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AN APPROACH TO IMPLEMENT DESIGN FOR ADDITIVE MANUFACTURING IN ENGINEERING STUDIES

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Abstract

This paper describes an approach to implement additive manufacturing technologies in engineering studies by analyzing a lecture, which is divided into a theoretical and a practical part. Focusing on the practical part, the concept of a design task is shown, in which students are able to examine the technology intensively by self-contained manufacturing of 3D-printed parts. Describing the concept of an open 3D-printing lab, the basics of fused deposition modelling, as an additive technology, are characterized. After defining project teams with six to eight participants each, a remote controlled electrical vehicle has to be designed by the students. During this process, the project teams have to fulfil a specific design objective, like for example applying internal structures or aiming towards a maximum functional integration. As a result of the case study, two vehicle concepts as well as applied design approaches are presented. Based on the gained experience, suitable design methods and tools to enable multicriteria design objectives are summarized and an estimation about optimization effort is given finally.

Keywords: Additive Manufacturing, Design for Additive Manufacturing (DfAM), Case study, Design education, Design practice

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1 INTRODUCTION

Most engineering studies are predominantly influenced by subtractive and formative manufacturing processes, such as milling or primary forming. However, additive manufacturing becomes increasingly more important (Gartner, 2014) (Gibson, Rosen and Stucker, 2015). Nowadays, engineers are working with additive technologies in industry (Fastermann, 2012). It has to be noted, that there are significant differences with regards to conventional manufacturing processes. One major challenge is rethinking product development with focus on an extended design space (Hague, Mansour and Saleh, 2003). 'Printing' an existing component by using additive manufacturing does usually not lead to success (Thomas, 2009). Rather, a process-specific adaptation has to be carried out to achieve an additional value. In order to enable this impact for a product, the possibilities, but also the challenges of additive manufacturing have to be known (Kranz et al., 2015).

Various approaches exist, which help engineers regarding design for additive manufacturing (DfAM). Based on sequential and iterative procedures, such as the general development approach for technical systems (VDI, 1993), necessary stages to achieve a product concerning DfAM specific conditions are described (Kumke, Watschke and Vietor, 2016). These general descriptions are implemented as quality assurance approaches in companies. Besides such frameworks, further approaches describe concrete step by step instructions to create an additive manufacturing oriented design (Ponche, et al., 2014). In addition to given manufacturing restrictions, extensions of the design space are analysed (Rias et al., 2016). For engineers who have been trained in conventional processes, it is difficult to adapt to these new approaches. Thus, the integration of additive manufacturing in engineering studies already helps to prepare for everyday life in industry.

On the one hand, theoretical fundamentals have to be taught, so that students can get in touch with handling additive manufacturing. On the other hand, the individual exercise with additive manufacturing machines is necessary to gain knowledge about real challenges. According to Dale, success of learners is significantly influenced by the independent application of knowledge (Dale, 1969). When it comes to exclusively hearing or reading information during lectures or presentations, a maximum of 10 % can be obtained by the learners. In practicing an activity, however, the learning rate can be significantly increased up to 90 % - with respect to the learning type of an individual person (Thalheimer, 2006). Transferring this approach to additive manufacturing, students in engineering studies should work on machines on their own. However, coordination with the theoretical input is indispensable.

In literature, approaches for additive manufacturing lectures are available, which are more or less based on the inclusion of practical aspects. Most of them focus on separate workshops, in which the participants learn to handle process fundamentals, e.g. slicing or setting parameters (Kostakis, 2015). In addition, specific aspects, such as security workshops about handling additive manufacturing, are offered (Zajons, 2016). Besides these general approaches, the processing of design tasks in university environment is also described (Türk, 2016). In this case, additive manufacturing is usually applied as a rapid prototyping technology in order to achieve the given objective. Thus, the focus of the product is its functionality.

This paper describes a concept for a 'Design for Additive Manufacturing' lecture, which is divided into a theoretical and a practical part and is closely linked to engineering sciences. Focussing on the practical part, a case study based on a design task to construct and direct manufacture a mechatronic product is analysed. As a demonstrator, a remote controlled electrical vehicle (RC vehicle) is used. Dealing with the practical part, the focus is not on the product exclusively, but rather on how the students work to achieve their goal. To ensure a measurement of this design progress, the students work on predetermined design objectives. These aim towards a concrete additional value compared to conventional methods, such as the application of internal structures or a highly functional integration.

