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Improved Approach to Implementing Design Education for Additive Manufacturing Using a RC Model Race Car

S. Junk ✉

Offenburg University of Applied Sciences, Germany

✉ stefan.junk@hs-offenburg.de

Abstract

The integration of additive manufacturing processes into the teaching of students is an important prerequisite for the further dissemination of this new technology. In this context, the DfAM is of particular importance. For this reason, this paper presents an approach in which a connection is made between methodical product development and practical implementation by AM. Using a model racing car as an example, students independently develop significant improvements of particular assemblies. A final evaluation shows that the students have significantly improved their skills and competencies.

Keywords: design education, additive manufacturing, product development, evaluation, computer-aided design (CAD)

1. Introduction

In the last decades, the variety of methods of Rapid Prototyping (RP) or Additive Manufacturing (AM) as well as their fields of application have grown enormously (Wohlers *et al*., 2020). One reason for this is the new possibilities that additive manufacturing offers with regard to the free design of components. Also, the number of materials available in this new technology has also risen sharply. In order to exploit the possible potential of these new, generative manufacturing processes, the special features of the layer-by-layer structure and resulting material properties must already be considered during the development and design of components and products (Diegel *et al*., 2020).

However, education and training are often still focused on conventional, i.e. formative and subtractive, manufacturing technologies, so that many engineers today have limited skills and knowledge regarding AM (Kriesi *et al*., 2014). To address this shortcoming, a number of textbooks and design guidelines have been edited. In addition, several universities have established lectures and seminars that consider design for AM (Klahn *et al*., 2018; Gibson *et al*., 2021). However, these courses typically utilize labs that provide access to a limited number of 3D printers. This allows students to use the labs, but unfortunately, they often lack a deeper understanding in terms of manufacturing technology and its capabilities and limitations in practical applications.

2. Literature review

The integration of AM technologies in teaching at universities has already been successfully practiced for several years (Unver *et al*. 2006; Celani *et al*., 2012). Today, there is a wide variety of learning materials for theoretical training in product development, ranging from introductory books to comprehensive journal paper offering a detailed description of the procedures and processes (Adam, 2015, Klahn et al., 2018, Diegel et al., 2020, Leavy, 2020). In practical education, various studies show that the use of AM ensures rapid accessibility of prototypes, which assures students of direct feedback

regarding the feasibility and usability of their product designs (Ford and Dean, 2013; Mostert-van der Sar *et al*., 2013; Widden and Gunn, 2010).
Until recently, the application of AM technology in education was limited by the fact that generally only a few devices were available in university laboratories. In addition, these devices often required specially trained operators. To overcome this obstacle, laboratories with a larger number of smaller 3D printers were increasingly established at universities (Chen at al., 2015a, Chen *et al*., 2015b). This has allowed larger groups of students to have direct access to the equipment in a shorter period of time. To overcome the drawbacks of traditional teaching, a new type of teaching using 3D modeling software and 3D printing technology was investigated. In this process, 3D printing makes it possible to obtain the designed products quickly and directly to help students measure the quality of the designed products. This new teaching methods improve the quality and efficiency of the design. In addition, the students' skills have been improved by combining the 3D printing technology with the design work in the students' practice (Hao *et al*., 2020).
Nevertheless, students in these labs are merely passive users of the technology and do not gain a deeper insight into the manufacturing process and the exact operation of the 3D printer.Another approach to teaching the specific requirements for creating components and products using AM is the use of do-it-yourself kits. Here, students first install a 3D printer as a kit and put it into operation. In doing so, they gain a good understanding of the structure of the components and thus of the function of the 3D printer. This understanding can later be used in generating components, e.g., in the form of design guidelines (Junk, 2014).
In previous studies, several identical 3D printers were used, which could only use building material and no additional support material. As a result, the design freedom was very limited. In addition, a software package was used that could only influence the data preparation to a small extent. Thus, there was limited room for variation in setting parameters and materials (Junk, 2017). However, these approaches have shown that the setup of 3D printers by students is very time consuming and error prone. In addition, support for problems from kit manufacturers is often limited. Furthermore, a disadvantage of imparting knowledge about additive manufacturing, which is still a new technology, is that the variety of processes and materials is constantly increasing. Moreover, existing processes are rapidly supplemented or even displaced by new ones (Junk and Matt, 2015).
New approaches to teaching Design for Additive Manufacturing (DfAM) rely on the use of design education platforms (DEP), which should lead to a simplification of the development process, especially for complex, mechatronic products. The DEP is used to standardize the components of a product and their interfaces, e.g. the components of a self-propelled robot. This is intended to reduce the effort required of instructors and increase the number of students participating (Heyden *et al*., 2020). New research was conducted to understand how knowledge of the possibilities (i.e. opportunistic - free design of surfaces) and limitations (i.e. restrictive aspects - need for support structures) of AM affects design outcome (Prabhu *et al*., 2018). Further research with different groups of students investigated how opportunistic or restrictive DfAM affects self-efficacy, outcomes, and technical goodness of designs. Since the results show a decrease in technical goodness in all groups, further investigation is needed in this area (Prabhu *et al*., 2020).

