

# New Approaches to the Application of Additive Manufacturing and Reverse Engineering in Design Education

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## Abstract

In addition to traditional methods in product development, the increasing availability of two new technologies, namely additive manufacturing AM (e.g. 3D-printing) and reverse engineering RE by means of 3D-scanning, offer new opportunities in product development processes today. However, to date only very few approaches exist those include these new technologies systematically in the education of students in the field of product development. This paper explores several ways in which AM and RE can productively be used in education. New to this approach is, on the one hand, that the students assemble and install the 3D-printers themselves, and on the other hand, that they are introduced to an approach that combines 3D-scanning followed by 3D-printing. In different case studies is demonstrated that students in design education are able to autonomously research and realize technical possibilities and limitations of these technologies, as well as economic parameters and constraints.

**Keywords:** *Design education, additive manufacturing, reverse engineering, 3D-Printing, 3D-Scanning*

## 1 Introduction

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 [1]. The tools currently used in additive manufacturing range from various metal and plastic powders through to polymers and 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. In addition to this, 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 [2]. Build-it-yourself 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 [3].

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. [4-5]. 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. This 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 [6]. 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 [7].

Individual printers made available to a large number of students are usually used. Therefore, each individual student only has limited access to a printer, making it more difficult for him or her to understand how they work and the ways in which they can be used for design purposes. In addition to this, if there is only one printer available then there is not much opportunity to try fast and simple print experiments, e.g. to test a design idea.

The use of AM technologies to train students is also being examined in comparable disciplines, such as architecture [8]. 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 [9].

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 [10-12]. For example, the Vaal University of Technology (South Africa) set up a laboratory with 20 personal 3D printers in 2011 [2]. 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.

### 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).

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 is used for the generative construction process in this instance. In this, an ABS wire 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.

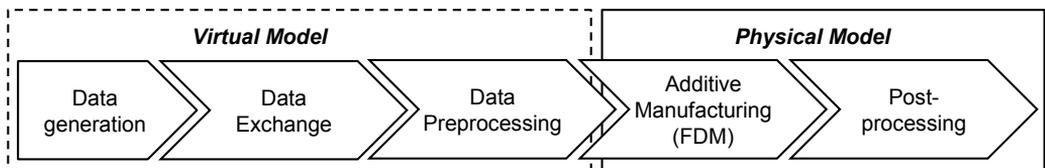


Figure 1 Process chain from a virtual to a physical model in additive manufacturing

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.

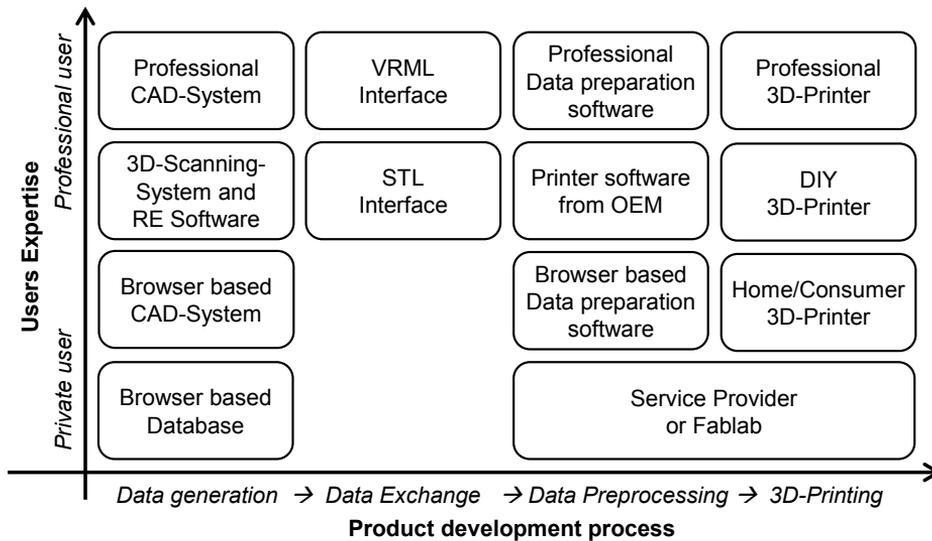


Figure 2 Ways in which the product development process can be implemented by different users

### 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.

### 3.2 Transferring the data

Essentially, two neutral data formats are used to transfer data from the CAD system or 3D scanner. One of these is the STL format, which offers a simple representation of the geometric data using triangulated surfaces. The VRML format is used when information on the surface relating to color or texture is also to be transferred, as it can transfer color information in addition to purely geometrical information, as opposed to STL.

### 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 Producing 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 [10]. 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.

