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NEW APPROACH FOR DESIGN EDUCATION IN DESIGN FOR ADDITIVE MANUFACTURING

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1. Introduction

In recent years a number of different processes for Additive Manufacturing AM, also called Digital Manufacturing or Rapid Prototyping RP, have established on the market. These processes offer the possibility to implement virtual component drafts directly from the CAD into real prototype components. This eliminates some process steps required for conventional, i.e. subtractive processes. Thus, the set-up of machine tools and programming of tool paths for cutting tools is no longer required. This results in significant timesaving [Junk and Tränkle 2011]. The materials used in additive manufacturing today range from different metal and plastic powders to polymer plaster and paper.

Nowadays, on the market for AM installations, there is a wide range of different machines size available. These range from offers for private users to professional solutions for industrial users that cannot only produce prototype parts but also series components. Current trends on the market for professional installations for AM are firstly the development of larger machines, so that the limitation to rather smaller components loses more and more importance.

Moreover in recent years a large number of systems entered the markets that offer private users the possibility to enter 3D printing for less than EUR 1,000 [Wohlers 2012]. Self-assembly systems that can be assembled and taken into operation by technically skilled private users in some hours are offered as lowest-cost option. In addition, operational systems ("home" or "personal 3D printer") which can be used directly by the user are also on offer. Finally yet importantly, at present this low-cost option is leading to a hype in the news coverage about AM and 3D printing in the daily press and on television which makes this new technology known to a wide public [Gartner Inc 2013].

In theoretical teaching at universities, the new possibilities and processes of AM have established themselves in many lectures and textbooks, e.g. [Gebhardt 2011]. The use of AM in practical teaching and research at universities had been focused on the development and use of expensive, professional systems in laboratories up to now. This offers students the possibility to gain hands-on experience with the new technology. As the number of this laboratory work is limited due to the generally low number of equipment in the laboratories, only a few students could be included in the hand-on training so far.

Recently, due to the current trend towards low-priced systems, universities were given the possibility to acquire a larger number of reasonably priced AM systems. The objective here could be to provide each student with his own 3D-Printer that it readily connected with the CAD system. Similar to a CAD laboratory, each student would have his own computer with CAD system and a 3D printer.

This helps students to use and understand the benefits of the new technology, namely the fast and favourable implementation of virtual designs in real sample parts. This means new designs and drafts can be printed directly from CAD. Subsequently the 3D models can be used for analysis and evaluation. This gives the student direct feedback from a real model to check and optimise his drafts.

In addition, such an AM laboratory helps the students to learn in a vivid and intuitive manner which design possibilities are offered by the generative manufacturing processes. The often deplored state that students are not in a position to use the new design freedom of the generative processes is thus overcome.

The downside of this approach of teaching AM in higher education however is that using operational 3D printers the students cannot get a deeper insight into the technology. This means that the functioning of the generative process and the interplay of the individual components of the system can be communicated theoretically at best. However, for conveying design for the additive manufacturing process, in-depth understanding of the functioning of the systems and also of the materials used is required. Therefore, this paper introduces a method how to convey to the students firstly the functioning of the AM system and the materials used. In addition, also the engineering design and practical use for the critical evaluation of designs is learnt by virtue of the new technology. The aim is to impart the competence for practical design, the design possibilities, but also the limits of the additive manufacturing to the students.

2. Literature review

The use of 3D printing in teaching to support projects in engineering design and mechanical engineering has proven itself for some years [Novakova-Marcincninova et al. 2012]. The use of 3D-printed models with FDM technology could do away with elaborate handmade models and therefore significantly reduce the design and optimisation efforts [Wilden and Gunn 2010]. Usually individual 3D-printers are used that are available to a large number of students. This means that the individual student has only limited access to this 3D-printer, which makes understanding the functioning, and the design possibilities more difficult. Furthermore, due to the fact that only one 3D-printer is available, quick and simple sample prints, e.g. to test a design idea, are possible only to a limited extent.

In related disciplines e.g. architecture, the use of AM technologies in the training of students is also examined [Silva and Lima 2013]. This highlights in particular the benefits of implementing design variants. A comprehensive study of the influence of this new technology on the training of architects has shown that the students were involved more in the development process, which resulted in greater creativity. Furthermore, they were inspired by the new possibilities to create models and prototypes and profit from the direct feedback by the physical and thus "tangible" models [Celani et al. 2010].

