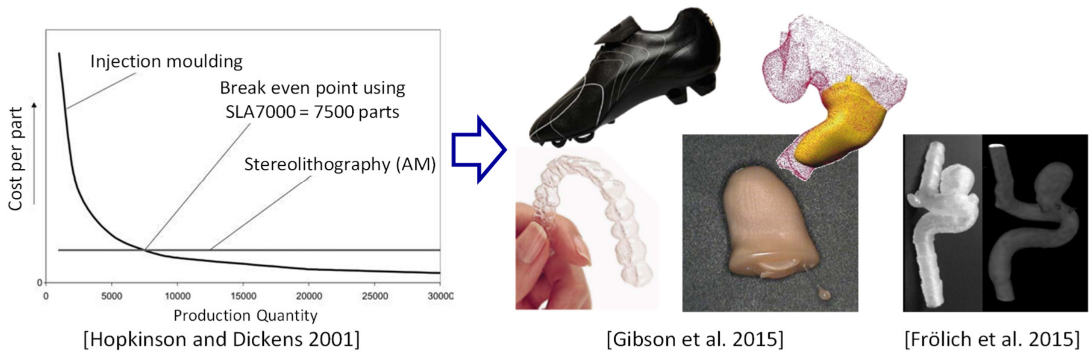

Figure 1. Costs of AM, compared to injection moulding, enable customised products

The principles of design for AM are summarized by Rosen, including design ideas that cannot be produced using conventional fabrication methods [Rosen 2014]. The potential of direct manufacturing by AM can be graded by lot size effects and the degree of customization [Lachmayer et al. 2015]. Multiple examples and advices for individualised, AM-fabricated components in products can be found [Masters et al. 2006], [Reeves et al. 2011], [Gibson et al. 2015]. The medical industry already uses AM to great effect: 17 million customer-specific, single-component orthodontic aligners in the dental industry are additive manufactured annually. Production through AM is possible for an entire product and for single components, such as plastic shells for in-the-ear hearing aids, of which more than 2 million are customised annually [Wohlers 2014]. The implementation of AM in product family design offers an increased design space, because AM reduces the compromise between commonality and product performance [Lei et al. 2015].

3. Research methods

A literature review is systematically performed to find existing approaches for implementing AM in the design phase of customised products. To conduct the research question, literature was examined for design processes in customised design, effects of production on design phase, use of AM in production, and application of AM for customization. After collecting data, design process types are concluded for customization through AM. Synthesis of the processes results particularly in process adaptations of established design approaches. Case of application of the described processes is the development of a personalised and adapted vascular replication system from the medical industry. The evaluation of the design processes in the case supports and completes the findings.
The aim is to analyse the impacts that the use of AM technologies can have on design processes for customization. The various AM technologies offer different material and geometric properties [Eyers and Dotchev 2010], [Spallek et al. 2016]; even so, there are diverse restrictions in material selection and production quality [Campbell et al. 2012], which is the subject of current research. Each AM technology requires different construction guidelines and knowledge of the product designer. Independently, it is assumed that the effects of different AM technologies on design processes remain similar, so that this paper considers the implications of direct production of end-use parts, without focussing on one specific AM technology.

4. Additive manufacturing for customised product design

The high potential of AM in individualised production (for example, for surfaces relevant to consumers) is based on activation through three-dimensional CAD data, on cost efficiency, and on the high

geometric freedom. Nearly every one-material part can be produced to individual desire under the condition that the geometry exists in digital mode [Piller 2006].
Current and suggested product design processes in the literature for customised products using AM, like in [Piller and Tseng 2010], were analysed concerning type of customization, production environment and source of individual data. An excerpt is provided in Figure 2.

