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FUNCTIONAL MODELING IN THE DESIGN OF ADDITIVELY MANUFACTURED COMPONENTS

E. Garrelts ✉, D. Roth and H. Binz

University of Stuttgart, Germany

✉ enno.garrelts@iktd.uni-stuttgart.de

Abstract

This contribution investigates how methods for functional modeling support designers with additive manufacturing. Therefore, two methods for functional modeling are examined. In this contribution a study with 32 participants is presented. The participants solved two consecutive design tasks, in which some participants were supported by functional modeling methods in the second task. The study shows that students have the most difficulties in dealing with the geometric restrictions of Laser Beam Melting (LBM). Furthermore, the support value of functional modeling was not able to be assessed.

Keywords: additive manufacturing, conceptual design, design methods

1. Introduction

The generic term Additive Manufacturing (AM) covers various processes that build up components layer by layer. A computer plans the strategy for building up these layers, while the manufacturing process itself is automated. AM processes thereby enable comparatively restriction-free designs of components; for example, undercuts and internal structures can be produced (Gebhardt, 2016). The cost of a produced component is more correlated to its weight than to its geometric complexity. Complexity in this context is a measure of the amount of functional elements in one part. Designers should therefore focus on functional requirements and lightweight structures, and achieve these by increasing the complexity of the components (Klahn and Mebolt, 2018; Poprawe et al., 2015).

One such process is Laser Beam Melting (LBM), an AM process for the production of metal components that is used in serial production (Wohlers, 2017). LBM parts are built up in a powder bed. In each layer, a laser melts the necessary cross-section of the component to be produced. The different welding seams of the layers then form the component. In addition to parameters influencing the geometric properties, such as powder layer thicknesses or scaling-parameters, influence the material properties. By changing parameters such as the laser power, laser speed, or hatch distance, the user can alter certain material properties, such as ductility (Gockel and Beuth, 2013) or density (Read et al., 2015). The possibilities of LBM with regard to component complexity exceed those of classical machining methods such as turning or milling. In addition to the geometric complexity inherent in additive processes, the variability of the material properties represents a further dimension of design freedom. The degree of complexity of the individual components that can be achieved is comparable to a component assembly. Therefore, one key difficulty in the design of components for LBM is mastering complexity.

Several authors recommend the use of functional modeling for dealing with potential complexity (for example Valjak et al., 2018 and Kumke, 2018). Since methods like function structures or function trees form part of the basic engineering curriculum, it seems natural that students and practitioners would opt for those methods.

1.1. Motivation

In order to promote competence in the design of additive components, three workshops were held at the authors' institute in the last two years. In these workshops, students were given an introduction to additive manufacturing alongside a database of useful information for AM design. The database, comparable to Doubrovski et al. (2012), Schumacher (2019), Valjak and Bojčetić (2019), or Weiss (2019), contained examples of additive components, additive solution principles, and also methodological advice. In the workshops, students were asked to design a glue gun that could be manufactured in an additive process: A heat element, a cable, and glue sticks were all supposed to be integrated into the component. Further requirements were hand-powered glue extrusion, strain relief for the cable, and the integration of all elements into a single case. The result to be delivered was a hand-drawn sketch and accompanying explanations of the design. In order to create a realistic situation, the participants were given internet access and a time restriction of 90 minutes. The students were also familiar with the object to be designed, which is similar to the components that practitioners design and redesign.

1.2. Problem statement

In the workshops held, no student used a form of abstract problem description, even though the database suggested doing so and despite some methods for abstraction being studied in prior training. Similar observations were made in a workshop with practitioners. In these workshops, a total of 80 participants were observed, 23 of whom had an industrial background. The following research question can be derived from these observations: How do existing methods for functional modeling help in the early phases of design for additively manufactured components?

1.3. Structure of this contribution

To answer the research question, methods recommended in literature are described, and also how the use of these methods varies the results achieved by students in engineering tasks within self-conducted experiments. A discussion is then provided on the conclusions that can be drawn from these variations of the results and the impressions of the use of methods on students. Section 2 of this contribution describes which methods for functional modeling exist according to literature, while Section 3 describes the design of the conducted study. The results of the study are illustrated in Section 4 and discussed in Section 5.

