Master thesis

CUSTOMIZABLE PERSONAL MANUFACTURING

A thesis submitted in partial fulfillment of the requirements for the
degree of Master of Science in Engineering

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Signature

EHRENWÖRTLICHE ERKLÄRUNG

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ABSTRACT

Past developments in the area of personal manufacturing, such as online platforms of CAD models, assist customers in printing of their favorite 3D objects. Nevertheless, there are still many barriers, since customers do not have possibilities to customize 3D models. To fix these issues, this thesis deals with the development of a concept for customizable personal manufacturing, with a 3D-customization tool as the central element.

The theoretical part focuses on the whole 3D-data preprocessing process, particular AM technologies and software interfaces, in order to understand the important connection between them.

The base of the practical part is the comparison of AM technologies, with the goal of getting a clear statement about the relevance of low-cost systems. The result, an evaluation matrix, affirmed competitive advantages for low-cost systems in combination with a customization software. Subsequently, a low-cost system has been tested with the aim to get the boundary conditions for the software development. Based on this information, a comprehensive software concept has been designed which integrates customers and developers. The approach is to provide one customization tool for both in order to reach a maximum of consistency, expandability and modularity.

The software tool “3DCustomizer” represents the result of this thesis. It helps developers to easily prepare 3D models for individualization purposes, whereas it enables customers to easily customize and print their favorite 3D object afterwards.

This new tool “3DCustomizer” is a big step towards crowdsourced and customizable personal manufacturing. It represents the basis for further developments with its vast modularity and expandability, as well as creative CAD developers, who are filling the platform with customizable 3D models.

KURZFASSUNG

Vergangene Entwicklungen im Bereich des Personal Manufacturing, wie beispielsweise Onlineplattformen für CAD-Modelle, unterstützen Kunden bei der Erzeugung ihrer favorisierten 3D-Objekte. Allerdings gibt es weiterhin viele Barrieren, da es Kunden aktuell an einfachen Möglichkeiten fehlt 3D-Modelle zu individualisieren. Um diese Probleme in den Griff zu bekommen, behandelt diese Masterarbeit die Erarbeitung eines Konzepts für individualisierte und eigenständige Fertigung mit einer innovativen 3D-Individualisierungssoftware als zentrales Element.

Um die fundamentalen Zusammenhänge zwischen den vielen technischen Disziplinen zu verstehen behandelt der theoretische Teil sowohl den umfangreichen Konvertierungsprozess der 3D-Daten, als auch Details über AM-Technologien und Softwareschnittstellen.

Ein umfangreicher Vergleich von relevanten AM-Technologien stellt die Basis des praktischen Teils dar. Ziel ist es, eine klare Aussage über die Relevanz von Low-Cost-Systemen zu erhalten. Das Ergebnis, eine Bewertungsmatrix, zeigt klare Wettbewerbsvorteile für preisgünstige AM-Systeme in Kombination mit einem 3D-Individualisierungswerkzeug. Darauffolgend wurde ein marktrelevantes und preisgünstiges AM-System getestet, um die Rahmenbedingungen für die Softwareentwicklung zu generieren. Basierend auf diesen Informationen wurde ein umfassendes Softwarekonzept erstellt, welches CAD-Entwickler und Kunden integriert. Es soll eine zentrale 3D-Individualisierungssoftware für Kunden und Entwickler entwickelt werden, um ein Maximum an Konsistenz, Erweiterbarkeit und Modularität zu erreichen.

Die Software „3DCustomizer“ repräsentiert das Ergebnis der Masterarbeit. Sie unterstützt CAD-Entwickler bei der Aufbereitung ihrer 3D-Modelle, um diese individualisierbar zu machen und Kunden zur Verfügung zu stellen. Kunden haben mit dieser Software eine einfache Möglichkeit diese 3D-Objekte zu individualisieren und ihr favorisiertes Modell anschließend zu drucken.

Dieses neue Individualisierungswerkzeug „3DCustomizer“ stellt einen großen Schritt in Richtung individualisierter eigenständiger Fertigung im Rahmen eines Crowdsourcing-Netzwerkes dar. Hohe Modularität und Erweiterungsmöglichkeiten der Software und kreative CAD-Entwickler, welche die Softwareplattform mit individualisierbaren 3D-Modellen füllen, repräsentieren die Basis für weitere Entwicklungen und sind die Garantie für weitere Fortschritte.

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1 INTRODUCTION

"Consumers know what works best in everyday products and given their own manufacturing tools, can prototype it. […] Companies that ignore their customers' talent for designing and making profitable, innovative products will lumber their way to obsolescence."[1]

Humans are striving for individuality. This could be expressed with physical appearance, clothing and career to name but a few. Currently, consumers are striving for individualized products as well, since this area is becoming more important and profitable for the industry. For example, several companies in the sports industry exceeded all expectations with new online tools for customers to individualize their favorite shoes and order them directly. In July 2013, Motorola presented their "Moto Maker", where consumers are able to customize different properties of the Smartphone, whereas 504 different variants are possible.

In order to achieve individualization improvements in the area of additive manufacturing, this master thesis, "Customizable Personal Manufacturing", deals with creating a new possibility for customers to easily individualize their favorite products. Customers are manufacturing these objects through small-scale and low-cost additive manufacturing (AM) systems by themselves too. The providing of customizable products is the responsibility of CAD-developers. They are using the same customization tool as the customers in order to achieve high consistency within this new customization concept.

This thesis will be very comprehensive, as this new concept builds up on some different technical areas (seen in Fig. 1), like CAD (designing and data preprocessing), additive manufacturing, and coding. Concepts, such as mass customization and crowdsourcing define the boundary condition of this thesis and provide these new concepts with a more far-reaching influence and a big room for further improvements. As a result, the new developed software 3DCustomizer, as illustrated in Fig. 1 as "Product", keeps metaphorically turning in the center. The fundamental knowledge of all of these areas will be elaborated in the theoretical part, which covers chapter 4 to 6.

Since this new concept of customizable personal manufacturing is based on open innovation, the idea of crowdsourcing and mass customization will be discussed first. Afterwards, "Additive Manufacturing" will be elaborated. A comprehensive technology-comparison of common additive manufacturing systems is the fundament of the practical part, so this chapter deals with the principles of these systems. In addition, the subchapter "Personal Manufacturing" indicates several statistics of the user-behavior concerning types of printed objects, data about the market and the users, but also with the chances, risks and challenges of these small-scale systems.

In order to feed an AM system with appropriate data, many data preprocessing steps have to be done. The chapter "Data Preprocessing" is concerned with all the levels of converting the data, starting at 3D CAD and ending with Code for the small-scale system. Everything in this concept is about intelligent and customizable 3D models, so especially the understanding of CAD is absolutely necessary. Therefore, the

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[1] Cf. Lipson/Kurmann (2010), p. 56.

subchapter "CAD" deals with the functionality, possibilities concerning designing and addressing variables as well as elements of 3D CAD.

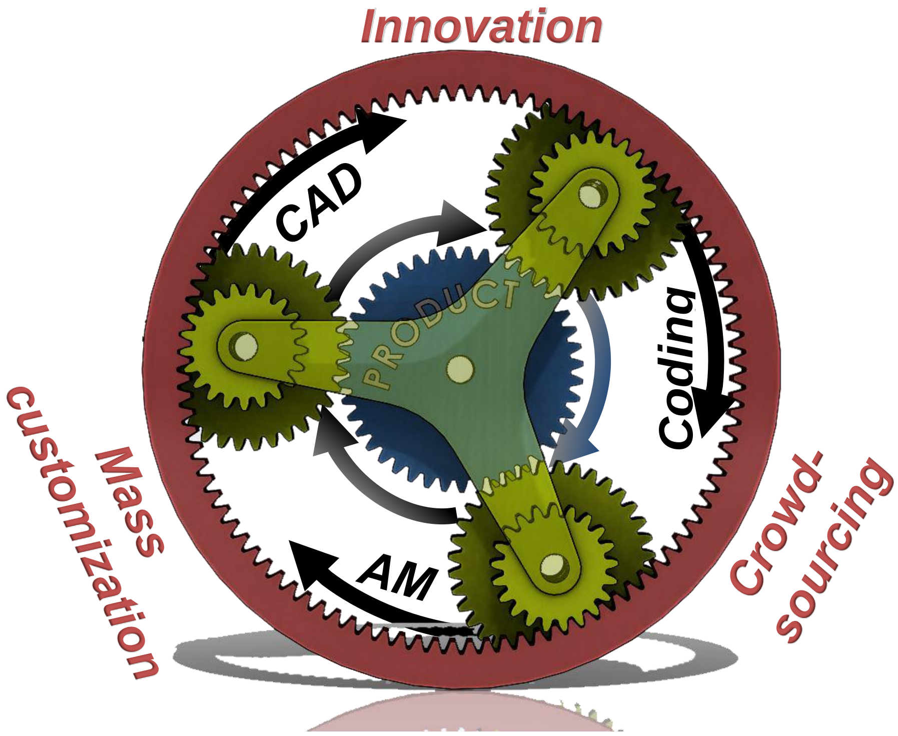

Fig. 1: Areas of the thesis, Reference: Own illustration.

The practical part comprises chapter 7 to 9. At first, a technology comparison should clarify the differences of certain properties between professional and small-scale low-cost AM technologies.

Based on these results, experiments and tests have to be done, in order to generate specific knowledge of the AM process and to get the boundary conditions for the software development.

Finally, the concept and realization of the software development will be elaborated in chapter 9, which will be the most comprehensive part of the thesis. Nevertheless, chapter 7 and 8 are providing the fundamental scientific findings and are important as well.

2 SCIENTIFIC AND EMPLOYMENT FRAMEWORK

The master thesis will be elaborated within an environment of different scientific institutions. The reason for this is that this thesis has started in 2013 at the CAMPUS 02 University of Applied Sciences in Graz and has continued at the San Diego State University on behalf of Marshall Plan Foundation to attend an academic exchange with a research paper as a result.

2.1 CAMPUS 02 UAS

The CAMPUS 02 University of Applied Sciences was founded in 1995. In this time, it was named after the well-known brand called ‘WIFI Steiermark GmbH’ for the development, preservation and management of University of Applied Sciences degree programs. In 1996, the first two degree programs, Automation Technology and Marketing, established in the part-time form. Finally, in 2001, the CAMPUS 02 brand called CAMPUS 02 University of Applied Sciences was introduced (see Fig. 2). Currently, the CAMPUS 02 offers five degree programs with the main objectives at the preparation and development in key positions in companies. In addition, all degree programs offer part-time programs and two of them offer a full-time program, too.

Fig. 2: Logo of CAMPUS 02 University of Applied Sciences, Reference: UAS (2013), accessed September 14th, 2013.

Moreover, this UAS puts great emphasis on research and development. The priorities in this area are based on the needs of the industry and economy and will help to promote the growth, innovation and enterprise development. Students benefit greatly due to the vast integration and interaction of CAMPUS 02 UAS with externals of the industry.

2.2 Marshall Plan Foundation

Austrian Marshall Plan Foundation (logo is seen in Fig. 3) delivers, based on a research contract, a scholarship for elaborating research work in the United States at a University. This academic exchange program was established to finance scholarships for academic exchange between Austria and the U.S. with a special focus on Technical Universities and Universities of Applied Sciences. This program is focused primarily on research in the field of technical sciences, whereas scholarship students will be asked to hand in a research paper of their research work.

Fig. 3: Logo of Austrian Marshall Plan Foundation, Reference: Foundation (2013), accessed September 14th, 2013.

Marshall Plan Foundation supports and benefits the cooperation between Austrian and American universities. The strategy of the Foundation is to develop social studies and economics research projects with different American universities.

2.3 San Diego State University

San Diego State University (SDSU) is a public research university located in San Diego. This University is the oldest and largest higher education facility in San Diego County. Founded in 1897 as San Diego Normal School, it is the third oldest university in the 23-member California State University (CSU) system, and is considered the flagship campus. San Diego State University has grown to offer bachelor's degrees in 84 areas, master's degrees in 76 areas and doctorates in 21 areas, since it was founded in 1897. SDSU has approximately 31,000 students and an increasing international emphasis that prepares them for a global future.[2]

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Fig. 4: Logo of San Diego State University, Reference: SDSU (2013), accessed September 14th, 2013.

SDSU's annual economic impact to the state of California is approximately $6.5 billion. Furthermore, they comprise more than half the region's teachers, entrepreneurs, engineers, and the local workforce for a host of other industries. Since 2000, SDSU faculty and staff have attracted more than $1.5 billion in contracts and grants for research and programs ranging from cardiovascular disease to marine biology.[3]

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[2] Cf. SDSU (2013), accessed September 14th, 2013.

[3] Cf. SDSU (2013), accessed September 14th, 2013.

3 INITIAL SITUATION, TASK AND TARGETS

Additive manufacturing has already been established in the industry. It is especially important, when there is a need of prototypes with high complexity and when this need has to be covered in an easy and fast way without the possibility to realize it with conventional production systems. Different technologies in this innovative area of production have already been developed. There are additive manufacturing technologies to print different types of synthetics, metal and ceramic-plaster mixtures. It is even possible to combine different materials within one print process or to print full-colored 3D objects.

Nevertheless, the systems mentioned before, are very expensive and they are especially developed for experts. These systems and workflows assume certain competences in the fields of CAD, CAM and Production Engineering. This allows to conclude that these systems with the current environment are not suitable for the mass market. For these reasons, additive manufacturing has not reached the mainstream users yet.

However, there is a big demand of additive manufacturing for the mass market, since individual products are of great importance for customers. Thus, a comprehensive new concept of personal manufacturing with big emphasis on individualization has to be developed and this will be the fundament of the practical part of the master thesis. This concept includes, on the one hand, categorized work processes and software tools for customers as well as developers. On the other hand, it also contains a comprehensive research of suitable data-conversion tools and the comparison of professional additive manufacturing systems with small-scale low-cost FDM systems. Based on these findings, a particular low-cost AM system has to be tested in order to get the boundary conditions for the software development.

The initial situation shows that there is a big demand of tools for assisting customers to handle CAD systems that deliver the basis data for additive manufacturing systems. Therefore, a comprehensive software concept will be created, whereas the aim should be consistency and modularity. This concept should include developers as well as customers. On the one hand, developers will be responsible for the filling of the software platform with CAD models. On the other hand, customers are able to customize the models which the developers prepared for the platform. Both developers and customers are using the same software tool

The main target of this thesis is to shape a new approach for customizable and crowdsourced personal manufacturing. In addition, this approach should be represented by a comprehensive concept, as well as a software tool as its core. However, in order to reach this main target several milestones have to be achieved beforehand, such as an evaluation matrix concerning AM technologies, as well as findings through experiments and tests of a small-scale FDM system.

4 OPEN INNOVATION

Open innovation defines the realization of accessibility to an innovation process of organizations or companies and the active and strategic usage of external people to be able to extend the innovation potential. Crowdsourcing and mass customization as specific areas of open innovation will be explained in the following subchapters.

4.1 Crowdsourcing

Crowdsourcing is about sharing work and has belonged to economics for a very long time. However, the appearance of Web 2.0[4] enables new possibilities to share ideas easily and connect people. As a result, companies use the so called “Collective Intelligence”[5]. Since customizable personal manufacturing targets the main purpose of crowdsourcing, the thesis deals at first with this topic. The basic idea of this thesis is about sharing work with engineers, hobby enthusiasts or artists. Crowdsourcing defines the basis of this concept. The next chapter, “Mass Customization”, builds upon crowdsourcing and shows how individualization with a community could work.

4.1.1 Definition

Crowdsourcing means taking tasks in a conventional way by an employee and a specialist and outsourcing them to a crowd or group of people. As a result, this describes a collective effort for a societal good. In addition, this could also mean competition and profit. Since companies outsource some of their problems, they are able to save money.[6]

4.1.2 Crowdsourcing with end users

The Internet has changed the way of how people deal with information. Social networks again have changed the way people live. These changes let people create, discuss and share experiences. There are already people who are developing applications for their mobile phones and sell them via several online download portals. These changes make people ready for open innovation, since they are willing to participate in the product development process. One expert is able to solve several complicated problems. In comparison, a whole community is able to solve a multitude of these problems in shorter time and for free. In this context, fora[7] in the internet are a very good example. There is nearly no issue, which had not already occurred or already been solved through the community.[8]

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[4] Web 2.0 is a new version of the Web, which goes beyond static pages and allows users to interact within social media dialogues.

[5] Collective Intelligence is group intelligence, which emerges from the competition, but also collaboration of many individuals.

[6] Cf. Klein (2013), p. 4.

[7] Fora (singular: forum) are spaces in the Internet, where people can interact through messages.

[8] Cf. Picot/Doeblin (2009), p. 123.

4.1.2.1 Participation

The first step of the process of open innovation with end users is to let them participate. Without participation, starting a dialogue will be impossible. Any form of interaction between company and users or developers must take place. This could happen via the Internet. Asking questions, giving answers and trying to show openness towards all sort of ideas is very important. Afterwards, if ideas are collected, the ideas and inputs have to be turned into something valuable for the company or the R&D[9] department. An ongoing dialogue between the company and the customer has to be sustained. Therefore, any outcome is shared back, unless profit has been made from these ideas. This is not just a sign of respect, but creates an enormous motivation for generating new ideas as well. When it comes to inviting people to participate, it is going to be hard work. Creating an online space, where people can interact, share ideas, and discuss would be a good start.[10]

4.1.2.2 Dialogue

The second step in this process is the dialogue itself. This is the step, where people browse and talk to each other, talk about their improvements or new concepts. Moreover, tools have to be provided for easy designing. In this way, sharing new ideas and concepts will become even more efficient and easier.[11]

4.1.2.3 Collect, create and share

The last step, “Collect, create and share”, is very difficult, since the potential of all the ideas, inputs, concepts or designs which come in should be correctly assessed. The ideas and inputs are all from outside professionals, designers or hobby enthusiasts, so it could be difficult for the company to deal with different opinions, which do not match the company’s current views. Nevertheless, the company has to evaluate and test them.[12]

4.2 Mass Customization

Crowdsourcing especially considers the integration of customers and developers in an innovation process. In contrast to the mass production of standardized products, an individual product or service could only work, if the manufacturer interacts with the customer. “Mass Customization” deals especially with the product individualization in combination with customers and developers inside a value chain.[13]

4.2.1 Product individualization

In general, a product embodies a combination of properties. The customer has specific preferences concerning the product and projects them on the product. As a result, customers shape an ideal product out of his preferences. This is called the ideal point and is shown in Fig. 5. The shorter the distance

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[9] R&D (Research and development) is an area which deals with applied research.

[10] Cf. Picot/Doeblin (2009), pp. 124-125.

[11] Cf. Picot/Doeblin (2009), p. 126.

[12] Cf. Picot/Doeblin (2009), p. 127.

[13] Cf. Reichwald/Piller (2006), p. 191.

between the ideal point of the customer and the point of the real product, the higher a product will be ranked by the customers. Consequently, it is quite difficult as a company to only provide one kind of service or product on the mass market, since customers have their own imagination of a specific product.[14]

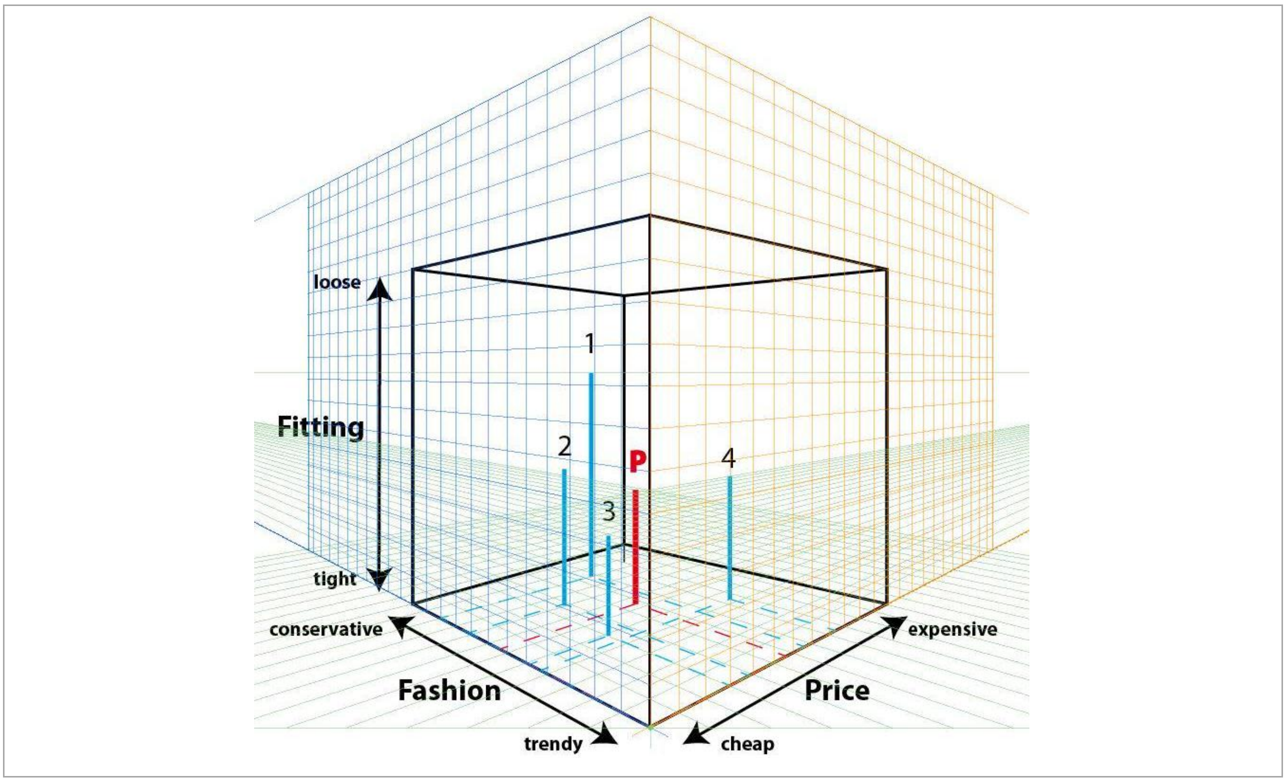

Fig. 5: Ideal points of a product from the view of customers, Reference: Own illustration based on Reichwald/Piller (2006), p. 194.

Mass production deals with collecting the preferences of the customers through market research, in order to get an idea of the preferences of average customers concerning a product. In addition, also individualization is possible with this concept through variant production. However, this concept has several disadvantages, since customers will never be sure if they have found the product which matches their preferences perfectly. This leads to the cognitive distance, which describes the negative condition after the purchase, since customers see other products which match their preferences better and become unsatisfied with their purchased product.[15]

Consequently, manufacturers can use this uncertainty of the customers, as they try to reach the ideal point of the customers through individualization. Product individualization deals with the modification of product properties concerning the preferences of the customers to reach the ideal point. The individualization leads to special manufacturing concepts, since the product can only be manufactured, when the customer order, according to their preferences, comes in. These concepts are called “on demand” and “make-to-order”.[16]

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[14] Cf. Reichwald/Piller (2006), pp. 193-194.

[15] Cf. Reichwald/Piller (2006), pp. 194-195.

[16] Cf. Reichwald/Piller (2006), pp. 195-196.

4.2.2 Principles and properties

Based on the definitions of mass customization, four layers or principles of product individualization can be derived (see Fig. 6). These will be explained in the following subchapters.

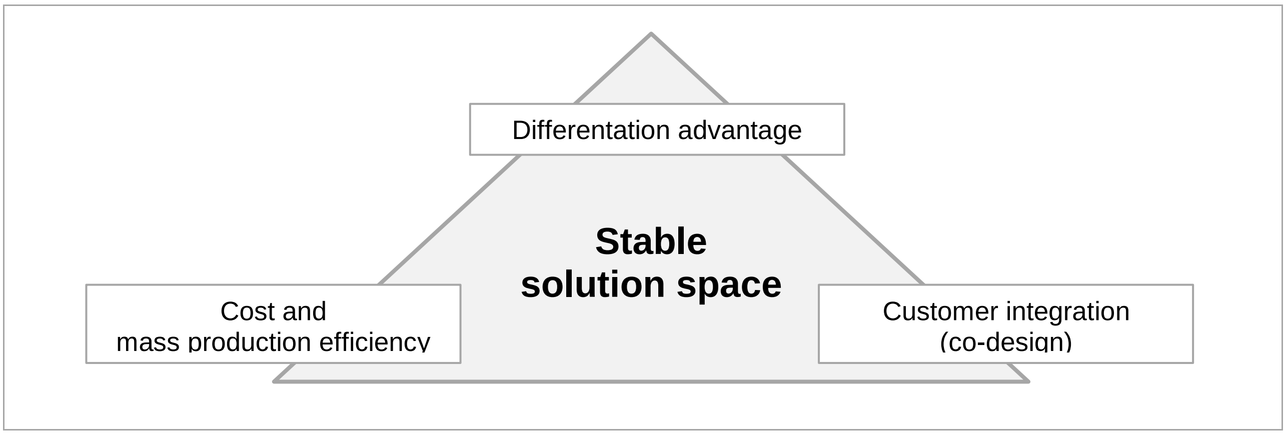

Fig. 6: Principles of mass customization, Reference: Reichwald/Piller (2006), p. 200 (slightly modified).

4.2.2.1 Customer integration (co-design)

The central element of mass customization is the integration of the customers, as also mentioned in chapter 4.1.2.1. Therefore, the solution space will be reduced in a customer-orientated way to get specific and controllable properties, which describe the product. After this process, the customers have the possibility to concretize their product by modifying of different properties of the product. To be able to self-design their product, customers need a platform to interact with the company and the product. These systems or platforms are called co-design systems.[17]

4.2.2.2 Differentiation advantage

The differentiation advantage arises from the adaption of certain product properties to the preferences of customers. This deals with the increasing of the benefits for customers, since the resulting individualized product has a bigger correspondence with the ideal point than the next best alternative of standard product. However, it is very difficult to find the right properties of the product, i.e. most of the customers have a desire of adaption.[18]

4.2.2.3 Costs and mass production efficiency

When it comes to prices of individualized products, companies try to keep them on the same level as mass products. But market research reveals that customers are willing to pay more for individualized products. This price difference corresponds with the increase of benefits for the customers. Nevertheless, the price difference has to stay in-between a certain zone. Through the integration of the customer, new knowledge is generated, which leads to more efficient behavior inside the company. This affects the

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[17] Cf. Reichwald/Piller (2006), pp. 200-201.

[18] Cf. Reichwald/Piller (2006), p. 201.

financial situation positively, since the costs are decreasing. These cost decreasing potentials are called "Economies of Integration".[19]

4.2.2.4 Stable solution space

Stable product and process architectures are major properties of mass customization. The individualization possibilities are limited and are illustrated in the solution space of the manufacturer. Successful mass customization systems are stable, but also flexible when it comes to a dynamic flow of individualized products. With the conventional mass customization, it is not possible to develop a completely new product as a customer. Thus, it could be called "standardization of individualization", since the design and choosing possibilities work greatly with the management of part lists, manufacturing processes and so on. The suitable definition of the solution space for mass customization is a major success factor of this concept.[20]

4.2.3 Concepts

The preceding explanations show that mass customization, among crowdsourcing, is a further concretization, when it comes to interactive value creation. Without the involvement of the customers and developers in the value creation process, products could neither be produced, nor be sold. Thus, new definitions concerning work sharing between manufacturers and customers have to be considered. Out of that, new different forms of mass customization can be distinguished. These concepts will be taken into consideration in the following subchapters.[21]

4.2.3.1 Assemble-to-order

Assemble-to-order or made-to-order-systems deal with the information about the ideal point of a customer, to manufacture an individualized product. So, this concept is about the assembling of different standard components (illustrated in Fig. 7) to make a new individualized product, according to customer requirements.

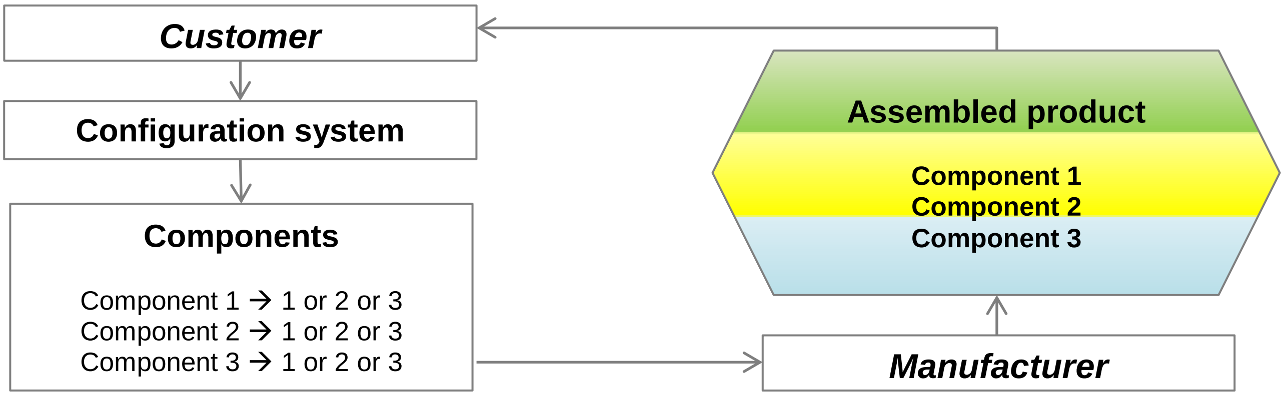

Fig. 7: Concept of assemble-to-order, Reference: Own illustration.

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[19] Cf. Reichwald/Piller (2006), pp. 202-203.

[20] Cf. Reichwald/Piller (2006), pp. 202-203.

[21] Cf. Reichwald/Piller (2006), pp. 207-208.

However, the customer is only able to choose a specific option. Also, this concept deals with customer-specific manufacturing, but the integration of the customer into the value creation process is limited, concerning product specifications.[22]

4.2.3.2 Development-to-order

Development-to-order or engineering-to-order is the highest form of value creation integration of customers. In this concept, the customer is integrated into the product development process. The modification of the product is not limited to certain parameters any more (therefore compare Fig. 7 and Fig. 8). Based on a new construction of the product, a new, individualized product will be manufactured. In general, this is the area of the conventional contract-based engineering offices which deal with specific customer requirements. However, nowadays, through the principles of mass customization, it is also possible to work with individualization as efficient as with mass production.[23]

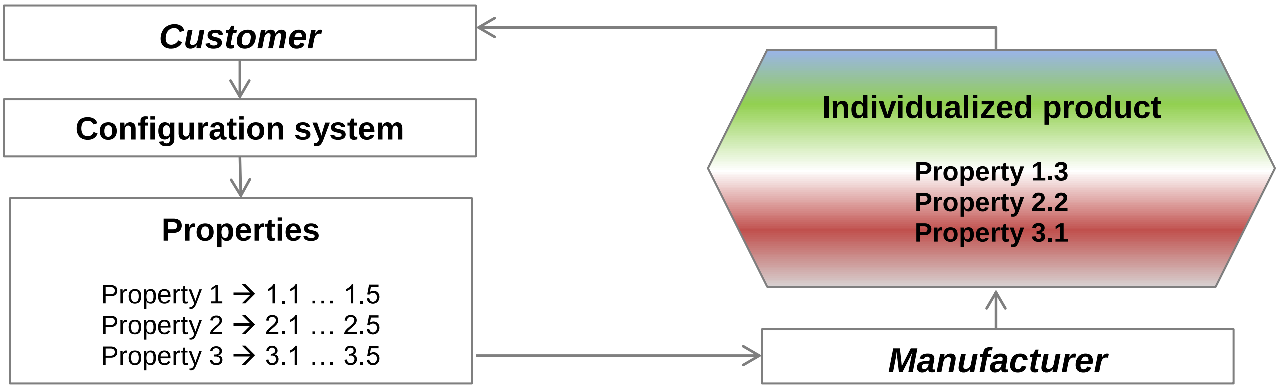

Fig. 8: Concept of development-to-order, Reference: Own illustration.