In order to create uncomplicated access to additive technologies for students, the application of a fabrication laboratory ('FabLab') is described. This FabLab can be occupied by the students at any time, so that they can work independently. In order to guarantee a regular and successful project progress for all participants, the students have to reach different milestones. Thereby, the design progress is evaluated and organizational aspects, such as project plan or the distribution of tasks, are clarified.

2 DESIGN FOR ADDITIVE MANUFACTURING LECTURE

In response to an increasing relevance of additive manufacturing (AM) students of engineering are offered the elective subject 'Design for Additive Manufacturing (DfAM)' as introduction to the topic. During the course, a combination of teaching theoretical basics and learning by doing exercises ensure the proper handling with AM processes. The participants learn to evaluate additive techniques in comparison to conventionally used (subtractive and formative) manufacturing processes. The restriction-oriented design for additive manufacturing and the complete exploitation of the physical design space represent more specific educational objectives.

2.1 Concept and Structure

Master course students who already possess skills in design theory, computer aided design (CAD), mechanics, methodology of product development and project/innovation management, constantly gain knowledge about additive manufacturing via the theoretical part of the lecture during the semester. In this lecture, elemental details of the AM process chain as well as characteristics of specific processes are presented. On the other hand, the participants are divided into several groups in order to work together on a specific design task. The objective is to develop a certain product and to manufacture it independently by using AM machines, which are based on the principle of Fused Layer Modelling (FLM). This practical part is considered to be the focus of the entire course. Thus, the basics being taught during the lecture shall be validated and questioned using the provided AM machines. Students are supposed to acquire knowledge about the challenges and the potential of AM through a 'learning by doing' procedure. Furthermore, the differently specialized group members can integrate their unique set of skills and their knowledge in order to manage and fulfil different work packages on their own. The overall structure of the course is summarized in Figure 1.