2. Methods for functional modeling

The conventional way of designing complex products is to break the product down into simpler elements. The elements can then be designed and optimized individually before being recombined into a whole product. This way, the designer does not have to deal with the complexity of the entire product at once, but only with elements of lower complexity. In mechanical engineering, abstraction takes place on a functional level in order to obtain a fragmented model of a machine or a component (Pahl et al., 2007; Lindemann, 2016; Otto and Wood, 2001).

2.1. Methods of traditional product development

According to Dörner (1977), abstraction is the omission of details. Abstract thinking ignores unimportant aspects of a given situation, sharpening the focus on what is essential. The result of this unbiased approach is a broad search field for solutions concerning elements of reduced complexity (Ponn and Lindemann, 2011; Pahl et al., 2007; Lindemann, 2016; Dörner, 1979).
On the abstract level, the product is described by several functions. A "function" in this context is not only a mapping of input variables to output variables, as in mathematics, but also the abstract, solution-neutral formulation of a task. The abstract formulation makes it possible to search for

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functional principles in bionics or design catalogues. The primary task of a product is its overall function, which can be divided into various subfunctions. In most cases, there are various ways of subdividing an overall function into subfunctions, which are termed "variants." The different variants are not "false" or "correct." Instead, they merely represent different ways of achieving the overall function (Pahl et al., 2007).

Lindemann (2016) describes three methods of functional modeling. The easiest approach is a functional list, which comprises a summary of the product functions. The second modeling method is a function tree. With this method of modeling, a further subdivision into subfunctions is undertaken, starting from the main function. The further the subdivision into subfunctions proceeds, the more "branched" the tree becomes. The third method of modeling involves a function structure, which is a net-like structure in which the individual subfunctions of a product are linked by flows. There are always the three flows "energy" (e.g., electric current), "substance" (e.g., water), and "information" (e.g., on/off) (Lindemann, 2016; Otto and Wood, 2001).

2.2. AM-specific adaptations

Due to the possible complexity of components produced using LBM, the application of functional modeling is one apparent means of aiding designers in conceptualizing parts for AM. This breakdown helps the designers to focus on less complex sections of the design, enabling complexity to be reduced to a level that can be dealt with. If a method can help address the complexity of complex products, it might as well help in the design of complex components.

Several authors (Boyard et al., 2013; Kumke, 2018; Lindemann et al., 2015; Rodrigue and Rivette, 2010; Valjak et al., 2018) recommend the use of functional modeling, while only Boyard et al. (2013) provide adaptions and validation of the used methods. Here, a three-dimensional functional representation is proposed. The individual subfunctions are represented by interlinked spheres. A higher complexity in the representation and generation of the functional modeling has been chosen to be able to fully map the complexity of additively manufactured products and to produce a complete separation of the functional level and design level.

2.3. The use of functional modeling in design for AM

From the description and intended use of functional modeling in conventional product development, it would seem that the use of functional modeling in design for AM is beneficial. However, abstract, functional modeling helps to broaden the solution space and address complexity. Literature also suggests doing so. Nevertheless, in the workshops of the authors, neither students nor practitioners applied these methods in the design of single-component systems. Since the data on adapting the methods for this use case is thin, experiments into the use of functional modeling in AM design are needed.

3. Design of an empirical study

In order to close this gap, a study was conducted to investigate how existing methods for functional modeling can help in the design of additively manufactured components. The design of this study is illustrated in this section.

3.1. Training of the participants

The participants of the study were taught the theoretical basics of additive manufacturing, and LBM in particular, before participating. A 15-page script was handed out one week before the study, and participants were requested to study its contents. Key points were discussed with the participants before the design tasks took place. This way, it was ensured that participants had a basic knowledge of AM.

Table 1 gives an overview of the sections of the script and their contents. Additionally, the literature sources of the script are indicated.

