

NEW APPROACHES TO TEACHING DESIGN FOR ADDITIVE MANUFACTURING

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Abstract

Additive Manufacturing and Reverse Engineering have increasingly been gaining in importance over the past years. This paper investigates the current status of the implementation of these new technologies in design education and also identifies current shortcomings. Then it develops two new approaches for the teaching of the necessary expertise for the design of 3D-printed components and illustrates these with case studies.

First, a workshop is presented in which students gain a broad understanding for the functionalities of additive manufacturing and the creative possibilities and limits of this process, through the assembly and installation of a 3D-printer. A second new approach is the combination of reverse engineering and 3D-printing. Thereby, students learn how to deal with this complex process chain.

The result of these new approaches can e.g. be seen in the design guidelines for Additive Manufacturing, which were developed by the students themselves. At the same time, the students are able to estimate opportunities and limits of both technologies. Finally, the success of the new course contents and form is reviewed by an evaluation by the students.

Keywords: Design education, Design for X (DfX), Reverse Engineering, Additive Manufacturing, 3D-Printing

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1 INTRODUCTION

Additive manufacturing, which has been growing in significance over the past years, offers several new opportunities for a design for sustainable life. Through the layered composition of additive manufactured products, for example, new forms and functions can be created that were not possible to date by using conventional manufacturing methods. As this new technology only uses the material necessary for the individual layers, products can be manufactured much more efficiently and eco-friendly than with subtractive procedures, in the course of which, as is generally well established, a large share of the bulk volume is turned into shavings.

A number of different generative manufacturing methods, also referred to as additive manufacturing (AM), digital manufacturing (DM) and rapid prototyping (RP), have become established in the market in recent years. These allow actual sample parts to be produced directly from CAD part models. This eliminates various process steps required with conventional, i.e. subtractive methods. For example, there is no longer any need to set up machine tools or program tool paths for cutting tools. This saves a significant amount of time and also energy (Junk and Tränkle, 2011). The materials currently used in additive manufacturing range from various metal and plastic powders through to polymers, composites and even paper.

There are many different sized machines for AM systems in the market at the moment. These range from products for private users through to professional solutions for industrial users which are capable of producing both sample parts and series components. One market trend in respect of professional AM systems is the development of larger and larger machines, with the restriction to smaller parts becoming increasingly less important. On the other hand, this technology holds great potential for in-home use, based on the by now low initial costs. This way, the direct inclusion of the consumer into the process of production is advanced significantly. A large number of systems that have come on the market in recent years allow private users to access the world of 3D printing for less than EUR 1000 (Wohlers, 2014). Build-it-yourself (BIY) kits that can be put together by technically-versed private users in a matter of hours and put into operation are the cheapest option. Apart from these, there are also plug-and-play systems, such as home 3D printers, that are all set up and ready to use. This attractive option is playing a key role in generating the current hype about AM and 3D printing in daily newspapers and on the TV, which is helping to popularize this new technology (Gartner Inc., 2013).

In respect of theoretical education at universities, these new AM possibilities and processes are now taking hold in many lectures and textbooks, like e.g. Gibson et al, 2010 and Berger et al. 2013. The use of AM in practical education and research at universities has been concentrated on the development and use of expensive professional systems in laboratories to date. Students have the chance to familiarize themselves there with the new technologies through practical work. As the amount of this laboratory work is limited due to the usually low number of systems in laboratories, only a few students have been able to gain hands-on training to date.

With the prices of systems continuing to fall, universities have been in a position recently to purchase a greater number of reasonably-priced AM systems for training their students. The aim can be to provide each student in a laboratory with his or her own ready-to-use home 3D printer connected to the CAD system. In this way, each student has his or her own computer with a CAD system and 3D printer available to them, similar to in a CAD laboratory. Students are able to use and grasp the advantages of the new technology, namely the ability to turn virtual models into actual sample parts, quickly and affordably. This means that models can be printed directly from the CAD system. Subsequently, the 3D models can be used for analysis and evaluation. Students receive direct feedback by means of a physical model, allowing them to test and optimize their designs. At the same time, the students learn in a visual and intuitive manner about the new design options on offer from generative, i.e. layer-by-layer processes in such an AM laboratory. Today, it is often lamented that additive manufacturing offers many possibilities and degrees of freedom to the production engineering, which are not known of the design engineers and therefore they do not use them. This new approach puts an end to frequent criticism that students are not able to benefit from the new creative freedom provided by generative approaches.