3. New approach to design education for AM

The literature review raises the question of how students can independently develop solutions in a course using methodical approaches in order to develop and implement a product to be manufactured using additive manufacturing. In this contribution, the specific course "Workshop Rapid Prototyping" will be used to investigate how master students of engineering and industrial engineering acquire the competence to understand the new manufacturing technology AM and to independently develop a design based on it. In particular, it is to be determined which competencies and to what extent they are improved by this course. Also, the question is to be clarified, which parts of the product development have a particularly strong influence on the acquisition of the competences.
In this way, a close and practical cooperation between manufacturing technology and design is established. At the same time, special emphasis is placed on the methodical approach to development, so that a multitude of ideas and targeted optimizations can take place. The new course "Workshop Rapid

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Prototyping" pursues several goals. On the one hand, students are to become familiar with the processes of additive manufacturing. This includes a critical assessment of the possibilities, but also the limits of this new technology. On the other hand, they should gain practical experience, especially with regard to the various materials and their useful applications. Finally, these experiences should also be reflected in the design, e.g. in the form of "lessons learned" and design guidelines.

3.1. Basic structure of the course

In this new course a remote-controlled racing car model is used as a practical example (see Figure 1). The CAD-data of the individual parts can be downloaded by the students from the freely accessible Internet platform "thingiverse" (https://www.thingiverse.com/thing:1193309). All necessary purchased parts (e.g. motors, servos and screws) will be provided. In addition, the students are given access to two different printers. For this purpose, training on the devices will be provided first. The students' task is to analyze and optimize certain assemblies. It must always be considered that additive manufacturing will be used in the production of the optimized assemblies. In addition, the students must develop criteria to evaluate the technical value of the optimization, i.e. target values must be defined.
This task is carried out in two or three teams of three to four students each. These teams have one semester to complete the optimization. Thus, the teams have a total of 90 hours at their disposal. During the processing, regular meetings with the lecturers take place in order to check the current status of the work and to clarify current questions. These meetings will be held separately for each team to maintain confidentiality. A practice session including a test race is held one week prior to the final presentation so that teams can evaluate the performance of their solutions and assess the gap between them and competing teams. At the end of the semester, a final presentation is held in which results are presented.