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Table 1. Overview of the content handed out to the participants prior to the design task

Section		Contents	Literature
1.	Additive manufacturing	Terminology and principle of layer-based manufacturing	Gebhardt (2016), Klahn and Mehboldt (2018), VDI 3405 (2014)
2.	Laser Beam Melting	Differentiation between LBM and other AM processes, machine components, and working principle; material properties, case studies, advantages, and disadvantages of the process	Gebhardt (2016), ISO 17296-2 (2015),VDI 3405 (2014), VDI 3405 - 2 (2013)
3.	Design limitations of selective Laser Beam Melting		
3.1	Layer and path approximation	Systematic accuracy errors and staircase effect	Adam (2015), Gebhardt (2016), Klahn and Mehboldt (2018), Weiss (2019)
3.2	Melt-process inaccuracies	Accuracy errors due to laser-power-induced sintering and melt-pool inaccuracies	Adam (2015), Weiss (2019)
3.3	Warpage	Curl effect and internal stress	Gebhardt (2016), Klahn and Mehboldt (2018)
3.4	Illustration of restrictions	Visualization of geometric restrictions of LBM (overhang, minimal structures, etc.)	
4.	Cost-effective design		
4.1	Cost of selective Laser Beam Melting	Cost models of LBM, cost-complexity and cost-weight comparisons, need for lightweight design, and functional integration	Gebhardt (2016), Klahn and Mehboldt (2018)
4.2	Use of support structures	Part orientation and overhang angles	Leutenecker-Twelsiek et al. (2016)
4.3	Finishing	Part removal and consecutive manufacturing processes	Gebhardt (2016), Klahn and Mehboldt (2018)

3.2. Tasks of the study

The criteria for choosing the tasks for this study were to find parts or modules that (1) have a relatively high complexity for a single component, (2) are generally known by all participants, and (3) are not likely to have been designed by any participants before the study.

The design tasks for the study had to be complex because only complex parts have been found to be suitable for additive manufacturing so far (Wohlers, 2017). In industrial design environments, the designers are very familiar with the components to be designed. In order to fulfill a realistic design task, participants should also know what they are designing. If they do not know the object to be designed, there is a high probability that some of the participants will spend a significant length of time deducing the functional principle of the design task instead of actually designing. If none of the participants have performed the design task before, the background of the participants will be comparable, and so will the results.

In order to compare the results of participants, it was necessary to have two design tasks: firstly, to identify the ability level of the individual participants and, secondly, to determine the level of influence of the design support method in question.

The aim of both tasks was to finish a hand-drawn solution sketch of a component to be produced using LBM. The sketch had to include defined shapes and specified dimensions of all geometric features. A transfer to CAD and subsequent production should be possible using only the sketch. A brief description of how the solution works had to be included in case this was not obvious. Additionally, the build-orientation of the component had to be specified.

3.2.1. Hole punch

Task 1 was defined as the design of a hole punch. Since it is a common office item, it was anticipated that every participant would be familiar with the general functionality. A design for production in sheet metal and injection molding consists of between 10 and 15 parts that can be partially or fully integrated using LBM as a mean of production. The requirements for the task were as follows:

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- The punch should be operated by hand.
- The paper size should be adjustable.
- Up to 50 sheets should be able to be punched at once.
- Paper scraps are to be collected.
- The release arm should reset itself automatically.
- The risk of injury should be minimized.
- Attention must be paid to ergonomic operation.

3.2.2. Stapler

The second selected task was to design a stapler. This task also involves a piece of office equipment that should be familiar to all participants. The common sheet-metal and injection-molding design is similarly complex to the hole punch. Further requirements for the task were as follows:

- The stapler should be operated by hand.
- 50 sheets are to be stapled at once.
- The release arm should reset itself automatically.
- The risk of injury should be minimized.
- Staples must be stored in the stapler.
- Attention must be given to ergonomic operation.
- Purchased parts are staples in packages.