Customised product design	[Gibson et al. 2015]	[Wohlers 2014]	[Reeves et al. 2011]	[Piller and Tseng 2010]	[Gebhardt 2012]	[Eyers and Dotchev 2010]	Type of customization	Production environment	Data source
Aligner (Align Technology) 17 million p.a.	■	■					Dental/ medical - Body-fitting	MTO	1.) Impression mouth + scanning 2.) Planning treatment
In-the-ear-hearing aids (Siemens and Phonak) >2 million p.a.	■	■	■		■	■	Medical - Body-fitting	MTO	Impressions from patients' ears + scanning
Footwear (Prior 2 Lever Nike)/ orthotics	■	■					Body-fitting	MTO	Impressions
Figure Prints (Pixisand, www.figureprints.com)	■	■	■				Consumer-oriented (e.g. gaming/ gifts)	MTO	Scanning, 3D-CAD, or open source data
Furnishing (MGX, Lamps, etc.)			■		■	■	Consumer-oriented	MTO/ SC	Parameterized, designer creativity, or customer's desire
Seats (motorcycle/ aerospace)				■			Body-fitting	MTO	Capture "deformed" shape + scanning
Dental restorations: crowns and bridges >19,000 p.d.	■	■		■	■	■	Dental/ medical - Body-fitting	MTO	Impression mouth
RepRap 3D-printer		■		■			Functionality/ consumer-oriented	SC	open-source, or designed by customer
Implants, maxillofacial and orthopedic surgeons/ biomedical devices	■	■				■	Body-fitting	MTO	Scanning, 3D-CAD
Self-customised toys, sculptures, etc.					■		Consumer-oriented	SC	Designed by customer, using shared designs or Meta Designs

■ Quoted in listed citation

MTO = Make-to-Order environment
SC = Self-Customization in Make-to-Stock environment

Figure 2. Excerpt of product designs in literature of customised, AM-fabricated products

The use of AM for customization in value-chains was identified through literature analysis. Customization using AM influences life cycle phases, as listed below, referencing the production environments presented in Section 2:

- Self-customization (SC) in make-to-stock environment: The increased number of home-based machines and multiple AM distributors allows self-customization of components. The customer designs and creates components in self-customization and fabricates them at home or under private responsibility using AM. Previous planning of conceptional designs of customer-relevant components may support the customer. This influences the design process when defining interfaces with AM design rules. Self-customization has restrictions: access to and knowledge of CAD systems; intellect of the customer; limits in quality and surfaces, particularly with low-quality desktop printers; as well as liability of the product [Hague et al. 2003]. This customization principle has little influence on product demand and customer connectivity, and therefore appears to be of limited interest to most companies.
- Assemble-to-order (ATO) does not benefit notably from applying AM and is not mentioned in literature. For product configuration, components are fabricated or purchased to stock and individually assembled (customised standardisation [Abdelkafi 2008]). A component prefabricated using AM may be relevant to functional integration or geometry freedom, but not to customization. The same degree of customization can be reached without AM, using conventional production systems, e.g. injection moulding.
- Make-to-order (MTO): Customised products are possible by involving the customer in the design of the product and implementing the main advantages of AM and the tool-less production. This results in a high degree of design freedom and economically viable small volume production. The MTO customization that appeared in the literature is often realised by surfaces acquired through scans or impressions of physical data (either from humans or items). Hague et al. explain that "the most profound implications of [AM] on design will be that […]

each component can be different, potentially allowing for true mass-customization of each and every product" [Hague et al. 2003]. This aim for "true mass-customization", approximated to the absolute idea of customization, is positioned in the make-to-order environment.

5. Influences of additive manufacturing on design processes for customization

Additive manufacturing is an enabler of different types of customised product designs, as presented above. AM's influence on design processes and the range of process types that result in design processes through the use of AM for customization will be analysed in this section. A detailed perspective is relevant, especially because of the advanced customization abilities with the use of AM and the increased degree of automation. The stock-to-order environment, with the self-customization of product features, has little influence on the design process. The make-to-order environment is the most mentioned application of AM for customization, as it has potential for companies. The levels of customisation as well as customer involvement in product processes differ in the MTO environment.
Different types of design processes are identified through the use of AM for customization in the MTO environment. Design customization through AM spreads a wide range of processes, where there are two distinct types: the often-applied pre-planned standardisation for customization (hereafter called "standardised individualisation") and the "true mass-customization" [Hague et al. 2003], with high levels of customization and customer-specific design (hereafter called "specific adaptation"). The transition of their characteristics is gradual. The key differentiators of the two types of processes are the scope of predictability and frequency of customer participation, which influences design tasks and processes. The characteristics are presented below and detailed in the following case from the medical sector of a personalised and adapted vascular replication system.