Lately, there are a number of approaches to use 3D printers in larger quantities even for the training of students at different universities all over the world [de Beer 2013]. For Example in 2011, a laboratory with 20 personal 3D printers was established at the Vaal University of Technology (South Africa) [Wohlers 2012]. However, continuous reports about the purchase of ready 3D printers are received. These approaches focus mainly on the application of the devices. However, as this permits the functioning to be conveyed only in a limited manner, the resulting guidelines for the design of components for 3D printing receive only limited attention.

3. Process chain in digital manufacturing

This document presents two different variants of how the process chain in digital manufacturing can be implemented by students within the framework of their training. Therefore, at first the complete process chain from virtual to physical model is described in general (Figure 1). A 3D data model is always a requirement for 3D printing. Therefore, the process chain in additive manufacturing starts with a virtual 3D model of the component to be manufactured.
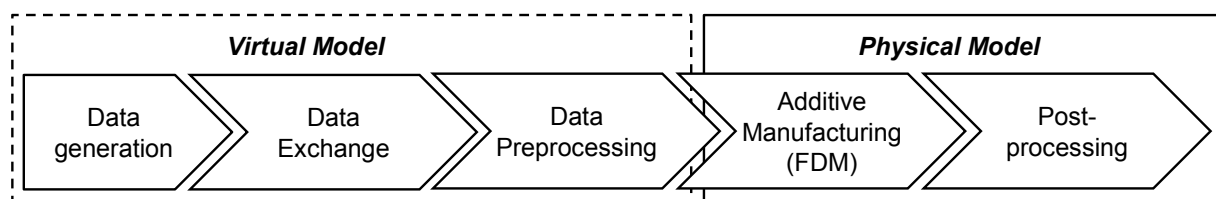

Figure 1. Process chain from virtual to physical model in additive manufacturing

The second step is the transfer of the 3D model to a data format that can be read by the AM system. The manufacturing process is divided into pre-processing and the actual, generative manufacturing of the component. In pre-processing, which is generally carried out with system-specific software, the 3D data is read and checked for consistency. Eventual errors in the model can be rectified. Sometimes changes to the texture, e.g. changing the colour, are possible. Furthermore, pre-processing determines the location of the component in the construction space. If required, a support structure is generated to prevent the overhanging components parts from breaking off during 3D printing. The most important part of this process step is slicing the component and the support structures into layers.

In this contribution the process "Fused Deposition Modeling" FDM is used for the generative manufacturing. An ABS wire is pulled into a nozzle and heated until it becomes viscous. Then it is applied to a base. Once a layer is fully applied, the base lowers or the nozzle is lifted and the manufacturing process starts again. The printed 3D component is then separated from the base in final post-processing. There are different applications for the implementation of each step in the process chain. These can be distinguished based on the user's experience from the rather inexperienced private user to the trained and experienced professional user (Figure 2). Therefore, a precise explanation of the different possibilities on how the students have used the process chain from the data generation till the manufacturing using 3D-Printing will follow.
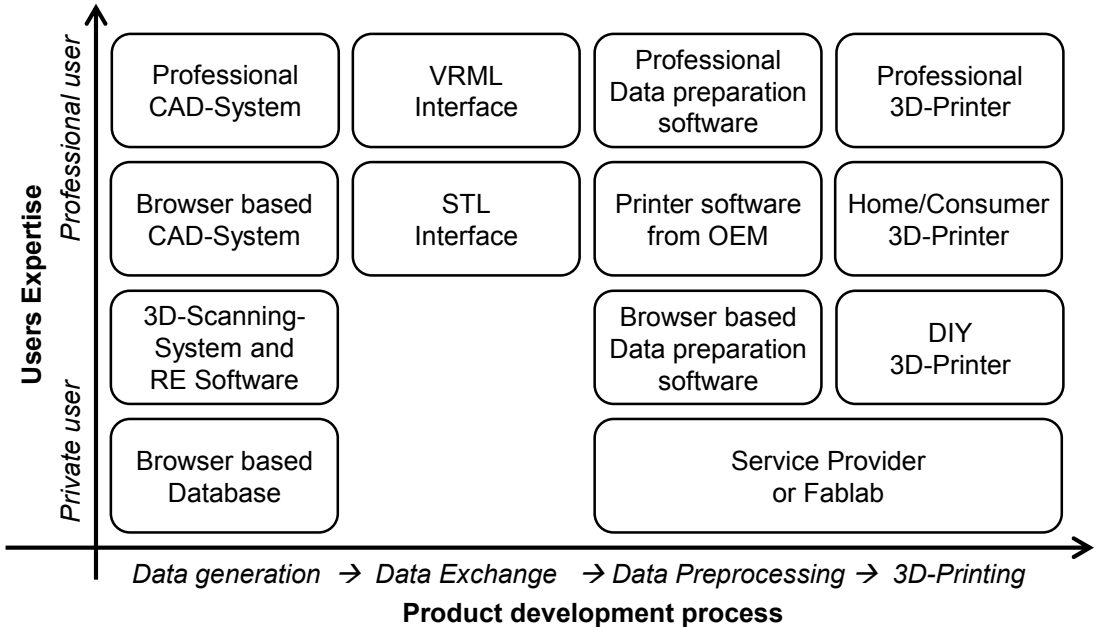