3.3. Evaluation of performance

Two experts with several years of experience in the design and production of LBM components evaluated the performance of participants in the study. The evaluation was conducted simultaneously, and points were awarded based on a consensus. In order not to have any inference to the participants, each participant was assigned a four-letter acronym. This way, the experts were not able to assess anything except the submitted sketch. For the evaluation, eight categories collated in three groups were used. A "0" was assigned, when the criterion was ignored, a "1" was assigned, when the criterion was considered, but the result was insufficient, and a "2" was assigned when the measures taken were sufficient.
Functional aspects of the evaluation included functionality, integration, and correct usage of elasticity and connections. The group of design limitations rated the suitability of the participants' sketches against the criteria "orientation," "overhang angles," and "warpage." Lightweight design in AM is classified as a cost-reduction measure. Table 2 summarizes groups and criteria. Furthermore, it gives a short description of the criteria and a reference to the script section in which the individual criteria were explained. The functionality of the design tasks was not described in the script. It was a precondition that participants can find working principles and design them.

Table 2. Evaluation criteria and description

Group	Criterion	Description	Script reference
Functional aspects	Functionality	How well would the design work, neglecting predictability?	Basic engineering curriculum
	Integration	Is the structure integrated into one or only few elements?	2; 4.1
	Elasticity	How well is the elastic element designed?	2
	Connections	How well are relative movements considered?	2
Design limitations	Orientation	How well is the build-orientation considered?	2; 3.3; 3.4; 4.2
	Overhang angles	Are there unfeasible overhangs?	2; 3.2; 3.4; 4.2
	Warpage	How well are measures taken against warpage?	3.2; 3.3
Cost	Lightweight	Is the structure lightweight / is consecutive optimization considered and possible?	1; 4.1

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3.4. Design of the study

In order to recreate a working environment as realistically as possible, all participants always had access to the internet via a computer provided to them, whereby *internet use was not regulated*. In addition, the subjects were given *access to information-platform content on the design of additively manufactured components.*

Figure 1 shows the study design in a compact way. Two groups (A and B) were formed to carry out the study and participated on two different days. The script and its contents were discussed first, then one design task was handed out. After finishing the first task, the second task was handed to the participants. The tasks were performed by all participants in the same room, and participants had *90 minutes to complete each design task.* During the study, comprehension questions were answered. Group A consisted of 13 students, while Group B consisted of 19. Group A first received the “hole punch” design task, then a second “stapler” design task. Group B processed the tasks in reverse order. The test subjects had a short break between the two tasks.

