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Rethinking System Boundaries for Better Utilisation of Additive Manufacturing Potentials – A Case Study

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Abstract
The potentials of additive manufacturing for objectives such as lightweight construction are not yet fully exploited. In this paper, the possibilities of integrative function and system modelling for this challenge will be discussed. In a design study, a triathlon trailer is designed considering the constraints of AM. A suitable system boundary is to be detected using the one-part device method. The findings of the study will help to understand in which form methods such as functional modelling can be applied or adapted for the application of additive manufacturing.

Keywords: *design for additive manufacturing (DfAM), additive manufacturing, function modelling, lightweight design, conceptual design*

1. Introduction

Additive manufacturing is increasingly being used for the manufacturing of end products. A particular advantage using AM is the design of complex shaped components which wouldn't be achievable using conventional manufacturing technologies.
Nevertheless, the potential of AM is not yet fully exploited in practice. A lack of knowledge is still named as one of the main reasons for that (Borgue, Panarotte, et al., 2018). The use of AM requires knowledge in various areas (Yang and Zhao, 2016). It can be distinguished into four categories: material, machine and process, digital tool chain, and methodology (Schmitt et al., 2021). Knowledge of the methodology is also referred to as Design for Additive Manufacturing (DfAM). These include any systematic support for designing using AM manufacturing technologies. Literature studies show that the early phase of the design process, in which the product architecture is defined, is considered to be of great importance for exploiting the potentials of AM (Schmitt et al., 2021). This phase is also of high relevance for the implementation of objectives such as lightweight design. Lightweight design is pursued through various strategies. Particularly great potential is attributed to the strategy of a conceptual lightweight design that aims to rethink the product at its conceptual level affecting its shape and product architecture (Schmitt and Gericke, 2020). At the same time, there is a great need for improved methodological support in this early design phases (Santos and Silveira, 2021; Valjak and Bojčetić, 2019; Yang and Zhao, 2016).
Yang and Zhao (2016) point out, that a radical innovation of a product requires a consideration of the functions and constraints of AM. Borgue et al. (2018) note that methods that consider both domains are still rare. In the context of product development, function models can be used to describe relationships between the features of a product such as functions, constraints, or solutions through abstract product representation (Ehrlenspiel, 1994). Eisenbart et al. (2013) have found that functions have the potential to be applied as cross-disciplinary and that function modelling provides a viable means to overcome design fixation and to explore new design alternatives (Eisenbart et al., 2017)

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Functions are also used when it comes to integrating AM into a system to a meaningful scope (Müller et al., 2019).

The purpose of this paper is to increase the understanding of the role of function modelling and system architecture modelling as a means to advance DfAM design support. For this aim, a redesign process of a triathlon aerobar was carried out. Among the objectives developed, a major focus is on weight. The redesign process is analysed in particular concerning the following questions:

- Can the advantages of integrated modelling of function and system architecture be used for conceptual lightweight design with additive manufacturing?
- How to identify the optimal system boundary for AM-based designs?

2. Background

Methods used for AM-based design were often not developed for additive manufacturing. In the context of AM, Lachmayer and Lippert (2020) refer to AM-independent methods for the definition of main interfaces (of product components, parts, and assemblies to each other), e.g., the one-part device (according to Ehrlenspiel et. al., (2007)). This is based on the assumption that the integral construction method is to be preferred for higher batch sizes. It also leads to better use of lightweight design potential (Gumpinger et al., 2009). The overall system is initially assumed to be one-part and subsequently necessary interfaces are added based on analyses of functional and manufacturing constraints. Other methods and tools such as design principles or design guidelines for AM can only be applied to the use of AM (Valjak and Lindwall, 2021). Ponche et al. (2018) distinguish between a global and a spatial approach when redesigning existing products and adapting to the conditions of AM. When using the spatial approach, the geometry is mainly kept and only minor adaptations of the existing design are done in order to comply with the selected AM manufacturing process. The global approach, with greater potential for implementing e.g. lightweight design, aims to redesign the product entirely based on the functional specification for the use of AM.

The approaches are further divided into opportunity-driven, restriction-driven, or hybrid approaches (dual) (Kumke, 2018). While opportunity-driven refers to opportunities through the use of AM and neglects the limitations, restriction-driven refers primarily to the limitations. The dual approach considers both equally. The dual approach can benefit from using function modelling (Borgue et al., 2019).