However, the disadvantage to this way of teaching about AM in universities is that it may not be possible to give students a deep insight into the technology through the use of plug-and-play 3D printers. In other words, information about the way in which the generative method works and the

interaction of the individual system components is best imparted theoretically. However, in-depth understanding of how the systems work and the tools used is precisely what is needed in the area of additive manufacturing to convey the right approach to design according to the relevant production task. Hence, this paper describes a method for teaching students about how an AM system works and the tools used. In addition to this, however, design and practical use are also taught so that students know how to critically evaluate designs using the new technology. The aim of this is to give students practical design skills and teach them about design options but also inform them of the limits of additive manufacturing.

2 LITERATURE REVIEW

The use of 3D printers has been a tried-and-tested way of supporting design projects in the teaching of mechanical engineering for some years (Novakova-Marcincinova et al., 2012). By using 3D printers with FDM technology, there is no need for intricate handmade models, which means considerably less design and optimization time and effort (Wilden and Gunn, 2010). In addition, Kriese et al. (2014) were able to demonstrate that students produced better results through the use of prototypes during the development phase while the work pressure has been considerably reduced.

The use of AM technologies to train students is also being examined in comparable disciplines, such as architecture (Silva and Lima, 2013). The advantages when using design versions are especially emphasized in this. It was shown in a comprehensive study on the impact of this new technology on the training of architects that students are more integrated into the design process and also become more creative. Additionally, they are enthusiastic about the new ways in which models and prototypes can be generated and benefit from direct feedback through the physical, and therefore “tangible”, models (Celani et al., 2010).

There has been a range of approaches recently to using greater quantities of 3D printers to train students as well at various universities around the world (de Beer, 2013, Ford and Dean, 2013, Mostert-van der Sar et al., 2013). For example, the Vaal University of Technology (South Africa) set up a laboratory with 20 personal 3D printers in 2011 (Wohler, 2014). However, there are repeated reports of plug-and-play 3D printers being purchased. Therefore, the main aim of these approaches is to have the devices used. However, as it is difficult to teach the way in which they work through this, the resulting guidelines on the design of parts for 3D printing can only be imparted to a limited extent.

The use of 3D scanners in the field of design education has already been discussed for several years. The studies by Ertu et al. (2006) show, for example, that students develop a better understanding in the evaluation of drafts and designs through the use of 3D scanners. This applies in particular to complex surfaces as are e.g. increasingly to be found with modern vehicles. Rodrigues et al. (2011) show how artefacts can be captured by 3D scanning. They can then be provided to the students via a web browser. Fang et al. (2012) demonstrate how the process chain from 3D scan to reverse engineering to CAD can be used to present the current status of 3D measuring to students. However, in all these cases only the application of 3D scanning in teaching is discussed, but there is no link to 3D printing.

The research by Virtanen et al. (2014) presents a method for a combination of reverse engineering and 3D-printing. The example used here, is the iterative product development for jewelry, which is realized using a metal based AM-method. The emphasis of this study, however, is not its implementation in design education.

3 PROCESS CHAIN IN ADDITIVE MANUFACTURING

At the beginning a 3D data model is always needed for 3D printing. The process chain in additive manufacturing begins with a virtual 3D model of the part to be produced. The second step is to transfer the 3D model in 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 part (see Figure 1).