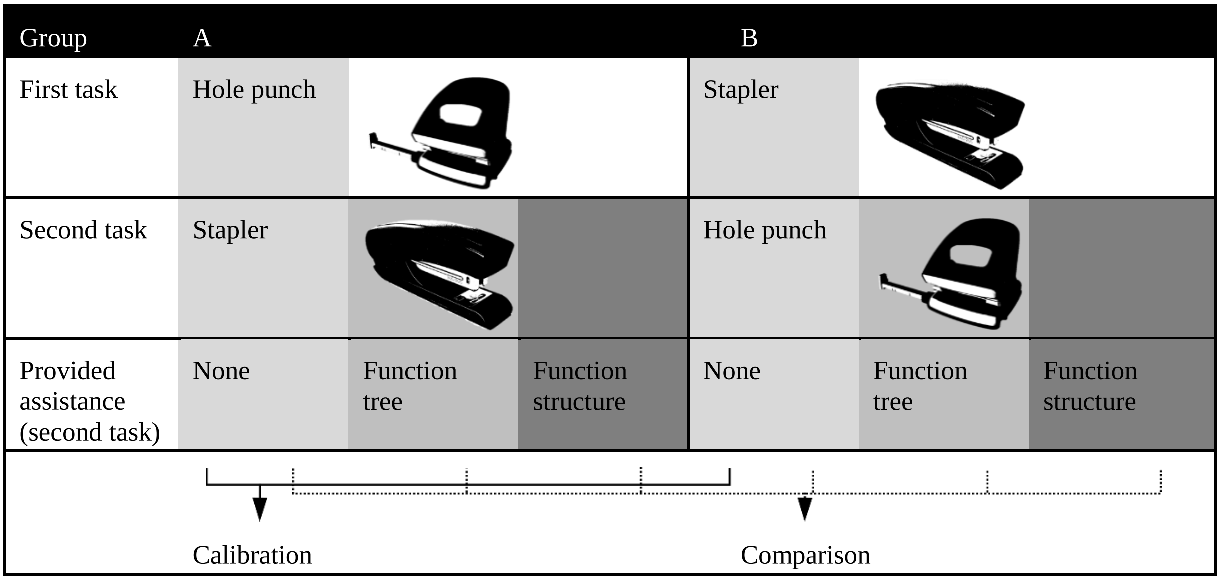

Figure 1. Compact visualization of the studies’ design

After the first task had been completed, the groups (A and B) were each divided into three subgroups, which received varying levels of design support. *The first subgroup* (6 persons in Group A; 5 persons in Group B) received *no support* in each case. In order not to lower the motivation of the first subgroup while the other two subgroups received the instructions, short extracts of entertaining short stories were handed out. The *second subgroup* (3 persons in Group A; 8 persons in Group B) received brief instructions on how to create *function trees.* In addition, this subgroup was given a compact exercise to practice setting up a function tree. The *third subgroup* (4 persons in Group A; 6 persons in Group B) received brief instructions on how to create a *function structure* in addition to a compact exercise. The participants were able to ask comprehension questions about the methodological support assigned to them, and these were answered. Group membership was assigned randomly before the study. Since not all assigned students participated, groups are not homogeneous.

In order to estimate the relative difficulty of the two design tasks, the two groups that did not receive any support were used as a comparison group. By comparing the changes in the results of the two tasks, conclusions can be drawn about the difficulty of the tasks. This assessment can also be used to compare the shift in performance of the other teams and enable evaluation of the design support method’s effectiveness.

3.5. Participants

Thirty-two participants took part in the study, all of whom were enrolled on master’s courses in engineering. An evaluation sheet was handed out after the study in order to collect participants’ opinions. As shown in Table 3, the self-assessed prior knowledge of participants is distributed across

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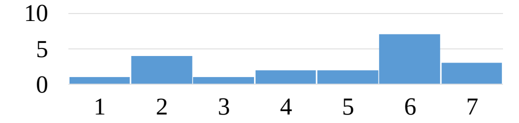
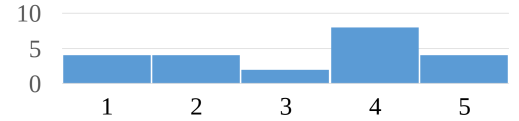
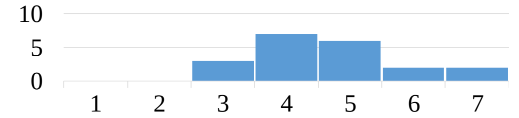
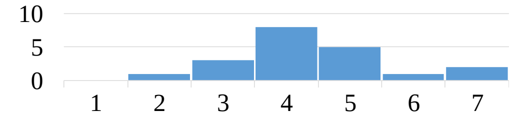
the entire scale. The participants also assessed the time required to complete the tasks in various ways. With a mean of 3.2, there is a tendency toward too little time. The two tasks were assessed by the participants as having a difficulty of 4.65 on average for the hole punch and 4.4 on average for the stapler. Both function trees and function structures were understood and applied correctly by the participants.

Table 3. Answers of the participants to a survey handed out after the study

How much prior knowledge of the design of additive components did you have before this event?	A lot of prior knowledge		No prior knowledge
How was the length of time for the design tasks?	Too long		Too short
For me, the design of the hole punch was:	Not challenging		Challenging
For me, the design of the stapler was:	Not challenging		Challenging

4. Results of the conducted study

This section presents the results of the conducted study. First, the absolute scores of the participants are given and then the shift in performance is summarized.