5.1 Standardised individualisation

Customization using AM is recommended for components where geometric individualisation can increase customer satisfaction, comfort, or product applicability. When there is one point of individualisation, customization and customer integration can be predefined by planning a standardised individualisation process. This is recommended when the shape of the product can be adapted to individuals. It is helpful if the contact surfaces are known and the customer-specific data can be measured. To distinguish it from customised standardisation in the assemble-to-order environment, which is also called standardised customization, the process is called standardised individualisation. The design process for such products is usually based on life phases of standard products [Pahl et al. 2007] for individualisation (Figure 3). In the early design stages, i.e. product planning, task clarification or conceptual design, the component to be individualised is defined. The non-recurrent development process contains conception and design of the whole product. During these process steps, the constraints of individualisation without performing customization are assessed.

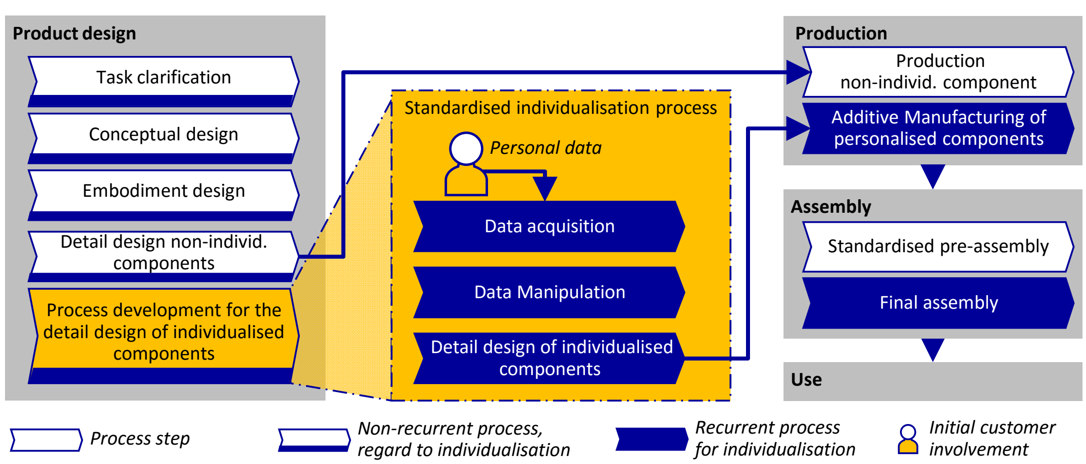

Figure 3. Standardised individualisation process

Standardised individualisation is remarkable because of the process development of the detail design of the individualised component, where the process for individualisation from initial customer involvement to the final production data is planned. The developed process is critical to the success of the standardised individualisation, because it recurs for each customization. Thus, the process for a usual individualisation case should be organised, standardised and able to be automated. The source and type of data, limits to individual geometry, manufacturability, and interfaces to other components are all considered during the development of the recurrent customization process.
The design phase ends after process development for individualisation. The detail design of the individualised component can occur in a speciality department or outsourced as point-of-delivery customization. Long product cycles result, because of high detail, planning effort and engineering work for the individualisation process. Standardised individualisation may benefit from modular product design with commonality of components and interface standardisation to the individualised component. No further requirement gathering as interaction with the individual customer is needed; instead, it is a transaction, where the product structure and part properties are not changed because of predictability of the product and customer demands.
This individualisation is mostly used in customer fitting components or form individualisation. This is currently the main use of AM for customization. A famous example of this process is in-the-ear hearing aids production, with its customization for user comfort and functionality [Masters et al. 2006]. In this process, an audiologist takes the physical impression (personal data), and sends the scanned data to the supplier. There, the design of the hearing aid is finalised in a standardised individualisation process, the individual components are additive manufactured, then sent back to the audiologist for further user fitting. Other examples of this process type are shoes, personal figure prints, and aligners in the dental industry, where the treatment plan influences the design of consecutive aligners for each individual customer [Gibson et al. 2015].