4.2.4 Configuration systems

The central point of the interaction with the customers is the configuration[24] phase. In the field of mass customization, the configuration process happens within a solution space. In this context, arrangement means to be able to assemble an object out of single parts. Design describes the possibility to modify existing elements and to intervene creatively.

Configuration systems represent the link between product development, production and customer demand and desire. The user interface is easy to handle and is fulfilled with arrangement and design possibilities as well as checking the production ability. This user interface is a form of communication interface with the customer and this communication should not last longer than a few minutes, when dealing with simple products, and consequently have little modification possibilities. The use of configuration systems is a major factor of efficiency.[25]

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[22] Cf. Reichwald/Piller (2006), p. 208.

[23] Cf. Reichwald/Piller (2006), p. 208.

[24] Latin: configuratio: means arrangement and/or design.

[25] Cf. Reichwald/Piller (2006), pp. 245-246.

5 ADDITIVE MANUFACTURING

Additive manufacturing has already been established in the industry in various areas. Since its invention in the 1980s, different technologies have been developed. Currently, there are additive manufacturing technologies which offer various principles to print synthetics, metal and ceramic-plaster mixtures. It is even possible to combine different materials in one print process or to print full-colored 3D objects.

This master thesis especially deals with customization tools in combination with small-scale FDM printers. However, since one major section of the practical part is a comparison of the industry-relevant AM systems, these compared technologies will be explained in this chapter as well.

5.1 Principle

The principle of additive manufacturing systems is basically the same for all building principles. In the XY plane the contouring is happening by generating layer after layer. The individual layers have a certain thickness, and this depends on the additive manufacturing process. However, the third dimension will not be built as a continuing Z-coordinate, but through successive adding of layers. This is why the staircase effect happens, as mentioned in chapter 6.4.2.2. Actually, additive manufacturing processes in general are no pure 3D processes due to the Z-steps. Strictly speaking, it has to be called a 2 ½ D process. The produced objects are very accurate, if only the XY plane would be evaluated. Nevertheless, the Z direction is due to the staircase effect being less accurate. To fix that issue, 3D-system manufacturers try to decrease the layer thickness, with the aim of minimizing these effects. An object with a high layer-thickness and consequently vast staircase effect is shown in Fig. 9.

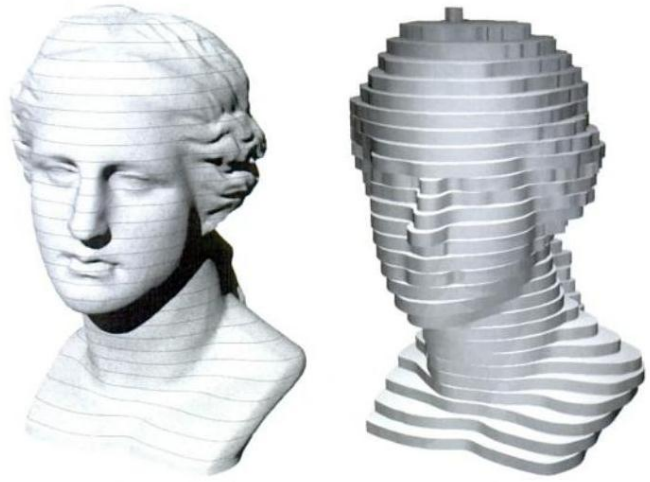

Fig. 9: Staircase effect (left: sliced volume model, right: produced layer object), Reference: Gebhardt (2007), p. 12.

5.2 Technologies

To get an overview of existing additive manufacturing systems and the categorizations, Fig. 10 reveals the most common AM methods. The framed blocks in the illustration are the AM technologies, which are considered for the technology comparison in the practical part of this thesis.

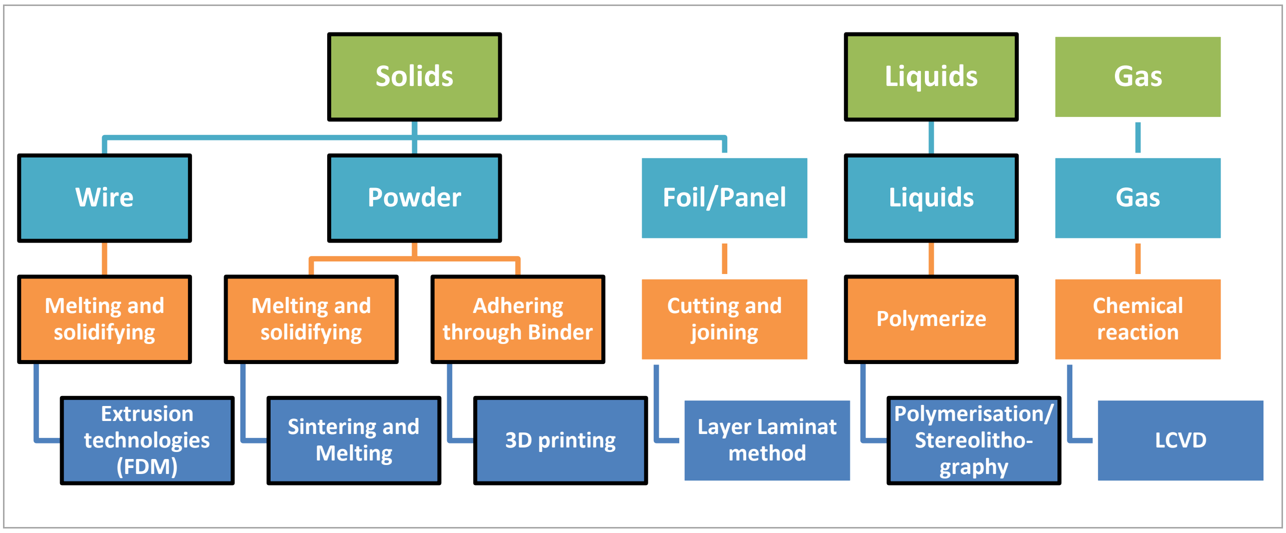

Fig. 10: Classification of additive manufacturing technologies, Reference: Own illustration based on Gebhardt (2007), p. 69.

5.2.1 PolyJet

The PolyJet principle deals with pasty materials, which are hardened through UV light. This principle has certain similarities with the stereolithography technology. In contrast, stereolithography machines work with liquid photo-curable materials (liquid monomers). Consequently, this leads to several disadvantages like the impossibility to print different materials during one printing process.[26]

PolyJet machines simultaneously apply support and building material on a base platform. Immediately subsequent, this pasty material is cured by high-power lamps, which are illustrated in Fig. 11. As a consequence, fascinating, high-complex, high-accurate and multi-material 3D objects are printable, which is a vast advantage of this principle. This is possible through continuous printing of water-soluble support material. Furthermore, several materials with different properties can also be printed.[27]

Each layer is built through simultaneous printing of the main and the support material. Simultaneously with the printing layer, two mounted UV lamps (the right and left of the print head) are responsible for the hardening. Independent of the model geometry, the entire XY surface of the platform (restricted to the main dimensions of the model) is always printed. Due to the low layer-thickness, high model accuracies are possible. However, there is also another reason for the low layer-thickness. The thinner the layer, the faster the curing of the material caused by the UV lamps will be.[28]

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[26] Cf. Gebhardt (2007), pp. 111-112.

[27] Cf. Gebhardt (2007), pp. 111-112.

[28] Cf. Gebhardt (2007), pp. 111-112.

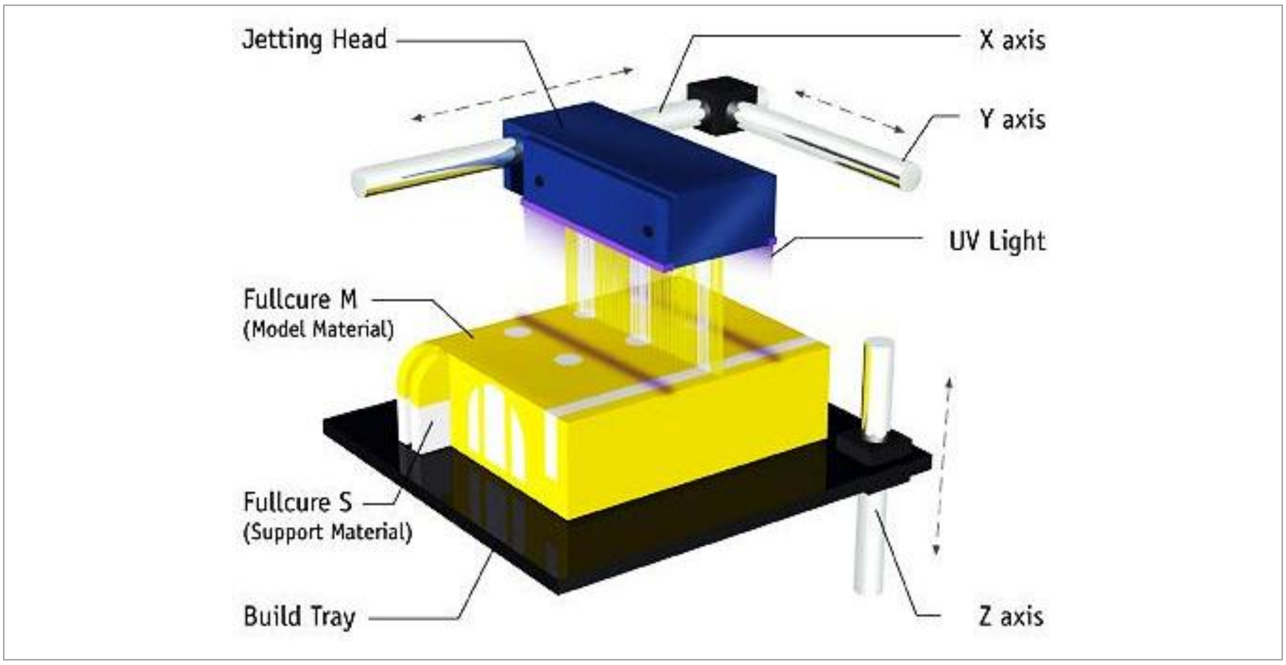

Fig. 11: Principle PolyJet polymer print, Reference: Gebhardt (2007), p. 112 (slightly modified).

5.2.2 Selective laser sintering (SLS)

This technology uses powder (i.e., metal or plastic) as its basic material is sintered with a laser. Thus, it is possible to use other material and it is also possible to choose from a bigger range of materials. In addition to metals and ceramic substances, which are sintered conventionally, plastic powder and casting sand can be processed as well.[29]

In laser sintering, a certain degree of porosity of the 3D model cannot be avoided. There are efforts to improve this by using suitable substances impregnating the porous form later (i.e., with liquid copper). A sintering plant basically consists of a container with a bed of powder with precompressed granules (20-50 microns). The energy source is usually a laser-scanner unit, which is deflected by a mirror and the powder bed is locally partially or fully melted by the laser (or other form of energy). After this process, the cooling takes place due to heat conduction. Consequently, the generated layer solidifies with the layer produced beneath, which has already hardened. The loose, non-solidified powder, remains as a supporting material. However, conventional printed support structures are also necessary in certain situations, but in most cases, no printed support structures are required (depending on the material and geometry of the model). After printing a layer, the building platform is lowered and a new powder layer is applied through a roller or a wiper. This process starts all over again. In Fig. 12, the principle of selective laser sintering can be seen. Furthermore, the melting of the powder particles through a laser beam is imaged.[30]

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[29] Cf. Gebhardt (2007), p. 121.

[30] Cf. Gebhardt (2007), p. 121.

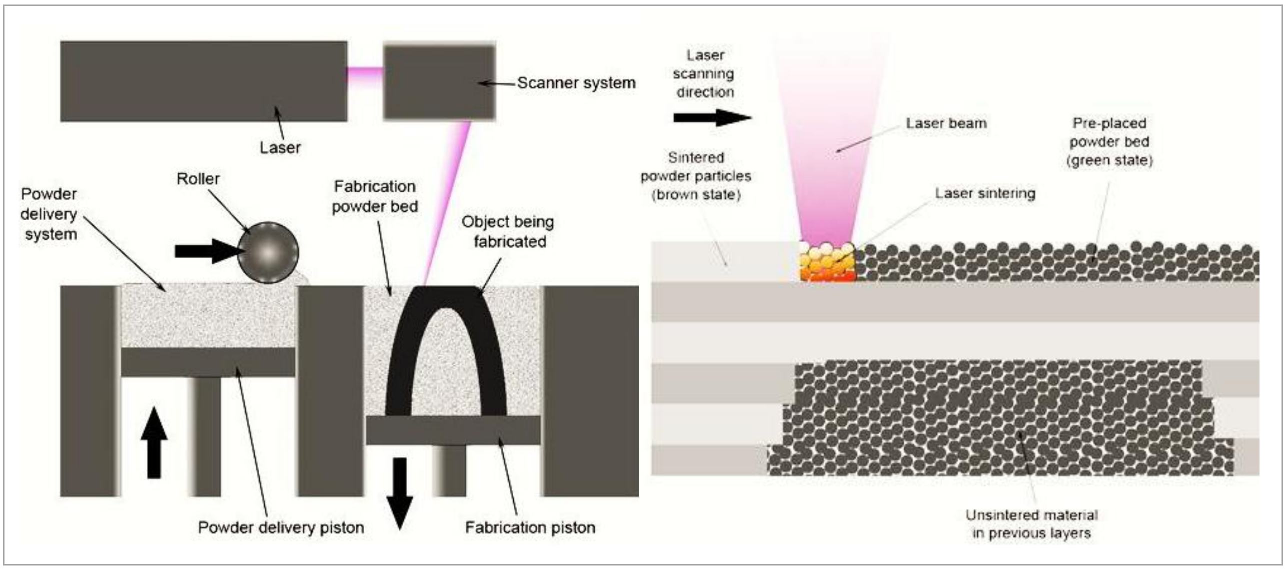

Fig. 12: Principle selective laser sintering, Reference: Academic.ru (2012), Online Source accessed September 08, 2013, p. 112 (slightly modified).

5.2.3 3D printing (3DP)

3D Printing machines have a space with three chambers lying in the plane of construction. Fig. 13 shows the principle with the main components of the 3D-printing process. In two of the three chambers, the building platforms are movable, which enables the powder (ceramic plaster mixture) in the chamber to raise or lower. The printhead unit is located above of the chambers on a XY portal. If the bottom of the hopper rises, powder material will be provided for the roller. This roller transports the powder by a horizontal linear movement into the building platform and equally distributes this powder there. Waste material passes into the overflow tan, is filtered and comes back into the reservoir. Now, there is a 0.1 mm thin layer provided for the bonding process. In the surface of this powder bed, liquid binder (including color) is injected through inkjet printheads (black, clear, cyan, magenta and yellow). Thus, the affected powder areas are solidified locally. The binder both generates the contour of the current layer and bonds this layer with the underlying layer. However, the unbounded powder acts as a support for the built object. After this step, the work platform travels downwards at the value of the layer thickness. Then, a further powder layer is applied, and again a layer is printed. Through this bonding process, the layers are bonded to each other in the vertical direction - consequently, a three-dimensional object is shaped. This process is continued until the final height of the component is reached.[31]

The unbonded powder is removed after the 3D-printing process with the assistance of a vacuum-station. Since the printed object in the raw condition is very fragile, this vacuum process could especially damage the filigree models. After this suction process, the printed objects are fed to the next station, called depowdering station. This process deals with removing of the residual powder with a compressed-air nozzle, which is remained from the vacuum station. All the unused powder will be extracted through various filters and finally end back in the vessel where it is ready for new jobs.

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[31] Cf. Gebhardt (2007), p. 210.

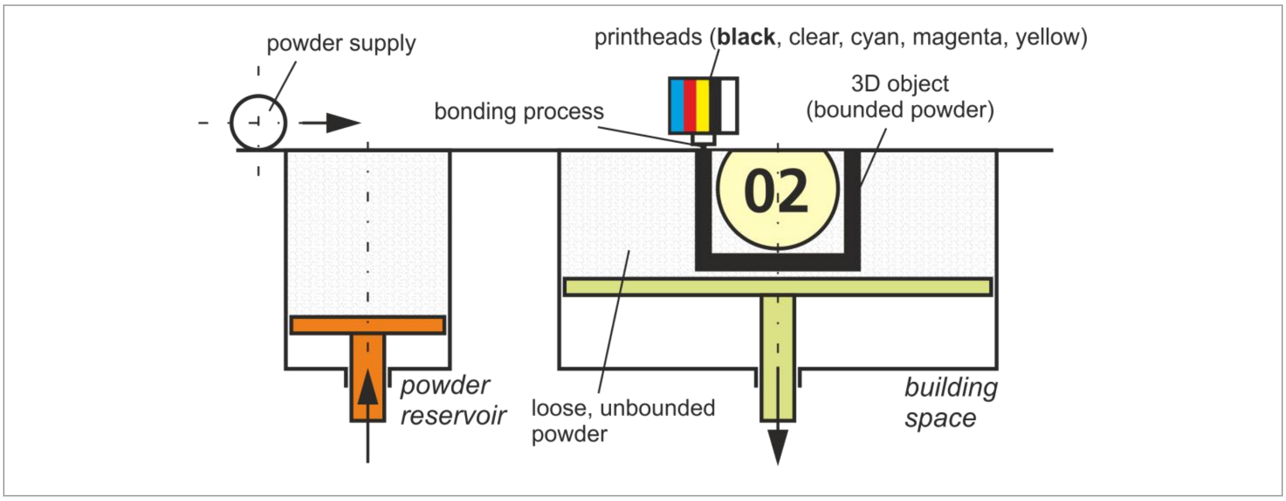

Fig. 13: 3D-printing principle, Reference: Own illustration.

The objects are in the raw condition after the printing process, so they do not have high stability and break very easily. Therefore, the last step of the post processing is to treat the objects with a special infiltrate (cyanoacrylate). This treatment is for improving the color and the material properties of the models. In general, the models will be soaked in a container filled with cyanoacrylate, to reach homogeneous results. This infiltration process leads to a chemical reaction - polymerization. Since this operation generates hazardous vapors and chemical burns, caused by contact with the skin, specific safety measures need to be considered.

5.2.4 Fused deposition modeling (FDM)

The FDM principle subordinates in the extrusion processes. Fig. 14 shows the fused deposition modeling process with the major components. Extrusion processes deal with thermoplastic material which is continuously pressed through one or more nozzles and dropped onto a platform. The thermoplastic material is available in the form of filament, and is wounded up on rolls. This thermoplastic material is heated by a nozzle just below the melting temperature and is brought to a pasty state. Subsequently, this pasty material is extruded on the platform or, if it is already a further layer, on the previous layer. The molten material cools down and solidifies upon contact due to heat conduction. The nozzle head is guided in the XY plane, to shape a layer of the constituent model. After completion of one layer, the building platform is lowered in the Z-direction by the set layer thickness. Consequently, the process starts again from the beginning of the next layer. [32]

Nowadays, the layer thickness of FDM machines ranges between 0.27 to 0.1 mm. Consequently, rough surfaces arise through this kind of extrusion method, and also if FDM systems are improperly configured. These rough surfaces resemble a bulges-like structure at closer look. To minimize this effect, but also to specifically control the material properties of the model, there is a special approach. Both the distance between the previous layer and the extruder, and also the flow of the molten thermoplastic material, are coordinated, so that track widths from 0.254 to 2.54 mm and thicknesses from 0.127 to 0.330 mm result, depending on the nozzle diameter. After a layer is completed, the building platform is lowered by a certain

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[32] Cf. Gebhardt (2007), p. 199.

fraction (1/2, 1/4, etc.) of the nozzle diameter. This results in an oval cross section of the molten material. During the extruding process, this oval cross section is formed, since the material is pressed onto the surface. This method enables relatively smooth surfaces and solid structures, depending on the surface tension and viscosity (a function of temperature). If there are overhanging model structures below a certain angle, then supporting structures are absolutely needed in this process. These support structures are manually removable due to their porosity. In some machines, the support structures are water-soluble.[33]

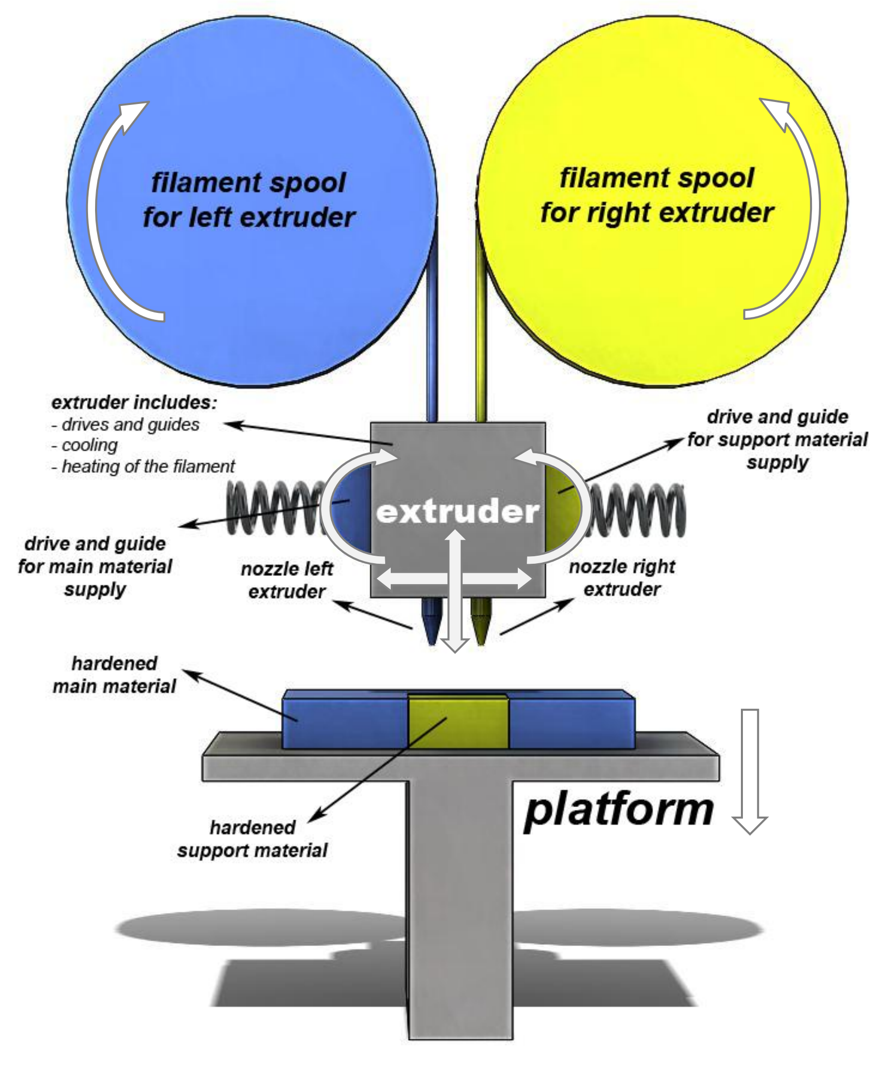

Fig. 14: Fused deposition modeling principle, Reference: Own illustration.

5.3 Personal Manufacturing

Since the price of machines for additive manufacturing is decreasing to a low level, personal manufacturing becomes more interesting for mainstream users. Moreover, media and news are broadcasting about this topic more and more. Consequently, they put this technology to the peak of inflated expectations in the product innovation process.

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[33] Cf. Gebhardt (2007), p. 199.

5.3.1 Introduction

Personal manufacturing is the generic term for cheap small-scale manufacturing machines based on the technology of professional machines used in factories. These machines could be small laser cutters, small-scale 3D printers, sawing machines and many more. If personal manufacturing is compared with personal computing, one can find some similarities. Personal computing needed over 30 years to bring the computers to the mainstream users at home. In order for that to happen, home-scale computers and consumer software had to be developed to make it easier for users to be able to work with this new technology.[34]

Actually, personal manufacturing made many steps forwards to bring the small-scale machines to mainstream users. Unfortunately, the usability is not yet progressed as the users would expect. There are usability lacks in data handling, product individualization and the whole manufacturing process.

5.3.2 Low-cost printers

The majority of the low-cost printers are based on the fused deposition modeling technology. This technology is explained in detail in chapter 5.2.4. However, to summarize, the raw material for FDM systems is plastic filament (PLA or ABS). This filament is guided through an extruder, where it is heated up to its melting point. Motion in the XY plane assures that the melted plastic filament creates the horizontal shape of the object. The motion of the Z-axis takes place in certain steps (layer height) and creates the 3D shape. The reason why the majority of low-cost printers are based on the FDM technology is the simple construction. For example, the extruder as the heart of a FDM machine, which is responsible for the feeding and heating of the filament, could be constructed and assembled very cost-efficiently. In addition, the drives for the XY-motion and the Z-motion could also be realized in a simple and inexpensive way.[35]

5.3.3 Areas of application

As mentioned in chapter 5.3.1, the democratization of production through personal manufacturing machines will be a major topic in the 21st century, as it happened in the 20th century with democratization of information through personal computers. Consequently, this will change the market as it is known up to now. There is not much market data about consumers and industry which are using personal manufacturing machines. Nevertheless, there exist statistics about the usage of additive manufacturing technologies in different areas of the industry. Fig. 15 shows that the areas consumer products/electronics, motor vehicles and medical/dental share over 56% of the market.[36]

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[34] Cf. Anderson (2012), pp.81-83.

[35] Cf. Fastermann (2012), pp. 24-25

[36] Cf. Lipson/Kurmann (2010), p. 27.

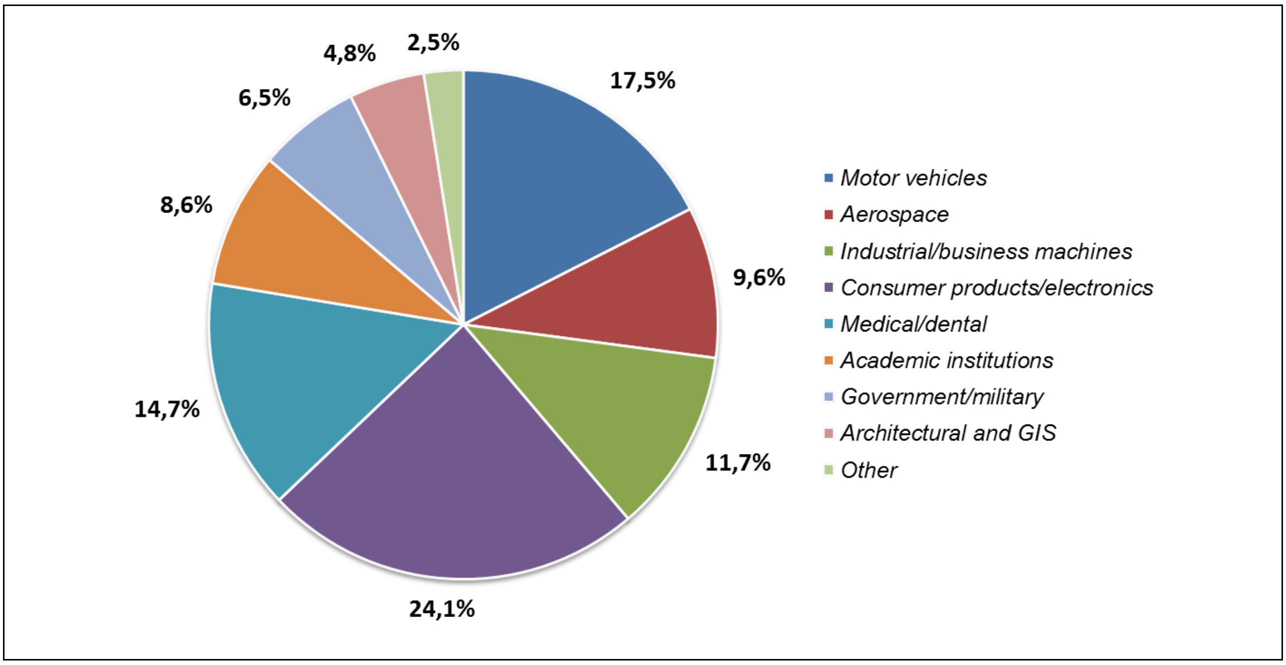

Fig. 15: 3D-printing services at industries, Reference Moilanen/Vadén (2013), accessed November 07th, 2013 (slightly modified).

Again, data about types of printed objects with small-scale machines is rare. Nevertheless, there is much data of professional 3D-printing service companies which work with professional additive manufacturing technologies (see Fig. 16). However, since consumers of professional 3D-printing services are the producers of the future, the data of this professional 3D-printing service companies is valuable. This data reveals what kind of models the customers would like to have. Furthermore, this also shows what kind of additive manufacturing technologies are needed to produce these 3D objects.[37]

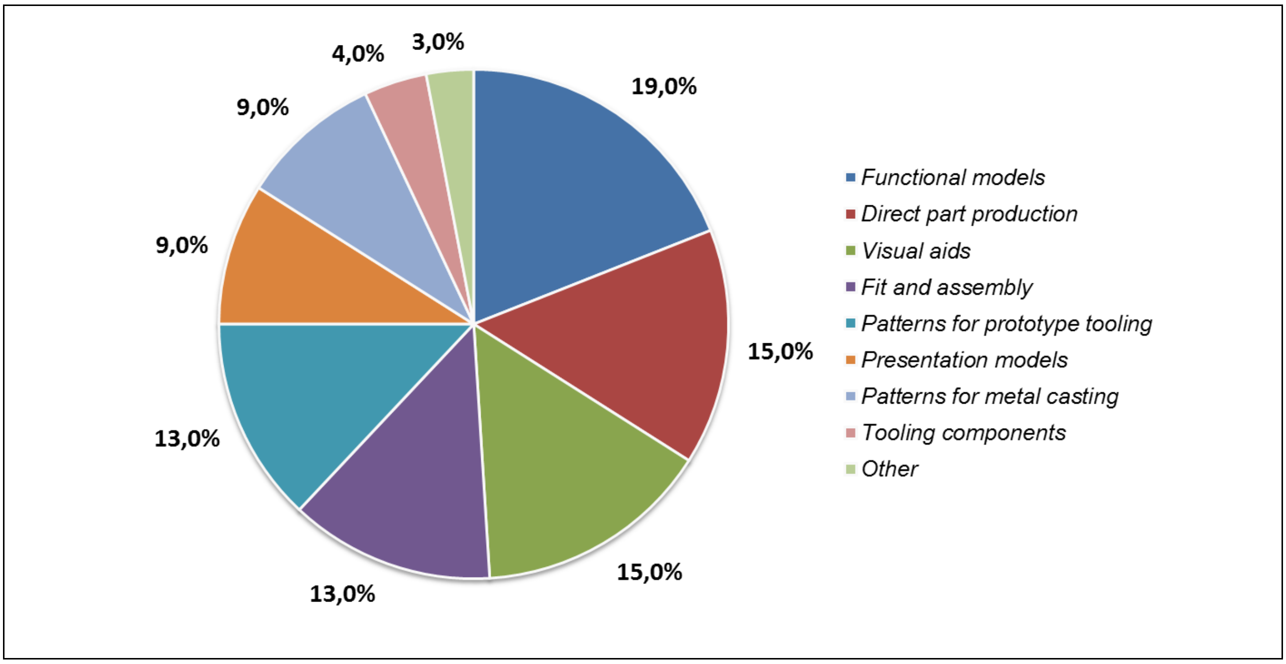

Fig. 16: Types of requested 3D objects, Reference: Moilanen/Vadén (2013), accessed November 07th, 2013 (slightly modified).