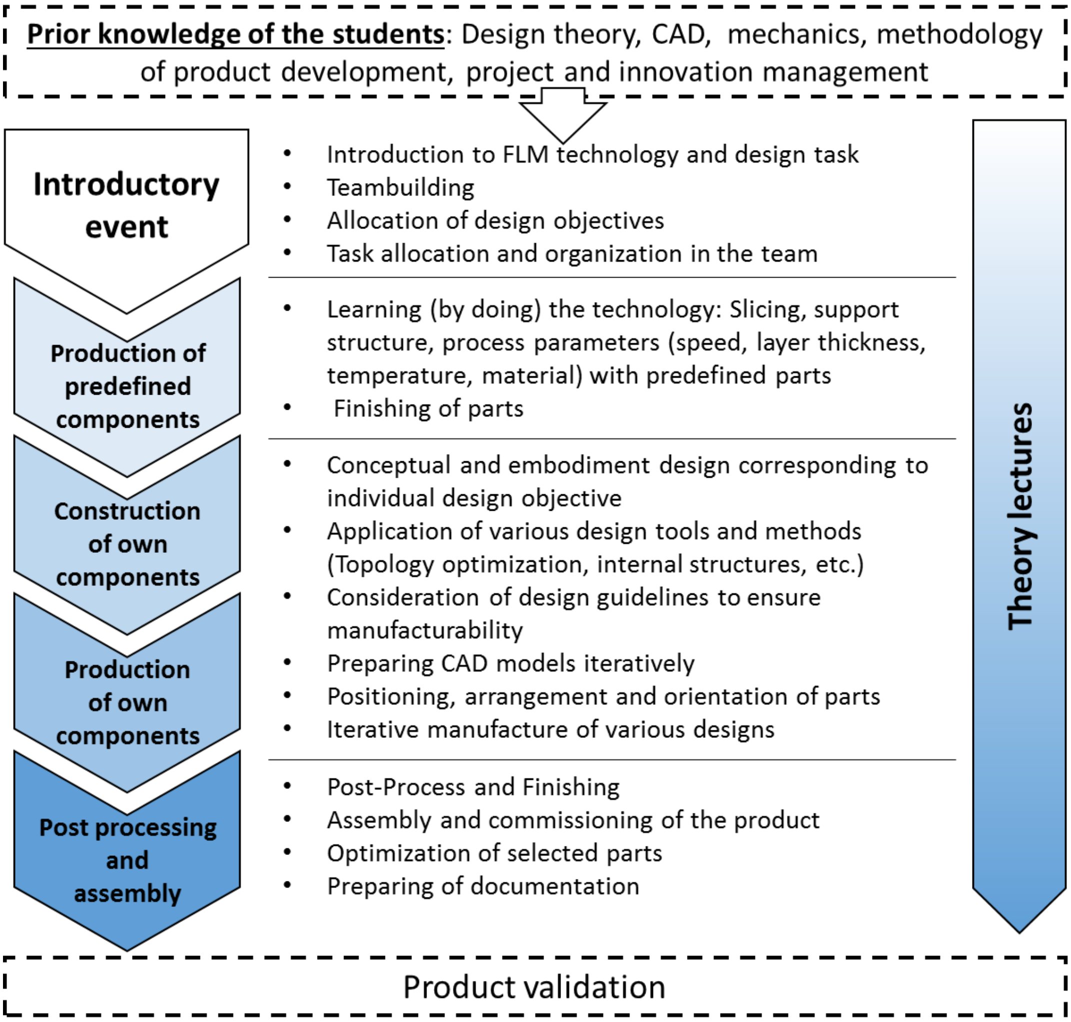


Figure 1. Concept for 'Design for Additive Manufacturing' course

The design task is scheduled into 5 steps. The first step is an introductory event to clarify the organisational aspects and convey basic knowledge about the technology.

In the second step, the predefined parts are produced in order to get a rough understanding of how to use an AM machine. The first approach to slicing, choosing parameters and positioning of the part on the building platform is realized by printing predefined parts which are needed to accomplish the given tasks. In addition to the printing process, the students perform the finishing process, reflect on their own results and estimate the quality of the printed parts. Using their first results, the participants have the opportunity to iteratively change parameter settings or the positioning/packaging of the parts on the building platform in order to increase part quality.

In the third step, the construction of own parts follows, which are necessary to fulfil the product function. The students design missing parts according to the physical design space (restrictions and dimensions). To do so, each group has to define a product concept which has to be optimized iteratively. One of the main challenges in building the missing parts is the restriction-oriented design that corresponds to the physical design space and fulfils the benefits of AM techniques. The necessary elemental information for this is given during lectures, focusing on design tools, design methods and design guidelines. Afterwards, the production and iterative improvement of the own parts is carried out in the fourth step.

In the fifth step, the post processing and the final assembly is intended to ensure the product functions and to optimize the final concept. After manufacturing the missing parts, the students assemble the desired product and have the possibility of optimizing it, e.g. by reprinting single parts.

At the end, the project groups have to test their products and validate their final results. The students will thereby demonstrate the product and its functionality. Furthermore, a conclusion of their expertise with regard to the manufacturing process as well as the strengths and weaknesses concerning both, the printed parts and the possibilities in design, are to be provided by the students.

The design tasks always include the building of a mechanically loaded product. The main objective is the design of structural parts in such a way that manufactured components show a near net shape geometry. Thus, the manufacturing system can be declared as Direct Manufacturing (VDI, 2014). To individualize the practical part of the course, each group is assigned a specific design objective. Table 1 shows objectives that represent the different benefits and narrow down the possibilities of design methods and design tools (Lippert and Lachmayer, 2016).

Table 1. Design objectives of mechanical loaded components for additive manufacturing

Material saving	Reduction of the material amount (and thus of the component weight) as well as resource saving by increasing the material utilization.
Functional integration	Realization of the most technical functions by using a minimal number of components.
Internal structures	Application of internal structures inspired by technical and bionic analogies to minimize the component weight with constant boundary conditions.
Force Flow adapted	Arrangement of the material according to an internal stress distribution for improving the mechanical properties.
Integrated channels	Application of optimized internal channels for the fulfilment of specific cases such as liquids, gases, electric lines or connections.
Customization	Adaptation of specific customer requirements by individual solutions or involvement of the customer in the development process.
Design	Realization of complex freeform surfaces as well as improvement of ergonomics and usability.
Net-shape geometries	Inclusion of predefined complex net-shape surfaces with regard to simulation results, such as flow-optimization or light distributions.

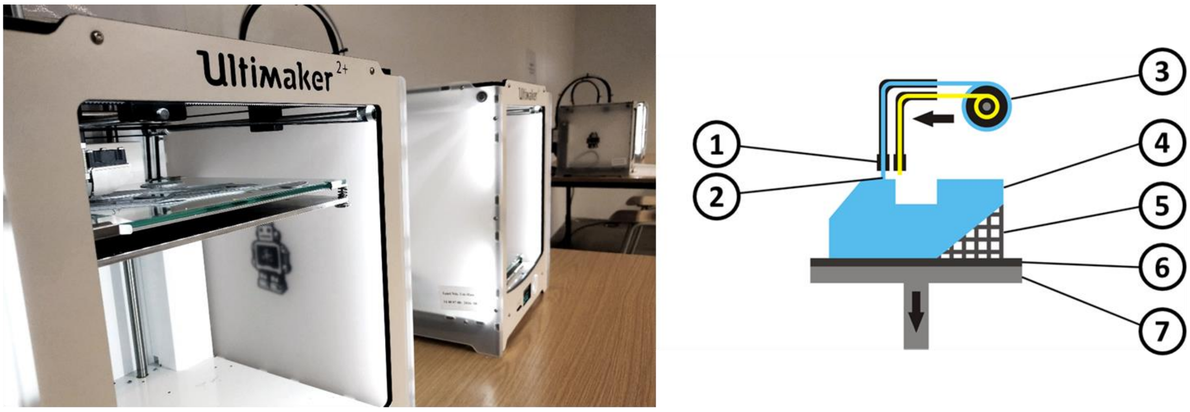
An exemplary task could be the construction of an ultra-lightweight product by using internal structures. Another example would be the mass customization in terms of modular concepts, integration of customers into the development process or shifting the production place to the customer (customer becomes producer).