5.2 Specific adaptation

The other type of customised design is using AM to react to customer demands, where the design phase can be redone to meet individual customer desires, resulting in a higher level of customization and shorter development time (Figure 4). In specific adaptation, the product can be adapted to customer desires within a fixed solution space or individual adaptations for design or engineering without changing the main product attributes or requiring a completely new engineered product.

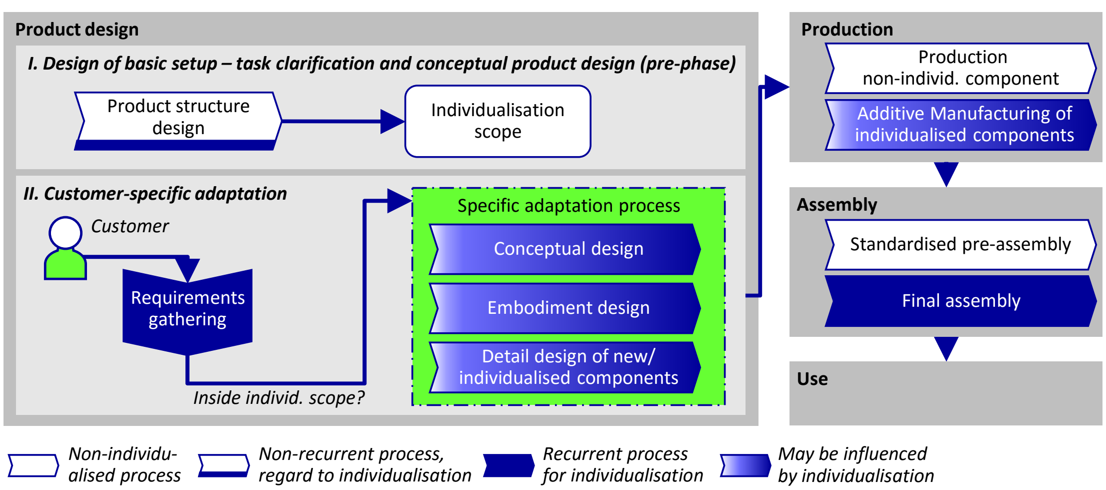

Figure 4. Specific adaptation process

In the first step of the design process a product structure design is executed for specific adaptation of the product: an individualisation scope is defined, circumscribing the core product structure with customizable features and an open zone for individualisation. Based on customer desire and the resulting requirements, the product design is adapted with acceptable levels of effort by influencing different steps

in the design process. The design process is repeated and redone for individual customer desires in a shortened period.
The disadvantage of specific adaptation is the high effort required in the preceding structural and conceptual product design, in which a user-independent product spectrum and the basic product potential is developed [Lindemann et al. 2006]. Methods of product family design, as described in [Eilmus et al. 2012], [Krause et al. 2014], support the separation of modules to minimize the degree of coupling of potentially unique components to other components. The advantages of AM are established here and offer further benefit to individual adaptation through functional integration and great design freedom. In contrast to standardised individualisation, the process types in specific adaptation are rarely named in literature, although they represent "true mass customization". There is huge potential for customization to become more efficient through the use of AM technologies.

5.3 Case of application: Design of an individualised vascular replication system

Specific adaptation depicts a design process that has high customer participation. A complicated process may result if standardised individualisation is integrated. This will be detailed here using an application case from the medical sector of a replication system of vascular diseases. During the research project ALSTER (founded by the Forschungszentrum Medizintechnik Hamburg), the vascular replication system was developed with patient-specific aneurysm models used to train neurovascular interventions for individual patients. The system was adapted to specific demands by the physicians. The freedom in design by AM has a high impact on the replication of branched cerebral blood vessels and their diseases, e.g. aneurysms. These replications can be used in training of aneurysm treatment. The two types of process, standardised individualisation and specific adaptation, are present in the case; it demonstrates the differences between them.
The basic vascular setup of the replication system reproduces a patient-specific brain aneurysm in a personalised rigid aneurysm model integrated for training of neurointerventional procedures (Figure 5). Components of the system, such as tubes, pump, catheters, aneurysm model mounting, fluid tank, and a replica aorta, were planned and designed (phase I) for interfaces adaptable to different vessel dimensions and changing positions of the aneurysm. The recurrent process for standardised individualisation of the personalised component, "aneurysm model", was based on angiographic personal patient data [Frölich et al. 2015]. Clinical 3D-rotational angiography data were acquired. The reconstructed images are transformed into volumetric models. In reverse engineering, the personalised vessel geometry is converted to a negative model with constant wall thickness. Standardised interfaces to silicone tubes are implemented at the major vessel.
This process for the design of the aneurysm model is standardised individualisation, so that it is similar to the design process described for in-the-ear hearing aids. The resulting standardised-individualised basic setup is the framework for the training system in which further individualisations are possible for the specific needs of individual customers. Here, the physicians are the users of the training setup. In the following, four specific adaptations (phase II) and their characteristics are described, comparing them to the basic setup (A…D in Figure 5):