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[37] Cf. Lipson/Kurmann (2010), p. 28.

If the application purpose is taken into consideration, then, 73% of the requested 3D objects (seen in Fig. 17) will have to be functional models. This means, that the material of the object should have appropriate mechanical properties to be able to withstand external influences. Only 27% of the requested 3D objects should have special properties concerning visual and presentation purposes. This is a vast finding which supports the purpose of the thesis immensely.

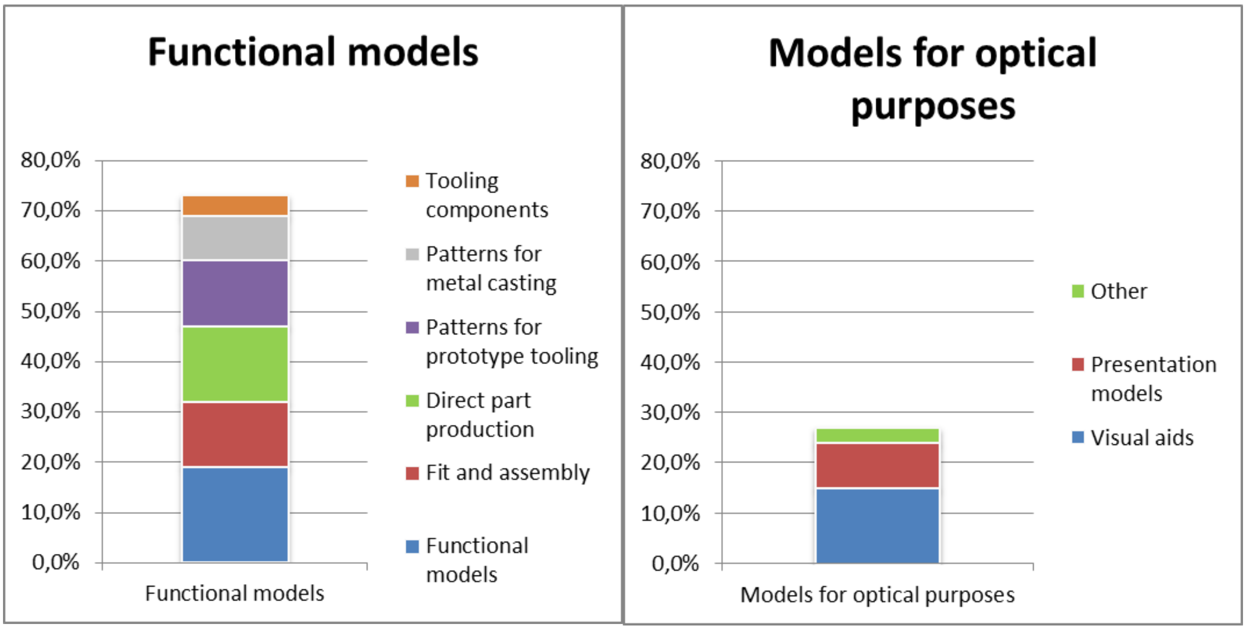

Fig. 17: Distinguishing between functional models and models for optical purposes, Reference: Own illustration.

5.3.4 Market and users

As mentioned in chapter 5.3.2 there are application purposes for additive manufacturing systems. At the beginning of this technology, mainly the areas mechanical engineering, aerospace industry, medical engineering and the automotive industry have been mainly used this technology. But, since the technology of professional AM systems has been improved and small-scale printers become more inexpensive, the application purposes extend dramatically. Mainstream users mainly use the technology for creating functional models, spare parts, arts models, decorations and many more.

However, the average mainstream user of these low-cost systems is highly educated, male and between 26 and 30 years old. This is the result of a statistical survey with the title “Manufacturing in Motion: First Survey of 3D Printing Community” of Peerproduction in 2012 which is illustrated in Fig. 18. Unfortunately, females are not using these systems yet. Only 6.7% of 3D-printing users are female, whereas about 76.5% of these users are male. The rest, 16.8% did not provide any gender information in this survey. As a result, there is a vast potential to extend the range of potential users.[38]

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[38] Cf. Fastermann (2012), p. 26.

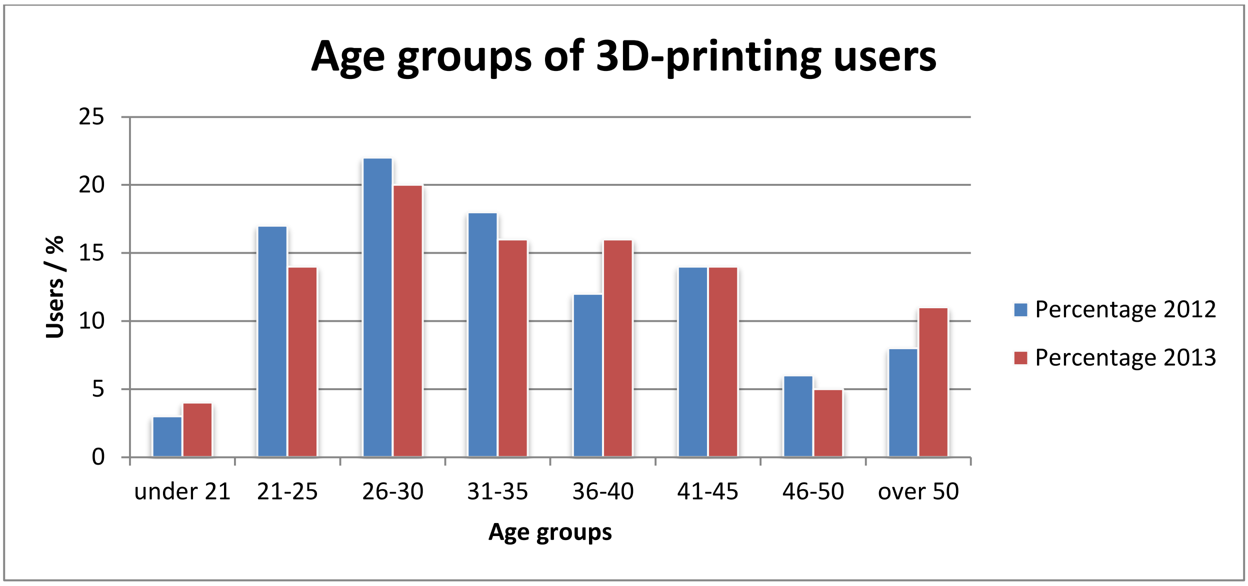

Fig. 18: Age groups of 3D-printing users, Reference: Own illustration based on Moilanen/Vadén (2013), accessed November 07th, 2013.

5.3.5 Share economy through FabLabs

FabLabs are accessible laboratories, which should help to force the sharing of knowledge and know-how of engineers, artists and hobby-enthusiasts. This will be realized through membership payments of the people, who want to produce something. Mainstream users have the possibility to visit these open laboratories to get involved in the production process and afterwards to work independently with the systems. The idea for these FabLabs has its origin in the USA. The main goal of the FabLabs is the democratization of the production, since every member of these FabLabs is industry independent to a certain extent.[39]

Fig. 19: Example of a FabLab, Reference: Amsterdam (2012), accessed September 12th, 2013 (slightly modified).

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[39] Cf. Fastermann (2012), pp. 85-87.

5.3.6 Challenges

Personal manufacturing has to deal with many challenges in different areas. Many barriers need to be addressed, like intellectual property issues, safety concerns and so on. But there are also some software- and hardware-related challenges concerning usability, reliability and much more. Some of these issues should be solved in the practical part of this master thesis.

5.3.6.1 Investments

Unfortunately, most schools, businesses and consumers do not work with small-scale manufacturing machines yet. Due to the low market demand, companies have not invested much money into different kinds of the market, like local manufacturing services, cheaper and better machines or low cost consumer design software. Nevertheless, the big investments will start as soon as investors see, that there is high potential and interest. Compared to the development of the personal computer in the 20th century, there are again some similarities. Pioneers and hobbyists have coded their own software applications for years, until investors tried to make a big concept out of the great small ideas and developments.[40]

5.3.6.2 Safety

Many things have to be considered regarding safety. There are several potential risks in the area of personal manufacturing which have to be evaluated.

Firstly, the small-scale machine itself could injure the producer, because of inaccurate or poorly made machine parts. Moreover, heated platforms, lasers and sharp parts are also potential risk for the buyers of the machine. Secondly, highly skilled designers have the knowledge to design weapons and share it via the Internet with the community. With personal manufacturing machines they will also have an easy possibility to manufacture their designed parts. Finally, liability should be mentioned as well. If a person gives another person a custom-designed part, manufactured with a small-scale 3D printer and this part hurts someone else, there might be liability issues.[41]

5.3.6.3 Low costs

A small-scale 3D printer is only suitable for personal manufacturing, if the price is very low, so that customers are able to buy this device. Currently, many companies are producing machines which are sold below $ 2000 and this trend will continue, since the media hypes this technology, so that people get interested in this field of technology.[42]

Furthermore, the follow-up costs have to be as low as possible. As mentioned in chapter 5.3.6.3, the most small-scale machines are based on the fused deposition modeling technology. The big advantage is that the raw material for this technology is very cheap and available at different retailers.

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[40] Cf. Lipson/Kurmann (2010), p. 75.

[41] Cf. Lipson/Kurmann (2010), pp. 75-76.

[42] Cf. Lipson/Kurmann (2010), p. 33.

In addition, the running costs of FDM machines are also not so high, compared to other technologies, since the drives of the axes are very small and the produced heat for the extruder and the platform, especially when printing PLA-material, is at a very low level.

5.3.6.4 Economic issues and recyclability

A major point in all areas of technology is the economic aspect and the recyclability in order to meet environmental standards. The majority of the small-scale FDM printers work with PLA[43]-filament as a raw material. The big advantage of PLA is that it is a thermoplastic polyester, which is derived from renewable resources, like chips or sugarcane. Polylactic acid is able to be recycled to monomer by a thermal depolymerization.[44]

Considered global, personal manufacturing could change the current economic issues dramatically. If items could be designed and manufactured locally, people in developing nations and underserved communities would have the possibilities to overcome their limitations in infrastructure. Furthermore, this would enable the possibility to create solutions for local needs by local people.[45]

5.3.6.5 Hardware-related issues

This subchapter deals with the hardware-related problems of small-scale 3D-printing systems. Currently, these systems are widely based on the same technology (fused deposition modeling), since the concept of this technology is very cost-effectively realizable. Consequently, the majority of the small-scale 3D-printing systems has to solve the same problems.

5.3.6.5.1 Reliability

This has a high priority importance for a customer, who works with such a small-scale 3D printer. Currently, the handling of such printers is not as user-friendly as it should be. There are many barriers for mainstream users, like designing of the object, data-conversion, finding the right settings for the 3D-printer software, getting the printer started and so on. These barriers make it very difficult to achieve satisfying results. Moreover, the inexpensive method of construction could also cause many issues, like feeding problems of the filament, adhesion problems of the object on the platform and material distortion because of temperature issues.[46]

5.3.6.5.2 Model quality and complexity

Customers expect great object quality from 3D-printing systems. Moreover, they want to produce whatever they want. Consequently, this means that small-scale 3D printers should be able to work with highly complex 3D data. Professional FDM printers already have a possibility to deal with overhangs. They have a dual extruder, one for the main material, one for the water-soluble support material.

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[43] Polyactic acid or polylactide.

[44] Cf. Garlotta (2001), p. 63.

[45] Cf. Lipson/Kurmann (2010), p. 51.

[46] Lipson/Kurmann (2010), p. 33.

Unfortunately, the majority of these printers always print this water-soluble material, although it would not have been necessary. [47]

Currently, small-scale FDM printers do not have a possibility to print with water-soluble support material. Furthermore, there is not much information about the accuracy of these small-scale FDM printers. These two topics, accuracy and water-soluble support material will be evaluated in the practical part of this thesis.

5.3.6.6 Software-related issues

Currently, the software is a big problem for customers. The first investments in this area enabled the possibility to arrange objects for printing easily. Moreover, companies have tried to increase the usability of the small-scale FDM printers with their own software solutions as high as possible. Unfortunately, there are still too many steps for mainstream users to start the printing process successfully and get satisfying results.

5.3.6.6.1 Usability

On the one hand, there are mainstream users, who want to print an object. So, they have several possibilities. The number of possibilities how to do something already decreases the degree of usability, because mainstream users could already be overwhelmed. One possibility is to download CAD files from several download platforms. The majority of these platforms will be filled by voluntary engineers, designers or hobby enthusiasts. Another way is, to design an object yourself. Therefore, knowledge of professional CAD software is necessary, since these tools are very complex. Finally, a way to individually customize 3D objects does not exist yet.

On the other hand, developers do not have the possibility or a platform to generate a customizable 3D model easily, so that mainstream users could handle that. There are several possibilities like macro-generating CAD tools, to generate small software applications for parameterizing CAD models. Regrettably, defined interfaces are missing, which would open completely new opportunities for platforms.

5.3.6.6.2 Model quality and complexity

The model quality and complexity could be, especially when working with small-scale FDM printers, a big problem. If the settings for the printer or the settings for the slicing software are wrong or badly defined, the result of the object will not be as expected. Moreover, the 3D CAD model may also not be well prepared for the 3D-printing process with a small-scale FDM printer.

Unfortunately, the current situation in the field of personal manufacturing reveals that it is not easily possible to print an object with the assistance of water-soluble support material. This function would enable possibilities to print high complex models. But, as a result, there is much rework, since the support material has to be removed within water.

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[47] Lipson/Kurmann (2010), p. 36.

5.3.7 Consumer-led product design

Consumer-led product design is the focus in this thesis. The democratization of production has already started and that means that also the product design should be the responsibility of the consumer, instead of the company. Accessible design software combined with personal fabrication technologies will enable the possibility for customers to design their own products. The reasons could be just for fun, for personal use or because the application is too specific for a standard product. Past developments in the field of consumer-led product design, like playlists for MP3-players, individual design for soccer shoes, or individual color design for smartphones show that customers love to design their products.[48]

Also, mass customization and crowdsourcing will play an important role in the big new concept of personal manufacturing. Currently, retailers offer customers a small set of choices to provide customers with a specific number of products. Crowdsourcing would enable the possibility to get help or input from online communities and experts to extend the offer for the customers. Past developments show that this principle works well, since Google, Apple and many more outsourced the development of software applications to experts and sell these applications via a central download portal. This concept of collecting not only ideas from a crowd of people, but also products, has been very successful.

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[48] Cf. Lipson/Kurmann (2010), p. 51.

6 DATA PREPROCESSING

Since each additive manufacturing system has to deal with data conversion, this chapter needs to be elaborated for the master thesis to understand the flow of data, as well as their properties, and to understand all necessary steps of these data conversions. Of course, in newer additive manufacturing systems this data-conversion process is hidden. Nevertheless, software and slicing tools of small-scale FDM printers are more accessible for developers than the tools of professional machines. This data-conversion process is even consciously accessible for customers and mainstream users, so they can deal with technical settings by their own. Consequently, these users are very often overwhelmed with the number of steps they have to do. To sum up, there are many optimization possibilities.

6.1 Introduction

Data preprocessing starts with a mathematical defined 3D CAD model and ends up with a machine-specified code. All the intermediate steps will be explained in the following chapters. Fig. 20 should give an overview of the most important types of data, when dealing with additive manufacturing technologies, especially with small-scale FDM printers.

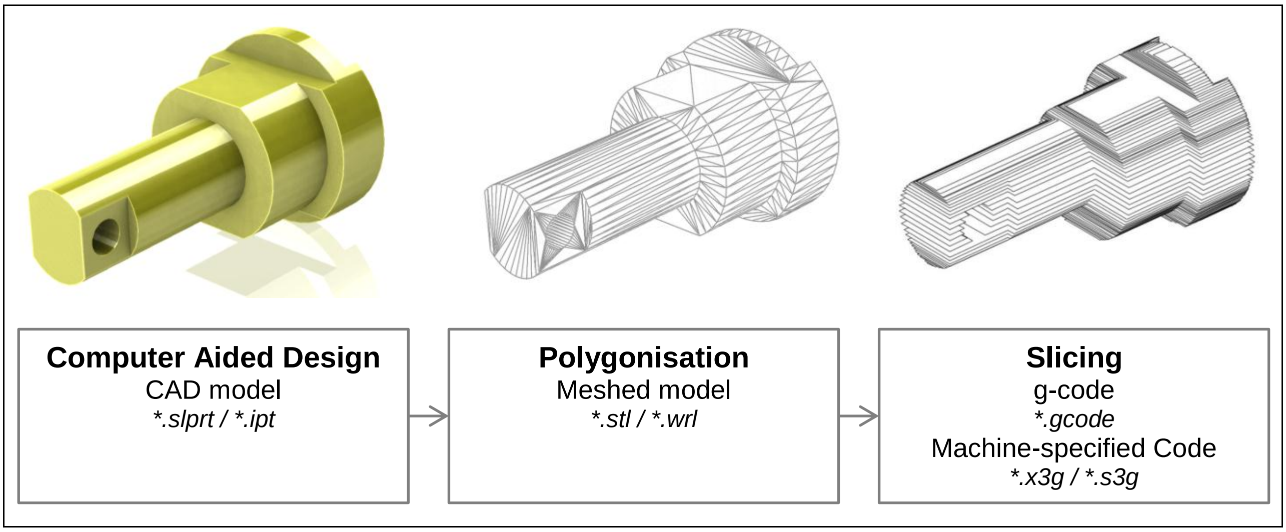

Fig. 20: Data preprocessing example, Reference: Own illustration.

6.2 CAD

In this chapter the fundamentals about CAD, its basic structure, principle of modeling and also controlling of certain variables will be evaluated, since the major part of the master thesis is dealing with parametrizable 3D models. Currently, 3D CAD is very important in many areas, like mechanical engineering, civil engineering, automotive industry, reverse engineering and many more. Architects are currently switching from 2D-CAD tools to 3D CAD tools as well.

6.2.1 Introduction

CAD (Computer Aided Design) is based on simple two-dimensional sketches, which are transformed with special functions (e.g. Features) into three-dimensional bodies. In addition, it is possible to generate many bodies and combine them in an assembly. Furthermore, with motion simulation moving parts, velocity, and acceleration can be simulated. The internal representation of all of these objects is vector-oriented. Models, which are designed through 3D CAD, are directly usable for additive manufacturing systems. Moreover, realistic video or picture renderings for presentation purposes could be generated.

6.2.2 Basic structure

CAD could be split into part, assembly and drawing. These are designations for types of data inside a CAD software tool. It is very important to understand the differences, in order to understand the fundamental idea of the master thesis.

6.2.2.1 Part

Parts are three-dimensional models. To generate a part, a drawing inside a sketch is produced and afterwards with different processes (i.e., CAD features), a three-dimensional model is being built up. These processes create the 3D shape and the designation for that is called feature-based modeling. The big advantages of this methodology are the defined interfaces, which make it easy for changes or modifications. Optimally, the sketches should be as simple as possible and the most of the 3D shaping is done by the features. To make changes or modifications, sketches can be modified inside the feature. There are many different feature types, which allow creating everything from the simplest geometry to more complex shapes.[49]

CAD software usually provides a feature tree. Basically, this is the history of the operations that have been applied on the part. The order of operations, or the history, is very important to the final state of the part. CAD-features are just like steps in building up a part. In general, the operations add material or remove it. Choosing conventional manufacturing methods for building a part with a CAD part does not make any sense.[50]

Modeling of multi-bodies is a specialized operation, which enables a huge amount of possibilities. This feature allows dealing with different bodies inside a part. Consequently, it is possible to make mathematical operations and to generate incredible 3D models. Considering an application purpose in small-scale FDM printing, there would be the possibility to easily generate support material out of the main material, independent of the complexity of the model. Furthermore, main material and support material can be saved in different part files afterwards. Subtraction multi-body operation could create the support material out of the main material, as seen in Fig. 21.[51]

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[49] Cf. Lombard (2013), pp. 16-17.

[50] Cf. Lombard (2013), pp. 19-20.

[51] Cf. Lombard (2013), pp. 937-938.

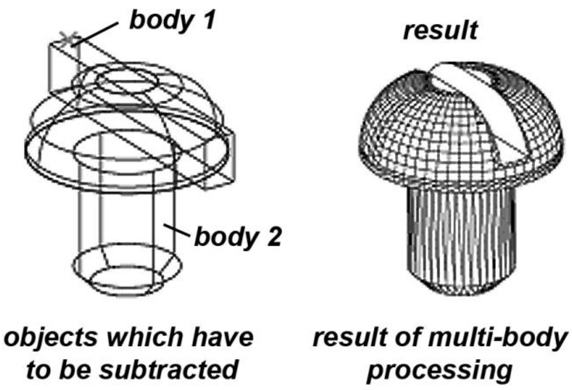

Fig. 21: Multi-body subtraction purpose, Reference: Autodesk (2012), accessed November 07th, 2013 (slightly modified),

6.2.2.2 Assembly

An assembly is a collection of parts, which are bounded together through references, like shown in Fig. 22. These references could also cause problems, since references can change within a part, when these parts have been modified. References can be surfaces, boreholes, edges and many more. Consequently, when parts are modified afterwards, the assembly could crash. So, references should be chosen carefully, especially when it comes to modifications and parameterizations.[52]

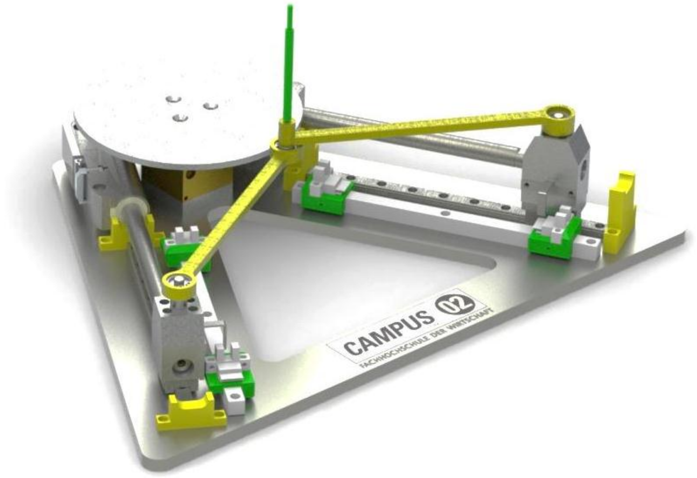

Fig. 22: Sample object of an assembly, Reference: Own illustration.

6.2.2.3 Drawing

CAD software sellers have been telling for 30 years that conventional 2D drawings will not be necessary any more. However, 2D drawings will still remain in the area of engineering and production. Nowadays, the big difference is the less need of 2D drawings, since the engineering-development process is fully carried out in 3D CAD. 2D drawings are just a snapshot of a 3D model with all the important information about tolerances, dimensions, surface roughness, and so on. Up to a certain extent, the generating of

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[52] Cf. Lombard (2013), pp. 459-462.

such 2D drawings works automatically, too. Moreover, these drawings could also contain different kind of tables, like parts or cutting lists.[53]

6.2.3 Modeling

The central object of this master thesis is the 3D model, which should be designed and prepared by a developer, designer or hobby enthusiast and later individualized by the customer. To understand the new concept of customizable personal manufacturing and the backgrounds, how things are working there, it is necessary to know the special properties of planes, drafts, features and configurations.

6.2.3.1 Sketches

Sketches are the 2D zone of 3D CAD software and the starting point of any three-dimensional processing. Sketching is like working with 2D CAD software. However, there are some special properties, which are fundamental for the master thesis.

Firstly, there are possibilities to reference difference objects like lines, splines or circles. These relations could be tangent, concentric, coradial, equal, offset, parallel and many more. Secondly, when adding a dimension to an object inside the sketch, a variable in the data base of the model will be generated. Thirdly, these variables could be referenced through mathematical equations. Consequently, the basis for automated parameterized models is provided.[54]

6.2.3.2 Reference geometries

Reference geometries such as planes, points, coordinate systems and axes are very important for designing with 3D CAD tools. These geometries are not physically touchable. Reference geometries are very useful when it comes to dealing with assemblies and connecting them together. In addition, this is a quite secure assembling method, since reference geometries are not changing through part modifications, like edges when bevels or roundings are added. So, the probability that relations get lost is much lower.

Planes are very often the basis for sketches and they are also used to represent faces. Axes are often used to represent the center of boreholes or to establish a direction. Coordinate systems are very useful when it comes to work with assemblies. The matching of the parts in an assembly becomes much easier if the orientation of the single parts is consistent concerning their orientation in the final assembly.[55]

6.2.3.3 Features

As mentioned, features are the tools inside a 3D software, which processes a three-dimensional model out of sketches and reference geometries, as seen in Fig. 23. There are several features, with different properties and input requirements. In general, these features can be split up into primary and secondary features. Primary features are those which are used frequently during a designing process. Secondary features are those, of course, which are used less frequently. During a designing process, several

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[53] Cf. Lombard (2013), p. 139.

[54] Cf. Lombard (2013), p. 100.

[55] Cf. Lombard (2013), p. 104.

different features can be used to reach the final result. In addition, there are many possibilities to reach this goal. The most common features, so called primary features, are the extrude and cut feature.[56]

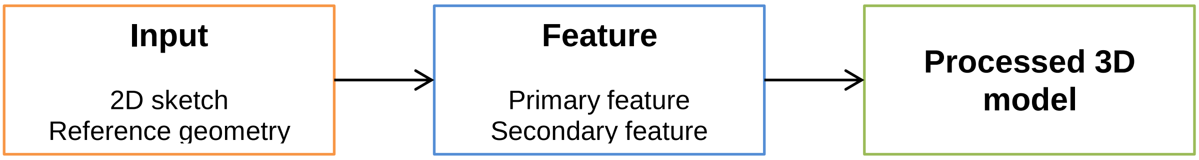
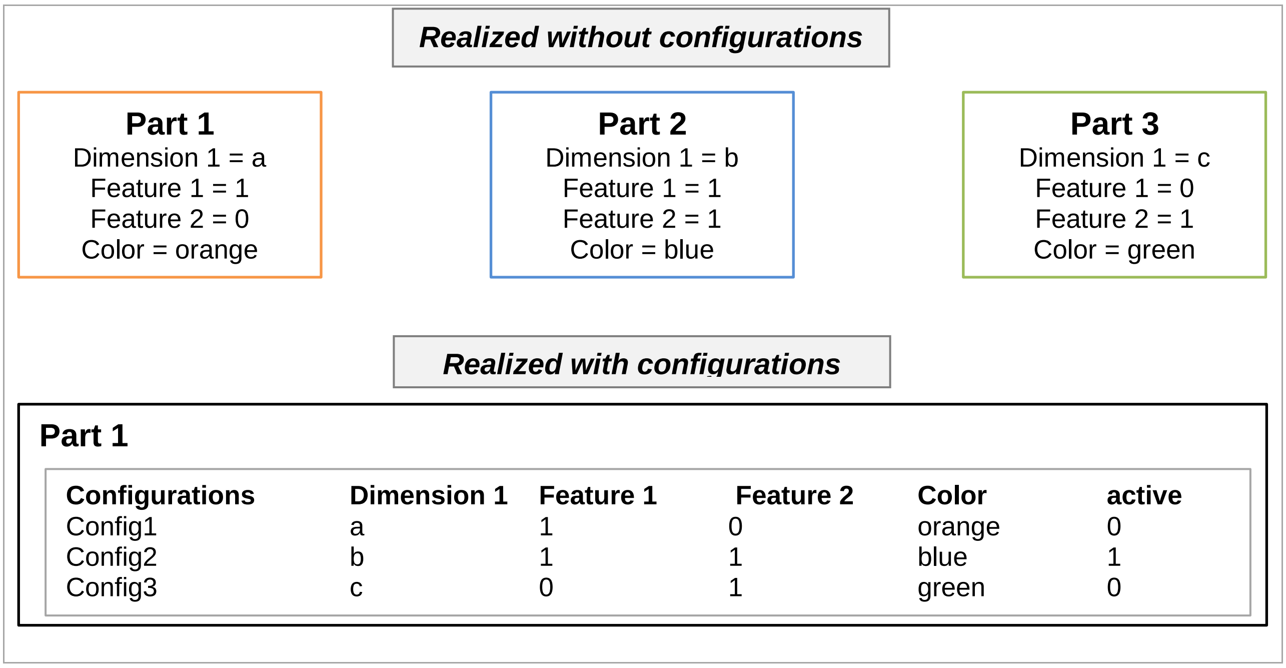


Fig. 23: Processing a 3D model with inputs and features, Reference: Own illustration.

6.2.3.4 Configurations

Configurations exist to make the designing process more efficient. With this tool, it is possible to make variations of a part. These variations are called configurations or configs and these include different values of dimensions, conditions of features (suppressed or unsuppressed) and also information about color and custom properties. Thus, this tool enables the possibility to have different variations inside a part, which greatly increases the efficiency of the designing process. Fig. 24 shows the vast difference of efficiency, when dealing with or without configurations. Assembly configurations could be realized as well. This could be apprehend through dealing with the configurations of the parts. An example of an application purpose for configurations inside a part is a socket head cap screw, because it has thousands of possible sizes. Assuming that configurations would not exist, the only way to get all parts of all possible screws is to design all those screws with their different sizes. With the help of configurations, only one part is necessary. As the fundamental design is the same, only dimensions and certain properties have to change. Thus, all that has to be done is making different configurations and changing the values in a table.[57]



Configurations	Dimension 1	Feature 1	Feature 2	Color	active
Config1	a	1	0	orange	0
Config2	b	1	1	blue	1
Config3	c	0	1	green	0

Fig. 24: Difference between conventional and config.-based design, Reference: Own illustration.

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[56] Cf. Lombard (2013), pp. 235-238.

[57] Cf. Lombard (2013), p. 375.

6.2.4 Controlling of CAD variables

There are several ways to change and modify variables of a 3D model. Since parameterizing of models deals with modifying of these variables, it has a high priority in the master thesis.

6.2.4.1 Feature tree

The feature tree is the history of the designing process of a 3D model. All the reference geometries, sketches and features are included. The way of modifying values of variables is just possible with the graphical user interface of the CAD software. Thus, by interacting with the feature tree and changing values inside of sketches, features and reference geometries, parameterizing of the 3D model is possible. Unfortunately, there is a big disadvantage, since automatic parameterizations are not possible by just customizing values in the feature tree. However, it is possible to adjust certain values and properties manually.[58]

6.2.4.2 Tables and equations

In general, tables with all used variables and values are always controlling 3D models in the background. In addition, this table is also accessible and modifiable. It is even possible to deal with mathematical relationships in form of equations. Therefore, in this case the 3D models are becoming intelligent and are getting a predictable behavior when they are modified. Each dimension in a sketch, feature or reference geometry is presented in the local table of the part. Moreover, the description of the variables is also changeable. Global variables could be defined to make the designing- and parameterizing-process more manageable.[59]

6.2.4.3 API

Many software tools provide an Application Programming Interface (API). This is an access tool, with a collection of routines and commands, which help to communicate with a few parts of the CAD software. The functions, methods and events will be accessed through different objects, like it is common in all object-orientated software tools. Fig. 25 shows an overview of the layers of the object hierarchy in SolidWorks.