About the conditions arising from manufacturing, an often unexplored potential of function modelling seems to be to combine conceptual considerations that affect both the product and the manufacturing process (Mercado Rojas et al., 2019). This combination is addressed e.g. by the Enhanced Function-means modelling (EF-M) method. EF-M builds on the function-means (F-M) approach. Here, the interaction of functional requirements (FR) and design solutions (DS) is described hierarchically. Terminology and meaning are based on the definitions of Hubka (Hubka and Eder, 1988).

Each design solution for the implementation of a functional requirements leads to further functional requirements. The F-M have been extended by conditions, that the solutions must meet. This represents the basis of the EF-M. In addition, the interaction of the solutions (DS) was added subsequently, which allows more complex relationships to be represented (Johannesson and Claesson, 2005; Müller et al., 2020).

The EF-M model has been proposed for the development of AM parts (Borgue et al., 2019). Advantages of EF-M generally are its suitability for the application of mass customisation, set-based design and design-space exploration. Disadvantages are, among others, the unclear and abstract modelling rules, as well as a needed geometric embodiment especially for the application to AM (Müller et al., 2020).

The following figure shows the methodological support in the design process for conventional developments (Methodology), as well as for the use of AM (DfAM). The spatial and global approach refers to a redesign of an existing product. The different variants (Var A/B/C) show the different impacts on the original design and which phases have to be included in the redesign process. The graded colour in the DfAM indicates that available methodological support usually emphasises later design phases.

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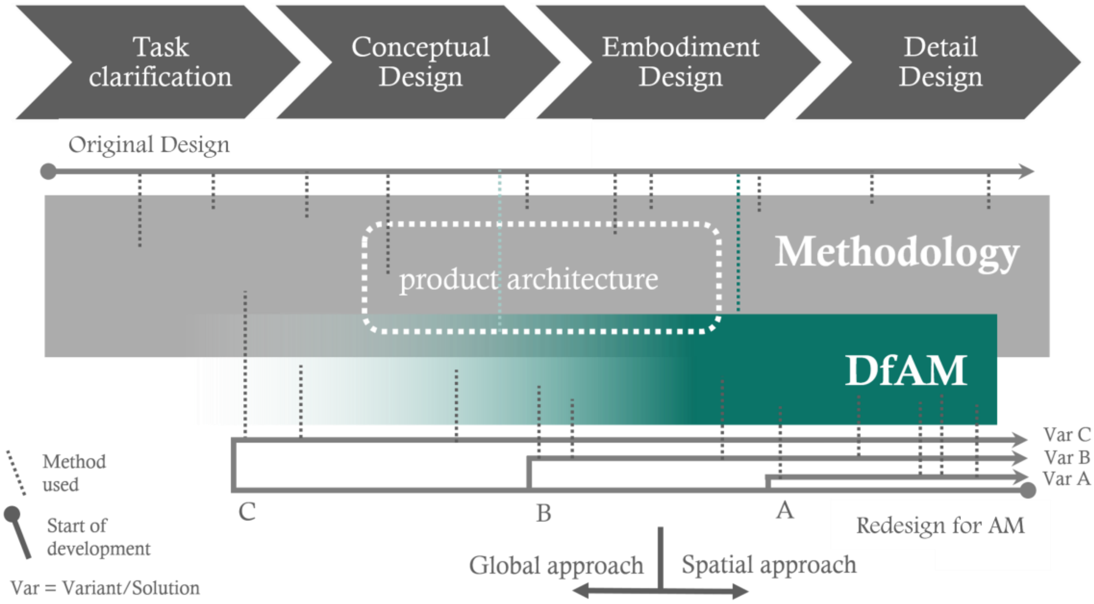

Figure 1. Influence of AM on the design process

It becomes clear that support in the design of structures for additive manufacturing depends on several factors and can have an influence on the entire design process. The tools are distinguished on the one hand according to the design phase in which the use of AM is dealt with. They also depend on the scope that is being considered for use in a product. Functional modelling has emerged as a particularly promising approach for global approaches.

3. Study Design

This paper reports a case study based on a student design project. The project aimed to redesign a triathlon aerobar for the use of AM. The redesigned aerobar should allow for customisation to individual users while reducing the weight of the areobar. As part of this project, it was necessary to determine required changes and analyse if these are technically possible.