4.1. Scores

The average scores of the participants for the design tasks were 6.75 for the hole punch and 7.31 for the stapler. The average scores of the participants for the different criteria are shown in Table 4. The boxes of the table are colored for clarity, whereby low average scores are colored red, and high average scores are colored green. Almost all participants achieved the full score in the category "Functionality." The lowest scores were in the category "Warpage," where participants received 0.31 and 0.41 points on average. The participant with the highest score for the hole punch achieved 14 points, while the one with the highest score for the stapler achieved 15 points. The lowest score was 2 points for both tasks, and the maximum score was 16 points in each case.

Table 4. Summary of the average scores of the participants

Group	Functional aspects				Design limitations			Cost	Average score
Category	Functionality	Integration	Elasticity	Connections	Orientation	Overhang angels	Warpage	Lightweight	
Hole punch	2.00	0.69	0.91	0.78	0.84	0.56	0.31	0.66	6.75
Stapler	1.94	1.03	0.81	1.00	1.00	0.56	0.41	0.56	7.31

4.2. Shift in participants' performance

Table 5 shows the difference in the average number of points achieved by the participants between the first and second task. For Group A, points received in the task "Stapler" minus the points received in the task "Hole punch" are listed. A positive number therefore implies an improvement, a negative

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number a worsening. For Group B, the opposite applies. The averages are also calculated with consideration of the number of participants in every subgroup.

Table 5. Difference in average points of the participants between the first and second task

		Functionality	Integration	Elasticity	Connections	Orientation	Overhang angle	Warpage	Lightweight	Sum
Group A	No support	0.00	0.33	0.33	0.33	0.17	-0.33	0.00	-0.17	0.67
	Function trees	0.00	0.00	0.00	-0.33	0.00	-0.67	-0.33	0.33	-1.00
	Function structures	0.00	-0.50	0.00	-0.50	1.00	0.25	-0.25	-0.50	-0.50
Group B	No support	0.00	-0.80	-0.60	-0.60	0.00	0.20	-0.40	-0.80	-3.00
	Function trees	0.25	-0.88	0.63	-0.38	0.00	0.13	-0.50	0.50	-0.25
	Function structures	0.00	0.00	0.50	-0.33	0.00	-0.83	0.17	0.17	-0.33
Average of A and B	No support	0.00	-0.18	-0.09	-0.09	0.09	-0.09	-0.18	-0.45	-1.00
	Function trees	0.18	-0.64	0.45	-0.36	0.00	-0.09	-0.45	0.45	-0.45
	Function structures	0.00	-0.20	0.30	-0.40	0.40	-0.40	0.00	-0.10	-0.40

The greatest difference in total scored points was found in the groups without support. Group A improved by 0.67 points on average, with Group B deteriorating by 3 points. The biggest differences in the scores for single categories was +1 in "Orientation" for "Group A - Function structures" and -0.88 in "Integration" for "Group B - Function trees." In these categories, the respective "other" group, which performed the tasks in the opposite order, did not see any change in performance at all.

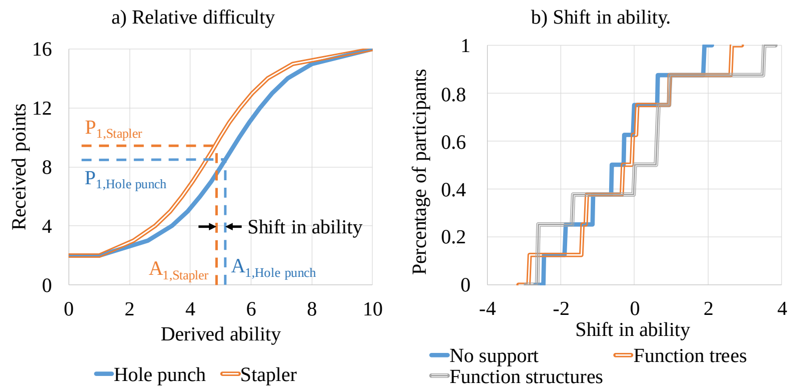

Figure 2. Relative difficulty of the design tasks and shift in the participants' abilities