Figure 2. Implementation possibilities in the product development process by different users

3.1 Generation of data

There are different possibilities for the generation of data. In the simplest of cases, an inexperienced user can download a 3D model from a web-based database. Users with basic knowledge in CAD can use browser-based CAD systems, the basic version of which is often available free of charge. Normally there are tutorials and webinars for independent learning of these simple CAD systems.Professional users, on the other hand, can select from professional CAD systems with a wide array of design elements and features. These systems, however, require comprehensive training and often long-standing experience in engineering design.

In addition, there is the possibility to scan existing objects using 3D scanners. As a rule, the identified scatter plot still has to be processed using reverse engineering software RE to transfer the point cloud to a surface model. Within this field, the market also offers professional users a wide range from simple and low-cost home applications to comprehensive and expensive hardware and software packages.

3.2 Data transfer

In essence, two neutral data formats are used for the transfer of data from CAD systems or from the 3D scanner. This also includes the STL format, which offers simple representation of the geometrical data using triangular areas. If information about the surface in terms of colour or texture is also to be transferred, the VRML format will be used as it, in contrast to STL, can also transfer colour information and textures apart from pure geometrical information.

3.3 Data preparation

Private users have the option to send the 3D data to a service provider who will execute the data preparation and the subsequent manufacture of the physical model on his behalf. If the user has his own 3D printer, he can usually use the software of the AM system's hardware manufacturer to read and prepare the data for the manufacturing process. This often permits a direct and accurate transfer of the print data to the system. In addition, there is a wide range from simple to professional software packages, which assume the data preparation tasks.

3.4 Production of physical models

Apart from the service providers, there are now also a large number of possibilities for the actual production of the physical model. These range from the self-assembly kit for technically skilled private users to affordable entry-level models in the form of home 3D printers. Today there are already over one hundred different systems of this kind on the market [de Beer 2013]. Professional industrial users can choose from higher-priced systems that generally offer a better quality, reduced assembly times and larger sizes compared to the systems for private users.