The results and approach in this paper were developed during a student project as part of a Master's thesis at the University of Rostock. The student, who is a professional triathlete, was jointly supervised by the first author of this paper and an experienced designer. The project had a duration of 20 weeks according to the study program. The advantage of this format is the insight gained by an engineer at the beginning of his career about the challenges that can arise when implementing AM in product design. The student has experience with additive manufacturing himself, as he is part of the maker community and privately uses an FDM printer. The methodological support has so far been limited to specifications, i.e. restriction driven approaches.

As the student had no industrial experience with regard to this product, he was interviewing professional designers of a company specialised in the field of triathlon aerobars. The manufacturer is a company that produces customised solutions for triathlon aerobars. They have first experience in using additive manufacturing.

Scientific publications, identified using the database Scopus, were used to complement the student's existing knowledge in order to provide a sound basis for design decisions. The literature search had an interdisciplinary character, since the design task incorporates aspects from medical and sports science in addition to the methodology in engineering and additive manufacturing. As a result, different methods were combined. The student decided to use the Enhanced-Function Means modelling in addition to established works such as Ehrlenspiel et al., (2007) and Bender and Gericke, (2021). The student's approach was continuously discussed with the supervisor without imposing specific methods for function or system architecture modelling.

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4. Redesign for AM of a Triathlon-Aerobar

Aerobars allow the driver's seating position to be lowered, thus reducing the effective cross-section in the direction of movement. A small component with a big effect. This is best described in terms of numbers. Air resistance takes up a large part of the energy applied when riding a bicycle. At a speed of 14 m/s, it accounts for 90% of the total resistance (Kyle and Burke, 1984). For economic and manufacturing reasons, aerobars are usually characterised by a simple geometric structure consisting of less complex components (see Figure 2). Adjustment mechanisms allow for a certain degree of adaptation to the athlete, but these solutions have disadvantages in terms of ergonomics, weight and aerodynamics and can even have harmful consequences for health (Bales et al., 2012). Customised solutions do exist in this area, but they require the production of complex carbon parts or the use of 3D-printed titanium, which is very cost-intensive.

This case study is a redesign of an existing product. The aim is to go beyond the "spatial approach". According to Figure 1, the goal is therefore to develop a variant C.

As a manufacturing process, fibre-reinforced polymers in the selective-laser-sintering (SLS) process are considered in more detail. Manufacturing requirements, as well as further requirements as a basis for decision-making in the course of the project, were collected in a requirements list. The approach to the project can be divided into four steps:

1. formulate potentials to ideal design (section 4.1),
2. one-part device (maximal theoretical system boundary → practical system boundary) (section 4.2),
3. changing constraints (determining design space) (section 4.3),
4. changing design space (increase in function integration/complexity) (sections 4.3/4.4).

Equivalent to the task clarification (of the design process), the first step was to analyse the existing system and the context in which it operates. It aimed to identify improvements and define boundary conditions. The definition of the system boundary was the next design activity. The goal was to widen the scope of the analysis of the design challenge before narrowing it down to a sound and technically feasible solution. This step, which aims to rethink the existing product architecture, followed the idea coined as “einteilige Maschine” (one-part device) by Ehrlenspiel et al. (2007). This approach proposes to basically ignore all existing physical interfaces of a product and to consider it in the first step as a one-part device (Ehrlenspiel et al., 2007).

The third major step has been to create a function model of the system. This was done according to the EF-M. This allowed a new design space to be allocated.

In the fourth step, new AM-related constraints are introduced and new solution variants are created for the resulting design space. Finally, a functional prototype of the preferred solution has been created.

4.1. Ideal Shape

For the analysis of the system, different aspects were combined and findings were accumulated. From the user experience of the student, the expertise of an aerobar manufacturer (interview), as well as scientific work, the following statements can be derived:

- Aerobars usually do not fit closely to the rider's arm due to different geometries, which causes turbulences (Wurnitsch et al., 2010).
- Rides on the aerobar can sometimes last for hours, which can lead to pressure points if the components fit poorly (Bales et al., 2012).
- Due to a high number of fasteners, the lightweight potential is not exploited.
- Additional functions are not integrated into the aerobar for reasons of complexity (Galvin and Morkel, 2001).