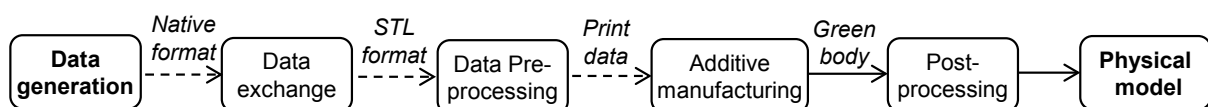


Figure 1. Process chain from a virtual to a physical model in additive manufacturing

In pre-processing, usually executed using system-specific software, the 3D data is read in and checked for consistency. Any faults in the model can be resolved. Some minor changes to the texture, e.g. the color, are still possible. The orientation of the part in the construction space is also determined in pre-processing. If necessary, a support structure is generated to prevent protruding elements of the part from snapping off during the additive manufacturing process. The slicing of the part, including the support structure, into layers is the most important part of this process step.

Fused deposition modeling FDM is used for the generative construction process in this instance. In this, a plastic filament is inserted into a nozzle and heated there until viscous. It is then applied to a base. Once one layer has been completely applied, the base is lowered or the nozzle raised and the construction process begins again. In final post-processing, the additively manufactured part is then separated from the base. The support structure may also have to be removed.

There are various ways in which each step in the process chain can be implemented. This can depend on e.g. how experienced the user is, from more inexperienced private users through to well-trained and experienced professional users (Figure 2). Therefore the various ways in which the students used the process chain is explained precisely below. In the simplest case a user can select a product from a 3D print shop. This means that a finished product (e.g. a protective shell for a smartphone) can be produced through generative manufacturing without any knowledge of the design and the production process. This case will, of course, not be discussed here in any more detail, as it is not conducive with regards to the education of students.

3.1 Creating the data

There are various ways in which the data can be created. In the simplest case of an inexperienced user, for example, a 3D model can be downloaded from an online database. Users with basic CAD knowledge can use browser-based CAD systems, the basic versions of which are often available free of charge. There are usually tutorials and webinars available for those wishing to teach themselves how to use such simple CAD systems. Professional users, on the other hand, may use professional CAD systems with a wide range of design elements. However, extensive training is needed on such systems and often many years of practical design experience as well.

There is also the option of using 3D scanners to capture existing objects. Usually, the point clouds created through this still has to be worked on using reverse engineering software to create a surface model from it. There are a wide range of offerings in this area on the market as well, from simple, affordable home applications through to comprehensive and expensive hardware and software packages for professional users.