In order to obtain a more significant statement, a statistical evaluation of the study using "Rasch Measurement Theory" (RMT) was conducted (Andrich and Marais, 2019). RMT considers abilities as latent traits that can only be assessed using tests. In RMT, the delta of the point difficulty and the participants' ability yields a probability of a task being correctly completed in the test. Much higher ability on the part of the test subject does not mean that the task is always fulfilled; rather, it simply means that the probability is high. Using the frequency of correct results, the difficulty of each given point can be calculated. In this paper, the relative difficulties of the points were calculated by comparing every given point with all other points. This calculation was based on the results of both groups without support. Difficulties were calculated based on data derived from the relative frequencies of correct results. The results are relative difficulties of all given points and, consequently, the difficulty of all given points on a scale with arbitrary origin and arbitrary unit. Here, the difficulties were plotted on a scale from 0 to 10. With these difficulties, the probable score of an imaginary participant with variable ability can be calculated. Figure 2a) shows this curve of the probable score for both tasks. Using this graph in reverse, the

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derived ability of a participant can be determined. As shown in Figure 2a) the abilities for both tasks can be determined, and the shift in ability of a participant between both tasks can be identified.
Using RMT, the difference in the tasks' difficulty levels can be calculated and subtracted. For a more detailed description of the theory and its application, the authors recommend Andruch and Marais (2019).
The shift in ability was calculated for every participant using this method. The cumulative distribution of shifts grouped according to the used design support is shown in Figure 2 b). In this figure, participants who received less than three points are neglected in order to avoid inaccuracy due to the low precision of ability measurement. The distributions therefore only show the change of eight participants in each case.

5. Discussion

The main limitation of the results of the study is the low number of participants. Every type of support was used by 10 and 11 participants, yet statistically unambiguous results are not attainable. Since previous knowledge on the topics "AM," "engineering design," and "design methodology" varies, so too do the participants' results in the design tasks (cf. Table 3 and Table 5). From the results, it also seems that the motivation of the participants decreased during the study. Scores in the second task conducted are lower on average than the scores of the first task conducted (Table 5).
Despite these limitations, the study demonstrates that the most difficult aspect for students in designing for AM is dealing with the design limitations (cf. Table 4). The difficulty of dealing with "Orientation," "Overhang angle," and "Warpage" is only addressed by achieving a lightweight design. Nevertheless, designing an integrated component with well-chosen functional principles is very challenging for most students.
Furthermore, the study indicates that the use of functional modeling alone does not improve the students' designs. The measurable influence was neither significant on the basis of points (cf. Table 5), nor on the basis of an elaborate statistical evaluation (cf. Figure 2). The authors see three possible reasons for this lack of support:

1. The tasks might not have been extensive enough, and students did not need to break down the functions. The average scores of participants (cf. Table 4) contradict this presumption.
2. Despite the required decomposition, it might be that students searched for an overall solution intuitively. If this is the case, the broadly distributed time assessment is the result of some participants first dealing with a descriptive method, then with an intuitive approach.
3. The core problem might be the appropriate selection, variation, and recombination of working principles. If so, abstract problem modeling is not the core difficulty for students.

6. Conclusion and outlook

This contribution investigates how methods for functional modeling can support designers in designing for AM. To this end, the three established methods were discussed, and two of these methods were examined further. The main scientific compliment was a study with 32 participants, who solved two consecutive design tasks, whereby some participants were supported by functional modeling methods in the second task. The study demonstrates that students encounter the most difficulties in dealing with the geometric restrictions of LBM. Furthermore, the support value of functional modeling was not able to be evaluated in this study.
The study has shown that an explanation and introduction to dealing with geometric requirements is not sufficient to enable novices to design components suitable for production with LBM. This finding implies that a readily comprehensible and time-efficient support method for novices might be a useful contribution. In future work, investigation will be conducted into the issue of a lack of prior methodological knowledge being the potential reason for the inability to evaluate support with functional modeling. In a comparison group, a study will be conducted into whether support in appropriate selection, variation, and recombination of working principles can help in designing for AM.

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