4. Caste studies on the use of 3D printers in teaching

Two case studies were carried out within the framework of a workshop with Master students in the industrial engineering course. The students worked in four work groups with three members each. The goal of the both case studies is to investigate two differnet ways in teaching design for additive manufacturing. At first, in both cases a commercially available "Do-it-yourself" DIY assembly kit for a 3D printer was assembled according to the FDM principle (see Figure 3).
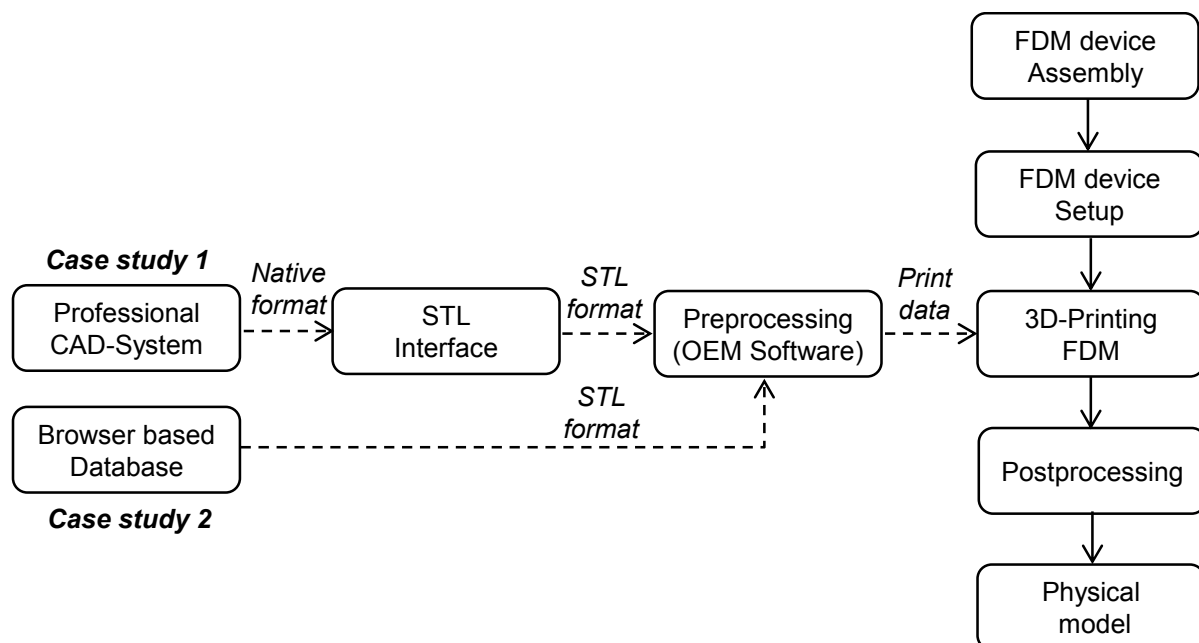

Figure 3. Connection of the product development process with the set-up and use of a "Do-it-yourself" 3D-Printer

The "fabbster" assembly kit is produced by Sintermask in Lupburg (Germany). After set-up and commissioning (shown in Figure 4, left), the students had the task to create two different components. On the one hand, a component must be downloaded from a freely accessible browser-based database. On the other hand, the students designed a component with a professional CAD system.

The components are then printed as demonstrated in Figure 4 (right) by using the DIY 3D-Printer.During post-processing the components are separated from the support plate and the support structures. Furthermore, the students are to document the experience gained in the workshop in the form of a design guideline for Additive Manufacturing and by means of an economic efficiency analysis.
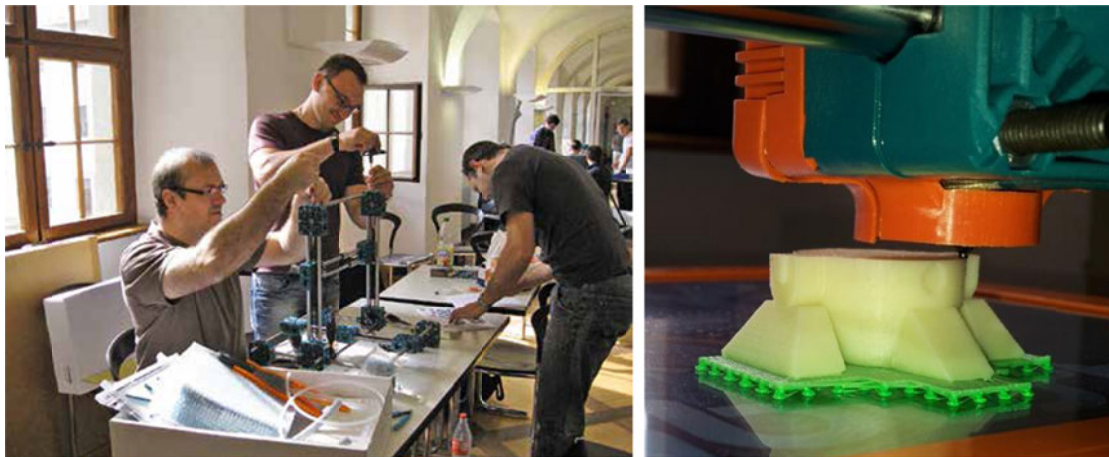

Figure 4. Students during the set-up of the Do-it-yourself 3D-Printer assembly kit (left) and 3D-Printer during manufacturing process (right)