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[58] Cf. Lombard (2013), pp. 19-20.

[59] Cf. Lombard (2013), pp. 357-358.

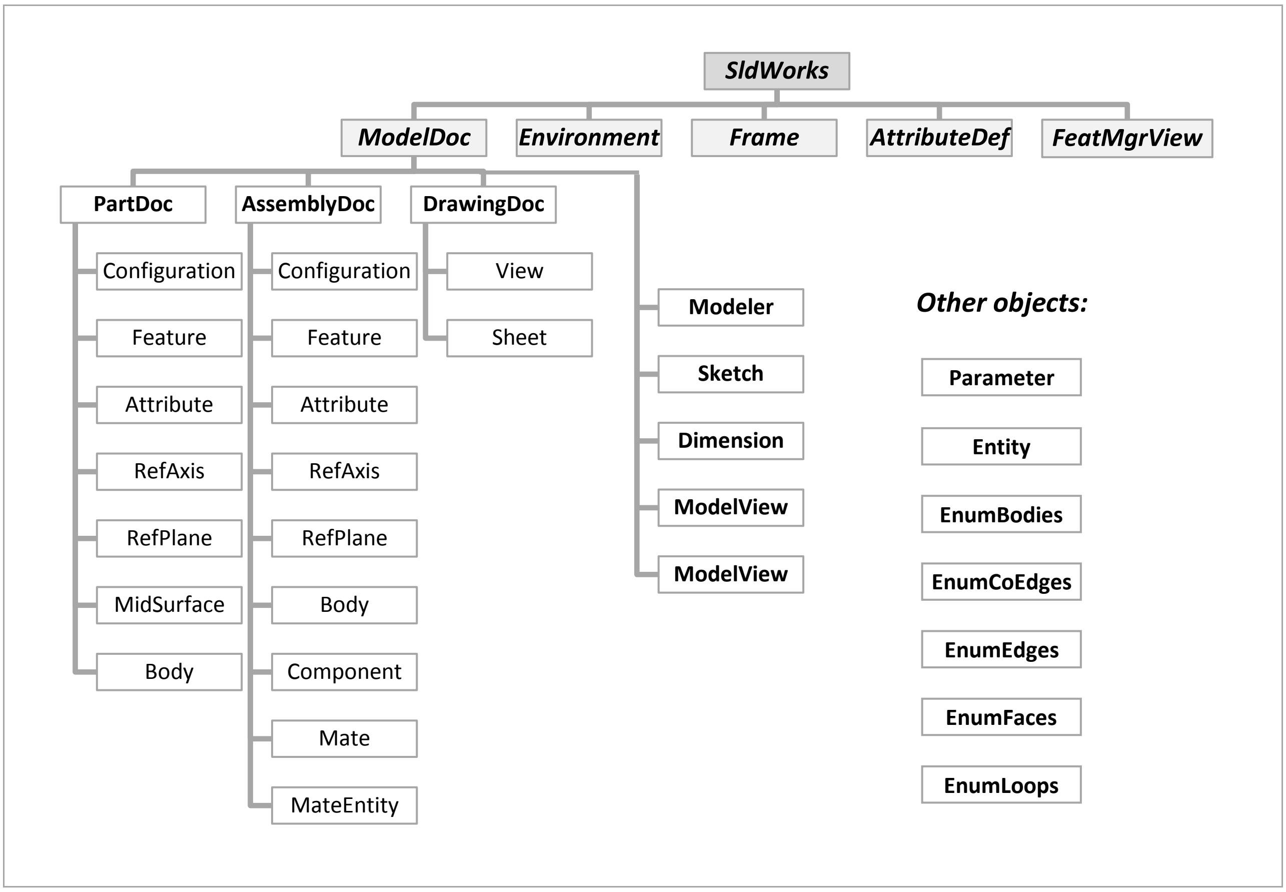

Fig. 25: Object model of SolidWorks, Reference: Own illustration based on Berlitz (2007), accessed September 09, 2013.

A common way to get to know the API is the Macro Recorder. Nowadays, many software tools offer such a feature, which allows you to record your steps that you have done in the software. In a CAD software-tool, you could record operations performed with the user interface. For example, if you want to automate specific operations, you are able to use such a macro recorder. This especially makes sense if you have several operations which repeat constantly. Nevertheless, this macro recorder also helps to get to know the commands and objects, when you want to program outside of the CAD software tool over the API.

6.3 Polygonisation

The second step on the long way to a real 3D-printed object is to get a polygon model out of a CAD model. Polygonisation means to generate a facets-based mesh. This mesh could be generated out of a point cloud, as it is common in the postprocessing process in the field of 3D scanning or, in the area of additive manufacturing, to generate a facets-based mesh out of a 3D CAD model. The generated mesh is a representation of the volume of the mathematical described surface model. Any subsequent modification is time-intensive and not recommendable.[60]

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[60] Cf. Tenbusch (2013), accessed August 26, 2013.

6.4 Slicing and Code Generation

The slicing process and the subsequent code generation are the last steps in the data preprocessing. The following sections of this chapter provide explanations concerning the slicing process out of a data mesh and the resulting accuracy issues. Furthermore, this section also deals with preprocessing settings, which have to be done, and the different types of codes.

6.4.1 Slicing process

All the subsequent explanations are illustrated in Fig. 26. The first step of the slicing process is the sampling process. Therefore, a certain input geometry is necessary such as STL mesh files. At first, a set of samples is generated. A sample is basically a plane orientated orthogonal to the Z-axis, which holds a Z-position and a set of segments. In fixed Z-sampling, all output Z-sampling planes have an equal height. As a consequence, this height is determined by the Z-resolution of the printer.

The second step is called triangle slicing. Therefore, the intersection set is computed between a sampling Z-plane and a triangle. In addition, this set is assumed to be a line segment.

The third step is called segment connecting. In this step, a set of line segments is taken and connected to a vector of rings. Initially, all segments are connected to line strings. The next steps connect these line strings to rings iteratively. If the end points of a line string are very close to each other, the line string is considered as a ring and can be inserted into the output.

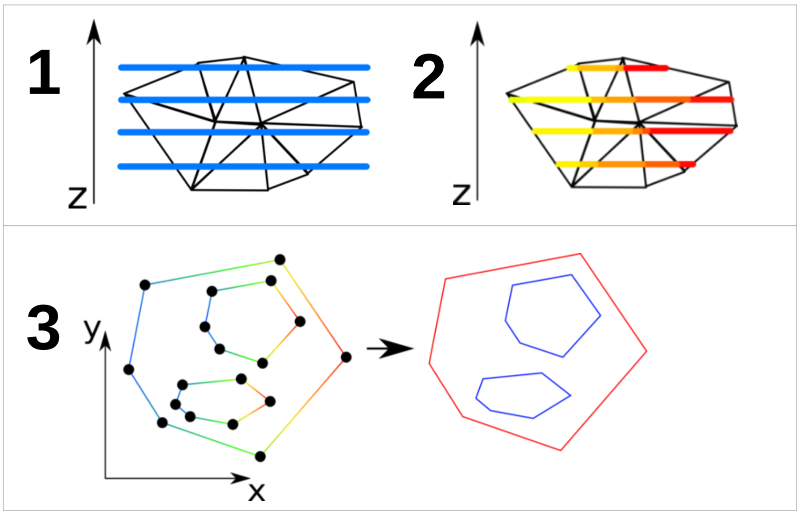

Fig. 26: Process of slicing, Reference: Hoffmann/Winkelmann (2013), accessed September 01, 2013 (slightly modified).

6.4.2 Accuracy issues

The following subchapters indicate the accuracy issues tessellation and staircase effect.

6.4.2.1 Tessellation

Tessellation deals with the unordered set of planar triangles as well as the outward pointing normals of these triangles. These are elements of a STL file. Tessellation approximates the surface of the CAD model.

Unfortunately, there are several disadvantages of tessellation:

1. Since tessellation is a first-order approximation of a CAD model, it often loses the intent of original design. Furthermore, any geometric and topological robustness that the original data once have had is lost. Fig. 27 reveals the tessellation issues on the left side.
2. Tessellation is a set of triangles with no topological information. This leads to frequent errors, such as gaps, overlaps, mixed normal, etc. The STL format carries a high degree of redundancy since each triangle is individually recorded and shared ordinates are duplicated within a file. Therefore, a need to recreate the topology of the CAD model is required.
3. An acceptable value of the chordal tolerance has to be defined. The chordal tolerance is the distance between the plane of a triangle and the surface it is approximating. To smooth the surface, the number of triangles has to be increased, but this leads to larger data files. A balance of the accuracy with the file size issue has to be found, especially for highly non-linear surfaces.
4. The slicing time of large STL files can be very high. In addition, slicing of these files can create numerous small segments to represent the contour of the cross section. These small segments are harmful to laser or nozzle scanning. Consequently, this would result in low productivity and surface finish. To solve this problem, methods for directly slicing the model without going through an intermediate format need to be developed.

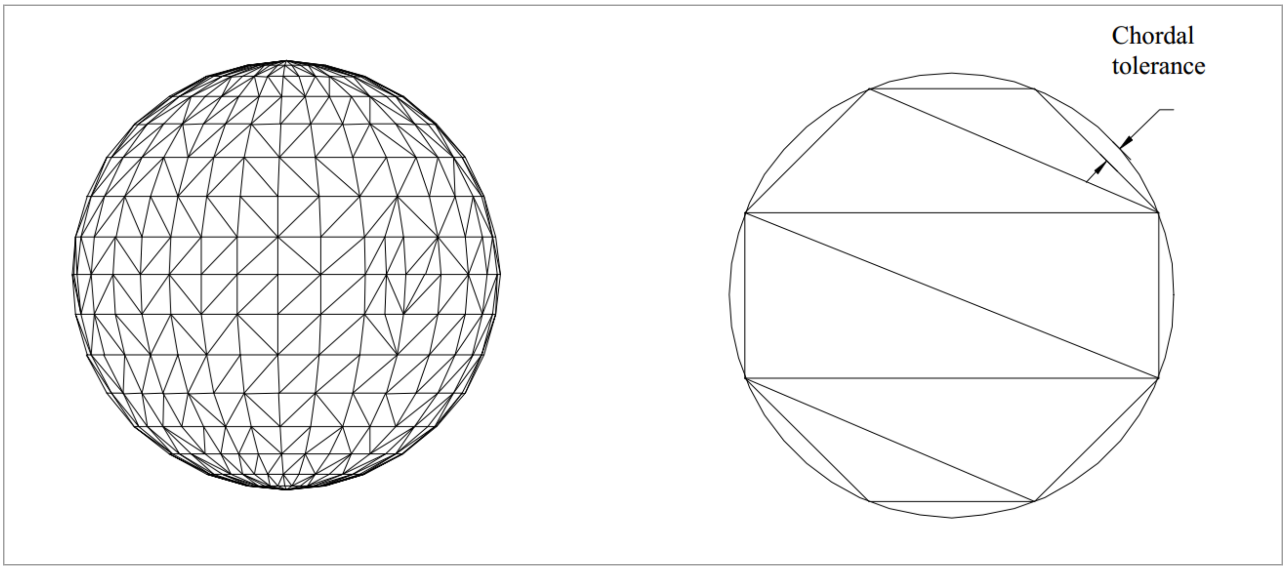

Fig. 27: Chordal distance (right) and tessellation of a sphere (left), Reference: Zhao/Laperrière (2013), p.3 (slightly modified).

6.4.2.2 Staircase effect

Tessellation is the first accuracy issue in the data conversion of a CAD model to a STL mesh. The subsequent slicing deals with the slicing of the model into a stack of layers. The shell of the part is a stepped approximation of the boundary of the original CAD model. Consequently, additive-manufacturing parts exhibit a staircase effect, which is seen in Fig. 28 on the right side, at the boundary of the part along the vertical direction. The level of this staircase effect depends on the layer height and the nozzle diameter of the FDM printer.

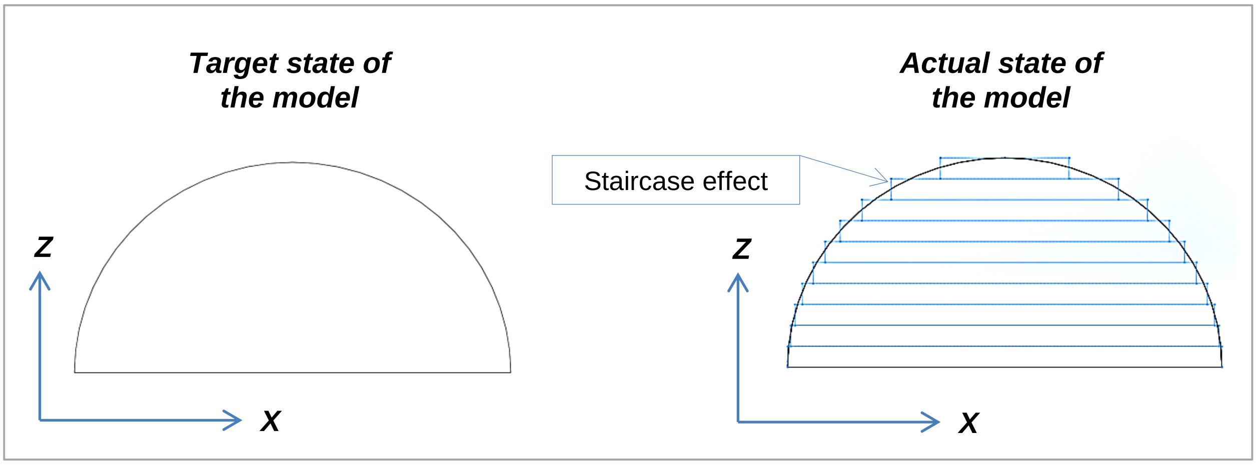

Fig. 28: Target state of a model (left) and staircase effect (right), Reference: Referred to Zhao/Laperrière (2013), p.3.

6.4.3 Code generation

Slicing is the process of virtually cutting a 3D model into a number of layers with a certain value of height. By slicing the 3D model, it is possible to generate moving-commands for each layer relatively easily. Among other commands, these moving commands are collected in a g-code file. G-code files for small-scale FDM printers mainly consist of a series of G1-moving commands, which are defining the XYZ-position of the extruder. Moreover, temperature, speed, and flow rate have to be considered as well.[61]

There are several slicing tools, which are able to generate g-code files out of 3D models, like ReplicatorG, Slic3r and Makerware. Nevertheless, there are mainly the same settings to choose before being able generating G-Codes. These settings have to be chosen carefully, since otherwise the quality of the result is not as expected.

6.4.4 Preprocessing settings

The following setting possibilities (shown also in Fig. 29) are producing the biggest effects on the quality of the final, printed parts. Moreover, some of them influence the duration of the print process or the weight and stability of the parts. However, also temperature and velocity are influencing the quality of the parts.

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[61] Cf. Pettis/Kaziunas France/Shergill (2013), pp. 68-71.

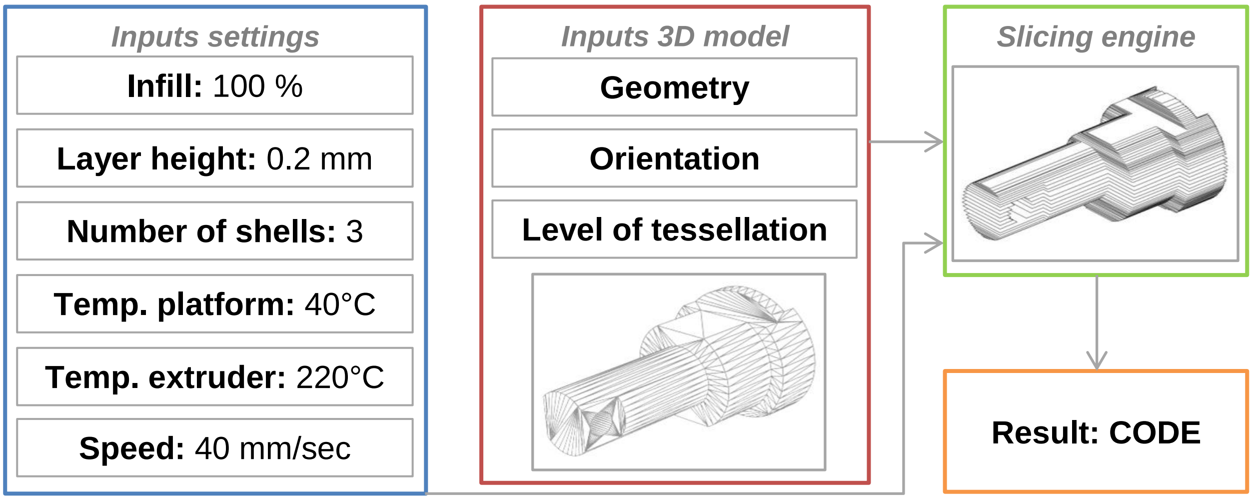

Fig. 29: Input- and output-relationship with sample values, Reference: Own illustration.

6.4.4.1 Infill

The infill defines the density of the material inside the object. The dimension of this parameter is percentage, wherein hundred percent means that the density of the material inside the object is at the maximum. In contrast, zero percent means that the object is hollow. A typical pattern of a 100% infill is shown in Fig. 30.[62]

6.4.4.2 Number of shells

Whereas infill deals with inner structure of the part, the parameter "number of shells" deals with the outer structure of the part. Every object starts with one outer shell, to assure the quality of the surface of the model, like it is seen in Fig. 30. The parameter "number of shells" deals with the thickness of the perimeter of the prints. For example, if this parameter is defined with four, the object will be printed with four concentric perimeters. On the one hand, the big advantage is that the parts get a stronger shell. On the other hand, the big disadvantage is that the process of making the perimeters is much slower than the process of making the infill.[63]

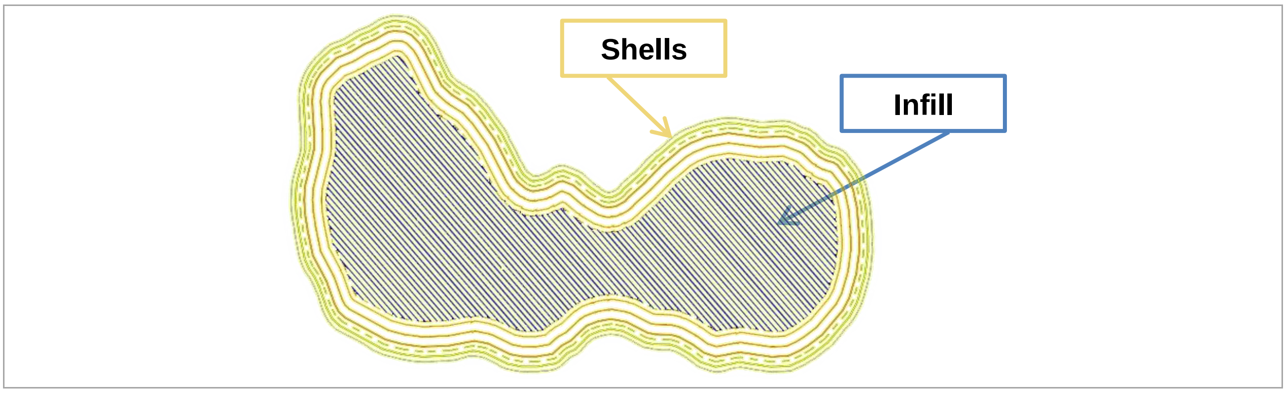

Fig. 30: Example of shells and infill, Reference: Hoffmann/Winkelmann (2013), accessed September 01, 2013 (slightly modified).

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[62] Cf. Pettis/Kaziunas France/Shergill (2013), pp. 70-71.

[63] Cf. Pettis/Kaziunas France/Shergill (2013), pp. 70-71.

6.4.4.3 Layer height

The parameter "layer height" defines the height of each layer. Currently, the default layer height of professional FDM printers is 0.27 mm. With small-scale FDM printers there is also the possibility to go beyond this value, such as 0.1 mm. Nevertheless, the building time is higher, as more layers have to be printed to reach the final model height. Moreover, it depends also on the complexity and the geometry of model, if such a small layer height makes sense at all. Therefore, knowledge about the building process and the printing system is necessary. Unfortunately, in most cases, mainstream users do not have this knowledge. Nevertheless, this parameter has to be set.[64]

6.4.4.4 Temperature

The temperature is a very important parameter for the building process. A distinction is made between temperature of the extruder and the temperature of the building platform. These temperatures vary depending on the use of materials. Small-scale FDM printers work mostly with PLA, PVA and ABS. Certain extruder and platform temperatures are defined for each processed material. If the temperatures are incorrectly defined, there might be problems during the printing process.[65]

6.4.4.5 Speed

The parameter "speed" is distinct into the feedrate (mm/s) and the travel feedrate (mm/s). Feedrate is the velocity of the extruder during the extruding process. Travel feedrate is the velocity of the extruder, when the extruder is not adding molten material, but moving from one point to another on the building platform. These parameters primarily influence the quality of the model and the building time.[66]

6.5 File types

The data-conversion process, which runs in the background of each additive manufacturing technology, is highly complex. To understand the new concept of the practical part of this master thesis, 3D models as well as the codes will be explained.

6.5.1 3D models

Additive manufacturing deals with the building of parts out of CAD data. Therefore, the following data formats are very important for these manufacturing principles. Since the STL and the VRML format are the most common mesh formats in this area, this chapter deals mainly with these two. In addition, CAD system-based models will also be explained, since they deliver the intelligence for the new concept of personal manufacturing.

6.5.1.1 CAD system-based models

If the data conversion process for an additive manufacturing system starts at a CAD system, CAD models are the first type of data to deal with. These models consist of information based on vector graphics. The

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[64] Cf. Pettis/Kaziunas France/Shergill (2013), p. 71.

[65] Cf. Pettis/Kaziunas France/Shergill (2013), p. 71.

[66] Cf. Pettis/Kaziunas France/Shergill (2013), pp. 71-72.

big advantage is that this type of data is able to store some kind of intelligence and possibilities to parameterize.

3D model management

3D models are generated through 3D worksteps. These worksteps are done by a user, which handles a 3D CAD system. As a consequence, this system has to have some management tools to be able to realize the 3D worksteps. The most common types of model management are explained:

1. Constructive Solid Geometry (CSG): This represents a model tree, which is a structured list of volume elements and their Boolean link, like merging, difference or intersection
2. Boundary representation (B-Rep): This deals with the building up of 3D models through surface-components. Surface components are surfaces, edges and points. Each surface is defined by their edges, and each edge is defined through their points. With this simple connection, any 3D model can be defined.
3. Voxel[67]- or Octree-illustration: 3D model with the voxel illustration consists of cubic volume-pixels. Each voxel is defined through its center and the coordinates. However, this method uses much of the storage and computational power.
4. Sweep Representation: 3D models, which are in the illustration model of the sweep representation are defined through a 2D conture and a transformation of the contour along the path. Only the contour and the path geometry will be saved.

Nowadays, CAD systems do not only use one of these methods, but save the 3D models as hybrid data models. These hybrid data models describe the 3D shape with the best matching and most efficient method.[68]

Geometry elements

CAD tools deal with different geometry-elements, to generate 3D models. They are divided into:

1. Analytical definable geometry elements, such as lines, circles, ellipses, curves, which can be described through analytical functions.
2. Parametrical definable geometry elements, like freeform geometries (curves, planes and bodies), splines, Bezier curves, base splines and NURBS. These curve-shapes are defined through their control points and their curve profile, which will be interpolated through the control points. The standard-freeform shape is in the most CAD software tools NURBS. These NURBS have several control points, which form a certain curve shape. The resulting prioritization of the control points could influence the curve shape strongly or weakly.[69]

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[67] Voxel=Volume pixel.

[68] Cf. Scheuermann (2013), p. 5.

[69] Cf. Scheuermann (2013), p. 5.

Curve transitions and consistency

If two elements have to be joined and the transition has to be harmonic, then it is called geometric consistency. Therefore, it has to be separated into three defined geometric consistencies:

1. G0: consistency of the location. This defines, that the start point of one element has to have the same X/Y/Z-coordinates as the endpoint of another element.
2. G1: consistency of the tangents. G1 defines, that the tangents, which are joining at the endpoints of the elements have to have the same direction.
3. G2: consistency of the curvature. In this case, the radii of the curvatures which are joining at the endpoints of the elements have to have the same value.[70]

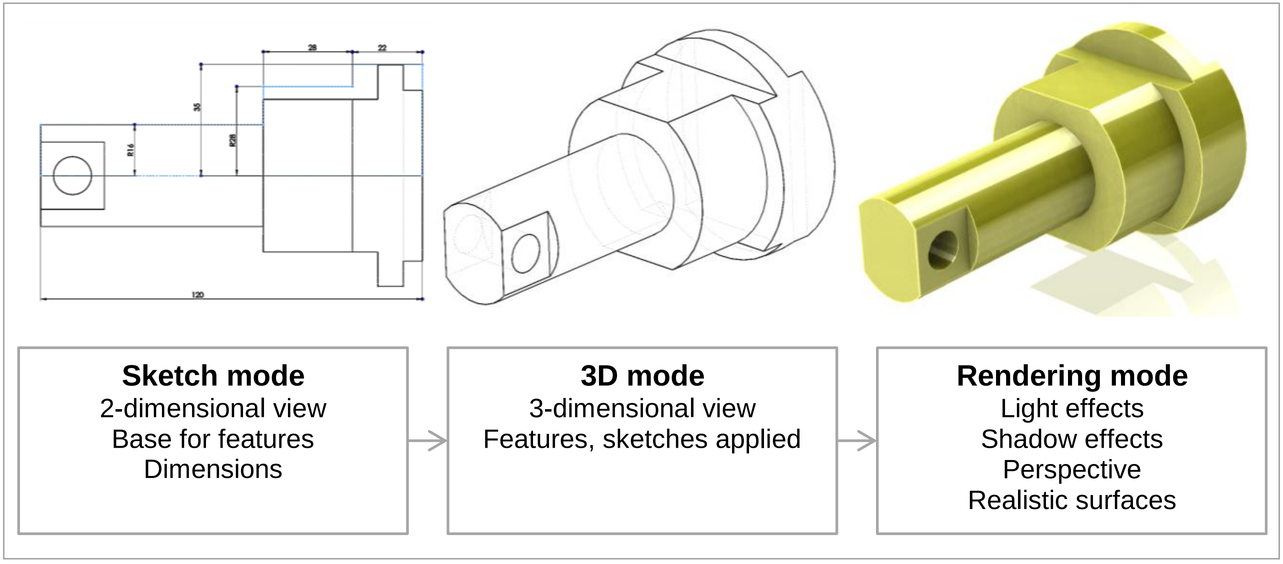

Fig. 31: Object geometry at CAD data-format, Reference: Own illustration.

6.5.1.2 Polygonized surface and volume models

The following data mesh types are the most common in the area of additive manufacturing. They seem to be very similar, but these data types have certain differences concerning properties and application purpose.

STL format

The STL file format contains the description of the surface through triangles. Each triangular facet is described by its three vertices and the surface normal. In a faceted surface, it occurs that three, four, but usually several triangles have a common vertex. This results in multiple entries in the description of the surface, which is excluded in the VRML format. Parts which are changing their properties continuously over the cross section cannot be driven with the STL format. This means, that it is not possible to describe colour information when using this data set. [71]

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[70] Cf. Scheuermann (2013), p. 5.

[71] Cf. Chua/Leong/Lim (2010), pp. 301-305.

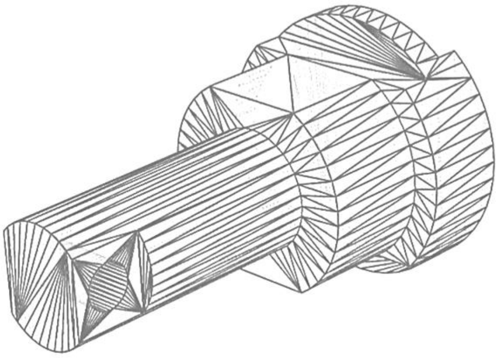

Fig. 32: Object geometry at STL data-format, Reference: Own illustration.

VRML format

The VRML format arose from the STL format. The main reason for the development of this special data format was the computer games industry with its increasingly complex avatars. In this area, there is the need of developing a big amount of three-dimensional information by providing low storage requirements at the same time. This is made possible by a special triangulated surface mesh, which is similar to the STL format, but has several important differences. In Fig. 33, possibilities of several forms of dealing with information on surface meshes with the VRML data set are shown. For example, the picture shows a monochrome triangulated mesh on the top-left, the figure in the top-right shows the mesh with light assignment. In the illustration, in the bottom-left colour texture and light reflection have already been allocated to the triangle mesh and the image on the bottom-right shows the body with lighting and texturing. [72]

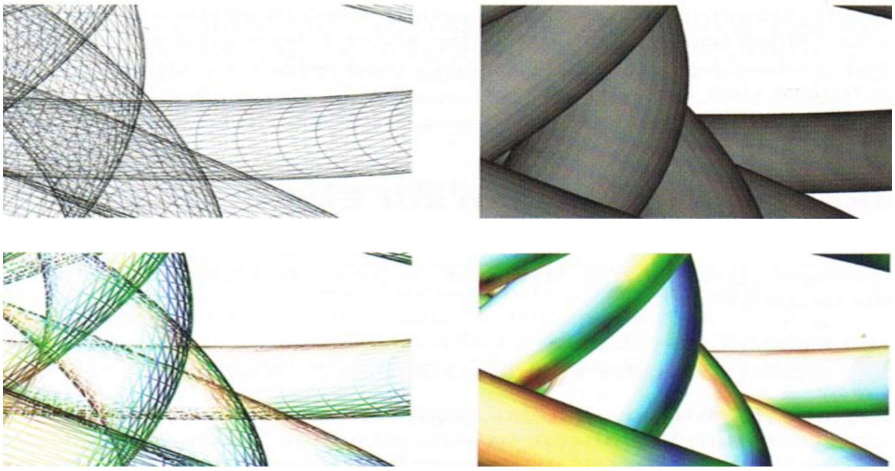

Fig. 33: Object-geometry at VRML-Data-format, Reference: Gebhardt (2007), p. 31.

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[72] Cf. Gebhardt (2007), p. 31.

6.5.2 Codes

Codes are the final step in the data preprocessing. The parts of the code represent the information of each layer of the 3D model. This chapter deals with the g-code, which is a readable and programmable code. That means, in this section of the data preprocessing it is possible to make several modifications and interventions. The machine-specified code is the code for the drives of the additive manufacturing system and is not very comfortable to read for humans.

6.5.2.1 Numerical control code

As mentioned, the numerical control code, also known as g-code, is the readable step in the preprocessing of the additive manufacturing process. g-codes are used in many numerical control (NC) applications like NC milling and turning. Of course, it is also used in additive manufacturing-processes like small-scale FDM printers. A g-code file is a CNC program, which consists of program numbers and -sentences. In these sentences, the workflow is described for each step. Fig. 34 shows a block structure with common commands and all necessary descriptions.