- The desire A of an individual customer is to increase the realistic setup of the training system and replace the standard, box-shaped mounting for the aneurysm model with an individualised head-mounting. The design did not underlie restrictions in design for production because the head model was fabricated using AM.
- The elasticity of a real vessel wall should be simulated by the currently rigid aneurysm model to train the coiling process for desire B. Depending on this additional function, a flexible material for production and other connectors to the standard model of the system are chosen. This increases the opportunities for training in the vascular system enormously.
- In desire C, the customer wanted to realise three inlets and outlets in vascular models, with the quantity depending on patient-specific vessel geometry. Here, the change in personal data influences the detail design process with the workflow of standardised individualisation and requires further components, such as connectors and tubes.
- Desire D influences manufacturing of the aneurysm model. The model is requested to have high transparency of the wall to enable an optical proof of device position. By changing the AM

technology from Fused Deposition Modelling to Stereolithography it was possible to raise the transparency without modifying the design.

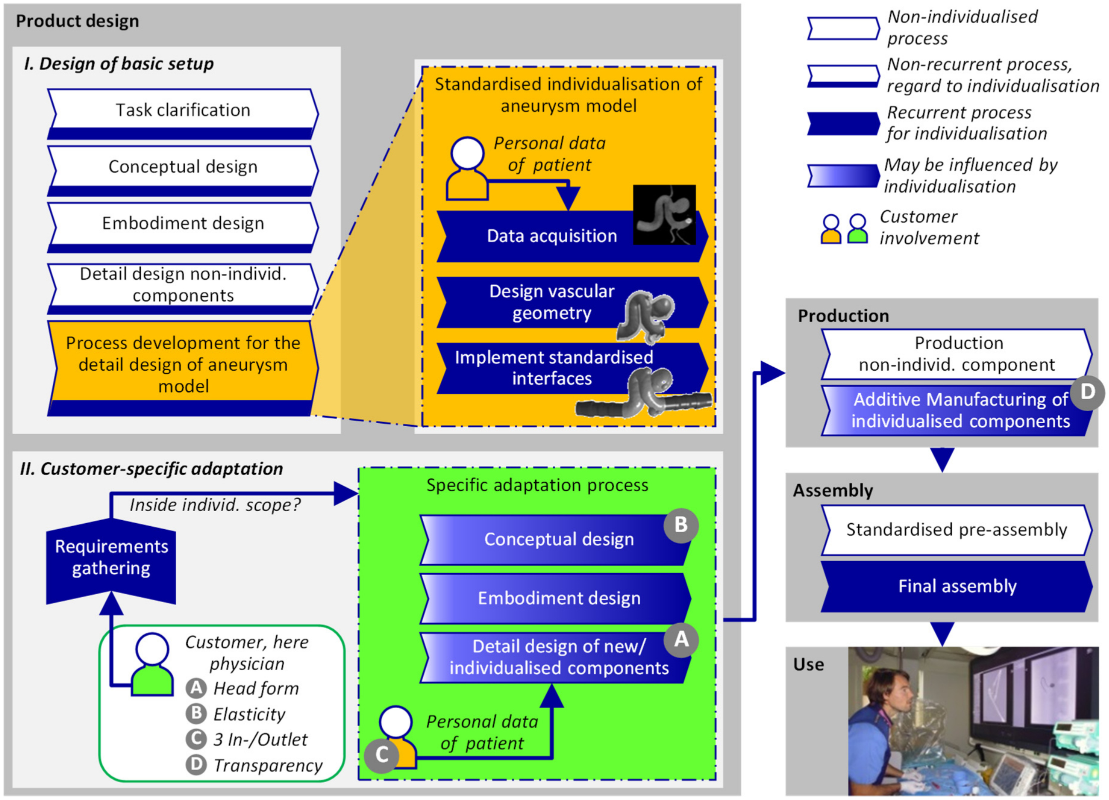

Figure 5. Process of specific adaptation of a vascular replication system

The application of the process types in the vascular replication system highlights the differences between the two processes. Individualised products are possible with varying effort and customer involvement, which leads to distinct degrees of customization. A standardised process for individualised standardisation is highly necessary to minimize the effort required for detail design. In the specific adaptation process, different design steps can be performed, depending on individual demands. Individualisation scope is difficult to define. It was case-specific decided if it is realisable or if the fulfilment of the desire requires specific design outside of the product scope (e.g. replication of stenosis, which is the narrowed area of a vessel with other treatment properties). Desires B and C are typical examples of progression of an isolated case to usual case, which was then implemented via standardised individualisation. In iteratively implemented standardised individualisation, type and volume of desired connector geometries for elastic or rigid models became selectable.

6. Discussion of process range

Individualisation of geometry and form has become more efficient due to AM. The realisation of customised design, e.g. with further functionality, can be reconsidered. The approach of the make-to-order environment is certainly not new, but offers greater significance because of AM's increased field of application. The breadth of design processes and the integration of AM spans across characteristics, such as frequency and intensity of customer participation, product cycle times, and predictability of standardised individualisation.

The grading of design processes can help researchers and developers learn from customised product development in general. In standardised individualisation there is no individualisation of functionality. Nevertheless, this type is of particular importance and is recommended for customer-specific data, where it is used by industry. This customization is plannable in user fitting, as the relevant components,