Case study 1: Data generation using a database

In the first case study, the students had downloaded the 3D models from a browser-based database. For this purpose, at first an internet search for possible data sources was carried out. The task in this case study initially was to select a suitable database for freely available 3D models. Interestingly all work groups used the same database "Thingiverse" by Makerbot Industries, New York (USA) (http://www.thingiverse.com). This database offers a wide range of different models from various topics, such as jewellery, household, mechanics etc. Students did also visit other databases, however these sources often had a significantly limited choice of models. Results from this case study are shown in Figure 5.
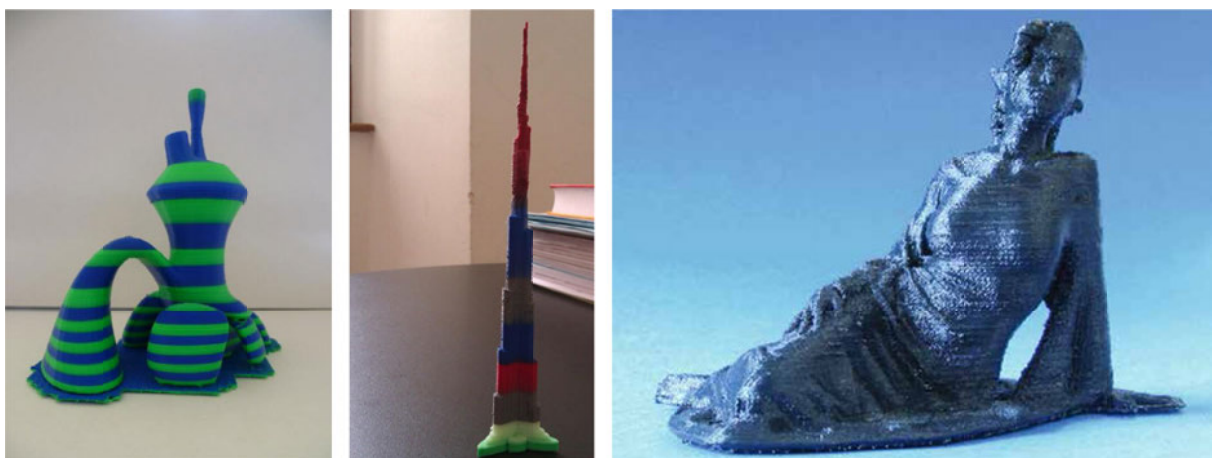

Figure 5. 3D-printed models using a database

An important criterion for the selection was that the 3D data models could be downloaded free of charge. From a technical point of view, the data models also had to fulfil some important criteria. The models had to fit in the construction space of the 3D printer. In addition, they should be producible without extra support structure.

The question about the data format for the data transfer to the software of the 3D printer for pre-processing usually does generally not arise, as the data is often already available as STL files in the database. Thus, also no colour information is transmitted, i.e. the models are monochrome. However, some groups have used the possibility to use different coloured building materials to perform a layered colour change of the physical models.

Case study 2: Data generation using a professional CAD system

In the second case study, students have used the professional CAD system CATIA V5 to generate their own drafts. The first experiences with the models from case study 1 were used to pay particular attention during the design phase so that the components could be produced using a generative manufacturing process. The design guidelines drawn up are listed in chapter 5.

The STL interface integrated in the CAD system was used for the data transfer. The task of the students was to select the different options of the interface (e.g. accuracy of representation, size of triangles) according to the requirements of the 3D printer. The size of the triangular facets in the STL format is of particular interest here. By virtue of a selection of large facets, the representation of curved surfaces is very coarse. A needless fine setting of the facet size bloats the data volume and file size unnecessarily.
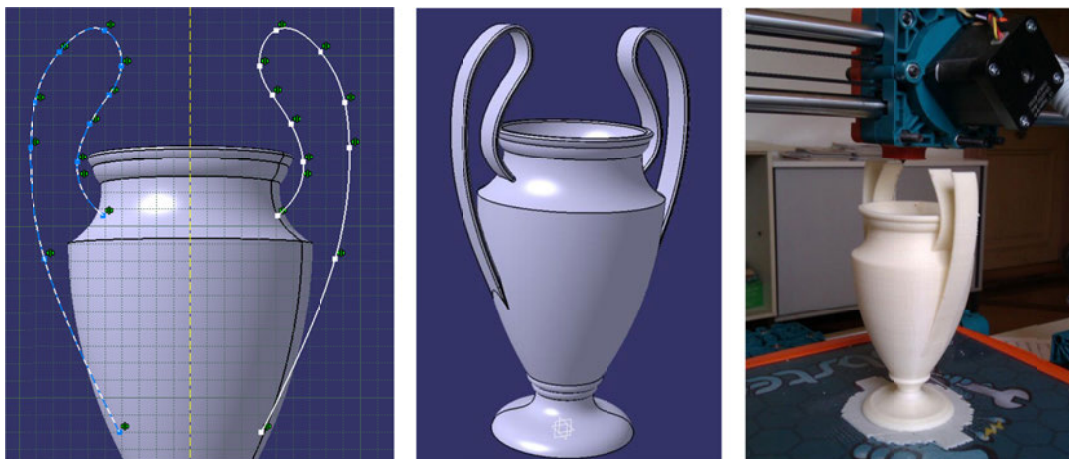