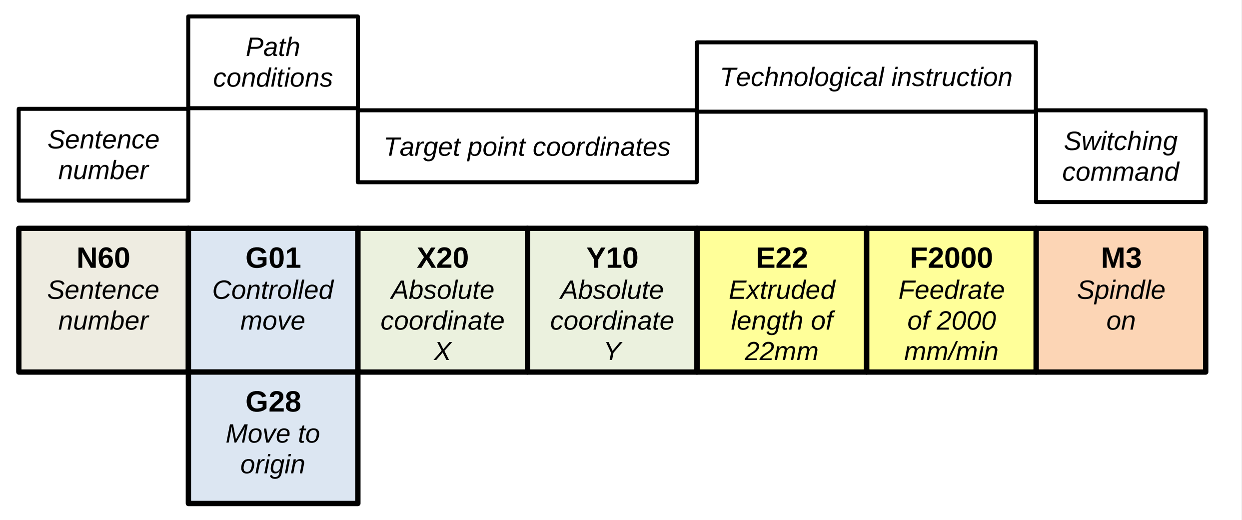

Fig. 34: g-code structure, Reference: Own illustration based on Dobler et.al. (2003) p. 49.

6.5.2.1.1 Path condition (G)

The number of the path condition defines the type of movement (rapid, linear or circular interpolation)

6.5.2.1.2 Target point coordinates (X, Y, Z, A, B, C)

The numbers behind the individual coordinates represent a certain defined point in the work space, where the machine has to move.

6.5.2.1.3 Technological functions (E, F, S, T)

These variables are used to define feed F (feed), spindle speed S (Speed) and tools T (tool)

6.5.2.1.4 Machine functions (M)

Machine functions are performed either at beginning, or when all other commands are executed at end of block. Tool change or the end of the program can be seen as typical examples.

6.5.2.1.5 Subroutine

For frequent recurring program sections, commands can also be grouped into sub-programs and then called as a subroutine.[73]

6.5.2.1.6 G-code definitions

To get an overview of the g-code definitions, the following table shows explanations to several different path conditions.

Path Condition	**Explanation**	**Path Condition**	**Explanation**
G0	Rapid Motion	*G30*	Go Home via Intermediate Point
G1	Coordinated Motion	*G31*	Single probe
G2	Arc – Clockwise	*G32*	Probe area
G3	Arc – Counter Clockwise	*G53*	Set absolute coordinate system
G4	Dwell	*G54-G59*	Use coordinate system from G10 P0-5
G10	Create Coordinate System Offset from the Absolute one	*G90*	Absolute Positioning
G17	Select XY plane (default)	*G91*	Relative Positioning
G18	Select XZ plane	*G92*	Define current position on axes
G19	Select YX plane	*G94*	Feed rate mode
G20	Inches as units	*G97*	Spindle speed rate
G21	Millimetres as units	*G161*	Home negative
G28	Home given Axes to maximum	*G162*	Home positive

Table 1: Explanation of different Path Conditions, Reference: Hoeken/Kintel/Mayer/Mets (2013), accessed September 01, 2013.

6.5.2.1.7 Examples

The following code sentences are an example of a real g-code of a 3D print with a Makerbot Replicator 1 with ReplicatorG as a host software.

```
M103 (disable RPM)
M73 P0 (enable build progress)
G21 (set units to mm)
G90 (set positioning to absolute)
M109 S50 T0 (set HBP temperature)
M104 S225 T0 (set extruder temperature) (temp updated by printOMatic)
(**** begin homing ****)
G162 X Y F2500 (home XY axes maximum)
G161 Z F1100 (home Z axis minimum)
G92 Z-5 (set Z to -5)
G1 Z0.0 (move Z to "0")
```

Example of a g-code: Real g-code of a 3D print with a Makerbot Replicator 1.

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[73] Cf. Baumann/Kaufmann/Schlipf/Schmid/Strobel (2004), pp. 252-253.

6.5.2.2 Machine specified code

Subsequent of the g-code conversion, there is another step of data conversion. The g-code has to be translated into a machine-specified, binary code, to make it easier for the microcontroller of the small-scale FDM printer to deal with the data. Therefore, there are the Sanguino3 g-code (S3G) and the newer X3G code. S3G code is the protocol by which certain AM electronics communicate with their host machine, as well as the protocol by which the host communicates with its subsystems. This binary code will be either wrapped into blocks and sent to the FDM printer via a serial connection, or written as raw binary data onto an SD card to be picked up by the MCU. The file extension of these generated files is either *.s3g or *.x3g. The S3G protocol is intended as a simplification of g-code.[74]

S3G only works for the FDM machine it was created for. G-code are generally the instructions for the tool path. One of the most CPU and time-intensive processes for a microcontroller is reading text (ascii) across a serial connection. This is the reason why binary serial streams are used, rather than just sending the text gcode. Consequently, printing from SD card does not let the microcontroller waste time reading and buffering from the serial port. Instead of that, the microcontroller can easily read block by block from the memory of the SD card.

6.5.2.2.1 Sanguino

Sanguino is an open source microcontroller board inspired by Arduino[75], and based on the ATmega644P, which is one the most powerful Atmel[76] atmega processor. The Arduino core has been ported to provide a usage with the Arduino host software.[77]

6.5.2.2.2 Definitions

PC:	A computer, which is connected to the host over the host network.
Host:	This is the motherboard on the machine. It communicates with the PC over the host network and with zero or more tools over the tool network. The host can control 3-5 stepper motors, as well as read and write to an SD card.
Tool:	This is an assistance motherboard on the machine. It communicates with the host over the tool network, and controls one toolhead, i.e., the extruder. The tool can have a platform heater, toolhead heater, extruder motor, or fan attached to it.
Host network:	The host network is the serial connection between the host and the PC.
Tool network:	The tool network is the serial connection between the host and zero or more tools.
Tool ID:	This is a unique address which is assigned to each tool. It allows to be addressed individually by the host.

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[74] Cf. Hoeken/Kintel/Mayer/Mets (2013), accessed September 02, 2013.

[75] Arduino is an open source electronics prototyping platform based on flexible easy-to-use hardware and software.

[76] Atmel is a worldwide leader in the design and manufacture of microcontrollers.

[77] Cf. Sanguino (2013), accessed November 08th, 2013.

Query command: A query command is a command that should be evaluated and acknowledged immediately. They are used for things like setting or reading temperatures.

Buffered command: A buffered command should be acknowledged immediately. However, the host may store it in a buffer for later execution. This should be used for commands that could take a long time to execute, such as motion commands.[78]

6.5.2.2.3 Architecture

In Fig. 35, the architecture of a S3G system is shown. There are two networks, called the host network and the tool network. Both networks have a single network master. The network master on the host network is the PC, and on the tool network is the host. The host network connects only with one slave device (the host), whereas the tool network can connect with more slave devices (Tool N).

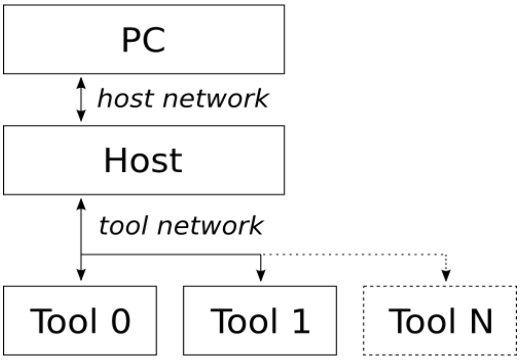

Fig. 35: Architecture of Sanguio3 g-code, Reference: Sayles (2013), accessed September 02, 2013.

6.5.2.2.4 Packet structure

A package is used to wrap every command. It ensures that the command received is complete and not corrupted. The binary data on SD-Cards is not wrapped in those packages, but written out directly to the card. The package contains the following bytes:

0:	Start byte.	This byte always has the value 0xD5 and is used to ensure synchronization.
1:	Length:	Length of the packet, not including the start byte, length byte or the CRC.
2 (1+N):	Payload:	The packet payload. The payload can be N bytes long.
2+N:	CRC:	The cyclic redundancy-check of the payload.[79]

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[78] Cf. Sayles (2013), accessed September 02, 2013.

[79] Cf. Hoeken/Kintel/Mayer/Mets (2013), accessed September 02, 2013.

7 TECHNOLOGY BENCHMARK AND EXPERIMENTS

The basis of the practical part of this thesis is a benchmark of different AM technologies as well as experiments with one market-relevant small-scale FDM printer. The reason for comparing different AM technologies is to evaluate, if there are major differences between professional and low-cost systems concerning accuracy of the produced 3D models. As a result, if there are any differences and problems, several solutions should be elaborated for the small-scale FDM printers to compensate these differences. These solutions for compensation are major inputs for the following chapters, especially the software development in chapter 9.

7.1 Benchmarking

To be able to perform a technology comparison, appropriate principles of measuring methods have to be declared. Therefore, chapter 7.1.1 deals with the selection of the most appropriate measuring method for comparing AM technologies. In addition, a reference model for the benchmark has to be found, in order to be able to indicate different aspects for the comparison. This topic will be discussed in chapter 7.1.2.

7.1.1 Measurement method

The aim of the measurement-method is the capturing of the accuracy of the AM technologies. Since the complexity of the benchmark model is relatively high, a 3D-scan method will be used to measure the benchmark models. Therefore, the smartSCAN^{TM} system from “Breuckmann 3D Scanner”[80] in combination with the evaluation software Polyworks^{TM} will be used. The main advantage of the 3D scanner is that it delivers the full three-dimensional surface of the measured object. Through actual-target comparisons[81], it is possible to evaluate each deviation in all captured areas of the 3D model. Due to this possibility, high qualitative evaluations could be accomplished.

Fig. 36: smartSCAN^{TM}- system from “Breuckmann 3D Scanner”, Reference: Breuckmann GmbH/Aicon 3D Systems (2013), accessed October 21st, 2013.

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[80] Breuckmann GmbH is an innovative pioneer and leading manufacturer of high-accurate optical 3D-systems for contactless measurement, digitalization and evaluation.

[81] Comparison of the STL-file and 3D-pointcloud of the 3D-scanning-results.

7.1.2 Reference benchmark model

An appropriate benchmark model is very important for the technology comparison. Measurement results should deliver as many possibilities for interpretations as possible. Consequently, based on the goal of the comparison, this benchmark model should have certain properties, to be able to evaluate as many categories as possible.

Due to consistency reasons of this master thesis, this reference model is also the reference for experiments with the new developed software in chapter 9. Therefore, this model has to have further certain properties like the possibility of meaningful customizations and having a value and benefit for an average customer.

7.1.2.1 Requirements

The requirements for the choosing of a reference model are illustrated in Table 2.

Requirements			
Multiple models	***Details and overhangs***	***Flat surfaces***	***3D customization***
More than 3 models	Several details <0,3 mm in Z-direction	Flat surfaces <20x20 mm in Z-direction	Innovative product
Small and large objects	Several details <0,3 mm in X/Y plane	Flat surfaces <20x20 mm in XY plane	Value for customers
	At least one overhang in Z-direction <40°		Open source
			Meaningful customization possibilities

Table 2: Requirements for benchmark model, Reference: Own illustration.

7.1.2.2 Virtual reality glasses as benchmark model

Based on the requirements an appropriate benchmark model is chosen. This special model is the result of an invention of Stefan Welker, a hobby inventor from Germany. This invention switches each Android Smartphone into virtual reality glasses. Providing that appropriate software applications are installed on the device, three-dimensional games can be played. The vast innovation is that the parts can be printed by the users themselves.[82]

Therefore, the single parts are already arranged in a meaningful way. Furthermore, the single parts are especially designed for small-scale FDM printers without the need of support materials. Fig. 37 shows the assembled version of virtual reality glasses for Smartphones, whereas Fig. 38 reveals the print layout of the single parts.

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[82] Cf. Jansen (2013), pp. 64-65.

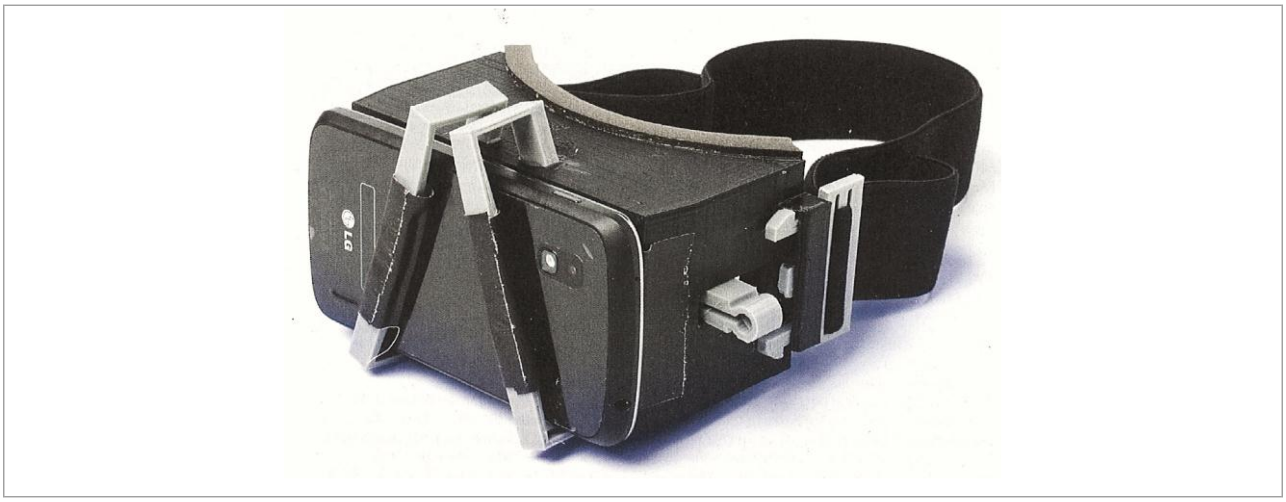

Fig. 37: Assembled virtual reality glasses, Reference: Jansen (2013), pp. 64-65.

Fig. 38: Print layout of virtual reality glasses, Reference: Own illustration.

This invention is called “OpenDive” and consists of a chassis, where the smartphone has to be slided in. The illustration of the 3D scenery as well as the capturing of the head movements is made through the Smartphone. Every Smartphone provides a gyroscope and an accelerometer, which are the main components of “real” head tracker. The display illustrates different pictures for the left and right eye, which are viewed through plastic lenses. The software for head tracking is coded in C[83], since Java[84] would have been too slow. Especially the real-time sensor-data preparation has a vast importance. Currently, with this device in combination with appropriate software and Android Smartphones it is possible, to play several games in 3D.[85]

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[83] C is a procedural programming language, which is nearly available for all computer-systems.

[84] The main Android developers use the object-orientated programming language Java for application development.

[85] Cf. Jansen (2013), pp. 64-65.

7.1.3 Compared AM technologies

To get a satisfying overview of current high-end additive-manufacturing technologies with plastic or similar material as a raw material, following technologies will be compared. These technologies are explained in chapter 5.2.

7.1.3.1 PolyJet

The Management Center Innsbruck (MCI) has delivered the benchmark part for the category PolyJet with their AM device, called Objet Connex350T. The principle PolyJet is a technology that produces objects through UV-hardened pasty polymer material. The detailed explanation is elaborated in chapter 5.2.1.

7.1.3.2 Selective laser sintering (SLS)

The parts for the category Selective Laser Sintering were delivered by the University of Maribor through their system EOS Formiga P100. SLS is a powder-based system, whereas the powder material (ceramics, plastic or metal) is selectively sintered through laser. Details can be looked up in chapter 5.2.2.

7.1.3.3 3D printing (3DP)

3D printing has no plastic raw material, but uses a ceramic plaster mixture. It bonds the powder selectively with printheads that deliver five colors. This technology is explained in chapter 5.2.3. The degree program Automation Technology at the CAMPUS 02 UAS delivered the benchmark parts concerning the category 3D printing with their device ZCorporation ZPrinter 650.

7.1.3.4 Small-scale fused deposition modeling (FDM) printer

FDM is an extrusion technology which creates 3D objects through heated extruding of plastic filament. More details can be seen in chapter 5.2.4. The results of this category have the highest priority, since this small-scale FDM printer directly belongs to personal manufacturing. For the comparison, the Makerbot Replicator 1 will be evaluated, as this device represents the majority of the small-scale FDM printers available on the market. The parts were printed with a dual extrusion version of a printer at the CAMPUS 02 UAS.

7.1.3.5 Professional fused deposition modeling (FDM) printer

Also, a professional FDM system, which is used in the industry, will be taken into consideration for the technology comparison. Therefore, printed parts from the Rapid Product Development (RPD) GmbH in Kapfenberg will be measured through the 3D scan system. RPD works with the FDM device called FDM Dimension sst 1200es.

7.1.4 Results

The previously mentioned AM systems will be displayed through results in this subchapter. Therefore, the 3D scan results will be discussed at first. Secondly, an evaluation matrix is shown with assessing of certain weighted categories.

7.1.4.1 3D scan results

Three benchmark parts were measured, in order to have enough material to interpret the results. Unfortunately, the results of the big benchmark object 1 (missing in Table 3) cannot be taken into consideration for the evaluation, since the results are distorted. The reason for this is that the part does not have a high stiffness, which leads to huge deformations. Nevertheless, the two smaller parts could be measured.

The process of the evaluation is that the polygonized models of the 3D scan will be compared with the target STL file. To be able to compare the benchmark parts through numbers and values, the overall standard deviation will be calculated, which is the average of a certain number of measurement points on the model. The final result is the average of the standard deviations of the two measured parts.

Table 3 illustrates the summary of the 3D scan results. As mentioned before, part 1 is missing due to distortion and deformation issues. Of course, the standard deviations of the single parts differ, but certain tendencies are visible. Through the measurement, three main accuracy areas (1: highest accuracy, 3: lowest accuracy) are detected:

1. Photo solidification systems (PolyJet)
2. Powder-based systems (3DP, SLS)
3. Extruding systems (FDM)

	Benchmark object 2		***Benchmark object 3***			
	Overall standard deviation / mm	**Rank**	**Overall standard deviation / mm**	**Rank**	**Average standard deviation / mm**	**Overall Rank**
Polyjet	0,089	1.	0,096	1.	0,093	1.
SLS Uni Maribor	0,135	2.	0,179	3.	0,157	3.
FDM RPD	0,245	5.	0,185	4.	0,215	5.
FDM Makerbot	0,181	4.	0,221	5.	0,201	4.
3D Printing	0,145	3.	0,145	2.	0,145	2.

Table 3: Summary of 3D scan results, Reference: Own illustration.

The 3D scan also reveals the ability of systems to generate smooth surfaces. Fig. 39 illustrates the results of one measured benchmark part. The PolyJet technology produces by far the smoothest surfaces. Extruding technologies (i.e., FDM) are also able to generate relatively smooth surfaces as far as it is possible with the higher layer thickness. Nevertheless, due to the melting of the plastic filament, the surfaces of the produced models at least seem to be smooth. In contrast, powder-based systems have worse surface qualities, although they are usually working with a smaller layer thickness. The reason is that the powder grain is either sintered or bounded, but not completely melted, which leads to a rougher surface.

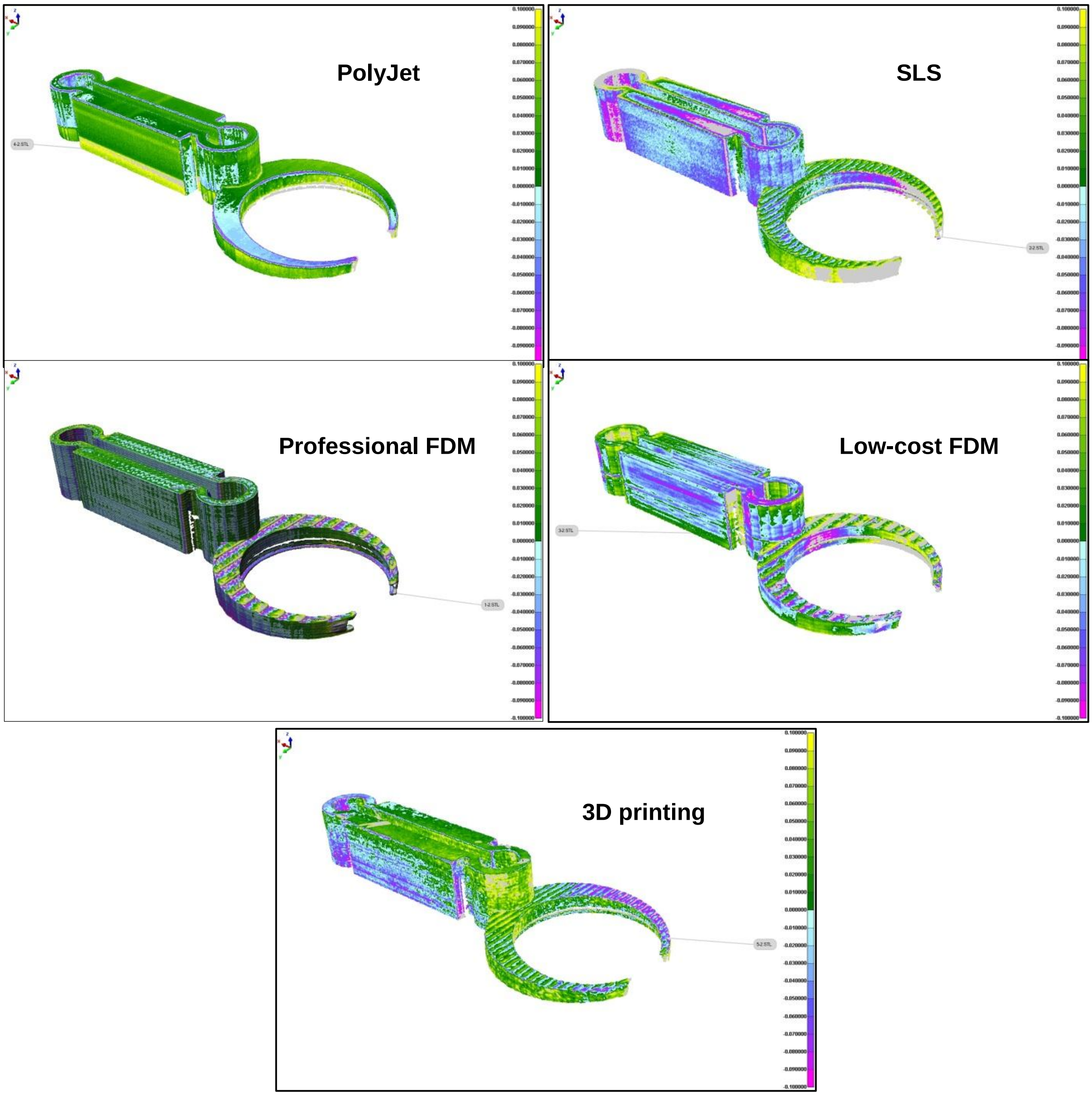

Fig. 39: 3D scan results from one benchmark, Reference: Own illustratoin.

7.1.4.2 Evaluation

The assessing of these categories is based on elaboration of information from the industry as well as the measurement results from chapter 7.1.4.1. In addition, subjective forecasts are made due to the development of the new software tool 3DCustomizer, which could influence the assessment of certain categories dramatically.

Firstly, the categories and the reason for the weighting will be explained. There are nine categories for assessing the AM systems. The sum of the percentage weighting amounts to 100%. The higher a certain category’s weighting, the more important is this category concerning the master thesis’ purpose. Furthermore, the higher the assessing of a particular AM system in a certain category, the better the rank of this AM system in this category.

7.1.4.2.1 Categories

Several categories have to be addressed in order to produce testifying results. The importance of the categories will be explained regarding the purpose of the thesis. The summarized assessing of these categories is illustrated in chapter 7.1.4.2.2. However, detailed explanations for the assessing, as well as some information can be looked up in the appendix in Table 5, Table 6, and Table 7 on the pages 96, 97, and 98.

Price

This thesis is all about personal manufacturing and average customers, which should be more involved in this area. Consequently, the price is highly prioritized, which leads to a higher weighting in the evaluation matrix. The price includes all the necessary investments to start up your system successfully the first time.

Follow-up costs

The follow-up costs deal especially with the costs after the commissioning and during the running business. Maintenance costs, such as for spare-parts as well as for raw materials are included in this category.

Velocity

The velocity is an important indicator for satisfying customers. Nowadays, customers are used to fast services, high-performance smartphones. Thus, they are not used to long waiting periods anymore. Nevertheless, the comparison tries to include this property as well. Therefore, several velocities or time-factors of the systems, such as prework and rework, as well as printing time, will be taken into consideration.

Overall accuracy

The overall accuracy deals with the accuracy of the results of the produced 3D objects. The higher the deviation of the produced 3D object from the target STL file is, the lower the overall accuracy is. In order to get very promising data, this section is part of the practical part of this thesis in chapter 7.1.4.1.

Surface quality

In the future, several 3D-printed objects have the ability to substitute products, which are manufactured in a conventional way. Therefore, the surface quality has to be as good as possible to be able to compete with mass-produced products, since customers have become extremely sophisticated in this matter.

Multi-color

When it comes to produce products for customers, the property multi-color has also a quite high priority as well. Certain product groups absolutely need more than one color, or even the whole color spectrum.

Multi-material

Not every product is homogenous in material concerns. Therefore, the property multi-material will also be addressed in the evaluation, although this property has not yet reached the personal manufacturing area.

But, as mentioned in chapter 5.2.1 multi-material 3D printing is already possible with professional AM systems.

3D-model customization

Since 3D-model customization is the major goal of this thesis, this property will also be assessed in the evaluation. Chapter 4.2 reveals the vast need and desire of customers to individualize products. As a result to these findings, a new customization software with high integration of low-cost printers will be developed, which is elaborated in chapter 9.

Prework

This category comprises all subsequent work steps of the user till the AM system is finally ready for starting of the printing process. Actually, professional AM systems have nearly the same difficulty and amount of prework processes. In contrast, when using low-cost systems the prework process is more difficult and time-intensive. However, due to the development of a new customization software this amount and difficulty would dramatically decrease for low-cost systems, which will be seen in the evaluation matrix.

Rework

Rework mainly describes all working processes of the user after the AM system has finished its job. Since this working load differs extremely between AM systems, this category is included in the evaluation. The less the working load for the user after the printing process is, the higher the rating for the AM system in this category.

Complexity of 3D models

Additive manufacturing is all about complexity of objects. Due to this high importance and considering that the level of complexity of printed objects differs between AM systems, this property has to be addressed in the evaluation.

7.1.4.2.2 Evaluation matrix

The result of the evaluation is seen in Table 4. Based on the weighting of categories and the assessing of the AM technologies, the evaluation shows that a low-cost FDM system, in combination with the new software tool 3DCustomizer, is the best in this evaluation. The details as well as some background information for the assessing can be looked up in the appendix on the pages 96, 97, and 98.

Categories	*Weighting*	Polyjet		SLS		Profess. FDM		Low-cost FDM		Low-cost FDM with 3DCustomizer		3DP	
	w	*x*	*x*w*	*x*	*x*w*	*x*	*x*w*	*x*	*x*w*	*x*	*x*w*	*x*	*x*w*
Price	***12,50%***	2,0	0,25	1,0	0,125	5,0	0,625	6,0	0,75	6,0	0,75	2,0	0,25
Follow-up costs	***12,50%***	1,0	0,125	5,0	0,625	4,0	0,5	6,0	0,75	6,0	0,75	4,0	0,5
Velocity	***7,50%***	4,7	0,3525	4,7	0,3525	4,0	0,3	3,0	0,225	4,7	0,3525	3,0	0,225
Overall accuracy	***7,50%***	6,0	0,45	3,0	0,225	1,0	0,075	1,0	0,075	1,0	0,075	3,0	0,225
Surface quality	***10,00%***	6,0	0,6	1,0	0,1	3,0	0,3	3,0	0,3	3,0	0,3	1,0	0,1
Multi-colour	***5,00%***	3,0	0,15	1,0	0,05	2,0	0,1	5,0	0,25	4,0	0,2	6,0	0,3
Multi-material	***5,00%***	6,0	0,3	1,0	0,05	3,0	0,15	5,0	0,25	4,0	0,2	1,0	0,05
3D-model customization integration	***12,50%***	1,0	0,125	1,0	0,125	1,0	0,125	3,0	0,375	6,0	0,75	1,0	0,125
Prework	***10,00%***	3,0	0,3	3,0	0,3	3,0	0,3	1,0	0,1	6,0	0,6	3,0	0,3
Rework	***7,50%***	3,0	0,225	2,0	0,15	4,0	0,3	5,0	0,375	6,0	0,45	1,0	0,075
Complexity of 3D models	***10,00%***	6,0	0,6	6,0	0,6	3,0	0,3	2,0	0,2	1,0	0,1	4,0	0,4
Sum	**100,00%**	**41,7**	**3,48**	**28,7**	**2,7**	**33**	**3,08**	**40**	**3,65**	**47,7**	**4,53**	**29**	**2,55**

Table 4: Evaluation matrix of AM systems, Reference: Own table.

7.1.5 Interpretation of results

This subchapter provides a summarized overview about the results of 3D scan and of the evaluation matrix.

7.1.5.1 3D scan

The 3D scan revealed that there exist differences between AM technologies, which have already been predicted. Nevertheless, it is very surprising that the accuracy and surface quality of the evaluated low-cost system is comparable with the professional FDM printers.

The PolyJet technology has achieved by far the best results in the categories surface quality and overall accuracy. However, this was no big surprise.

7.1.5.2 Evaluation matrix

The evaluation matrix, illustrated in Table 4, and especially the summarized illustration of the results in Fig. 40, reveals very clearly that powder-based systems are not suitable for the area of personal manufacturing, respectively for customers. In addition, the PolyJet technology is also not suitable for personal manufacturing, due to reasons like high acquisition costs, high follow-up costs and time-intensive prework and rework. Professional FDM systems, as well as low-cost systems without 3D-customization integration do also not fit into a customer-based AM world, but they are close. As a result, the category low-cost system with 3D-customization integration achieved by far the best results and was assessed the most often with the highest grade of six.