2.2 3D-Printing Lab

For the practical part, a 3D-Printing Lab was established containing 3D printers based on Fused Layer Modelling (FLM) technology. The students are allowed to work with a total of twelve 'Ultimaker 2+'.

As depicted in Figure 2 (a), every workplace (six in total) is equipped with two printers. Furthermore, a general Workstation with PCs, which have Cura (recommended slicing programme) and AutoDesk Inventor (CAD programme) installed, is accessible.

As depicted in Figure 2, a thermoplastic polymer thread is fused via FLM technology. A nozzle heats the filament which can be extruded on the building platform due to its lower, heat-induced viscosity. After being applied on the building platform, the polymer cools down and hardens, therefore creating the first part of the desired structure. The printing head can be moved freely in the x-y-plane and is computer-controlled. The building platform can be moved along the z-axis. Polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) are provided to the students and with that a chance to think about the optimal material for every single part to be printed. To ensure the safety of every participant from toxic gases which come up while printing with ABS, the housing of the printers can be sealed off completely.



Components:

1. Extruders with heated nozzles
2. Line application
3. Filament (PLA material)
4. Generated component
5. Support structure
6. Building board
7. Construction platform with lifting table

Figure 2. (a) 3D-Printing Lab with twelve fused layer modelling machines and (b) the functionality of the process

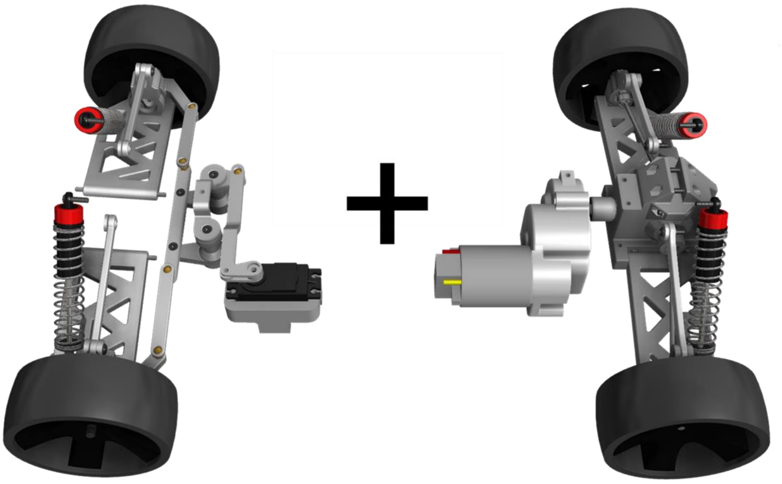
3 CASE STUDY: REMOTE CONTROLLED ELECTRIC VEHICLE

For further explanation of the concept (see section 2) the course 'Design for Additive Manufacturing' from the winter semester 2016/ 2017 is described. Within this project, about 40 students worked on the design task, taking different design objectives into account. The participants were grouped into five project teams, with six to eight team members each.

3.1 Design Task

As for the design task, the students have to construct a remote controlled (RC) electrical vehicle. Hereby, the vehicle concept should consider both conventional solutions as well as the impact of additive manufacturing. In addition to CAD competencies and thus the learning of additive manufacturing opportunities and challenges, the project groups have to organize themselves within the framework of the given time schedule (compare Figure 1) as well as to distribute the work packages independently. In order to define an elementary project plan, the concept of the vehicle has to be agreed upon initially. To facilitate this step, the predefined CAD model has a parametric structure, so that a basic dimensioning in order to influence the driving characteristics can already take place at an early development stage. E.g. the wheelbase, the centre of gravity or the track setting can be controlled by adjusting parameters.