## 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 students studying "Industrial Engineering and Business" [13]. There were several working groups with 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.

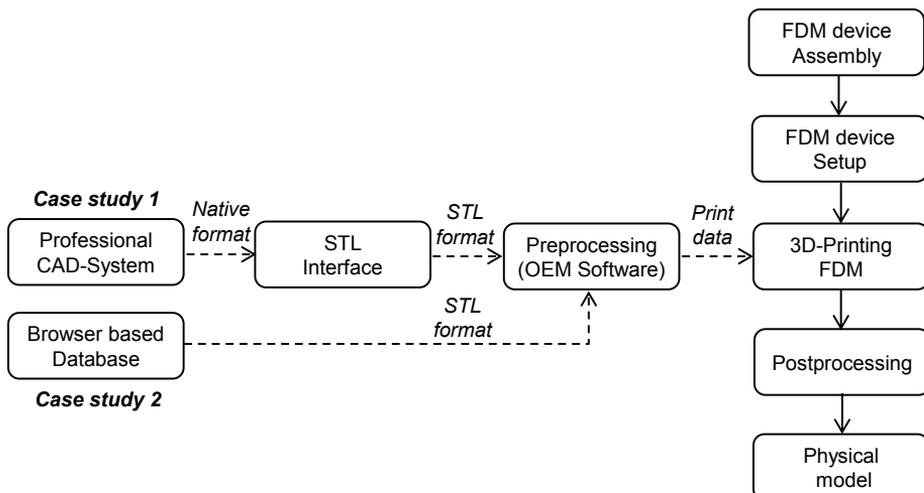


Figure 3 Connecting the product development process to the setup and use of a 3D printer in case studies 1 and 2

#### 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.

#### 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.



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

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.

#### 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 7). 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).

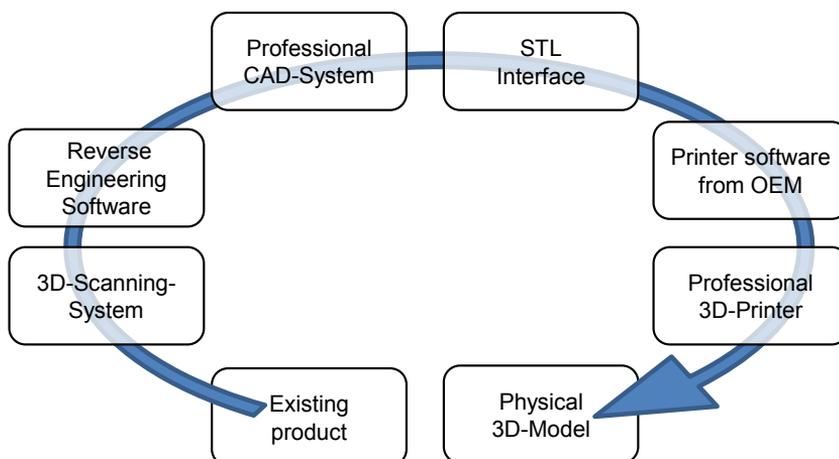


Figure 6 Combining reverse engineering RE with subsequent 3D printing in case study 3

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 AM 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 of a color reconnaissance.

## 5 Discussion of the findings

In case study 1, a suitable database with freely available 3D models first had to be selected. All working groups ended up using the Thingiverse database from Makerbot Industries, New York (USA) [14]. This offers a wide range of different models in various themes, e.g. jewellery, household, mechanical, etc. Other databases were also checked but these often had considerably fewer models to choose from.

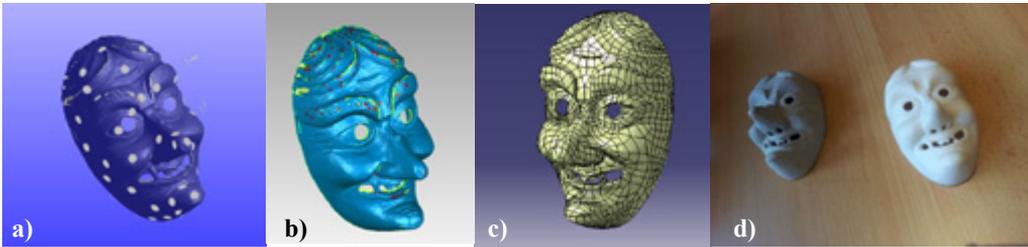


Figure 7 Outputs from the 3D scan: points cloud (a), surface reconstruction (b), CAD software (c) and Additive Manufacturing (d) in case study 3

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):

- 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  $45^\circ$  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.

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 individual 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.

## 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. 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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