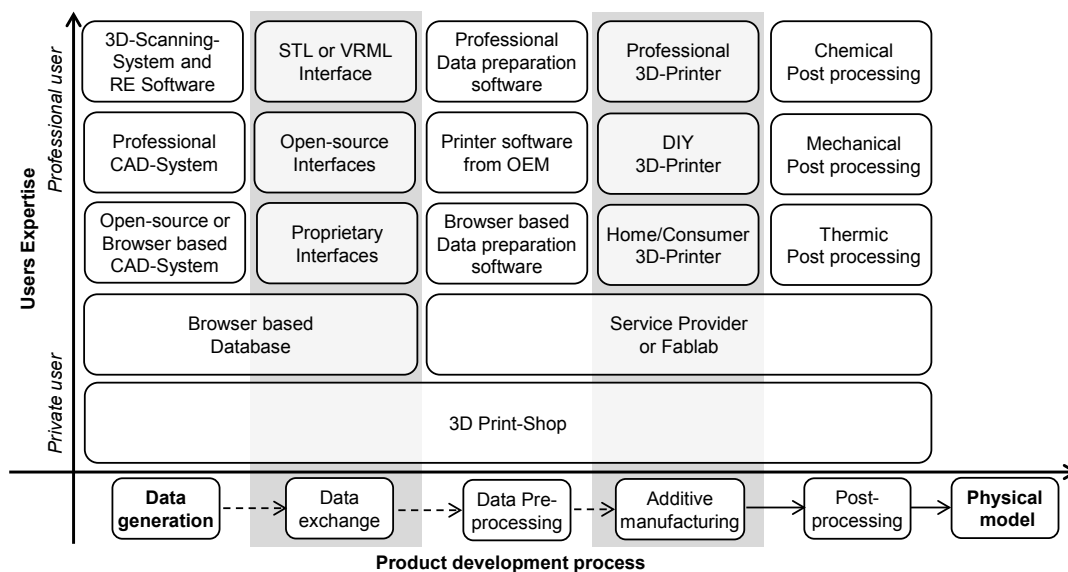


Figure 2. Implementation of the product development process by different users

3.2 Transferring the data

Usually a data transfer via an interface is required, as the native data formats of CAD systems cannot be directly imported by AM equipment in most cases. To date, STL is the established format for the data transfer. This format, which is integrated in numerous CAD and 3D scanning systems, transfers the geometries from CAD as simplified triangular areas. Additional neutral formats like e.g. VRML and more recently also AMF can also transfer other information in addition to the geometry data like, e.g. colors or textures. Aside from these there are also proprietary data formats like OBJ, which were developed by a number of equipment providers but they are to some extent also accepted for input by neutral software providers. In contrast, a data conversion via an interface is in general not necessary if data models from databases are used, because this data is already provided in a format suitable for the transfer of data for additive manufacturing.

3.3 Preparing the data

Private users can send 3D data to a service provider who will prepare the data and then produce the physical model for them. Users with their own 3D printers can usually use the software provided by the AM system hardware manufacturer to prepare the data to be read in and for the manufacturing process. This often allows for direct, error-free transfer of the print data to the system. In addition to this, there is also a range of simple to professional software packages that can handle these data preparation tasks.

3.4 Additive manufacturing the physical model

In addition to service providers, there are a large number of other ways of producing the actual physical model. These range from build-it-yourself kits for technically gifted private users through to affordable beginner models in the form of home 3D printers. There are already over 100 different systems of this type on the market (de Beer, 2013). More expensive systems that usually offer better quality, shorter build times and larger build sizes compared with systems for private users are available to professional industrial users.

3.5 Post processing

If the user orders a 3D-print in a print shop or with a service provider, these businesses will, in general, also provide the post-processing of the physical model. Using a home printer or a professional AM-system requires post-processing by the user. This, first and foremost includes the removal of the supporting material. This step can be done either mechanically, e.g. by detaching, or chemically, e.g. by dissolution in an alkaline bath. Some procedures, like e.g. 3D printing, include an additional chemical post-processing step, resin infiltration. Some other methods offer thermal post-processing in the form of the melting out of a supporting structure made of wax, as an additional alternative.

4 CASE STUDIES ON THE USE OF 3D PRINTERS AND 3D SCANNERS IN DESIGN EDUCATION

Two case studies were initially dealt with as part of a workshop with Master's program students studying "Industrial Engineering". There were several working groups with two or three students in each.

A typical build-it-yourself kit for an FDM 3D printer was initially assembled in both cases (see Figure 3). This kit was called "fabbster", and is produced by the company Sintermask in Lupburg (Germany). Once the printer was assembled and ready for operation, the students were tasked with creating two different parts.

Firstly, a part had to be downloaded from a freely accessible database. Secondly, the students had to design a part using a professional CAD system - CATIA V5 in this instance. The parts were subsequently printed. These parts were detached from the construction platform and support in post-processing. The students also had to document their experience from the workshop in the form of AM design guidelines and with a profitability study.