Figure 6. 3D-printed models designed by students using a professional CAD system

5. Results from both case studies

Both case studies resulted in various design rules that are to be observed both when choosing components from a database and also for the new design and drafts of components optimized for additive manufacturing (see also Figure 6):

- In order to achieve a good adhesion of the components to the base plate and the support, the components should have a maximum surface area and thus have good adhesive properties.
- As fast movements and therefore vibrations are generated during the manufacturing process, especially with high speed, which are then also transferred to the component, thin cross sections in the lower component area should be avoided.
- Very filigree cross sections should be avoided as these can hardly be represented.
- Curved forms are preferred at the cross section transitions as sharp edges are difficult to represent.
- Overhangs that are not supported by a structure should be designed at a maximum angle of 45° to the vertical.

- The size of the construction space of the 3D printer has to be maintained (230mm x 230mm x 210mm). Components projecting from this construction space naturally can be scaled using the software in pre-processing.
- Layered colour changes are possible by using different coloured construction materials during the manufacturing process.

During the actual manufacturing of the components it was established that adherence to the temperature for melting the construction material is important. Similarly, the feed speed has great influence on the quality of the printed parts. This permits the implementation of even complex geometries and smooth surfaces by reducing the feed. However, this leads to a significant increase in the time required for construction.

As an additional task, the students identified the individual consumptions in terms of efficiency. These include the consumption of building material, energy and space requirements. Moreover, the acquisition costs and the depreciation were determined. This helped the students to determine the total cost for each component.

The relationship between the technical properties of the 3D printers, the materials used and the boundary conditions for the design of the components resulting hereof, could be conveyed by virtue of this new form of teaching. The use of freely accessible databases awakened the awareness of the students about the wide variety of applications of 3D printing.

Due to the required independent design in case study 2, the students had to change their attitude. Beginning with a consumer attitude in case study one (database user) they were encouraged in case study two to explore themselves the possibilities and limitations of 3D printing in an active and creative manner. The self-developed design guidelines could be tested within the scope of the workshop for their practical suitability. Students could gather important experience on the geometric design, stability and colouring of the models.

Based on the experiences or both case studies, the students were able to understand how a design process for additive manufacturing works. By the huge number of practical work the students now understood clearly the boundary condition for the design process but also the limitation of the additive manufacturing technology.

An important part of this new approach is the fact that students built up the AM devices themselves. This led to a deep understanding of manufacturing process which is a necessary prerequisite for a successful design process. As the additive manufacturing is a quite new manufacturing process compared with conventional which means subtractive manufacturing processes this approach offers an alternative way for the design education.

6. Summary and outlook

This document contains the results of a new approach to convey knowledge about the design of components and products for 3D printing. This approach does not only convey the use of 3D printers in teaching. In addition, within the framework of a workshop the students assembled several 3D printers themselves and then started operating them. The workshops conducted have shown that students show great enthusiasm for the current topic "3D printing". In particular the use of the self-assembly kits have led to a deep understanding of this new technology.

This workshop shall be offered and expanded in the future for further development of this topic. The design possibilities are to be expanded using additional features in the hardware. This includes e.g. a heated base plate, which simplifies the adhesion of the models. There are also plans for extension with additional support material so that the design of overhangs is substantially simplified. Using these extensions, students can then learn how the technical specifications in the hardware reflect in the design of the components and how these limitations can be lifted.

Moreover the use of 3D-scanning devices in design education for the generation 3D model form existing components and products is under investigation. This will offer the opportunity to the students to combine the additive manufacturing with the reverse engineering process. Thus they can understand the needs in data acquisition and data transfer in both technologies which become more and more important in the product developing process.

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