An ideal shape that would solve all the above-mentioned issues was the starting point. This shape was designed actively ignoring all typical manufacturing constraints assuming a fully 3D-printed device (also ignoring all AM related manufacturing constraints). By parameterising the entire shape to fit the shape of the driver, the aerobar could support the rider’s arms completely. This would eliminate pressure points and reduce air resistance. Furthermore, interfaces in the stem system would not be necessary if not only the aero bar but the entire front-set (aero bar, stem and fork) were manufactured

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integrally, thus reducing weight caused by unnecessary fasteners and interfaces. Furthermore, the design freedom of additive manufacturing could be used to integrate additional functions, such as an additional brake lever in the aerobar.

4.2. One-part Device

For the definition of the system boundary, the entire bicycle system is initially assumed to be a one-part machine or a rigid body. Due to the function of the front set to enable steering by the relative angle of the fork to the overall system, an interface to the frame is necessary. Due to the high overall height when integrating the handlebar system, stem and fork, a further interface must be provided. Given the limited build space in most AM machines, a further interface can be defined. Conventional handlebar widths are around 400 mm. In another dimension, the difference in height between the handlebar and the aerobar, the angle of the rise of the aerobar and the handle adds up to more than 250 mm. Depending on the stem and arm dimensions, the length is between 450 and 550 mm.
In addition, the following aspects argue for the separation of handlebar and aerobar. In modern triathlon bikes, the handlebar and stem are integrated into a single unit (handlebar-stem unit) which is embedded in the geometry of the frame to lower the aerodynamic drag of the bike. This means that individual solutions would have to be developed for each bike, which would considerably increase the development effort. To provide an economically viable solution that can be used on different bikes this requires an interface that does not include the handlebar-stem unit. In addition, the weight-saving in the area of the interface between handlebar and trailer can be assumed to be comparatively small. There is much greater potential for optimisation at the assembly points within the aerobar, such as the clamp for the carbon extensions, which consists of many individual parts (compare Figure 2). The findings of the initial analysis of the system boundary result in the limitations of the aerobar to be modified, which are shown in Figure 2.

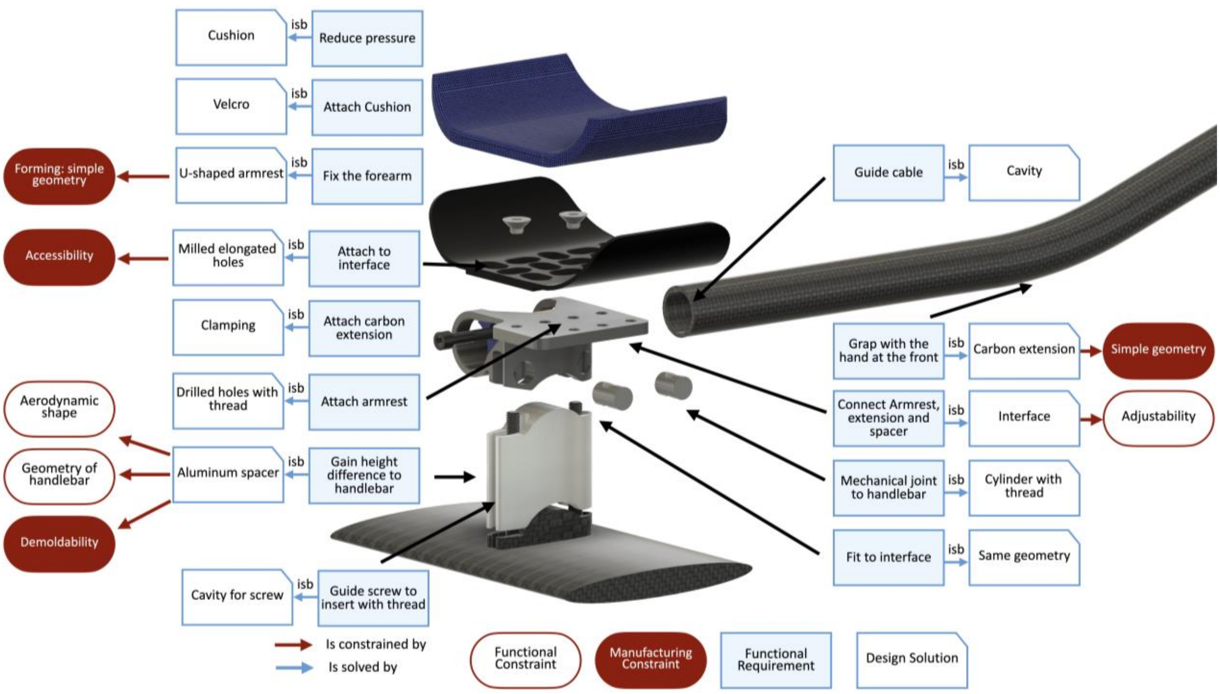

Figure 2. Function model and product architecture of a conventional aerobar

4.3. Integrated Function and Product Architecture Modelling

Function Modelling

The main function of the system, which was defined as the system boundary in the previous step, can be described as *Providing support for rider in an aerodynamic position*. To determine the sub-