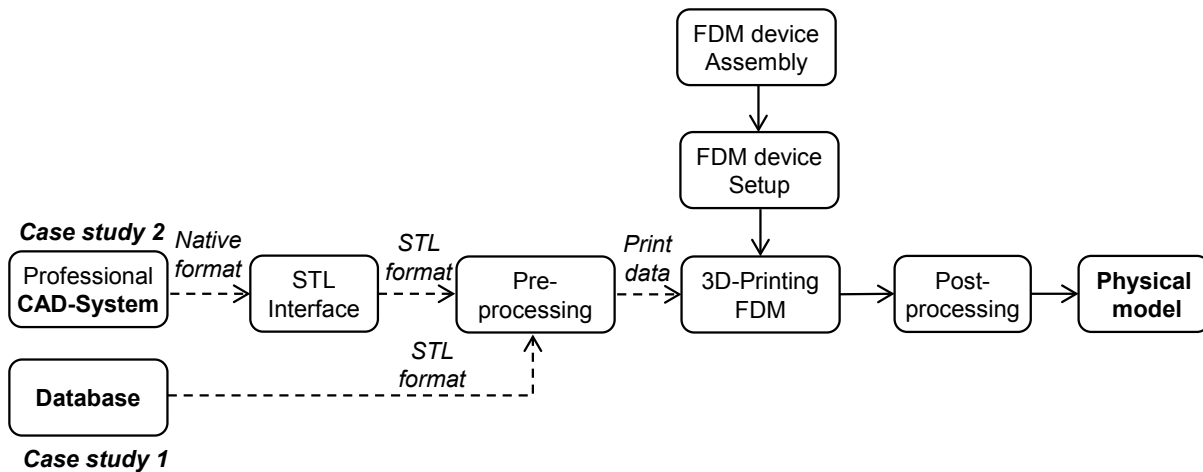


Figure 3. Connecting the product development process to the setup and use of a 3D printer in case studies 1 and 2

4.1 Case study 1: Data generation using a database

The students took a 3D model from a database for the first case study (see Figure 4). First they looked online for possible data sources. One important criterion was that the 3D data model had to be free to download. The data model also had to meet certain technical criteria. The model had to fit in the 3D printer's installation space, for example. It also had to be possible to produce it without an additional support structure.

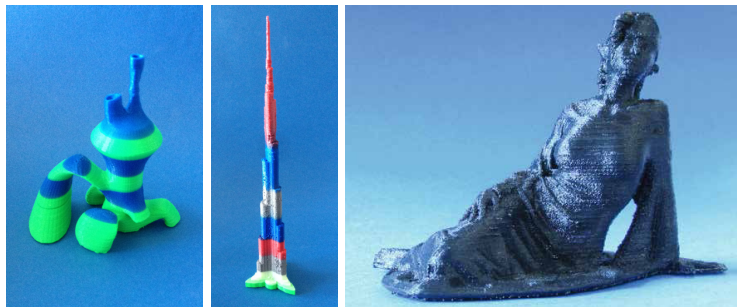


Figure 4. Examples of parts from the database (case study 1)

The data format for the data transfer to the 3D printer software for pre-processing wasn't really an issue here as the data was often already available in STL format in the database. Therefore, no color information was transferred either, i.e. the models were monochromatic. However, some groups took the opportunity to use different colored construction materials in order to change the color of the various layers of the physical models. In both case studies, 1 and 2, post-processing was done by mechanical detaching.

4.2 Case study 2: Data generation using a professional CAD system

In the second case study, the students used the CATIA V5 professional CAD system to generate their own parts (see Figure 5). Their initial experience from their attempts in case study 1 was used in this to ensure right from the design that the parts could be produced using a generative manufacturing process. The design guidelines developed are listed in Chapter 5. The STL interface integrated into the CAD system was used for the data transfer.

The students were tasked in this regard with selecting the various options for the interface (e.g. precision of the representation) according to the requirements of the 3D printer. The size of the triangular facets in the STL format is of particular interest in this. If large facets are selected, curved surfaces are very roughly depicted. If the facet size is set unnecessarily finely, the data volumes and thus the file size are unnecessarily inflated.