As depicted in Figure 3, the parts of the predefined CAD can be distinguished through three categories. First, there are purchased components, which already exist as prefabricated parts. Second, predefined parts are only available as digital models and have to be produced later. Third, various relevant parts are missing, which have to be designed as well as manufactured.



Purchased parts
- Actuators, electronics and energy source
- Dampers / springs and wheels
- Connecting elements

Predefined parts
- Gear
- Differential gear
- Rear and front axis

‚Missing' parts (design space)
- Chassis
- Rear and front damper structure
- Front chassis mount

Figure 3. CAD model of the predefined parts for the design task

In addition to manufacturing predefined as well as missing parts by using the 3D-Printing Lab and thus Fused-Layer-Modelling (see section 2.1), precise parts with high longevity can be produced by using selective laser melting. Thus, metal parts can be produced to increase the degree of fulfilment of different functions, such as the differential gear. Therefore, a cost-benefit assessment has to be carried out by testing the plastic gear wheels and then planning the further procedure for changing individual parts. In contrast to the remaining parts, which the students can produce independently using the FLM machines, the SLM parts have to be commissioned in the workshop.

As mentioned in section 2.1, the main objective of the construction task is the implementation of at least one benefit compared to conventional manufacturing technologies and with regard to the design objective. Especially for the construction of the chassis, the rear and front damper structure as well as the front chassis mount, the individual objectives have to be considered. Table 2 shows the predominant design objectives of the five project groups.

Table 2. Specific design objectives for the five project teams

Project team	Predominating design objective
1	Maximum material saving
2	Functional integration and integrated channels
3	Weight reduction by internal structures
4	Force flow adapted geometries and bionics
5	Mass Customization and Design

3.2 Project work

For the application of the FLM machines located in the 3D-Printing Lab, the project groups are supported by tutors from higher semesters, who have experience with the technology as well as with restriction oriented design for additive manufacturing. For example, the tutors assist the students with regard to the parameter settings, the slicing process or the positioning of components in the process chamber in order to avoid support structures and thus post-processing effort. In addition to the tutors and the basic knowledge, which is taught in the lecture, the students are provided with instructional protocols, which describe step-by-step instructions for processing specific tasks. For example, protocols for parametric modelling, using the slice-software (Cura v.2.1.3) or applying selected design tools and methods are available. Instructions for dealing with FEM simulation software or simple topology optimizations are provided.

With regard to handling the predefined parts, assembly instructions are available. As exemplarily illustrated for the assembly of the differential gear in Figure 4 (a), these contain a parts list as well as the interfaces of the parts to each other. Furthermore, Figure 4 shows the process steps for manufacturing and mounting the differential gear. After the FLM process (b), in which the filament is processed, the inner parts (c) are assembled. Besides the housing and the distance sleeves, a purchased shaft as well as bevel gears manufactured with SLM are used.

For a better functionality, the internal components are lubricated so that the surface roughness can be compensated to a certain extent. Afterwards, the outer housing parts are assembled (d). In addition to the FLM parts, two purchased bearings as well as screw connections are used. Finally, Figure 4 (e) depicts the application of the differential gear in a final RC electrical vehicle.