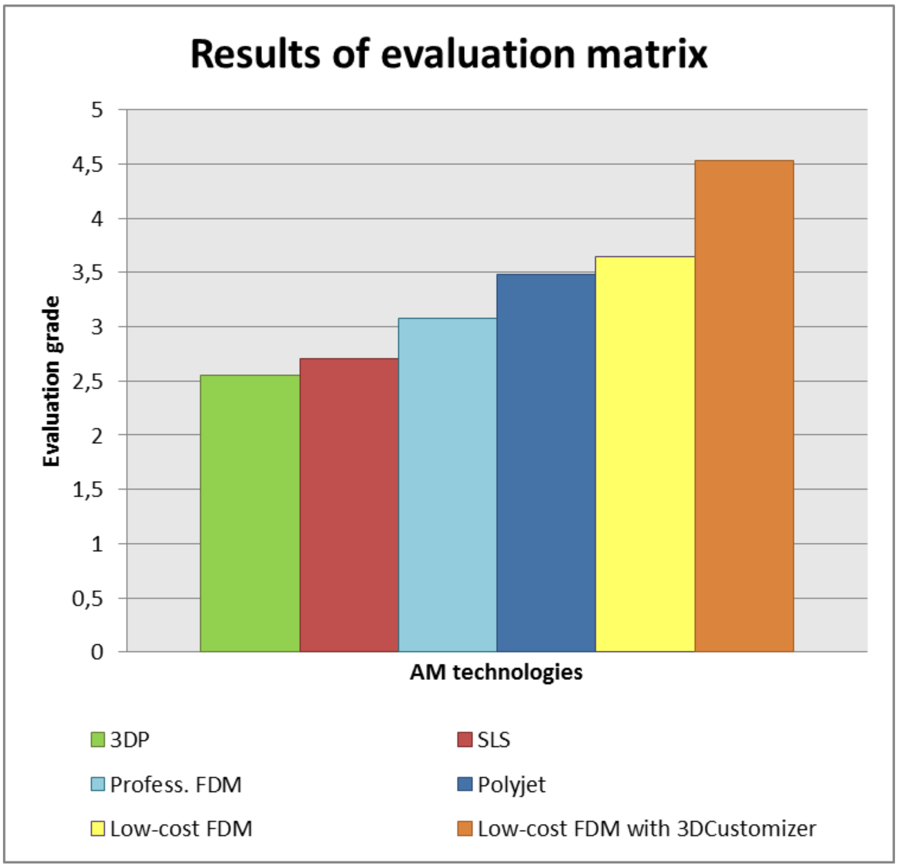

Fig. 40: Overall results of evaluation matrix, Reference: Own illustration.

These results constitute a solid basis for further research, since it is now proven that low-cost systems in combination with 3D-customization opportunities provide a vast advantage for customers.

7.2 Experiments

This chapter deals especially with clarifying of several issues of the low-cost system. Therefore, the low-cost printer Makerbot Replicator 1 was tested in the laboratory at CAMPUS 02 UAS during several projects. In addition, this chapter should be seen as a summarized illustration of the findings, elaborated during the testing period. Moreover, these findings will also be considered in the development of the 3D-customization software.

7.2.1 Technology

The chosen low-cost system for the experiments and test is called Makerbot Replicator 1 and schematically illustrated in Fig. 41. This system is based on the fused deposition modeling principle, which is explained in chapter 5.2.4. Actually, the main advantage of this system is the low acquisition price and the low follow-up costs, which was also discovered and considered in chapter 7.1.5.2.

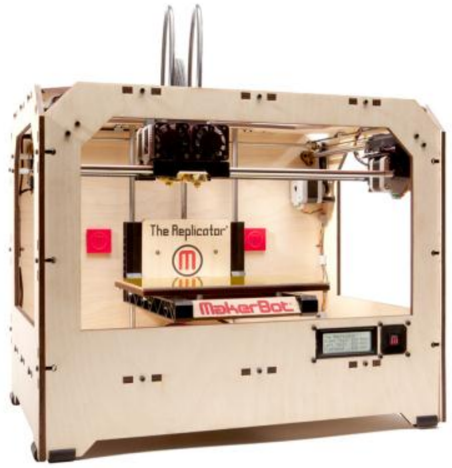

Fig. 41: Makerbot Replicator 1, Reference: Newman (2012), accessed November 07th, 2013.

7.2.2 Materials

Basically, this low-cost system is able to handle plastic material in form of filament, wired on a spool. There have to be distinctions between main and support material. Actually, support material as an own material, like water-soluble material, is not yet ready for the mass market, since there are several issues.

Officially, there are three main materials available: ABS, PVA and PLA. Currently, these materials are in 1.75 mm filament spools available. The findings reveal that these materials differ dramatically when it comes to temperatures. Other materials will be tested by developers and hobby enthusiasts all over the world. Nevertheless, these special materials have not been taken into consideration for tests.

7.2.2.1 ABS

ABS is widely known in the industry and has already been established as a reliable plastic. However, this material is, compared to PLA, hard to handle, since the temperature of the extruder has to be a certain value higher than if PLA is used. But, the experiments have also shown, that the major challenge of handling ABS is the constant keeping of the temperature level of the build volume. Therefore, the entire volume of the FDM printer has to be closed, in order to keep the temperature constant. The reason for this is to decrease the deformation of the printed object, which is a result of temperature differences inside the material.

7.2.2.2 PLA

PLA is, compared to ABS, quite easy to handle. The temperature level of the extruder is lower than at printing ABS. In addition, there can be much higher temperature differences between environment and printed object. However, the experiments revealed that it could be advantageous to set a certain temperature for the platform, which increases the adhesion between the first layer of the object and the platform.

7.2.2.3 PVA

The third official material is PVA, which is water-soluble. This material was especially tested for support purposes. PVA is not suitable as a main material. However, more details concerning PVA as a water-soluble support material are revealed in chapter 7.2.4.1.

7.2.3 Reliability

During the testing period, several issues concerning reliability have been elaborated. Especially problems with the guiding of the filament and the adhesion of the printed model on the platform have been indicated.

7.2.3.1 Filament issues

After several weeks of using the Makerbot Replicator 1, the extruder caused several printing cancellations, due to insufficiently thoughtful design of this part of the FDM printer. The filament, as seen in Fig. 42, is guided through knurled rollers. However, after a while of using this knurled surface of the rollers becomes dirtier, because of plastic abrasion. Consequently, the surfaces of rollers become more flat, which leads to a lower degree of roughness. In addition, there are actually no coil springs like indicated in Fig. 42, which would be acting as constant force between the rollers, to keep pressing the filament for optimal guiding.

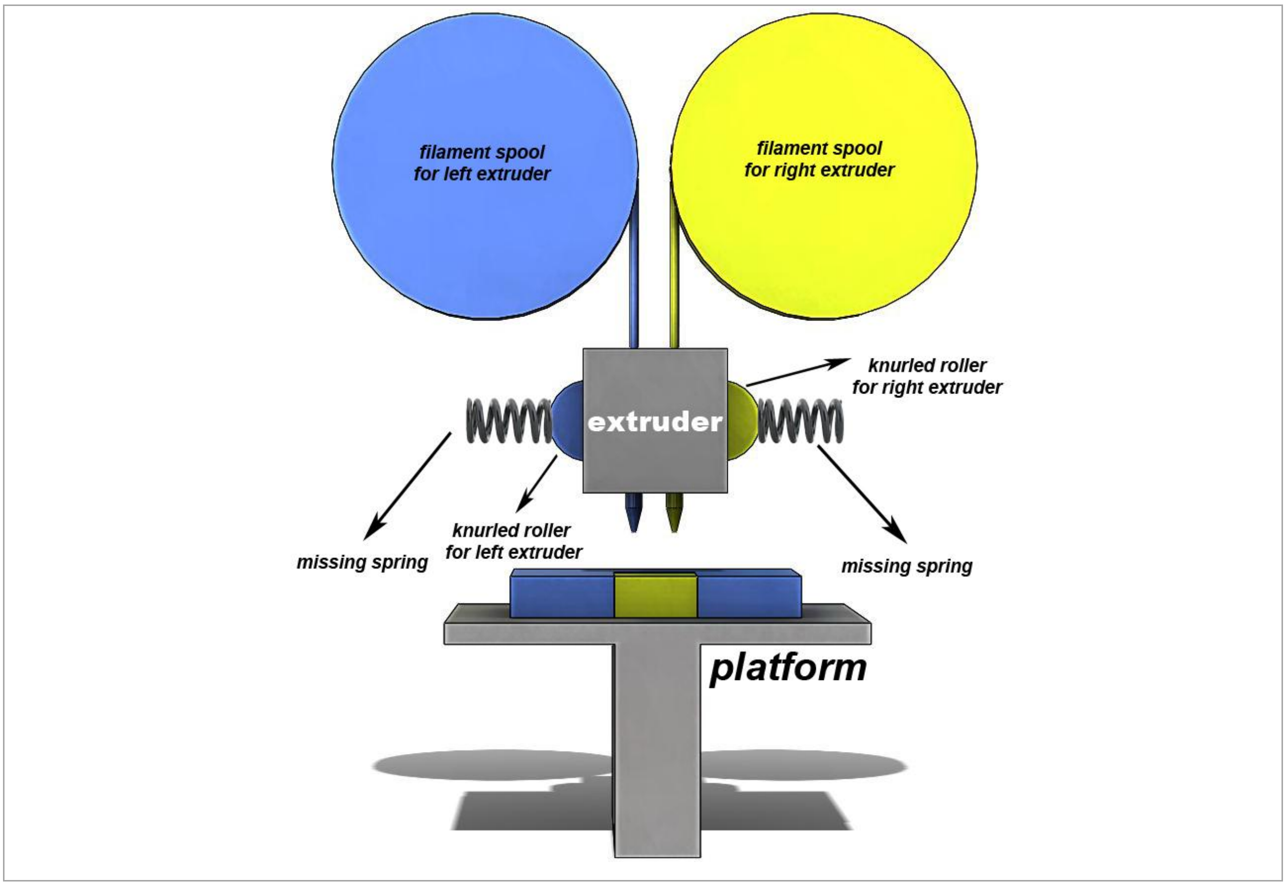

Fig. 42: Filament guiding-issues at the Makerbot Replicator 1, Reference: Own illustration.

As a result, these missing springs lead to several printing cancelations, since the rollers could not guide the filament during the print anymore. On the one hand, the reason could be a changing diameter of the filament, which is impossible for the extruder to compensate. On the other hand, the reason could be the low degree of roughness due to plastic abrasions on the rollers.

7.2.3.2 Adhesion on the platform

When using a low-cost system the first time, the most common issue is an adhesion problem between the first layer of printing and the platform. Following solutions have been elaborated during experiments:

7.2.3.2.1 Start distance between nozzle and platform

The start distance between the nozzle and the platform is very important for satisfying printing results, respectively a successful print. Therefore, the distance between the nozzle and the platform has to be adjusted as well as possible, as illustrated in Fig. 43. In addition, this has to be verified over the entire platform surface, because of unevenness of the platform.

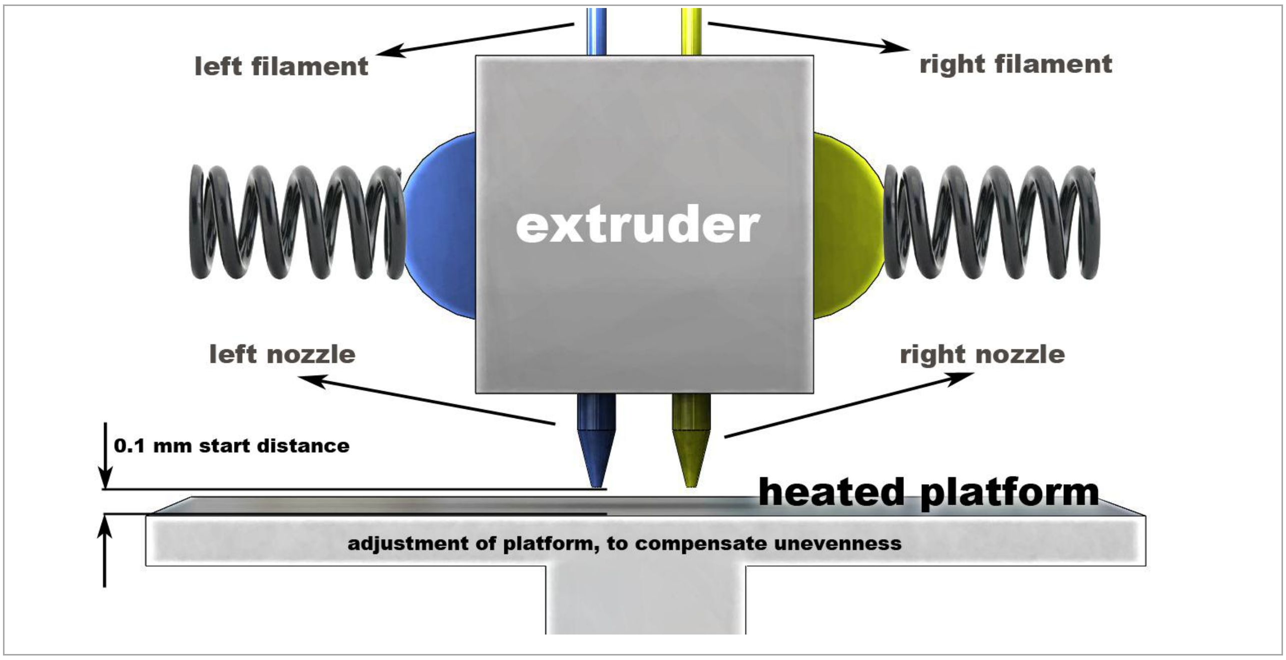

Fig. 43: Start distance between nozzle and platform, Reference: Own illustration.

However, the evenness adjustment of the platform has to be performed, when the platform is already heated, to assure that the temperature deformation is taken into account.

7.2.3.2.2 Heated platform

For the purpose of this thesis, the used material is PLA, since the tested device does not offer the appropriate construction, which is needed to print ABS. Nevertheless, it is officially claimed that PLA could be printed without heated platform. During the experiment, it has been discovered that the adhesion is higher with a temperature set-up of the platform at about 40-50°C, which also leads to more satisfying printing results. It should also be considered that too high temperatures of the platform lead to deformation of the object, which is seen in Fig. 44.

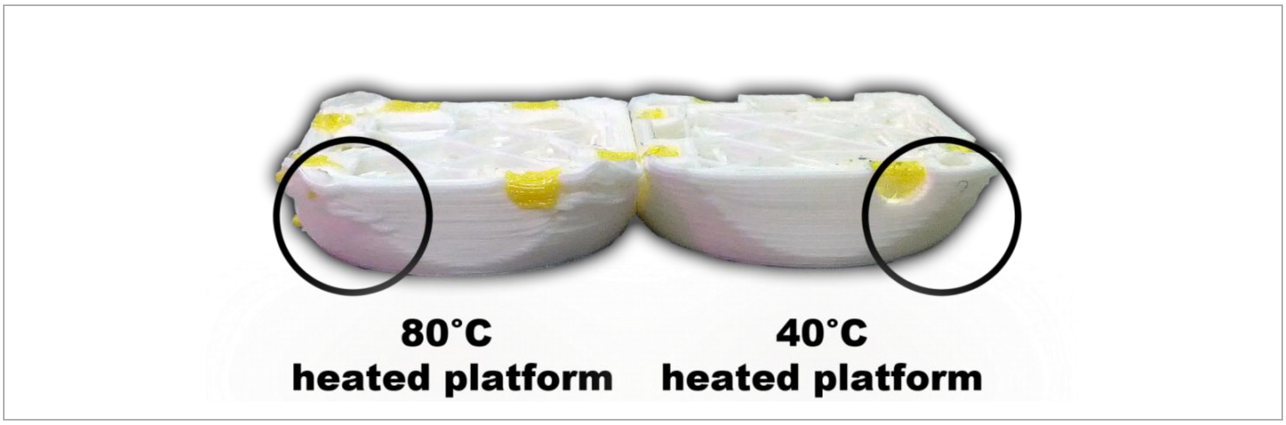

Fig. 44: Differences of temperatures of the platform, Reference: Own illustration.

7.2.3.2.3 Grease-free platform

To provide a smooth surface for the first printed layer, a Kapton-tape should be carefully applied on the platform. In order to avoid unevenness due to entrapped air bubbles, the tape has to be applied as flat as possible.

Besides the start-distance issues, a second issue is a dirty surface of the Kapton-tape. Even if dirtiness is not seen at first sight, it has to be cleaned with a soft alcohol solution. It has been found out that grease on the surface avoids a good adhesion between platform and the first printed layer. As a result, a successful 3D print is impossible.

7.2.4 Complexity of printed objects

This subchapter deals with the findings in complexity concerns. It has been proven that a high complexity is possible with low-cost systems. Several possibilities to increase the level of complexity have been elaborated in experiments.

7.2.4.1 Support material

To use another material as a support material, the Makerbot Replicator has to have two extruders, so that two materials can be extruded at the same time. Therefore, the Makerbot Replicator has been upgraded for dual extrusion. After this, first experiments revealed that several issues occurred when printing ABS and PVA or PLA and PVA at the same time. An appropriate temperature set-up could not be found. Consequently, the results of the objects were not satisfying, like seen in Fig. 45.

Picture 1 reveals the condition after the printing process has finished. PVA and PLA materials have been printed together in one printing process. After that, the PVA material had to be removed, and dissolved in water, which is seen in Picture 2. This dissolving process could last, depending on the PVA volume, the temperature of the water, and the degree of motion of the water, one to three hours. Picture 3 represents the finished model after this dissolving process. Unfortunately, through an inappropriate temperature set-up, several filament pieces have been deposited inside the PLA material, which caused holes in the object after the dissolving process. The microscopic illustration in picture 4 reveals the holes in the material after the dissolving process.

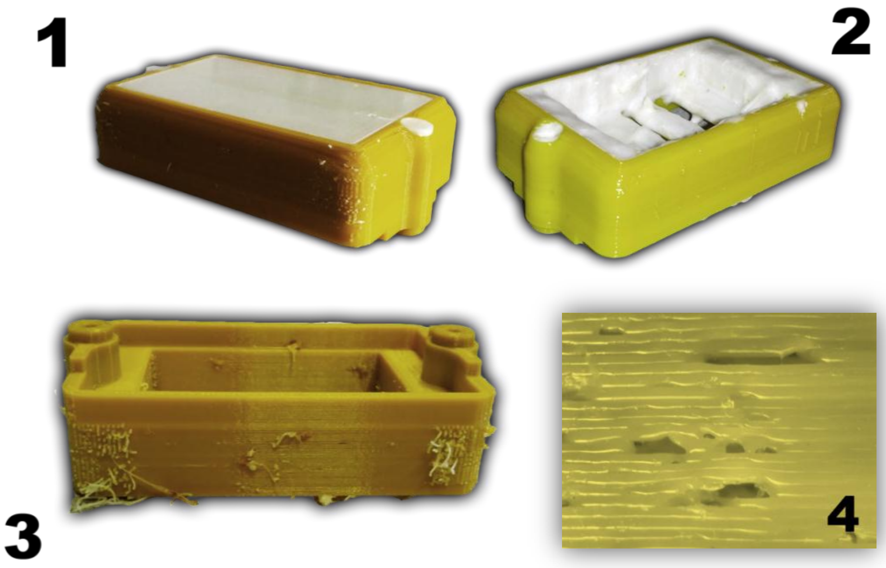

Fig. 45: Experiments with PVA as a water-soluble support material, Reference: Own illustration.

7.2.4.2 Overhangs

Most of the professional FDM printers always print water-soluble and main material at the same time, in order to provide high complexity without the need of thinking if support material is needed or not. However, it is not necessary to assist the main material all the time with support material. Fig. 46 reveals a printed object with high complexity, several overhangs below 45° and many details. The experiments have shown that high complexity is also possible without support material, as long as certain overhang-angles are observed.

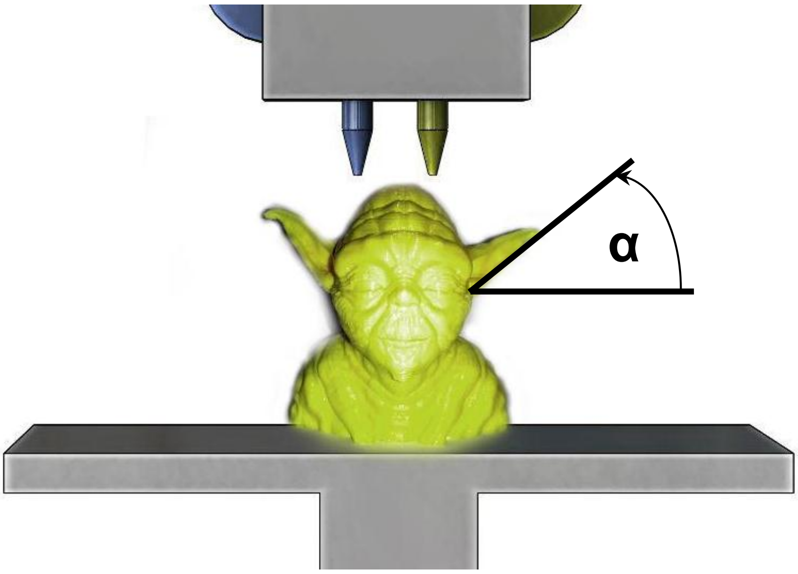

Fig. 46: Possible overhangs, Reference: Own illustration.

The main advantage of printing without support material is that less rework is necessary, since the object is immediately ready after the printing process, due to the missing support structures. Further ideas, based on this advantage, will be explained in chapter 7.2.4.3.

7.2.4.3 Technology-based modeling

Chapter 7.2.4.1 points out that printing of an object with the assistance of support material is on the one hand not strictly necessary, and on the other hand not very user-friendly. Reasons for this are the time-intensive rework processes and the unacceptable losses in quality.

In contrast, chapter 7.2.4.2 indicates the big advantages of printing with FDM without support structures if certain angles of the object are maintained.

These findings lead to the following conclusions:

- 3D models, which have to be printed with low-cost FDM printers, should be individually prepared for this technology. This includes the maintaining of certain angles of overhangs and the elimination of 90° overhangs.
- To avoid wrong model-alignment issues, an individually prepared STL file should also exist, which already includes the whole print-layout with all parts to be printed.

8 NEW CONCEPT OF PERSONAL MANUFACTURING

In chapter 7, all the basic research which represents the fundament for this chapter has been done. Consequently, based on these findings a new concept will be elaborated to be able to develop a 3D-customization software tool.

8.1 Categorization in Certain Areas

To get an overview, a schematic main concept which is based on the initial situation, the findings from chapter 7, and the resulting new ideas have been elaborated. Basically, personal manufacturing will be categorized into two main areas: factory and laboratory.

Firstly, the area “Laboratory” will be illustrated, since this section includes all working steps, which are necessary for a successful 3D print with a low-cost FDM system. Subsequently, the area “Factory”, with its distinctions, will be displayed.

Fig. 47 reveals that only developers are able to perform these working steps, due to the need of a comprehensive knowledge in certain areas of CAD and additive manufacturing.

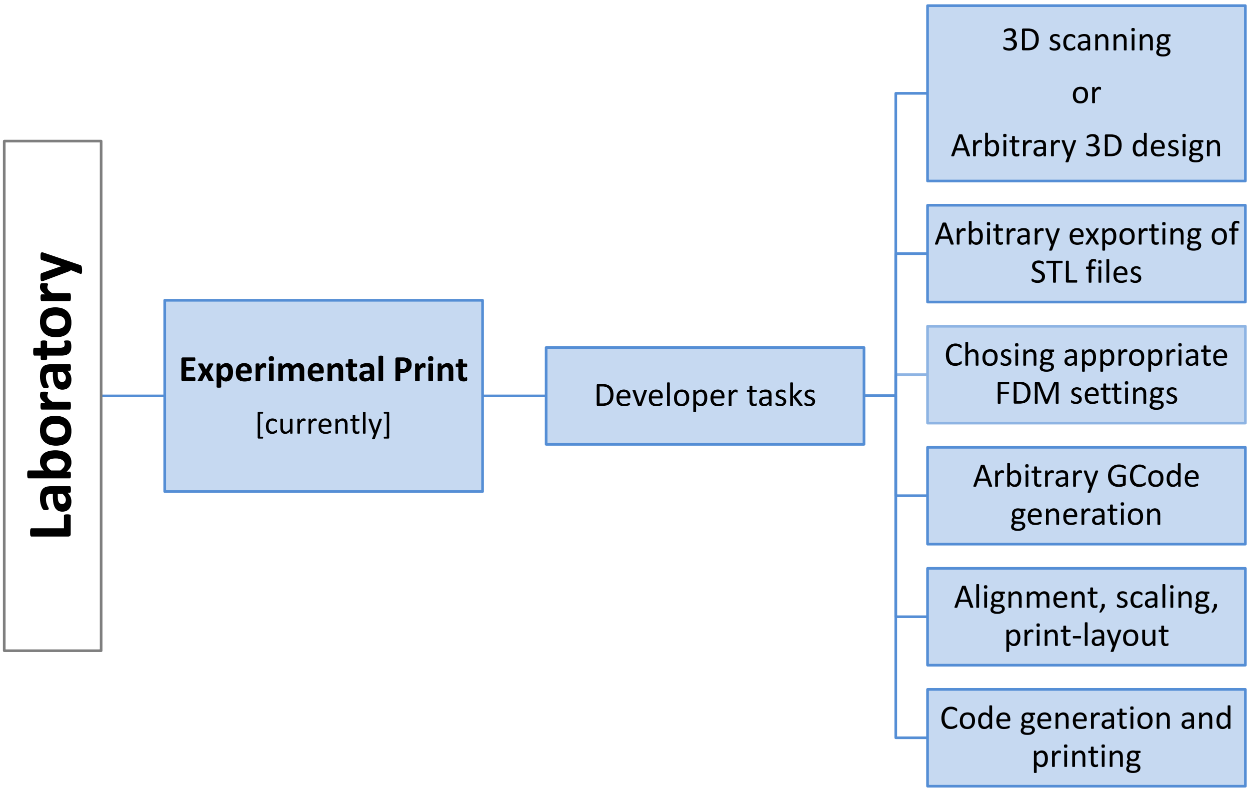

Fig. 47: Laboratory: Experimental Print, Reference: Own illustration.

As a result, the area personal manufacturing has tried to increase the level of usability for customers and hobby enthusiasts. Therefore, the area factory has developed. Currently, only one subordinated area which is called Plug&Play print has developed. Fig. 48 points out that there has already been a distinction between developers and customers, to share several work packages. In addition, some kind of public

Internet access has been established, in order to reach as many customers as possible. However, there are still lacks in consistency and usability for customers.

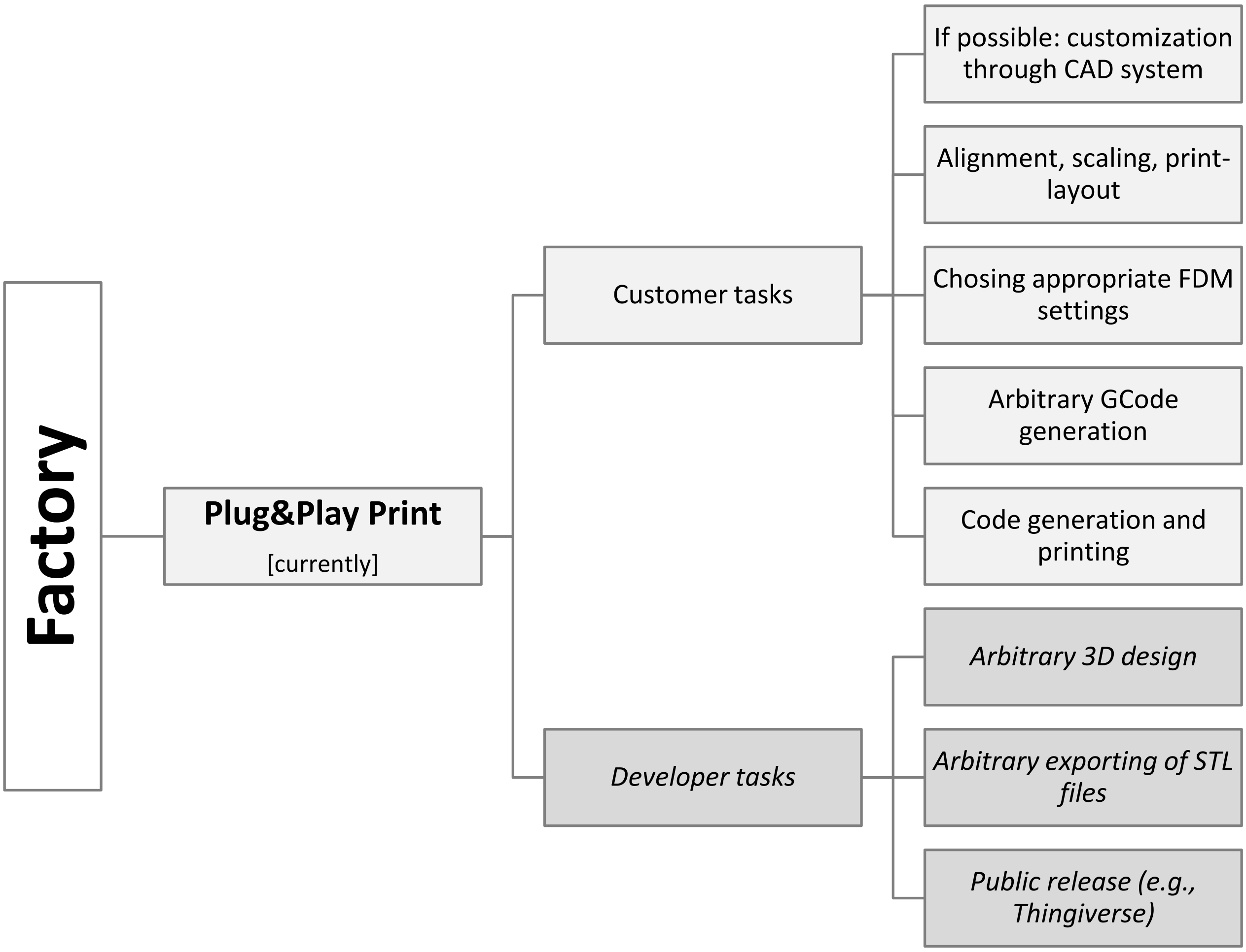

Fig. 48: Factory: Plug&Play Print, Reference: Own illustration.

Unfortunately, the work packages of the customers are still comprehensive and still presuppose certain competencies. Finally, Fig. 49 shows the main concept of the customizable print, subordinated in the area of factory. Moreover, it is revealed that the number of work packages is dramatically reduced, which has following reasons:

- “Preparation of customizable CAD model with 3DCustomizer” includes the standardized designing of a mathematically-related model, as well as a linked print-layout assembly. Developers are preparing their model with the 3DCustomizer in order to make this model customizable.
- “Release of ini-file and config-file for software” means that there will be a defined interface at the customization software to allow developers easily to release their customizable model. In addition, developers can choose their favorite g-code initialization file, which stores all information concerning g-code settings.