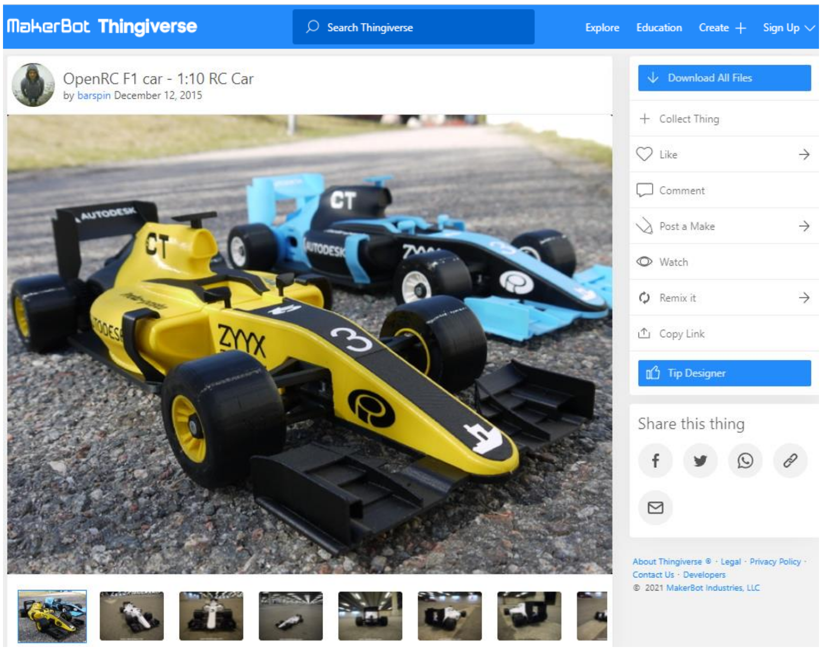

Figure 1. Screenshot from internet platform "thingiverse" (thing:1193309)

The evaluation of the students' work is done in two parts. In the first part, the presentation of the results, the technical value of the optimization and the precise presentation of the technical and cost changes are evaluated. In addition, a race with the radio-controlled model race cars will take place, in which the acceleration and the driving time for a certain course will be measured. This should show to what extent the design changes lead to better results in practice. In addition to the times for driving along the race track, concrete measured values are also recorded. These include, for example, the time taken to change tires or the size of the turning circle, including a comparison of the left and right turning circles. With the help of these measurements, which are also included in the evaluation, the quality of the optimization

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can be assessed. Furthermore, the students determine the costs and production time of the components in order to be able to make an economic evaluation.

3.2. Previous experience

This course has already been carried out twice. In this article, the third, further improved implementation of the course is presented (see Table 1). Already during the first execution of the course it could be shown that this approach leads to a successful transfer of important knowledge about additive manufacturing (Junk, 2020). However, it has also been shown that students still lack certain methodological skills in designing. In addition, the first execution of the workshop shows that the race car, as downloaded from the Internet platform, still has significant weaknesses.
Therefore, in the second edition of the course, special attention was paid to expanding the students' design skills. By working methodically using the SPALTEN problem solving methodology (Albers *et al*., 2005), all teams developed new and innovative approaches for optimizing particular assemblies of the given model race cars (e.g. chassis and wheels).

Table 1. Evolutionary stages of the courses

	1st edition	2nd edition	3rd edition
Design methodology	General product development methods	SPALTEN problem solving methodology	SPALTEN problem solving methodology
Organizational improvements	n.a.	Practice (test race)	Practice (test race)
Technical improvements	- Lightweight design - Functional integration - Optimization of wheels	- Robustness of chassis - Adjustment of the turning circle - Quick change of wheels	- Front axle suspension - Quick change of the front spoiler
Technical problems	- Breakage of suspension - Imprecise steering	- Breakage of the suspension - Front spoiler breakages - Insufficient suspension	- no severe technical problems
Number of participants	8	7	13
Number of teams	2	2	3

In the process, many aspects could already be developed virtually, thus saving important resources in AM. The joint work in the team has developed and strengthened essential key skills of the students. Through competition between the teams, different approaches were pursued and compared in a final presentation and during the race. In terms of organization, an additional "practice" or test race as a first comparison of the solutions proved particularly useful, as the weaknesses of the solutions became visible here and a new motivation for optimization arose. For technological improvement, certain assemblies, such as the steering and wheel suspension, were selected for targeted optimization. In addition, students developed a way to change wheels as quickly as possible. However, the second edition of the course also showed that other weaknesses exist. For example, the wheel suspension often breaks and parts of the front spoiler break off. In addition, ground contact is poor, which could be improved by a suspension system, for example.

3.3. Methodical design and implementation using additive manufacturing

At the beginning of the second and third edition of the course, the theoretical knowledge of the students is specifically expanded through a training using a methodical approach for problems solving and design. In order to learn a methodical approach, they will be familiarized with the development method "SPALTEN". The SPALTEN methodology describes a universal approach for handling problems with different boundary conditions and degrees of complexity. With its help, a minimization of effort and time as well as an optimization of the solution can be achieved in connection with a maximization of safety when solving the problem. It was first published by in 2002 and has been consistently developed

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and applied over the past 15 years. This methodology has proven to be very successful, as it has been shown in an extensive study that many PhD students use the skills they learned during their training in practice later on (Albers *et al*., 2015).