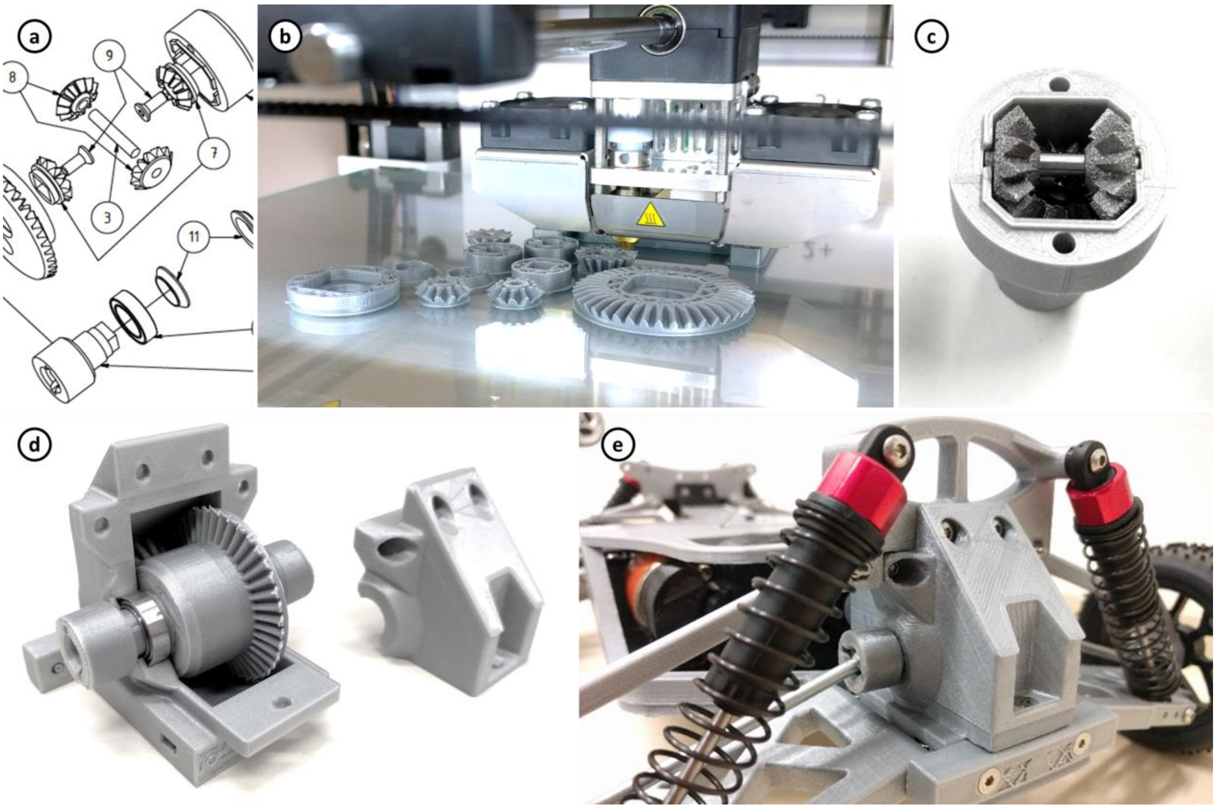


Figure 4. Process for the additive production of a differential gear a) predefined production drawing b) FLM process c) FLM housing in combination with SLM gear wheels d) assembly with purchased parts e) installation in vehicle

After producing the predefined parts, the project teams start building up the missing parts. Concerning the different design objectives, the components differ in topology, shape and dimensions. Thereby, various design tools and methods are used. Based on the example of bionic inspired and force flow adapted geometries (Project Team 4), Figure 5 depicts the front chassis mount. After setting the simulation environment by defining the material properties and applying external forces, the simulation results are manually converted into a CAD volume model. After that, the model is simulated by using FEM (Ansys Workbench 17.0) and adjusted iteratively. Besides the stress oriented detailing of the model, design guidelines are considered to improve manufacturability. The resulted model, which is detailed towards homogeneous stress distributions and corresponds to the possibilities of FLM, is finally manufactured. By estimating deviations of the physical and the digital model, an iterative adaption of the CAD model takes place. For example, holes in the vertical braces are optimized.

After all predefined and missing parts are manufactured, the RC electrical vehicle can be completely assembled. Furthermore, the mounted model is analysed with regard to optimization potential. By commissioning the vehicle in a first test drive and thus analyzing the mechanical loads on the parts, the optimization potentials can be identified.

Thereby, the students focus on specific parts and adapt them in an iterative procedure. In order to achieve a consistent consideration of the individual design objective in the vehicle concept, the predefined parts can also be optimized in addition to the missing parts. For this optimization of the final model the students have 3 weeks of time.