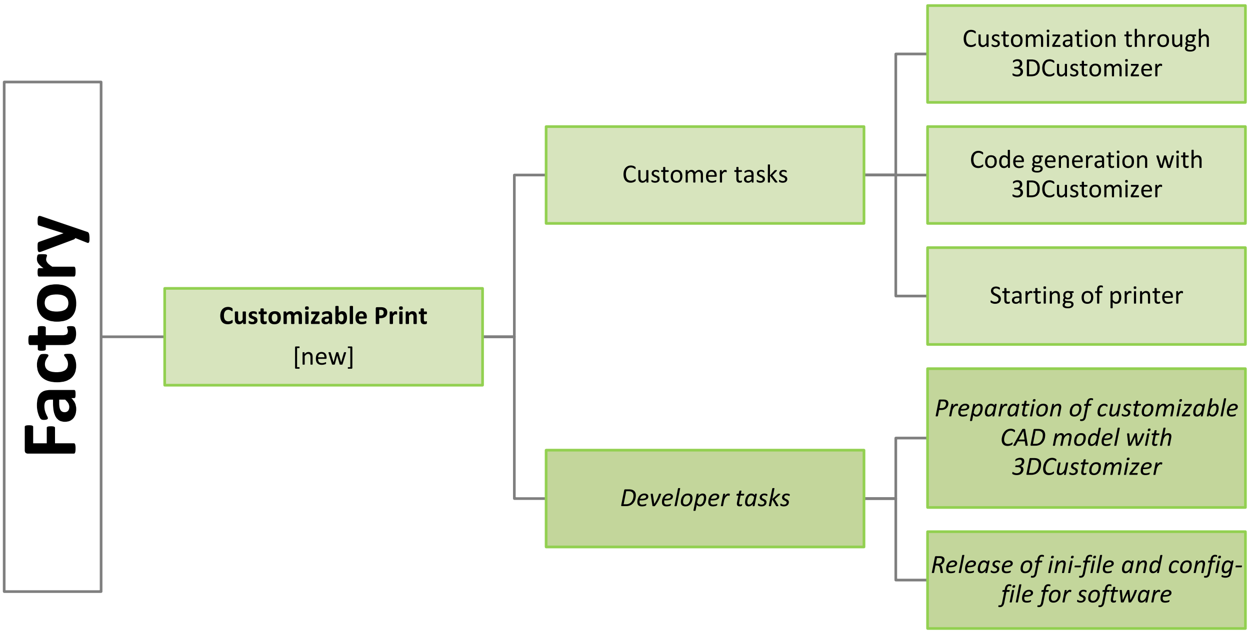

Fig. 49: Factory: customizable Print, Reference: Own illustration.

8.2 Mass Customization

Basically, the initial situation of personal manufacturing was already elaborated in chapter 5.3. Currently, personal manufacturing is becoming more popular. The prices have already reached the limits, where customers would be able to buy low-cost 3D printers. Unfortunately, these customers do not have any idea where this system could be used.

This concern can be compared with the development of personal computers as well. At a certain time, the technology was already quite powerful and relatively inexpensive. However, usable tools which provide users with an added value were missing. Considering the personal manufacturing area, similarities can be seen. Also, price and performance are acceptable, but usable tools with an added value are missing.

As a result, the interface to the customer is missing and this chapter tries to fulfill this gap with a comprehensive concept. Based on this concept, a 3D customization tool on a lower development stage will be developed.

The main ideas of mass customization, subordinated to open innovation, have been explained in chapter 4.2. Since this thesis is focused on customization of 3D models, the theoretical schematic model of “Development-to-order”, seen in Fig. 8, will be extended with specific new components. The result of this extension operation is illustrated in Fig. 50.

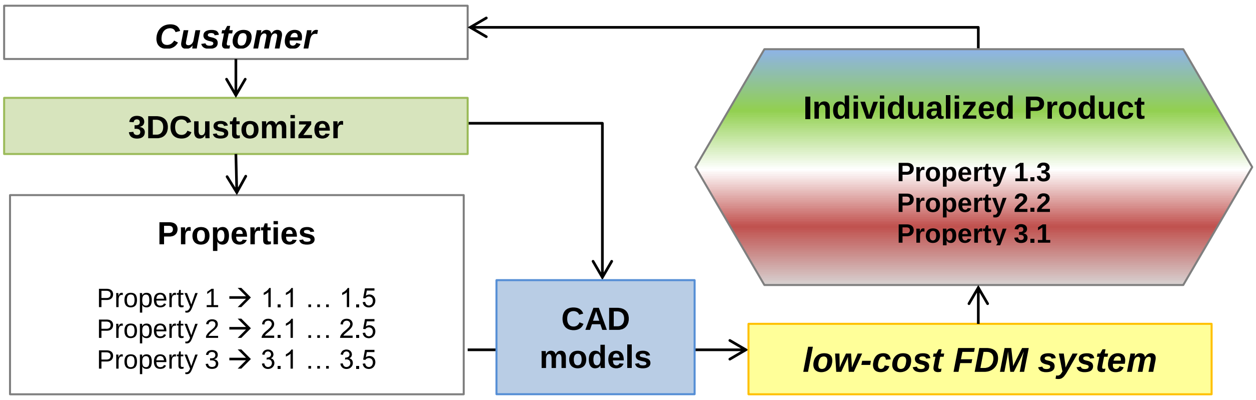

Fig. 50: Specified concept of development-to-order, Reference: Own illustration.

The configuration system will be called “3DCustomizer” from now on and it will also be the heart of the new concept. In addition, the concept was enlarged due to the integration of “CAD models”. Instead of “Manufacturer”, “low-cost FDM system” takes place, which will produce the customized 3D models. As a result, an individualized product with the chosen properties through the 3DCustomizer will be manufactured.

8.3 Developers and Customers

As mentioned in chapter 8.1 personal manufacturing has to be distinguished into certain groups of people. There are several reasons for this, especially when it comes to an integration of customers without technical competencies. Thus, customers should…:

- … have an interface which is as easy to use as possible,
- … not worry about parameter of the g-code,
- … not worry about aligning and scaling of STL-files in the building volume, and
- … not worry about using support material or the observance of certain overhang angles.

These are all work packages within the responsibility of the developers. In order to be able to distinguish in these two groups of people, developers and customers, clear and standardized interfaces have to be established.

Therefore, Fig. 51 illustrates the basic relations between data and tools, as well as the sharing of workpackages between developers and customers. It reveals that customers only have to deal with the new 3DCustomizer software and the loading of the related project files into the software. In contrast, developers can access all tools, such as the CAD tool and the slicing tool. Actually, there are certain rules in creating CAD models, in order to establish standardization. In addition, developers also have to deal with the 3DCustomizer to create their customizable models.

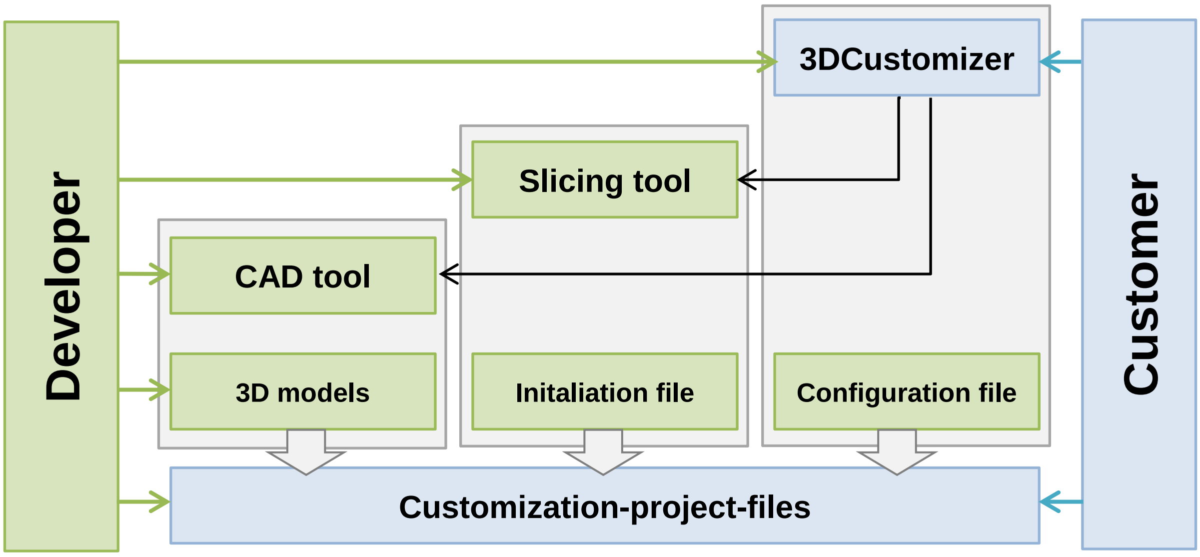

Fig. 51: Developers and customers within 3D customization, Reference: Own illustration.

8.4 Ecology

This new concept could immensely influence the ecology in the future. Several theoretical aspects have already been explained in chapter 5.3. However, this subchapter deals with several hypothetical views into the future, as well as facts.

8.4.1 Recycle management

The community project RepRap[86] is one of the pioneers in the area of personal manufacturing. Their idea is to build self-replicating manufacturing machines. Several RepRap-printers have already been developed, like RepRap Mendel[87], which is able to replicate all of his plastic parts. The basic hypothetical thought of RepRap project is to build a printer where you can use the printed parts as a raw material to print new parts.

These ideas can be projected onto the new concept of personal manufacturing. Fig. 52 shows the basic idea of using AM products as a raw material. Products will be developed especially for a certain AM technology, to be able considering every certain property of the AM technology. Based on this assumption, products will be homogenous, which is an excellent initial situation for further considerations. As a result, these products could be prepared again for the certain AM technology.

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[86] RepRap is humanity's first general-purpose self-replicating manufacturing machine.

[87] RepRap Mendel is the second printer that was officially presented by the open source community.

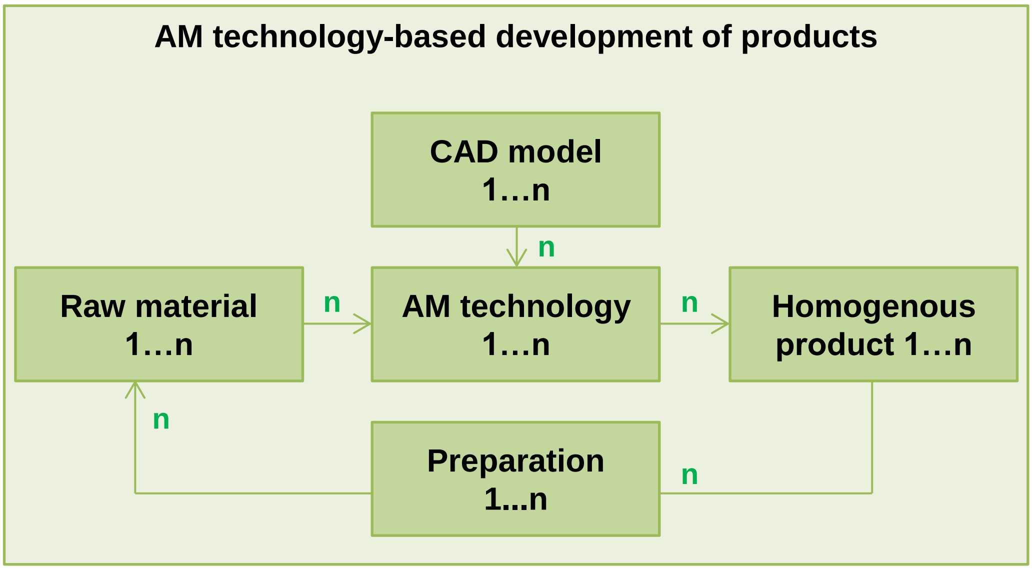

Fig. 52: Recycle management additive manufacturing, Reference: Own illustration.

8.4.2 Transport and production

If people start to produce their products by themselves, several product groups will not be manufactured in central locations anymore. Consumers will have the possibilities through low-cost printers and software tools to produce some of their goods locally. All they need are printers, raw material and CAD data. The printers could be localized in a print shop, as mentioned in chapter 5.3.5, or they own a low-cost printer at home. Raw material could be shared through the community. Based on the idea of recyclability of products in chapter 8.4.1 products could be used again as raw material. CAD models are just digital data, which can be downloaded from the internet. Considering the new developed software-tool 3DCustomizer, this concept suits perfectly for the possibility of updates. This idea is elaborated in chapter 8.5.2. These ideas show that transport and production will change dramatically through the local sharing of raw material and AM technology and the local manufacturing of products.

8.5 Change of Industry

Not only the ecology will change, but also the industry will. Since several goods will be produced locally by the consumers themselves, the industry has to concentrate on other things and create new areas.

8.5.1 Consumer behavior

Personal manufacturing could change the way we see or deal with our products, if consumers would be able to print some of their goods by themselves. On the one hand, people will have a stronger connection will their self-manufactured products. On the other hand, the way people search for their favorite good will change as well. Consumers will try to find data in the Internet, reading reviews and ratings and download these files.

8.5.2 Development and open source

Several goods will be printed by the consumers themselves. So, the industry has to create new areas, in order to keep the connection to the customer. The production will still provide products for customers, but in form of digital data. Consequently, the industry could establish processes which deal with the updates of digital products. Like software applications, also CAD data could be updated.

Considering the new software tool 3DCustomizer, the customizing-features can also be added, and updated. If consumers detect a problem with one of the 3DCustomizer models, they can directly share the issue with the community. Consequently, the responsible developer can easily update the CAD model, as well as the ini-file and the config-file.

As a result, the industry has to concentrate on new areas, in order to keep the contact with the costumers. Nevertheless, there will be many new possibilities with the democratization of production.

9 3D CUSTOMIZATION

Finally, this chapter absolutely deals with the customization of 3D models. All previous chapters represent the preparation through theoretical elaboration, comparisons, tests, experiments and creating concepts, to be able to develop such a comprehensive tool like the 3DCustomizer.

9.1 Main Customization Concept

Subsequently, the customization concept is explained, to understand the relationships between the software-tools and CAD models, as well as the interfaces for developers and customers.

9.1.1 Preparation of 3D models

3D models represent the central element in this 3D-customization concept. These models are mathematically related, which has a major importance in this concept. Thus, the theoretical basics therefore have been explained in chapter 6.2. Basically, this concept deals with two assemblies, the mathematically-related model and the linked print-layout. Both have to be designed by the developer, since this is a requirement for the 3DCustomizer software.

9.1.1.1 Mathematically-related model

Developers have to design an assembly of the product, which includes all parts and relations, as well as mathematical equations, if necessary. This model represents the central element for customization, since the 3DCustomizer accesses all parts, properties and variables through this assembly. If 3DCustomizer changes one property or dimension, the whole assembly will be rebuilt. Consequently, everything changes as a result of the relations between the parts and therefore it is very often only necessary to change one parameter in order to change all parts, which is illustrated in Fig. 53.

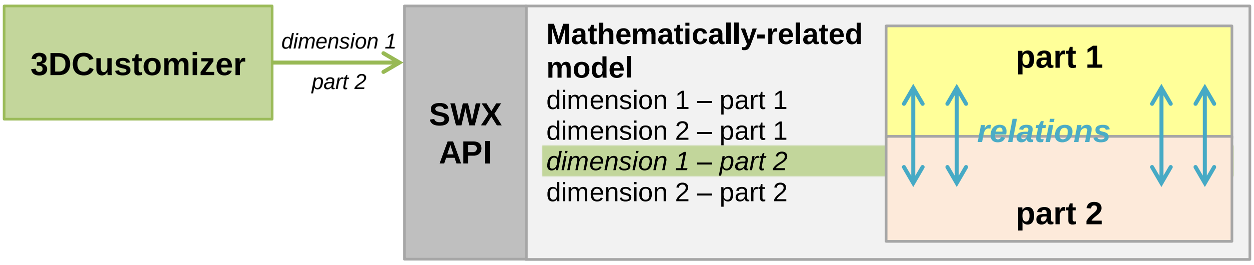

Fig. 53: Accessing the mathematically-related model, Reference: Own illustration.

9.1.1.2 Linked print layout

Since a mathematically-related model cannot be printed as a full assembled product, a second assembly, called linked print-layout has to be designed. All the parts in the print-layout are linked with the parts in the mathematically-related model as seen in Fig. 54. Also in this assembly, relations have to be defined, in order to provide certain distances between the models and the building volume borders.

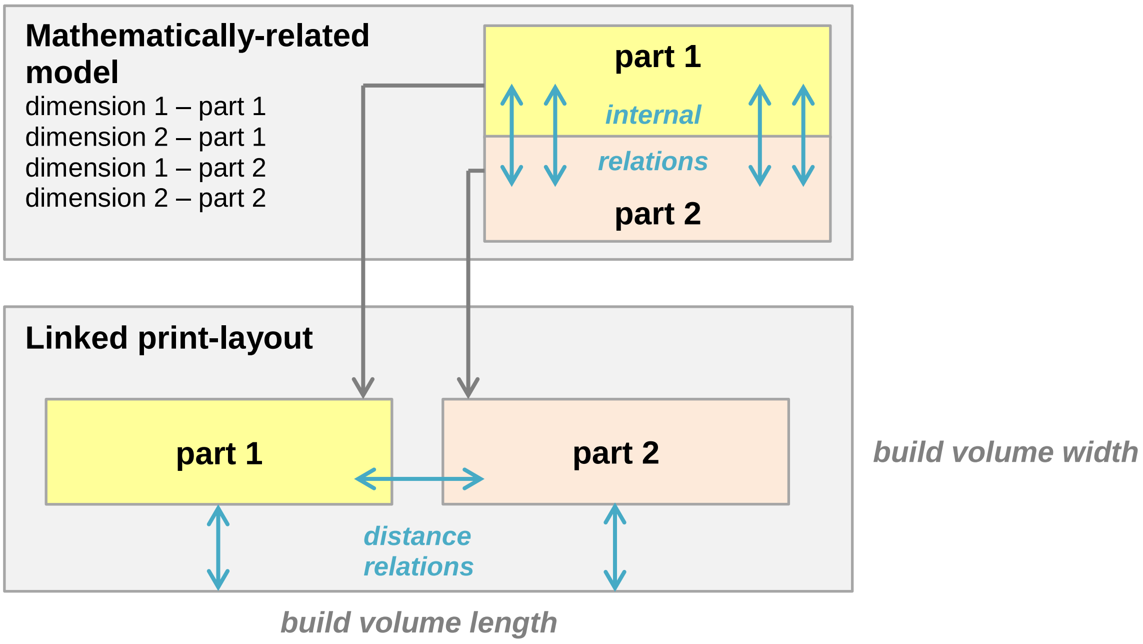

Fig. 54: Accessing the linked print-layout, Reference: Own illustration.

9.1.2 Independence and universality

The 3DCustomizer should be able to deal with all assemblies designed in SolidWorks. Therefore, the fundamental code has to be as abstract and universal as possible. Developers should be able to choose their favorite customization feature, as well as set only a few parameters, like variable name, part and assembly name. Based on this information, customizing of the assembly is already possible. More details concerning this matter, especially the coding, are presented in chapter 9.5.1.

9.1.3 Modular and expandable customization features

It is very important to keep software up-to-date. Therefore, programmers must think beforehand about the design of their code, in order to be able to update or extend the software. 3DCustomizer should also have such a flexibility to deal with updates and extensions. Between all functions there have to be certain borders. A special case exists concerning customization features, since these are the core of the 3DCustomizer. All customization features are modularized, especially the blocks inside the customization features. This modularization is partly illustrated in Fig. 55. The modularity of these customization features is very important, since new innovative and useful customization features will be integrated in future. The first developed customization features can be seen in chapter 9.5.2.

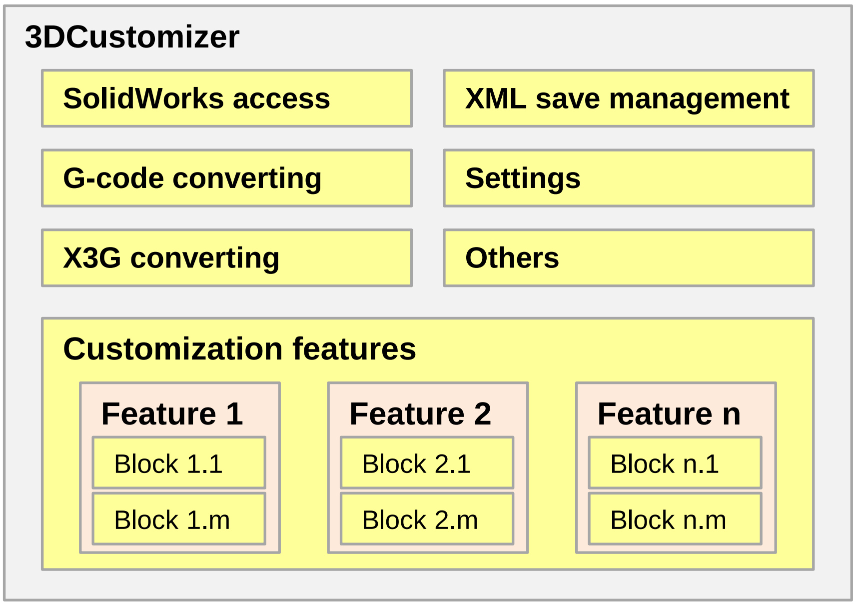

Fig. 55: Modularity and expandability, Reference: Own illustration.

9.1.4 Interface between developer and customer

The next evolution step of the programming concept is the interface between customers and developers. As being said, standardization and modularity have a vast importance. Modularity is already mentioned and conceptually explained in chapter 9.1.3. This property is also very important for the realization of a defined interface between developers and customers.

9.1.4.1 Realization of user modes

Fig. 56 reveals the basic realization of user modes. The fundamental idea is to make the customization features and the blocks inside the features activatable. This provides the developer with possibilities to choose their favorite features and the amount of blocks. Consequently, developers can individually shape the software for the 3D model.

This activatable function enables a possibility to examine which properties have to be saved for the configuration files (see chapter 9.1.4.2). However, the main advantage of this function is to be able to easily switch between developer and customer mode. All customization features and blocks which are not used, respectively activated, by the developer will not be shown in the customer mode.

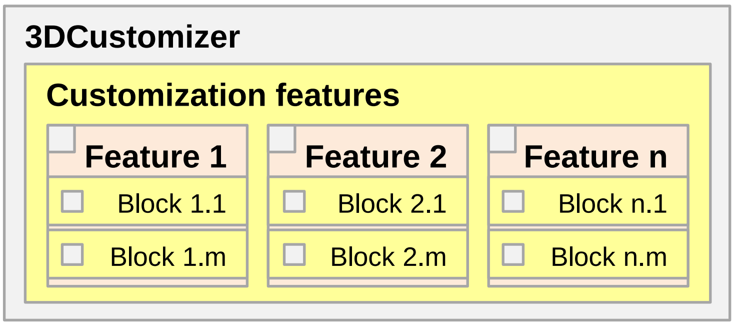

Fig. 56: User modes through activation of features of blocks, Reference: Own illustration.

9.1.4.2 Configuration files

Also, the way of saving the developer's settings will be elaborated. Basically, the 3DCustomizer is blank, but packed with lots of possibilities for customizations. As already explained in chapter 9.1.4.1, developers are now able to choose their favorite customization features, which they want to use for customization purposes of their 3D model. They also would like to choose the number of blocks inside the customization feature. So, these settings (active or deactivated and model-specific parameters) have to be saved, in order to be able to load them again. This information has to be stored in a certain configuration file. Finally, a defined interface has established.

9.2 CAD development

The CAD concept in this customization concerns is already elaborated in chapter 9.1.1. However, this chapter especially deals with the methodology for CAD developers to create these models. This includes the rules for the designing process, as well as the knowledge of the necessary assemblies.

9.2.1 Rules

Since everything in this new customization concept is about simplicity, also the rules are quite clear and comprehensible.

The most important rule is that two assemblies have to be created, as explained in chapter 9.2.2: a mathematically-related model and a linked print layout. Even, if the customization process only has to deal with a model that consists of one part, this part also has to be transferred into the mathematically-related model and the linked print-layout, since these two assemblies represent the interface for the software.

Moreover, external references, which are described theoretically in chapter 6.2.3.2, have to be defined, if the assembly consists of more than one part and if the parts are directly related. For example, if the length and width of the main body of an electronic housing should be modified, also the case should change its width and length to fit into the main body. Therefore, external references in assemblies represent a clear and comprehensible function for CAD developers.

Furthermore, several features, which are activated or deactivated together, have to be put into a shared folder in the feature tree of the CAD software. This especially makes sense for the customization features, called "Activatable features" and "Design", which are accurately explained in chapter 9.5.2.

With the current state of customization features, no more rules are explicitly necessary. However, the CAD developer has to take care of a clean designing process and accurate references.

9.2.2 Assemblies

On order to be able to test the new customization software 3DCustomizer, the benchmark model was used for first experiments. The motives and backgrounds for the choice of the model could be looked up in chapter 7.1.2. Subsequently, the mathematically-related model and the linked print-layout are explained with the help of the benchmark model.

9.2.2.1 Mathematically-related model

The mathematically-related model is the central element for the customization process. The CAD developer includes every needed part in this assembly. With the help of external references, parts can be linked, which greatly increases the efficiency of customization. It is very important to design the model as thoughtfully as possible. Developers have the responsibility to test as many customization scenarios as possible, to assure as less error messages as realizable.

Fig. 57 illustrates the benchmark-model with all needed parts. External references are absolutely necessary in this case. Since the dimensions of the main part (2) will be changed, also the smartphone-holders (1) have to automatically change their length as well. This is solved with linking of parts through external references.

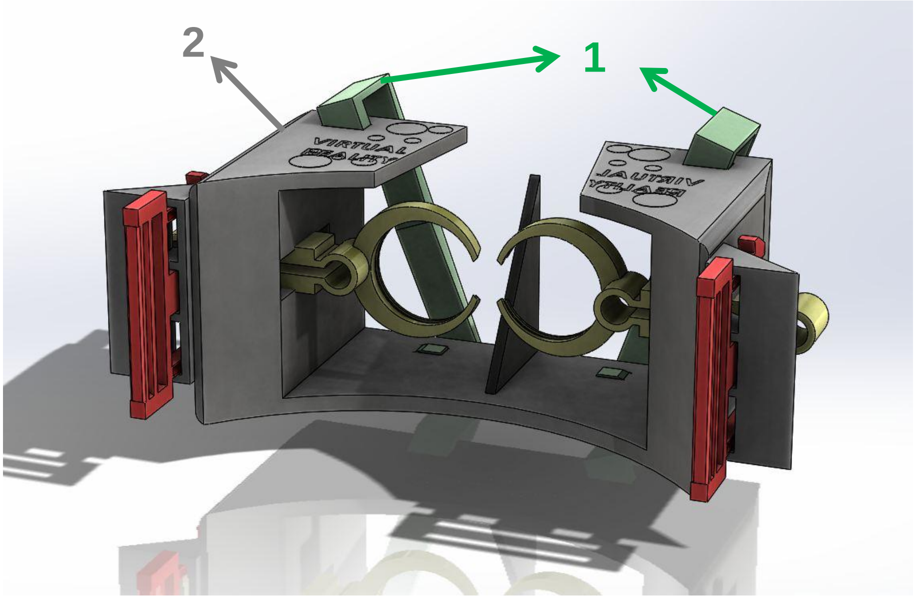

Fig. 57: Mathematically-related benchmark model, Reference: Own illustration.

9.2.2.2 Linked print layout

The mathematically-related model cannot be printed in this assembled condition. Therefore, a second step has to be done. The parts will be aligned inside a given design space (maximum dimension of the printer's building space) by the CAD developer. Fortunately, the parts of the print-layout are directly linked with the parts of the mathematically-related model, which decreases the level of complexity for the CAD developer.

Nevertheless, particular links have to be created to assure that the parts do not collide or reach the limit of the design space. Fig. 58 displays the print-layout of the benchmark model. The transparent cuboid represents the design space, which has the maximum dimension of the Makerbot Replicator's building space. This print-layout is already optimized for printing without support structures and ready for further data conversion into STL and g-code.

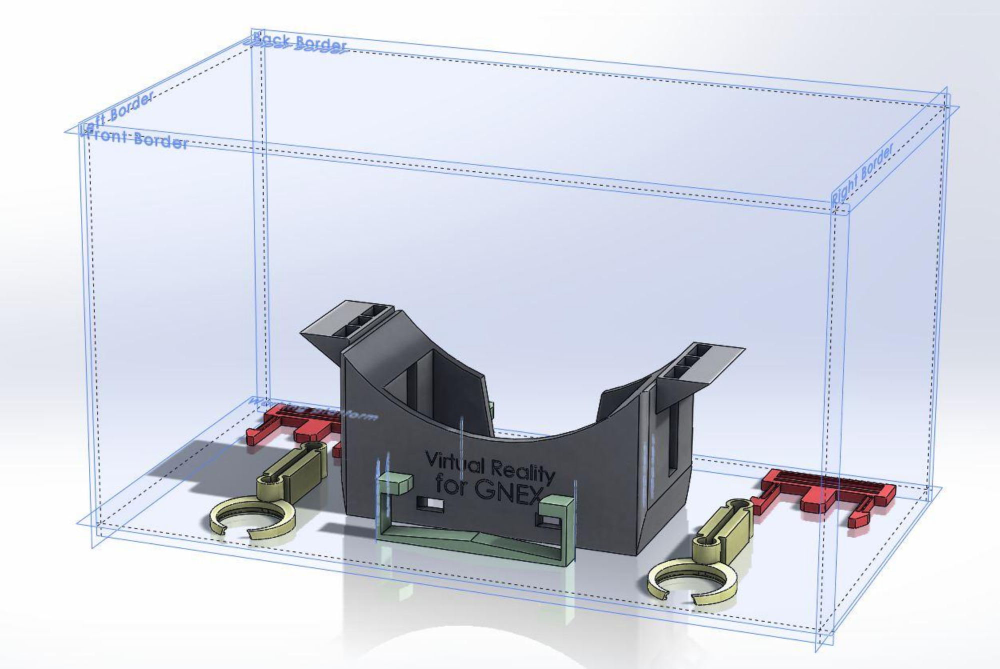

Fig. 58: Linked print-layout of benchmark-model, Reference: Own illustration.

9.3 Programming Interfaces

The following subchapters present the programming interfaces which are used within this software development. It focuses on the purpose and way of usage of these interfaces.

9.3.1 SolidWorks

SolidWorks API, which is described in chapter 6.2.4.3, is the main interface of the 3DCustomizer. This is the interface for the customization purposes of the 3D model. SolidWorks API provides several possibilities to access variables inside the model, respectively to modify several settings.

Basically, the development process has been assisted by the macro-recorder of SolidWorks. In order to get several code implementations for certain model accesses, design actions have been recorded with the macro-feature. Afterwards, the code has been evaluated and the necessary information was filtered. This filtered information was then used for the coding of the 3DCustomizer features.

With reference to data preprocessing, elaborated in chapter 6.2, this interface mainly deals with the conversion of data from SLDPRT into STL. In other words, the responsibility of the interface is the Polygonisation of CAD models, besides the customization purposes. Only the linked print-layout has to be converted into a STL-file.

Fig. 25 in 6.2.4.3 in the theoretical part shows the object model of the SolidWorks API. Unfortunately, several model actions are not recorded by the macro function of SolidWorks. Therefore, the object model provides some information, especially about the object “Dimension” and “Sketch”. In order to perform certain changes in sketches, such as text and dimensions, the successfully accessing of these objects is absolutely necessary.

9.3.2 Slic3r

Slic3r is a slicing tool, especially developed for additive manufacturing purposes. The main goal of this tool is to create gcode-files out of STL-files. Chapter 6.4 deals with this topic. Slic3r offers accessibility via “Command-Line Interface” (CLI). This means, commands can be send to this tool, when wrapped into a certain code structure.

The main usage of this tool is to create a gcode file, out of the converted print-layout. AM low-cost printers are different when it comes to gcode-files. Each printer needs special settings, like position of homing, extruder speeds, etc. In order to consider all these specific settings, Slic3r offers a possibility to deal with these issues. The so-called initialization files (ini-files) store all the information of the settings. Consequently, different machines could also be used with 3DCustomizer, unless initialization files are prepared. In addition, these initialization files could also be used for accuracy or speed settings. For example, if a CAD developer claims to prioritize accuracy over speed for his or her 3D model, he or she could choose the initialization file with the lower speeds.

9.3.3 ReplicatorG

When dealing with a Makerbot Replicator as a printing-device, a possibility for printing PC-autarkic exists. This means that gcode-files can be converted into machine-specified code (X3G or S3G), saved on a SD-card and printed directly from there without the need communication between a PC and the printer. Usually, software on a PC translates each gcode-command into machine specified code and sends it to the machine sequentially.