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functions, for a better understanding of the product and as preliminary work for the EF-M, a product architecture is created. For this purpose, a reference product is modelled in CAD and its subcomponents are assigned to their functions. The result can be seen in Figure 2. The main components are the curved carbon fibre reinforced polymer tube and a formed aluminium sheet. This allows the arm to be stretched forward. A spacer ensures the height offset of the device to the handlebar. The other components are responsible for the adjustability of the mentioned components.

Enhanced Function-Means Modelling

In the EF-M model, different components interact with each other in different ways. The following table shows which kind of components can exist in the EF-M (left) and which relationship these components are able to have (right). As can be seen from Table 1, functions can only be implemented by one solution (1/1), other relations, like solutions can also lead to several "Functional Requirements" (1/n).

Table 1. Components and Relations in the EF-M, according to (Johannesson and Claesson, 2005)

Components		**Relations**			
Functional Requirement	FR	DS to FR	(1/n)	requires function	rf
Functional Constraint	CF	FR to target DS	(1/1)	is solved by	isb
Design Solution	DS	FR to non-target DS	(1/n)	is influenced by	iib
Manufacturing Constraint	CM	DS to C	(1/n)	is constrained by	icb
Configurable Components	CC	C to DS	(1/n)	is partly met by	ipmb
Design solution (variant)	a, b, …	DS to DS	(1/n)	interacts with	iw

The first step in applying the EF-M method is to create an enhanced function-means model for an existing product. For reasons of space, the EF-M of the reference product is not shown. Sub-areas that have been changed significantly are described. Between the original EF-M and the EF-M of the redesign, an adjusted model is created. This is simplified by removing constraints and associated DS and FR. It serves as a transitional model to the redesign, in which the design pace becomes visible. Due to the removal, it no longer represents a complete logically closed model.

The components shown in Figure 2 are colour-coded in the model as Configurable Components. The distinction between body and area is created via the numbering (CC-Body.Area).

Starting from the main function of the entire product and the associated design solution, there are four sub-functions. These form the main function of the constituent components. The constraints imposed by the manufacturing processes usually affect the components as simple geometry. Functional constraints are external requirements beyond the functional requirement that limit the further design solution. The adjustability of the system was introduced as a Cf. Based on the main function of the overall product and the associated design solution, four sub-functions result, which in turn build the main function of the components. The constraints imposed by the manufacturing processes usually lead to simple geometries of the components. Functional constraints are external requirements that go beyond the functional requirement and constrain the further design solution. The adjustability of the system was defined as Cf.

Contrary to the less regulated EF-M method, another Functional Requirement was added between the original and redesigned EF-M. This was intended to create a targeted search for new design solutions. In this way, it was intended that the search for new design solutions would be targeted at the new requirements. Starting from the transitional model, the tree branches are redesigned according to the new constraints. In this way, a new architecture with several variants is created. The variants are highlighted in yellow as design solutions. Four variants (a to d) were designed in two versions each (e and f). These versions distinguish between the integration of the armrest and production as a separate individual part. Variant a represents a topology-optimised structure for additive manufacturing to carry the forces with a carbon shell to create the aerodynamic shape. Variant b consists only of the outer wall, the wall thickness of which varies according to the stress curve. Variant c, on the other hand, has a minimum wall thickness throughout and forces are to be carried by a lattice structure inside the structure. Variant d envisages not manufacturing the component directly by additive manufacturing but printing a mould which is then laminated.