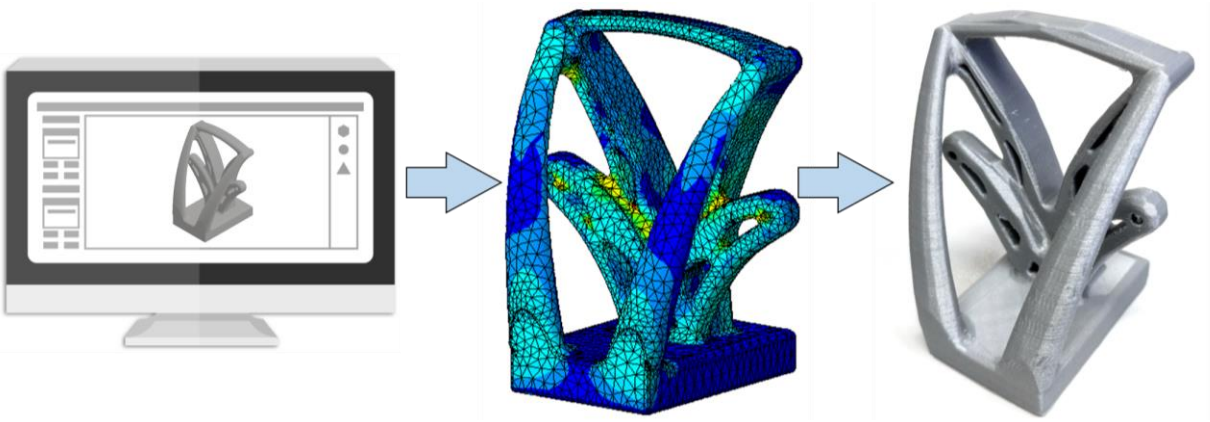


Figure 5. Example of a bionic front chassis mount by topology optimization

3.3 Final RC electrical vehicles

For the evaluation of the models, a product validation is carried out by the five teams. In a first part, the students compete against each other in a driving challenge. Here the RC vehicles have to be tested with regard to maximum speed or the mechanical testing while driving a predefined course.

In addition to the driving tasks, which validate the functionality of the vehicle, the project groups have to present their physical models in comparison to the digital versions. Thereby, the students justify the shape of the constructions and describe the additional value compared to conventional manufacturing technologies. Based on the example of the chassis, Figure 6 depicts different occurrences, which are shown in the final presentation. Besides an assembled RC vehicle including a standard chassis (a), different forms are shown which take the advantage of additive manufacturing into account. Figure 6 (b) depicts a solution by using honey combs as internal structures (Project team 3). Due to the maximum dimensions, the chassis is manufactured in two halves and bolted together. In order to increase the stiffness of the structure, struts are provided in a star-shaped arrangement below the curved honeycomb surface. Figure 6 (c) shows the result of the project team 1, who strived to reduce the material expenditure as much as possible. The parameters of the CAD model has been adapted to achieve the minimum dimensions of the chassis, which is limited by the amount of purchased parts. Due to the reduction of the dimensions, the chassis can be manufactured as one piece without joint interfaces. The cause of a weak spot can be reduced and thus a filigree component can be designed.