The SPALTEN problem solving method consists of seven consecutive process steps: In the situation analysis, all necessary information about the situation is collected, organized and documented. The information serves as a basis for the further development process. The goal of problem containment is to define the problem at hand based on the information previously collected. Typical correlations are to be identified. In addition, the various pieces of information are to be specified. Among other things, this data forms the basis for comparing the target and actual situation. In the next step, alternative solutions for the previously described problem are generated. Various creativity techniques can be used to support this. For this purpose, a high quantity of solutions should be aimed for. When selecting the solutions, the previously generated alternative solutions are compared with each other and evaluated based on criteria. The selection of the criteria is to be defined in relation to the problem. In the consequence analysis, risks and opportunities for the selected solution are determined. Afterwards, in the step "decision making and implementation", the implementation of the mental solutions into reality takes place. In this implementation step, plans are already drawn up and implemented. In the last step of the problem solving method, the recapitulation and learning, the reflection of the problem solving process and the documentation of the knowledge for future processes takes place (Albers *et al*., 2015).

In addition, the consideration of the problem-solving team plays a decisive role in the SPALTEN methodology. The process should always start with the definition of the team, which should be continuously reviewed and adapted. During the process, ideas for approach and problem solving (measures) are continuously generated in the team. Often, however, the ideas cannot be acted upon directly. These ideas should be immediately fixed and stored in the Continuous Idea Storage (CIS) in order to be able to use them in the course of the product development process.

To strengthen the practical knowledge of the students, they will be trained on two 3D printers. These will first include a 3D printer that uses fused filament modeling (FFM), or material extrusion. This printer can be used for a huge variety of components in the field of car body and chassis, as it offers sufficient strength. In addition, the process and the printing materials used for it are relatively inexpensive. For the production of tires, on the other hand, a 3D printer based on the Polijet modelling (PJM) process is used. This offers the possibility of processing various plastics in pure or mixed form. So, it becomes possible, for example, to produce rigid rims and rubber-like tires in a single work step.

4. Methodical product development in the 3rd edition of the course

This section explains the developments from the third and thus current edition of the course. The successful implementation of the teaching concept in the first and second edition of the course has now been applied for a third time with the improvements from the second edition. A total of 13 students in 3 teams took part in this course. The additively produced racing cars with radio remote control of all teams are shown in Figure 2.

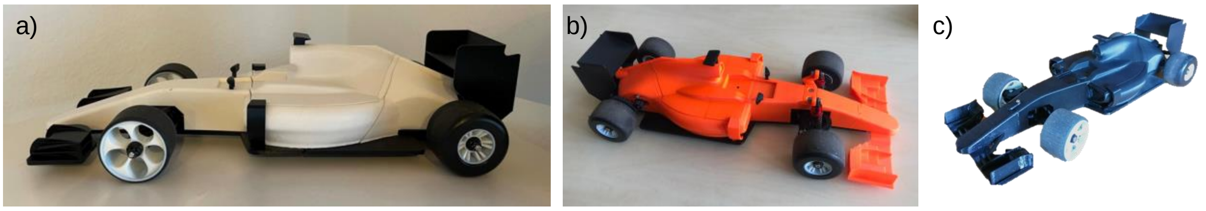

Figure 2. Additively manufactured RC racing cars: a) team 1, b) team 2 and c) team 3

Using team 2 as an example, the application of the SPALTEN problem solving method can be demonstrated here. First of all, a situation analysis was carried out. This shows that when driving over uneven road surfaces, the vehicle is hardly controllable. In addition, there is a frequent occurrence of fractures in steering knuckles and steering components at the front and wheels falling off. In the previous course, the steering system was already optimized and a quick-change system for wheels was installed.

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The problem definition includes the determination of the available time and a corresponding time schedule. Concrete problem definition in this edition is development of a suspension for at least one axle and an improvement stability of the chassis. In addition, a front wing is to be developed that can be replaced as quickly and easily as possible (e.g. in case of damage or breakage)
In the development of alternative solutions, each team member first developed their own creative ideas. These were then discussed within the team and developed further together. During this collection of ideas, a total of eight solutions were developed for the suspension, with only the front axle being suspended, and seven solutions for the quick change of the front wing. All solutions are fixed with the aid of labeled sketches.
To enable selection of the most promising solutions from the large number of solutions developed, both pairwise comparisons and a utility analysis are carried out. For this purpose, the students define catalogs with criteria such as complexity, feasibility, material consumption and costs.