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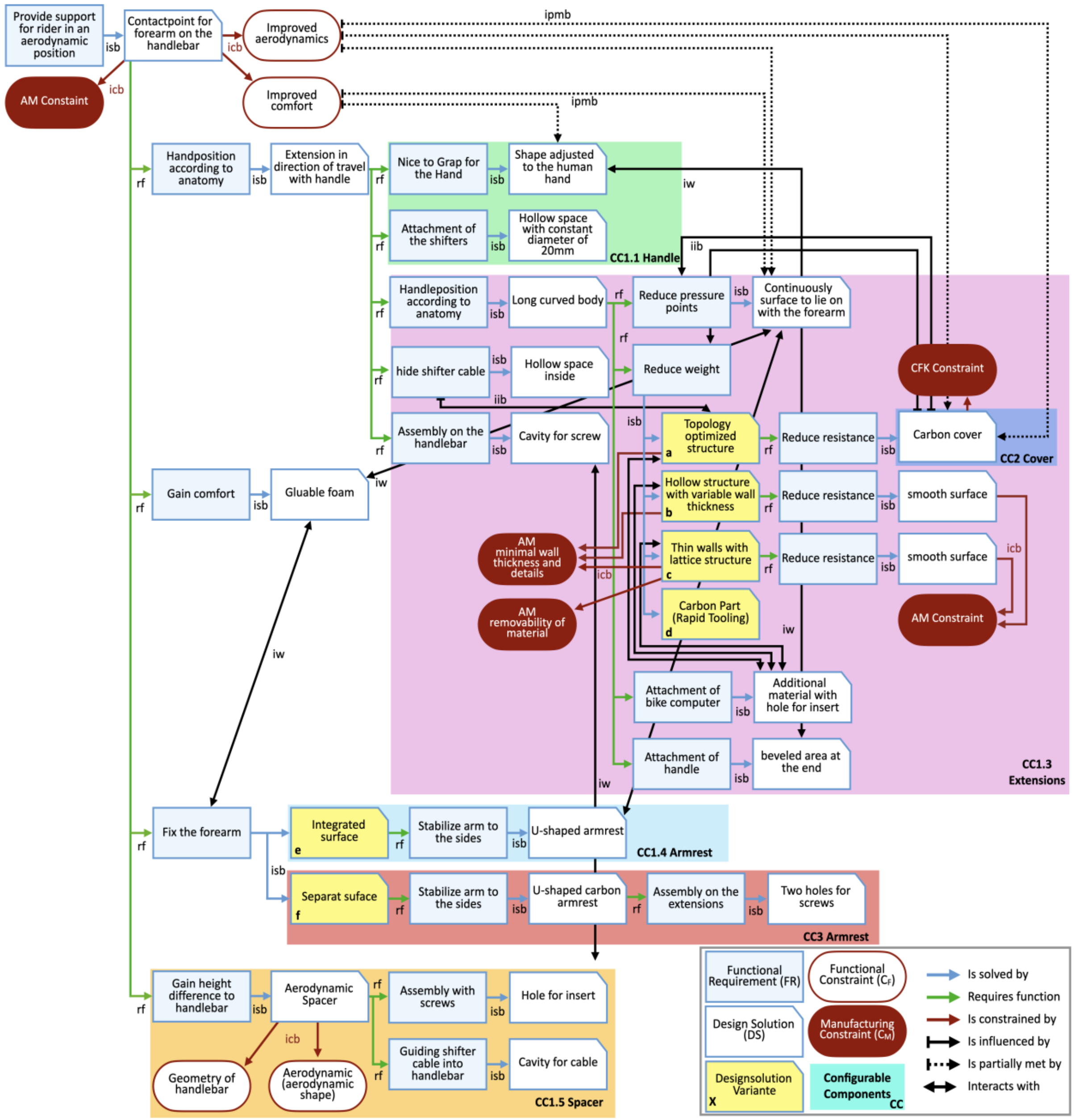

Figure 3. Redesigned EF-M for additive manufacturing

In the evaluation of the variants, it can be emphasised that the requirements are fulfilled by the variants. The integration of an additional brake lever is not implemented here to ensure compatibility with third-party suppliers. For variant d, the production effort is assumed to be significantly higher than for variants a-c due to the large share of manual manufacturing processes.

It is difficult to make a statement about the effectiveness of the approaches (a to c) for implementing the objectives. Both topology optimisation and lattice structures represent approaches with great lightweight potential. Prior knowledge in the field of topology optimisation was an argument in favour of variant a for the student in this project. In addition, the estimated increased modelling effort and risk assessment for lattice structures (variant b) were mentioned as further reasons for variant a. For thin-walled profiles, complicated failure mechanisms due to buckling are added (variant c). Within the scope of this project, the topology optimisation approach is therefore pursued further. Due to the advantages of the integral design and the lower number of interfaces, the pairing with variant e is implemented.