e.g. those that are in contact with the user, are well known. Here, the focus of future research is on the automatisation of the individualisation process and data acquisition. In contrast, specific adaptation has not been exceeded, although AM can be highly beneficial in individualisation. It has to be demonstrated how relevant specific adaptation is to industrial applications and whether AM can enable "true mass-customization".
Standardised individualisation describes one usual, predefined case for customization. Specific adaptation facilitates isolated cases of individualisation for one specific customer. If a desire arises with increasing frequency, the individualisation can be standardised with a high degree of maturity in the product specification. Standardisation is not pre-determined, but is implemented afterwards. The division between usual and isolated individualisation cases is not fixed, but is a good description of the difference in the permitted involvement of the customer. The focus is on either the development of a standardised process or on the adaptability of components.
The levels of individualisation and customer levels of influence change the design process. A detailed differentiation of the design processes should be included in Customised Design for AM. Various levels of customization in the strategies are clarified due to the distinction between customer and personal data in the application case: the personal data are used in the personalised design, but no deeper interchange with the data source – in the case, the patient – were realised. Customer demands – physicians being the customer in the case – and the following requests were analysed and assessed in product design with increased design effort. Even if this is a special case on vascular replication systems and this separation of customers and personal data is not usually found in other applications, the differences in customer involvement and the resulting implications for the design are revealed.

7. Conclusion

The supply of customised products benefits from additive manufacturing. Different customization strategies are possible. With the focus on the influences in the design process, this paper identified a range of customization characteristics. Two types of customization in the make-to-order environment were presented: standardised individualisation, with preceding process development, results in a defined degree of customization for user involvement; specific adaptation shows that customer desires influence the previous design process steps. The different levels of customer involvement require different design and adaptation methods for individualisation processes to make differentiation in this range meaningful. As well as research on AM technologies to reduce current production and material limitations and enhance the industrial application of AM, future research needs to specify the design processes and strategies for the types of customization available through AM. Automatization processes are necessary for standardised individualisation, with specific attention on company standards and product programs. Further evaluation of how specific adaptation can be integrated into companies and whether they are able to deploy the AM-specific opportunities to fulfil customer demands is required.

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