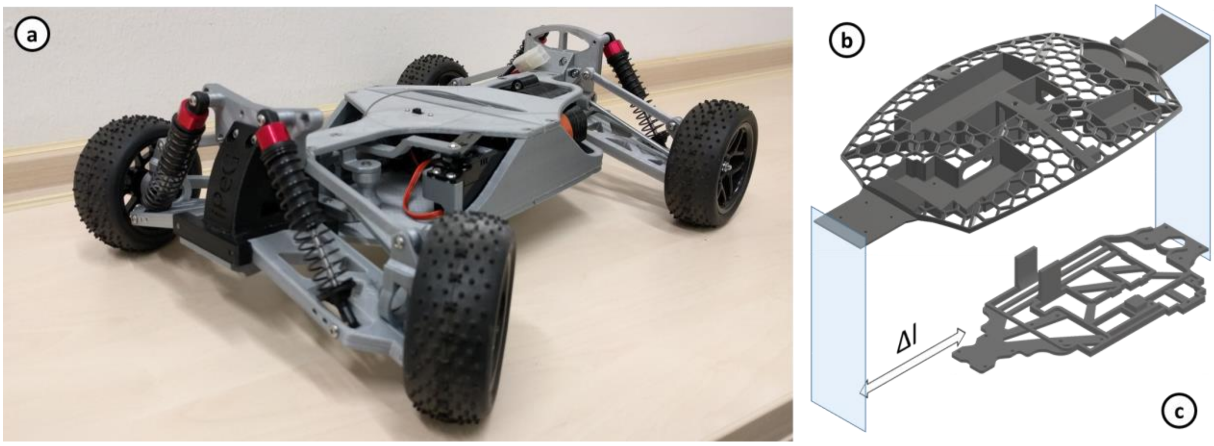


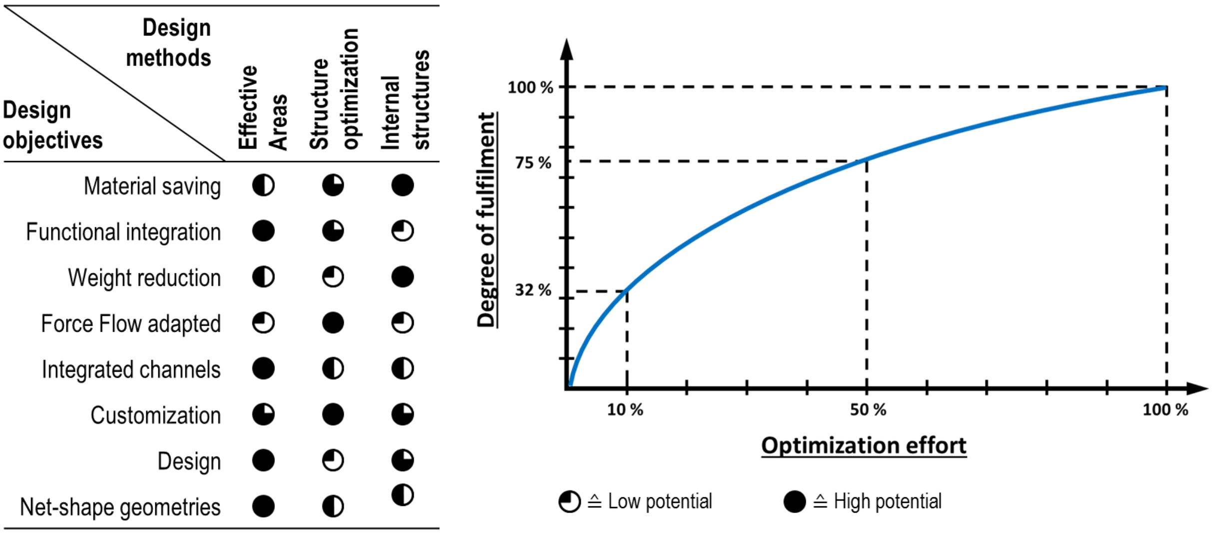
Figure 6. Example of a final RC-vehicle a) assembled standard model b) force flow adapted/ bionic chassis c) chassis with maximum material saving and smallest possible size

In a third part of the final product validation, the project teams have to describe the applied design tools and methods used to achieve their specific design objective. Thereby, a statement about the usability to fulfil the given task has to be made. Based on this, the students have to describe the concrete challenges during the design task. Finally, an estimation about the different parts for suitability in additive manufacturing has to be given.

4 CONCLUSION

The analysis of the RC electrical vehicles (see section 3.3) shows that the applied design tools and methods have different advantages and disadvantages to fulfil predominating design objectives. Figure 7 depicts three exemplary design tools, which were used during the case study as well as their potential to achieve specific design objectives. As design tools, a manual effective area based approach, the application of structural optimization tools and the integration of internal structures are presented.

The integration of internal structures has a high degree of suitability for maximum weight reduction. A high functional integration - thus the fulfilment of a maximum number of functions with a minimal number of parts - can be achieved through a manual approach using the effective area based design. Furthermore, structural optimization tools are particularly suitable for the flow adaption and thus for the design of individually loaded parts of the vehicle.



Design objectives \ Design methods	Effective Areas	Structure optimization	Internal structures
Material saving	◐	◕	●
Functional integration	●	◕	◔
Weight reduction	◐	◔	●
Force Flow adapted	◔	●	◔
Integrated channels	●	◐	◐
Customization	◕	●	◕
Design	●	◔	◕
Net-shape geometries	●	◐	◐

Figure 7. Applied design methods and optimization effort to achieve multicriteria design objectives

In addition, the case study shows that the optimization effort increases drastically in relation to the fulfilment of a design objective. Figure 7 (b) depicts a qualitative estimation of this relation. If the weight of a part should be reduced by the application of internal structures, a rough transmission of a lattice structure into the design space is implemented without great effort. However, the subsequent optimization of the structure - in order to reduce stress peaks and to homogenize the stress distribution - requires a considerable amount of additional effort. Even during the final detailing of the components to achieve a manufacturing-compatible design, the optimization effort increases exponentially. Many iterations to ensure a '3D-print oriented design' and a subsequent validation by the manufacturing are necessary. A constant adjustment of internal stresses is also indispensable.

During the project implementation different levels of prior knowledge could be identified. This is due to the fact, that some participants already knew the technology from their own interest and motivation. Nevertheless, a basic introduction to the technology is essential in order to achieve the same level of knowledge within a project group. In general, students have marginal inhibitions while using new technologies. The independent use of the 3D-Printing Lab can be classified as positive, because the students get to know the real challenges of a technology and not just place an order in the workshop. For future implementations of the 'Design for Additive Manufacturing' course, a reduction of predefined components can be considered so that the design space is increased. Furthermore, the inclusion in an earlier (bachelor) semester is useful to reach a larger number of students.

Due to the increasing importance of additive manufacturing, both in private and industrial sectors, practicing with and the examination of the technology is indispensable. Currently, an additional course as part of a design project is planned, in which students of the second bachelor semester are working on a design task through the application of computer-aided methods. Through the physical validation by using 3D printers, an increased learning effect for the students is expected. Here, the major challenge is the inclusion of all students, as around 500-700 students were enrolled in the past semester.

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