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4.4. Modelling & Prototyping

First, a basic model of the aerobar is designed in a CAD programme according to the developed product architecture. The model is parametrically constructed and variables are provided for the body dimensions, such as the forearm diameter and the length of the forearm. Other input variables include the height of the aerobar surface above the handlebar, the angle of attack, the internal angle and the angle of the grip. The topology optimisation is generated using the CAD proprietary program from Creo (version 7.0). The load assumptions are taken from DIN EN ISO 4210-5 (*Beuth*, 2015), which deals with the test force for handlebar stems. By optimising the topology, a reduction in volume of 42% can be achieved, starting from the initial model (Figure 4; left; grey transparent). The final weight of one aerobar is then 200.9 g. The aerodynamic carbon shell is laminated using the said initial model. With a density of 1.2 g/mm³ of the printed PDX material and a volume of 209.9 mm³, this results in a weight of 252 g. Adding the laminated cover (20 g) results in a weight of 272 g per aerobar. In relation to the conventional reference model (400 g/side), 32% of the mass can be reduced.

Figure 4. Modelling steps of a FDM-printed topology-optimised prototype

Due to the adapted shape to the rider, the athlete`s arm lies evenly on the aerobar. This improves the ergonomics. The number of interfaces has been significantly reduced from ten to four compared to the conventional reference product, which has a positive effect on the weight. Although the costs cannot be compared validly, the use of plastic in 3D printing reduces the costs considerably compared to titanium printing. However, the results are to be regarded as prototypes and use under real conditions requires practical validation in addition to simulation of the FE programme due to the anisotropic properties in additive manufacturing.

5. Discussion & Conclusion

This paper aims to improve the understanding of the role of function modelling for DfAM. For this purpose, a triathlon aerobar was redesigned in a case study. With the help of various methods, it was investigated which changes are senseful and which are technically possible to exploit the full potential of AM. The boundary conditions relate to an SLS process with fibre-reinforced plastics.

First, the conditions and potentials of an existing triathlon bike with regard to the main function of the aerobar were analysed and an ideal solution was defined. The detection of the system boundary for this project was initially carried out using the one-part device method. Starting with the integration of the entire system as a single component, this was successively reduced in dimension. The method was a suitable way to break away from existing solutions with regard to the system boundary.

Based on the defined system boundary, an integrated function and system model was created using the EF-M model. This method allows manufacturing conditions to be represented in the function model and defective design spaces to be filled with new solutions.

Although function models have an abstraction level in order to be able to represent as many scenarios as possible, an adjustment is often necessary. This is shown by the evolution of models such as the EF-M. This design study also partially deviated from the suggested procedure of the EF-M.

A promising approach was considered further. This is based on a parameterised and topology-optimised model with a carbon shell. In addition to the main goal of saving weight, this also includes improved ergonomics and a potential improvement in aerodynamics. The abstract and at the same time clear representation of the EF-M can be advantageous for the consideration of the impact of the design variants on the overall concept. While some of the above-mentioned design solutions are obvious by

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cleaning up the EF-M model, additional methods (e.g. creative methods or computational design for AM) appear to be advantageous for identifying less obvious solutions.

It should also be said that conceptual lightweight design does not automatically result from the approach. Additively manufactured structures have the potential of lightweight design but require a design that exploits the advantages of AM. This still requires knowledge about the principles of lightweight design.

However, the designers' lack of knowledge is cited as one of the main reasons why the potential of AM is not yet fully exploited.

Questions about processes or materials, for example, are usually easy to answer. When it comes to the question of whether a system exploits the potential of AM, the answer will be less easy to answer. But similar questions also arise independently of AM in the design process. Function and system modelling is a tool for the goal of designing systems and products optimally from the beginning. It can also be applied to the goals of additive manufacturing. Function modelling approaches such as EF-M and IFM that allow integrated modelling of a system`s functionality and architecture provide a basis for an appropriate adoption of systems and products for the use of AM. Thus, these approaches can also be used to decide on a suitable system boundary for the use of AM. To harness its potential for the optimal application, further insights are needed into what further adaptation of existing tools would be helpful.

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