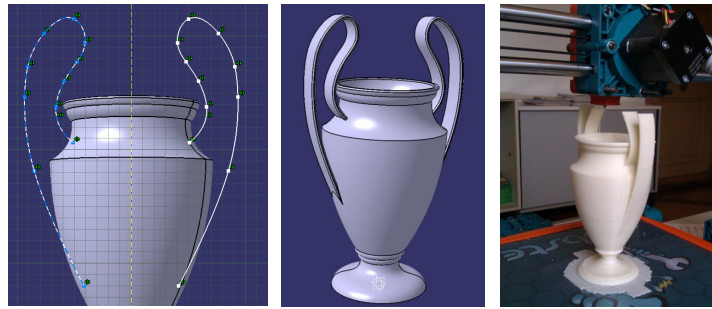


Figure 5. Sample part designed by the students (case study 2)

4.3 Case study 3: Data generation using reverse engineering

In a third case study, the students were tasked with turning an existing product into a physical model, i.e. combining reverse engineering and 3D printing (see Figure 6). The aim of this task was to create a replica of an existing art object. The students used a 3D scanner (Zscanner 700 from ZCorporation) to plot a mask traditionally used for the Easter carnival in the Black Forest region (see Figure 6). Subsequently, the data in the form of a points cloud was edited using professional software to, for example, fill in any gaps and delete artefacts. After this, the revised scatter plot was edited using surface reconstruction so that it could be read into a professional CAD system (CATIA V5 from Dassault Systèmes).

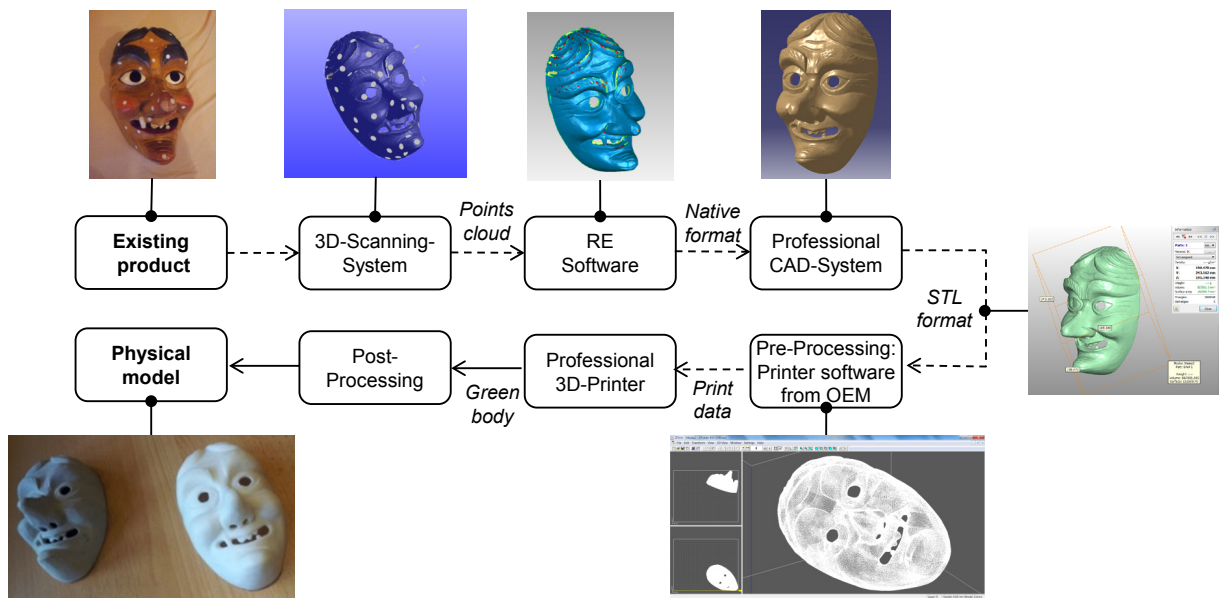


Figure 6. Combining reverse engineering RE with subsequent 3D printing in case study 3 including screenshots from the software packages used in the different process steps

In the second part of the case study, the CAD data was initially transferred via an STL interface from the professional CAD system to the 3D printer's software. Unlike case studies 1 and 2, two professional additive manufacturing devices (ZPrinter 450, 3DP and HP 3D-DesignJet, FDM) were used for this study.