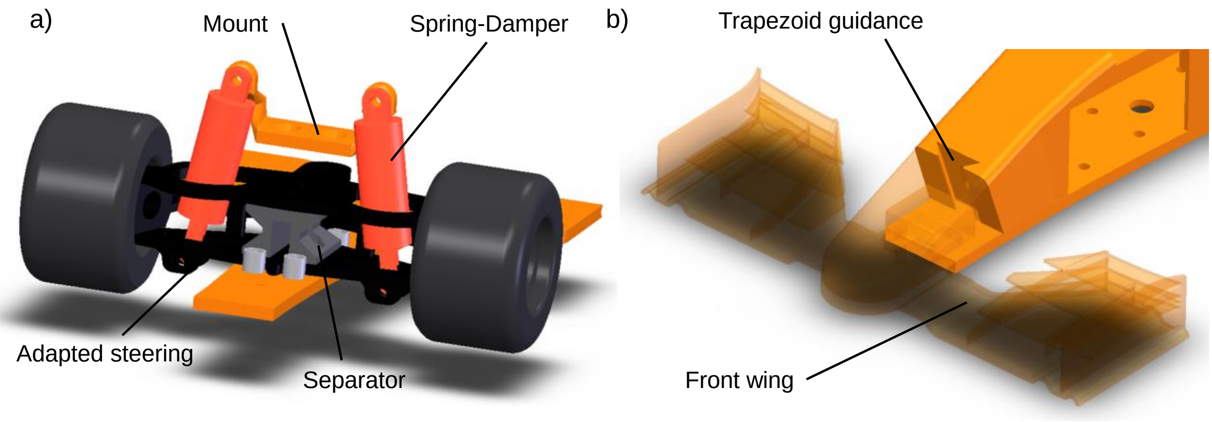

Figure 3. CAD model of the solutions developed: a) spring-damper system with steering, b) quick-change system for front wing with trapezoidal guidance

In the scope analysis that now follows, a SWOT analysis is carried out for the various solutions. Since this procedure is very time-consuming, it is only applied to the three best selected solutions for the two tasks suspension and front wing. After these extensive analyses, an informed decision can be made. Team 2, for example, decided to develop an externally mounted spring-damper system. Prefabricated parts, which can be purchased cheaply in model shops, are used for this. The system is connected to the body and chassis via newly developed mounts (see Figure 3 a). The quick-change system for the front wing was implemented using a trapezoidal guide. An inexpensive standard part, a grub screw with spring-loaded ball, was also used to prevent unintentional loosening of the front wing (see Figure 3 b).

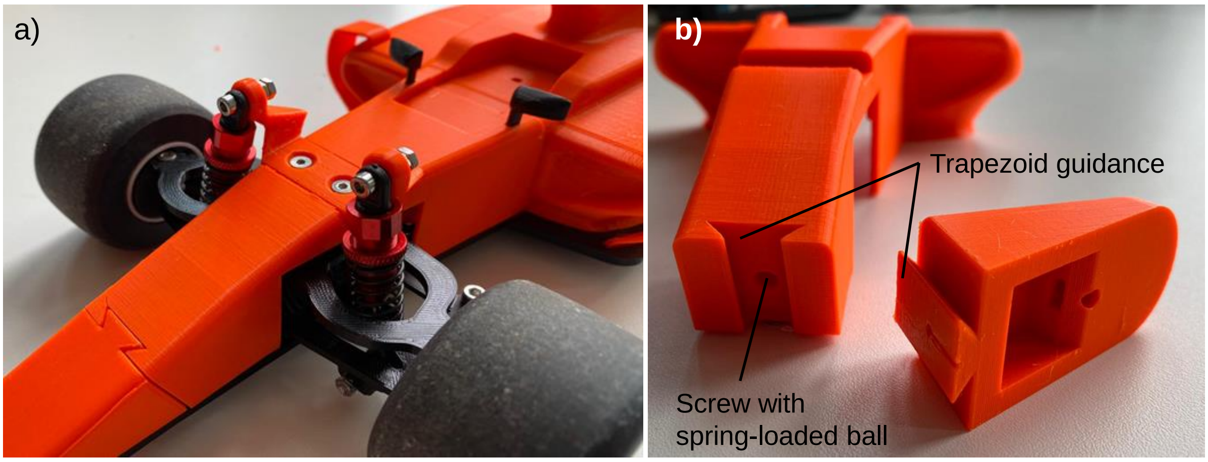

Figure 4. Implementation of the solutions: a) spring-damper system with optimized suspension, b) front wing with trapezoidal guidance and optimized fit