3DP uses a polymer plaster as the construction material and it is solidified using a binder. Colored prints are also possible as the construction material can be dyed using colored ink, similar to an inkjet printer. This option was not used in this case since the used 3D scanning system did not dispose a of a color reconnaissance.

In the 3D printing, chemical post-processing by means of inflation with an epoxy resin was used. Chemical post-processing was also used with FDM, here in the form of the dissolution of the supporting structure in an alkaline bath.

5 DISCUSSION OF THE FINDINGS

In case study 1, a suitable database with freely available 3D models first had to be selected. The working groups ended up using several freely accessible databases. These databases offers a wide range of different models in various themes, e.g. jewelry, household, mechanical, etc. Further databases were also checked but these often had considerably fewer models to choose from.

Various design rules that have to be adhered to when selecting parts from a database and designing new parts emerged from case studies 1 and 2 (see also Figure 4 and 5):

- For the parts to adhere well to the base plate and support, they should have as big a base as possible and therefore good adhesion.
- Thin cross-sections in the lower section of the part should be avoided as there can be fast movements and therefore vibrations during the build process, especially if the construction speed is high.
- Very delicate cross-sections should be avoided as these can be difficult to represent.
- Curved shapes are preferable during cross-section transitions as sharp edges are difficult to represent.
- Projecting elements not supported by a support structure should be designed with a maximum angle of 45° to the vertical plane.
- The size of the 3D printer's installation space must be observed (230 x 230 x 210 mm, LxWxH). Of course, parts protruding beyond this can be scaled using the software in pre-processing.
- The color of each layer can be changed by using different colored construction materials during the construction process.

It was shown while the parts were actually being produced that particular care should be taken here to ensure the temperature needed to fuse the construction material is maintained. The feed rate also has a big effect on the quality of the printed parts. For example, even complex geometries and smooth surfaces can be achieved by reducing the feed rate. However, this also increases the construction time considerably. But the student could also recognize the limitations of the FDM technology, like e.g. poor surface quality, only small number of materials available or long manufacturing time. With respect to profitability, the students initially determined the individual consumption volumes. These included the materials used for the construction material, the energy consumption and the space required. The procurement costs and depreciation were also calculated. The students were able to derive a manufacturing price for each part from this.

It was found in case study 3 that the students had to master a range of software packages in order for them to be able to perform each individual task needed to complete the work. Initial success was quickly achieved with the scanning and surface reconstruction. However, many gaps and “shaded areas” had to undergo post-processing due to the product's complex geometry. It became clear to the students that a significant number of processing steps are needed to achieve high representation accuracy. It was also shown that high representation accuracy is associated with large data volumes. Therefore, it became clear towards the end of the processing steps in particular that the hardware used was reaching its limits as it took longer and longer to process the geometrical data. The 3D scanner used did not record any color information, so it wasn't possible to use color in the physical model.

5.1 Evaluation results

To be able and review the value of the course and its reception by students attending the course, evaluations with questionnaires were done. In the process, the following criteria were evaluated by the students in case studies 1 and 2:

- The laboratory experiments provide valuable insight into the practical activities of the relevant field.
- The laboratory experiments are very interesting and are – as far as you are able to assess – state of the art.
- The laboratory experiments are didactically well prepared
- The laboratory experiments substantiate / increase your interest in the field.
- The laboratory experiments encourage participation
- During group work each and every student has ample opportunities to participate in the execution of the experiment.

In the evaluation, students can indicate in how far they agree with the individual criteria. The analysis of the student evaluation results (see Figure 7) has shown that the students agree that the experiments have inspired their interest in the new technology. Furthermore, the teaching of practical knowledge received very good reports. What is more, the active inclusion of the students in the experiments, as well as the collaboration during the test preparation of the 3D printer was widely approved of. Although the didactical performance of the tests received a good evaluation, there is still some need for improvement. But overall the total of the selected criteria was assessed to be between good and very good. Compared to the mean value of all other courses this represents an above average result.

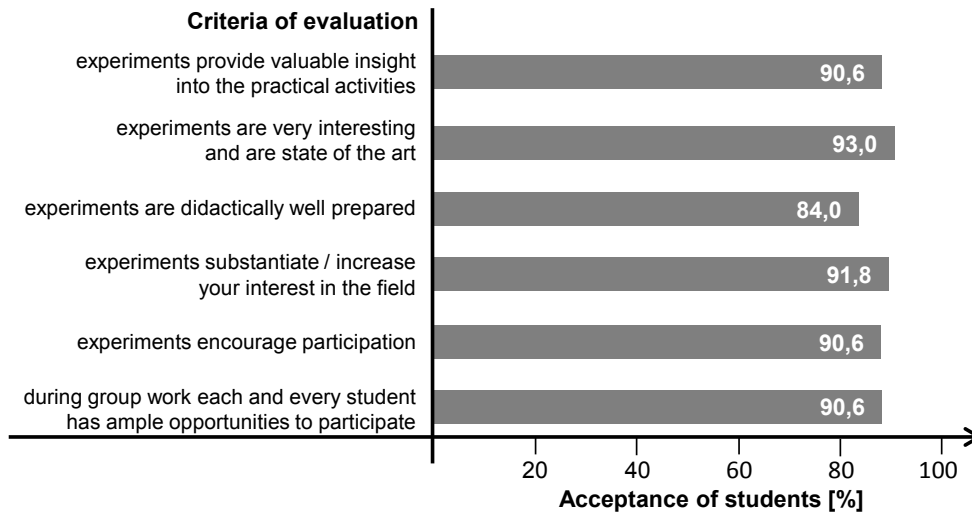


Figure 7. Results from evaluation by students

6 SUMMARY AND OUTLOOK

The results of a new approach to imparting skills for part design for 3D printing are presented in this paper. This approach is not solely about teaching students how to use 3D printers. In addition to this, students independently assemble and operate several 3D printers as part of a workshop. The workshops held showed that students are enthusiastic about the current topic of 3D printing. The use of build-it-yourself kits in particular led to a deep understanding of this new technology. In another case study, the continuous application of reverse engineering, from the scanning of the product to 3D printing, is demonstrated. Both technologies are thus linked.

It was also possible to demonstrate the connections between the technical properties of a 3D printer and the materials used and the resulting part design constraints through the new type of education. By using freely accessible databases, the students were made aware of the wide variety of areas in which 3D printing can be applied.

Using the independent design required in case study 2, the students were turned from consumers (database users) into active and creative users grappling with the possibilities and limits of 3D printing. They were able to test the design guidelines they came up with themselves (see Chapter 5) in the workshop and see whether they applied in practice. In this way, the students were able to gain important experience with the geometric design, stability and color scheme of the model. The students could discover the possibilities and limits of the optical scanning of products through the practical use of 3D scanners. In addition to this, they learned the steps needed to prepare the captured 3D data to allow for 3D printing.

This workshop should also be offered in the future and enhanced to further develop this educational topic. The design possibilities should be extended by using additional hardware features. These include, for example, a heatable base plate, which will make it easier for the models to stick. Additionally, an enhancement to include additional support material is planned to significantly simplify the design of protruding elements.

The usage of a printer building set that is able to process different materials would also further the student's knowledge immensely. To improve the didactics of the curriculum, the course will be revised. Furthermore, different 3D printers will be investigated with regard to their possible

applications. In particular, 3D printers of especially simple structure that are easy to use, use different materials and allow for the use of supporting material shall be the focus here. This would allow teaching multifaceted constructive skills with regard to the design and the selection of different materials.

Using these enhancements, students will then be able to learn how technical hardware specifications impact on part design and how these limits might be overcome. 3D scanning and printing should also be further combined. For example, in addition to the product's geometry, its texture should also be captured in the future so that it can be integrated into the data preparation for the 3D printing.

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