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Finally, the developed approaches are implemented by means of additive manufacturing. During this implementation in practice, regular reworking and learning is necessary. For example, the upper suspension of the springs has been optimized several times. The geometry of the steering system has also been adapted to increase the installation space for the springs (see Figure 4 a). Several optimization loops were required for the trapezoidal guide on the front spoiler to find a clearance-free and smooth fit (see Figure 4 b). Among the "lessons learned", for example, is that the direction of pressure is crucial for accuracy and the stability of the components. In addition, the washout support material offers many advantages. Fits have proven printable, but are difficult to adjust. Care must be taken to ensure well-cleaned print surfaces and print heads during manufacturing.

5. Evaluation of the course

In the following, the evaluation of the students' learning outcomes on the basis of different surveys is presented. In addition, the contribution of the individual phases of the product development and the course to the optimization is examined. In order to determine the learning success of the students, the self-assessment of the participants in the course was determined with the aid of a questionnaire. The first step was to find out how the knowledge of the participants differed in several areas before and after the workshop. For this purpose, the participants could indicate their knowledge with the help of points (see Figure 5). These self-assessments of the participants were asked by means of questions in the form of "How do you assess your practical knowledge in the field of rapid prototyping?" The scale of points ranges from "very little knowledge" (1 point) to "very good knowledge" (6 points). The areas surveyed can be divided into general skills (practical and theoretical knowledge of AM, knowledge of vehicle construction), design skills (methodical and sustainable design) and additive manufacturing skills (data preparation, printing times, assembly of additively manufactured products). Significant improvements in competencies and skills can be seen in all areas. On average, participants improved by almost one level on the point scale (+0.91 points). Since all participants are Master's students, the moderate improvement is so to be expected due to their extensive prior knowledge.

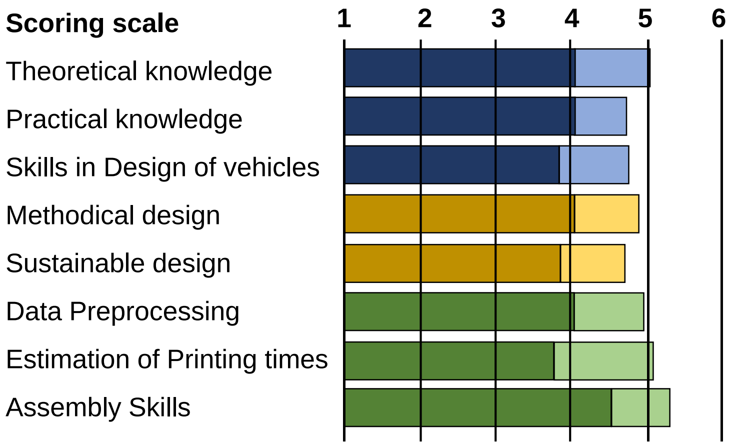

Figure 5. Comparison of knowledge and skills before and after the course

Particular improvements can be seen in the areas for estimating the necessary printing times (+1.31 points) and practical knowledge of additive manufacturing (+1.0 points). The competencies for design have also both been significantly improved (+0.85 points each).

In an additional survey, the participants were asked what contribution various parts of the course had made to the optimization of the product (see Figure 6 a). This showed that the test drives and races made a decisive contribution to optimization with over 40%. This is followed by brainstorming in the team and feedback during regular presentations. Interestingly, training in methodical design is cited by participants as contributing only 12% to product optimization. This very low contribution of the methodological approach to the overall result is surprising, because during the presentation the students state that this training in design methods was particularly helpful.

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In addition, participants were also asked which phase of product development accounted for the largest share of optimizations (see Figure 6 b). Here it shows that almost all phases of product development contribute an equal share of 22-25% to the optimization of the product. Only data preparation for additive manufacturing has a comparatively small share of less than 10%. This may be due to the fact that, for example, there is a lot of freedom in design or CA Design, and important practical knowledge is acquired during test runs. At the same time, only relatively few parameters can be set during data preparation and the ranges in which these settings can be changed are usually narrowly limited.

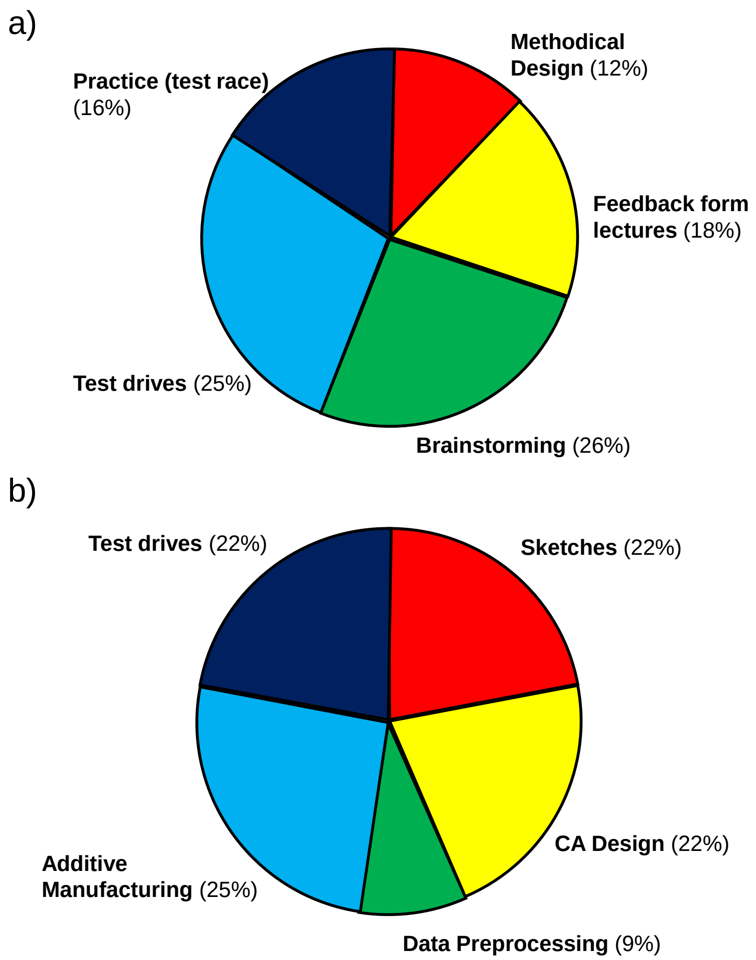

Figure 6. Feedback of the students: a) Contribution of the parts of the course to the optimizations, b) Contribution of the phases of the product development to the optimizations

6. Conclusions and Outlook

The presented course "Workshop Rapid Prototyping" has shown also at the third execution that the students are enabled to develop innovative technical solutions for demanding tasks. In the process, the students acquire both important knowledge of methodical design and the ability to implement it with the help of current additive manufacturing processes. In particular, the students developed a new suspension and adapted it to the existing chassis. They also developed a very practical solution for quick-change of the front spoiler. In both developments, all steps of the SPALTEN method were successfully applied. This includes in particular the application of extensive analysis and evaluation methods.

The evaluation of the course shows thoroughly positive feedback from the students. For example, a survey of the participants showed that significant progress was made in various areas through the development of competencies and skills. In addition, the survey shows that all parts of the course are involved in the optimization, with the practical parts in particular, such as test drives and test race, driving the optimization forward. Optimizations occur relatively evenly in all phases of product development. Only data preparation has a below-average share in the optimization.

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Based on the predominantly positive feedback, the rapid prototyping workshop will be offered and improved in the coming years. The first step will be to investigate whether other assemblies of the race car are also suitable for optimization. To this end, for example, the introduction of additional suspension for the rear axle is to be investigated. The principle could also be transferred to other examples, e.g. model aircraft. Since new processes in additive manufacturing are currently coming onto the market (e.g. fiber-reinforced 3D printing or Continuous Liquid Interface Production CLIP), these new processes and materials should also be integrated into the course in a meaningful way.

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