However, the SD-card alternative greatly increases the usability of such systems. Therefore, also a machine code-generator will be integrated into the 3DCustomizer, since the tested device is a Makerbot Replicator 1, which offers this functionality, as mentioned.

ReplicatorG is a comprehensive software tool for AM technologies. There exist many possibilities for adjusting of settings, especially concerning gcode. However, this tool is especially needed for the conversion of gcode into machine-specified code.

In order to offer a command-line interface, independent software developers invented a plug-in for ReplicatorG especially for this purpose. As a result, it is now possible to access the conversion feature of ReplicatorG with certain commands, without needing to load the graphical user interface. Thus, ReplicatorG is running in the background during the conversion background.

9.4 User Interfaces

This chapter deals with the user interfaces of the software 3DCustomizer. Firstly, the fundamental idea for the design of the user interface will be presented. Subsequently, it is continuing with explanations concerning the interfaces for the developer and the customer.

9.4.1 Thoughtful design

3DCustomizer is all about modularity and expandability. Therefore, the graphical user interface has to be as structured as possible. In addition, the arrangement of the GUI components has to be comprehensible, so that developers and customers do not have any usability issues. Thus, also the iconography was closely scrutinized. It is inspired by current flat-design webpages and mobile operating systems, in order to provide users with interfaces they like and are already used to.

Fig. 59 already illustrates the customizable benchmark-model, which has been prepared with the 3DCustomizer. Nevertheless, the purpose of this illustration is to get a close look at the main components of the 3DCustomizer.

Number 1 reveals the action bar. This consists of several setting options, separated for customers and developers. In addition, help topics are also included in this bar. However, this action bar does not look the same for developers and customers due to the switching mode (see chapter 9.1.4.1, 9.4.2 and 9.4.3).

Individual headers as well as a title picture can be chosen in component number 2. This, of course, is a developer function and cannot be changed by the customer.

Component 3 includes all the customization features. They are sorted through a TabControl[88] and can easily be extended in future. Fortunately, there are already many new ideas for customization features, so the number of TabPages[89] will increase in near future.

In previous chapters, several times the name “feature blocks” was discussed. Component 4 shows one of these feature blocks, which are part of a customization feature. They could also be extended, if it is necessary in future. The number of feature blocks depends on the customization feature and its purpose. At least, feature blocks consist of a checkbox (to activate or deactivate blocks), dimension name, value, variable name and part name.

Component 5 is the customization area. This includes the button to confirm and perform the changes. Moreover, there is also a checkbox in order to activate or deactivate the whole customization feature. This would be the case, if the developer does not need this customization feature. Consequently, in customer mode, this deactivated feature (the whole TabPage) would have been hidden.

Component 6 is a notification center, which consists of a textbox and a progress bar. This component is for providing information about conversion processes, saving processes and so on.

Finally, component 7 gives the developer a possibility to enter a name for the customization feature. Consequently, this is one of many details which helps to increase the usability for the customer.

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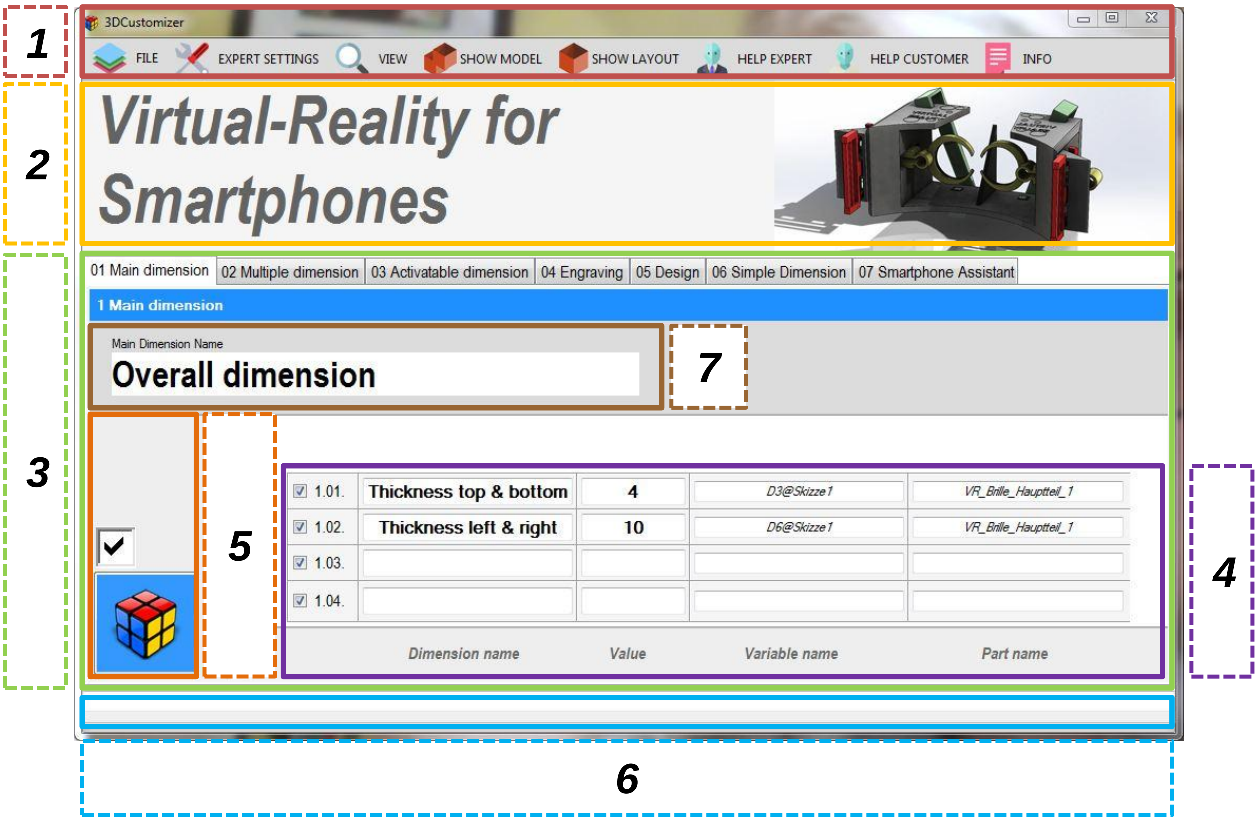
[88] TabControl is a graphical user interface tool, to be able to easily switch between windows through “tabs” (buttons)

[89] TabPages are the single windows of the TabControl.



Main Dimension Name: Overall dimension

☑

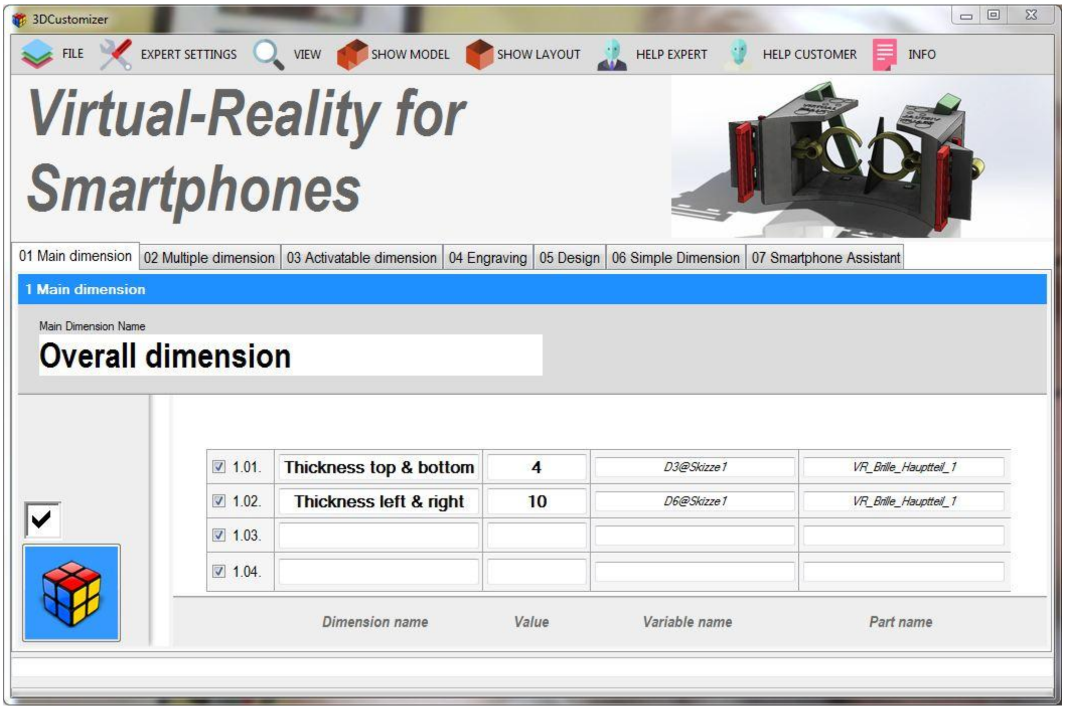
	Dimension name	Value	Variable name	Part name
☑ 1.01.	Thickness top & bottom	4	D3@Skizze1	VR_Brille_Hauptteil_1
☑ 1.02.	Thickness left & right	10	D6@Skizze1	VR_Brille_Hauptteil_1
☑ 1.03.				
☑ 1.04.				

Fig. 59: GUI components of 3DCustomizer, Reference: Own illustration.

9.4.2 Developer interface

The CAD developer can use all the interfaces and components of the 3DCustomizer. Every textbox is activated and nothing is hidden, in order to provide the developer with all the possibilities for preparing his or her 3D model for the customer. Fig. 60 illustrates an example of a developer-mode window, whereas it can be seen that neither one customization feature (TabPage) or button in the action bar is hidden, nor one textbox or checkbox is deactivated.

Basically, the process for the developer begins with his or her 3D model, which has to be loaded through the action bar. Assuming that the mathematically-related model and the linked print-layout have been well tested, the developer begins choosing the customization features, which are necessary for his or her purposes. The features which are not needed will be unchecked in order to hide them for the customers. Subsequent to this procedure, the developer searches for the dimensions (variables of sketch-values), which should be controlled, and fills them into the textboxes as well as names and start values. All the feature blocks which are not needed must be unchecked in order to hide them from the customers. Finally, the configuration file which includes all the information, previously entered, will be saved.



Main Dimension Name: Overall dimension

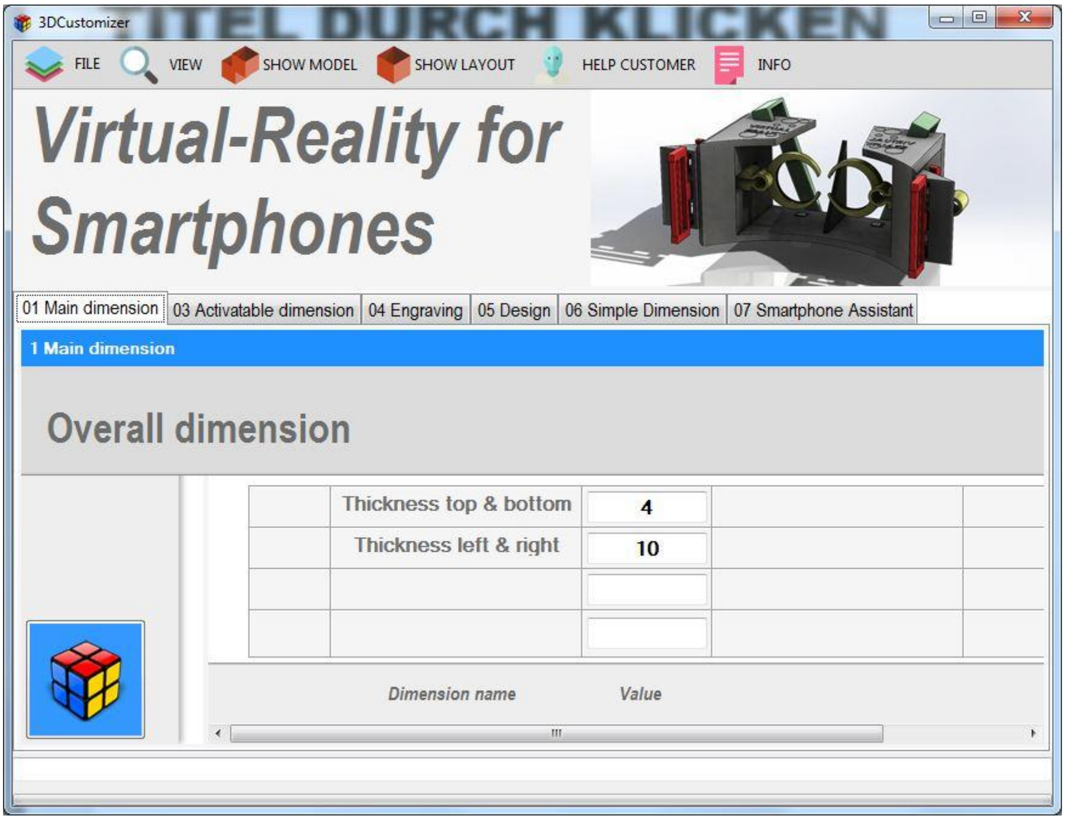
	Dimension name	Value	Variable name	Part name
☑ 1.01.	Thickness top & bottom	4	D3@Skizze1	VR_Brille_Hauptteil_1
☑ 1.02.	Thickness left & right	10	D6@Skizze1	VR_Brille_Hauptteil_1
☑ 1.03.				
☑ 1.04.				

Fig. 60: Example of developer mode, Reference: Own illustration.

9.4.3 Customer interface

In general, the customer interface is the same as the developer interface. Actually, the whole software is the same because of consistency concerns. Nevertheless, the developer interface with all the possibilities for performing settings and filling in variable names would have been overwhelming for customers. Therefore, everything not used by the developer or not necessary for the customer is hidden or deactivated in the customer mode.

Fig. 61 shows the customer mode of the interface shown in Fig. 60. It can be seen that there are certain valuable differences, which increases the usability for the customer a lot, due to less distractions. For example, customization feature 2 was not used by the CAD developer, and therefore it is hidden. Moreover, all checkboxes are hidden, since this is especially a function for developers, as well as the labels and textboxes concerning part and variable names. Also, the action bar does not show “Expert settings” and “Help Expert” anymore.



Dimension name	Value
Thickness top & bottom	4
Thickness left & right	10

Fig. 61: Example of customer mode, Reference: Own illustration.

9.5 Development of Software

Since the customization concept, the CAD concerns, the programming interfaces as well as the user interfaces are finally elaborated, the way is paved for the development of the software. Hence, the major parts of the coding will be presented in the following subchapters. Basically, source code is not illustrated in the subchapters, apart from a few exceptions where it is necessary to provide an example for explanations.

9.5.1 Array-based coding

Array-based coding means that nearly everything was wrapped into arrays in order to be able to access every label, textbox, checkbox, value, etc. effectively through loops. Otherwise, it would have been impossible to provide a modular and expandable software tool. The following extract from the source code, textbox array of customization feature 1, shows the principle of putting certain variables into matrices and arrays. TabPages, checkboxes and many more are initialized like this.

```
tb_1_0 = new TextBox[,]
{{ this.tb_1_1_1, this.tb_1_2_1, this.tb_1_3_1, this.tb_1_4_1 },
 { this.tb_1_1_2, this.tb_1_2_2, this.tb_1_3_2, this.tb_1_4_2 },
 { this.tb_1_1_3, this.tb_1_2_3, this.tb_1_3_3, this.tb_1_4_3 },
 { this.tb_1_1_4, this.tb_1_2_4, this.tb_1_3_4, this.tb_1_4_4 }};
```

Extract from source code: textbox array of customization feature 1.

Array-based coding keeps the core of the software as compact and efficient as possible. Furthermore, other features like saving and loading of configuration files need to access such arrays, because otherwise it would cause the code to burst at the seams.

9.5.2 Development of modular customization features

Subsequently, the customization features of 3DCustomizer will be explained. It has to be remembered that these customization features can be easily extended in future.

In addition, the figures in this chapter mainly deal with the differences of the user interfaces of the customization features of the 3DCustomizer. Since it would be distracting to illustrate all these figures within the body of the thesis, they are collected in the appendix on the pages 99 to 102.

9.5.2.1 Main dimension

Main dimension is a basic customization feature, which primarily concentrates on the main dimensions of the model. Usually, developers want to have a feature, where they can control the maximum or minimum size of their model.

Basically, as seen in the example of the source code below, only the textbox-array and the checkbox-array have to be provided for the customization function. Everything else is performing in the loops by checking the current state of the checkboxes and the maximum size of its array. Only if the developer has checked the particular block of the customization feature, certain actions like changing of dimensions in the model are performed. Although, developers have vast freedom in interacting with the software and much information has to be collected, the code is still quite tight.

It also has to be noticed, like seen in Fig. 62 in the appendix on page 99, that the checkboxes and textboxes are aligned like a matrix, which simplifies and accelerates the software development significantly.

```
        private void customize_01_Main_Dimension(TextBox[,] tb_1_0, CheckBox[] cb_1_0)
        {
            swDoc.ShowNamedView2("*Dimetrisch", 9);
            myDimension = null;
            for (int i = 0; i < cb_1_0.Length; i++)
            {
                if (cb_1_0[i].Checked)
                {
                    //change dim1
                    if (tb_1_0[1, i].Text != "")
                    {
                        double dim1_temp = Convert.ToDouble(tb_1_0[1, i].Text) / 1000;
                        myDimension = ((Dimension)(swDoc.Parameter(tb_1_0[2, i].Text+
                                                   "@"+tb_1_0[3, i].Text+".Part")));
                        myDimension.SystemValue = dim1_temp;
                    }
                }
            }
            swAssembly = ((AssemblyDoc)(swDoc));
            swAssembly.EditAssembly();
            swApp.ActivateDoc2(openAssemblyName, false, ref longstatus);
            swDoc.ShowNamedView2("*Dimetrisch", 9);
            boolstatus = swDoc.EditRebuild3();
        }
```

Extract from source code: customization feature 1.

9.5.2.2 Multiple features

Like the customization feature, main dimension, this is also a basic feature. It concentrates on the fundamental principles of 3D designing and does not offer luxurious and additional functions. In this case, the CAD developer has the possibility to deal with his or her multiple CAD features in SolidWorks. For example, boreholes which are copied around an axis on a circle, as well as cut-outs for leds, parallel to an edge, can be controlled with this customization feature.

Fig. 63 on page 99 reveals the graphical user interface of this customization feature. At first glance, it has some similarities with the feature “Main dimension”, but differs in the usage purpose for the CAD developer.

9.5.2.3 Activatable features

This customization feature is also a so called basic feature inside the 3DCustomizer. Activatable features create a possibility to perform radical changes in CAD models. The reason for this is that it can activate and deactivate folders of CAD features in parts. Of course, developers have to design their model appropriately, so that deactivating of a certain number of features does not cause any issues. But, this is one major part of the rules in preparing models for the 3DCustomizer, as defined in chapter 9.2.1.

The huge advantage is that also dimensions can be changed, besides the possibility of activating or deactivating of a group CAD features. For example, if a CAD developer creates a special electronic housing for electronic engineers and wants to deliver a customization possibility, he or she will use the 3DCustomizer. Now, this customization feature could deal with cut-outs for buttons of electronic housings with certain geometries. The CAD developer might ensure to provide cut-outs for buttons of different manufacturers or just different kinds of buttons. However, this customization feature offers the possibility to activate or deactivate a group of CAD features and, at the same time, to access certain dimensions. In this example, it would have been possible to switch between different cut-outs, based on different buttons.

With reference to the appendix on page 100, Fig. 64 shows the graphical user interface of activatable dimension and how it was used within the preparing of the benchmark-model.

9.5.2.4 Engravings

Engravings provide the CAD developer with a tool to make writings customizable. There are many different applications for writings in form of engravings. However, engravings are very important when it comes to individualization and therefore it is also integrated in the 3DCustomizer.

Fig. 65 on page 100 illustrates the interface for the developer with all necessary textboxes and checkboxes.

9.5.2.5 Simple dimension

This feature is basically the same as the customization feature “Main dimension” with the only difference that it focuses on any dimension of the 3D model. So, “Simple Dimension” also accesses dimensions of the model and is able to change their values. Nevertheless, this distinction between “Main Dimension” and “Simple Dimension” had to be done, since otherwise it would have cause confusion and misinterpretations.

9.5.2.6 Design

All previous customization features are called “Basic customization features”. They are focusing on the main purpose of the accessing and changing of values of the 3D model, without providing any additional help or function for the CAD developer. Nevertheless, these basic features are necessary and certainly used most.

However, the modularity of 3DCustomizer offers a possibility to integrate more powerful customization features, which are more focused in certain areas. Basic customization features are necessary, but the powerful and more focused customization features are the ones which enable vast progress and success. Therefore, two powerful customization features have been developed to show the competitive advantages of the 3DCustomizer.

The customization feature “Design” offers a possibility to activate and deactivate a set of CAD features, with the focus on the design of the model. Therefore, a function to upload photos of different designs was implemented. Developers have to prepare their model as usual to be able to switch between certain designs and put these design-specific CAD features into a folder in SolidWorks (similar to “Activatable dimensions”). Photos of these designs have to be loaded into the 3DCustomizer. When the customer switches between the designs afterwards, he or she will be provided with a preview of the 3D model. Fig. 66 on page 101 shows the graphical user interface of the customization feature “Design” for the customizing of the benchmark-model design.

9.5.2.7 Smartphone assistant

The most powerful customization feature yet is the Smartphone assistant due to its simplicity for developers and customers, as well as its focus on Smartphones. This feature was especially developed for Smartphone purposes, like cellphone holders for cars.

The fundamental principle is the same as within the customization features “main dimensions” and “simple dimensions”. It is all about accessing variables and changing them. However, Smartphone assistant is more specific and performs based on data, which the developer does not have to provide. Currently, there are dimension data of six popular smartphones implemented in the 3DCustomizer.

Basically, CAD developers have the possibility to link dimensions of their model with dimensions of the smartphones. For example, the benchmark-model offers a holder for smartphones, as well as a cut-out for the display. Then, the CAD developer must link the cut-out with the display dimensions and the holder with the thickness-dimension of the smartphone. As a result, the developers are now also benefiting from the increases in usability due to more embedded data in the software. Subsequently, when the developer has finished his or her preparation of the model and is providing the model and the configuration file for the customers, they only have to choose their smartphone model and several customization processes are performed automatically.

Just based on this principle, thousands of specific applications could be implemented for every conceivable area. Fig. 67 on page 101 illustrates the graphical user interface for the Smartphone assistant. It has to be kept in mind that the values shown in the picture are automatically added into the textboxes without any assistance of the developer. Developers just have to link the values to certain dimensions in the 3D model.

9.5.3 Configuration files

When developers have finished with the preparation of their 3D model, their settings have to be saved into a configuration file. This is handled with XML files. Below, an example of how the saving of settings basically works inside the 3DCustomizer is illustrated.

Again here, the array-based coding reveals advantages. The XmlWriter[90] only has to access the arrays of the checkboxes and the textboxes inside a loop to get the information. Consequently, new customization features can be easily integrated in the future, whereas only a few new code lines are needed.

```
        private void saveConfiguration(String fileName)
        {
            XmlWriterSettings settings = new XmlWriterSettings();
            settings.Indent = true;
            XmlWriter writer = XmlWriter.Create(fileName, settings);
            writer.WriteStartDocument();
            writer.WriteComment("This file is generated by the program.");
            writer.WriteStartElement("AssemblyInformation");
            /****************************/
            /* Saving of the user input */
            /****************************/
            // Saving of settings of customization feature 1
            for (int i = 0; i < tb_1_0.GetLength(1); i++) // lines
            {
                writer.WriteAttributeString("Developer-input_feature-block_cb_01_" +
                Convert.ToString(i), Convert.ToString(cb_1_0[i].Checked));
                for (int a = 0; a < tb_1_0.GetLength(0); a++) // columns
                    writer.WriteAttributeString("Developer-input_feature-block_tb_01_"
                    + Convert.ToString(i) + Convert.ToString(a), tb_1_0[a, i].Text);
            }
        }
```

Extract from source code: saving of customization feature 1.

As a result, the software 3DCustomizer is only valuable with its configuration file, since everything concerning variable names, initialization values, and so on is stored in these files. The vast advantage is that 3DCustomizer offers a great flexibility within this concept. Customers have installed the software on their PC or laptop and only need the CAD files and the appropriate configuration file.

9.5.4 Auto-save

Auto-save is a feature, which assures that changes concerning settings in the software will not be lost. Therefore, 3DCustomizer automatically accesses the function SaveConfiguration[91] when the interface is closed by the users. In this case, a configuration file will be saved into the default project file path. When the user starts 3DCustomizer again, this configuration file will be loaded. Consequently, changes cannot be lost. However, if unintended changes have been saved, there is always the possibility to load the default configuration file.

---

[90] XmlWriter is a helper module to write an XML document. It handles character data and constructs different types of markup, such as comments, tags, and processing instructions.

[91] SaveConfiguration is especially coded for 3DCustomizer and handles all the saving operations of the settings and inputs.

9.5.5 Mode-switching

Everything is about modularity and consistency in 3DCustomizer. Consistency could only be provided, since just one software tool is needed for both developers and customers. However, distinctions have to be made concerning the interface and this is where mode-switching plays an important role.

This switching between developer and customer mode is very important, since customers do not need all these overwhelming functions and textboxes, as well as buttons in the action bar. Therefore, several parts of the interface can be easily deactivated or hidden, due to the thoughtful main programming concept explained in 9.1.4.1. Through the implementation of checkboxes, respectively checkbox arrays, developers activate every feature block they need. Everything that is not needed will be deactivated. As already mentioned, whole customization features can also be deactivated.

The extract of the source code below illustrates several hiding and deactivating processes. Again, everything is about accessing arrays through loops.

```
        // Loop for deactivation of certain TextBoxes (columns)
        for (int a = 0; a < tb_temp.GetLength(1); a++)
        {
            tb_temp[0, a].BorderStyle = BorderStyle.None; // changing the
                                                             borderstyle (flat)
            tb_temp[0, a].BackColor = Color.WhiteSmoke; // changing the color
            tb_temp[0, a].Enabled = false; // deactivating - no user interaction
            tb_temp[2, a].Hide(); // Hiding of texboxes in certain columns
            tb_temp[3, a].Hide(); // Hiding of texboxes in certain columns
            if (i == 6) // special case for tabpage 6 // not necessary for customers
                           to use the textboxes
            {   // changing the borderstyle (flat)
                tb_temp[1, a].BorderStyle = BorderStyle.None;
                tb_temp[1, a].BackColor = Color.WhiteSmoke; // changing the color
                tb_temp[1, a].Enabled = false; // deactivating - no user interaction
            }
            if(i==4)
                bt_5_0[a].Hide(); // Hiding of Buttons for pic-Upload
            if (i == 2 || i== 4)
                tb_temp[4, a].Hide(); // Hiding of "Folder"-column in TabPage 3 and 5
            // Loop for deactivation of certain Textboxes (not activated lines)
            // runs as long as the maximum of COLUMNs is reached
            for (int o = 0; o < tb_temp.GetLength(0); o++)
            {   // Checking if certain checkboxes of the lines are activated
                if (cb_temp[a].Checked == false)
                {
                    tb_temp[o, a].Hide(); // Hiding of certain Texboxes
                    if (i == 4) // when tabpage 5 is reached
                        rb_5_0[a].Hide(); // Hiding of certain Radiobuttons
                }
            }
        }
```

Extract from source code: customer mode-switching of certain parts of the interface.

9.5.6 G-code conversion

In order to provide customers with gcode files after the customization process, a function to generate these files has to be implemented. As mentioned in chapter 9.3.2, the chosen slicing tool is called “Slic3r”, and it is accessible via command-line interface.

The extract from the source code below shows the main operations for the slicing process. The executable file of Slic3r has to be accessed and opened based on the given file path. Subsequently, the operations have to be provided through specific commands. Actually, these operations consist of only one complex command, which includes the loading of the initialization file (see chapter 9.3.2), the STL file, as well as the output (path and name) for the gcode-file.

Since, this is an ongoing process and the duration depends on the complexity of the STL file (linked print-layout), threading and delegates have to be implemented. Otherwise, the graphical user interface would not be accessible. Both “Converting” and “statusConverting” (seen in the source code extract below) are threads which are running in the background. The accessing of the graphical user interface is important, because the customers and developers must be informed through the notification center (see chapter 9.4.1) about the current state of the conversion process. Thus, the accessing of the graphical user interface occurs through delegates. Two of these delegates (“StatusRefresh” and “ProgressBarRefresh”) are invoked in the statusConverting thread, seen in the source code extract below.

```
        private void Converting() // Thread 1
        {
            process = new Process(); // Starting of process
            // Hiding of the command-window
            process.StartInfo.WindowStyle = ProcessWindowStyle.Hidden;
            process.StartInfo.RedirectStandardInput = true;
            process.StartInfo.RedirectStandardOutput = true;
            process.StartInfo.UseShellExecute = false;
            process.StartInfo.FileName = "cmd.exe";
            // File path of slicing tool
            process.StartInfo.WorkingDirectory = @"C:\Slic3r";
            process.StartInfo.Arguments =
            @"/c Slic3r-console.exe --load config.ini --output """ + openFilePath +
            openLayoutName.Replace(".SLDASM", ".gcode") + @""" """ + openFilePath +
            openLayoutName.Replace(".SLDASM", ".STL") + @"""";
            myThread2 = new Thread(statusConverting);
            myThread2.IsBackground = true;
            myThread2.Priority = ThreadPriority.Lowest;
            myThread2.Start();
            process.Start();
        }
        private void statusConverting()// Thread 2
        {
            int a = 0;
            while (true)
            {
                StatusRefresh("Generating of g-code" + " Please wait...");
                Thread.Sleep(10);
                a++;
                ProgressBarRefresh(10, a, ProgressBarStyle.Marquee);
                if (a == 10)
                    a = 0;
                if (process.HasExited)
                {
                    StatusRefresh("");
                    ProgressBarRefresh(0, 0, ProgressBarStyle.Blocks);
                    myThread2.Abort();
                }
            }
        }
```

Extract from source code: gcode conversion with threading.

9.5.7 X3G conversion

ReplicatorG is a great tool for converting STL files into gcode files. Within this software tool it is also possible to convert these gcode-files into s3g or x3g data files. These are the file types, which are suitable for the usage on SD-cards. These SD-cards will be connected with Makerbot machines. S3G and X3G (only for Makerbot-firmware version 7 and higher) are machine-specified codes.

The developed 3DCustomizer has to provide a function which allows converting gcode-files into S3G and/or X3G-files. Unfortunately, there are only the open source tool ReplicatorG and several Python[92] scripts in the internet community concerning this specific topic.

Since ReplicatorG is an open-source tool, and also the code of this tool is accessible for developers. Fortunately, external programmers assisted this thesis in order to adapt and shorten this code. This code has been minimized to offer only a convert-function (gcode into S3G or X3G). A command-line interface has also been added, which allows 3DCustomizer to interact with this shortened ReplicatorG-tool.

The following example of a command-line interface input shows the new CLI-accessibility, as well as the command structure for the converting process.

```
cd C:\ReplicatorG\Patch noGUI\replicatorg-0040-windows\replicatorg-0040

replicatorG.exe

replicatorg [-1] -m "The Replicator Dual" -i "benchmark_model.gcode" -o "
benchmark_model.x3g"
```

Example of CLI input: X3G conversion.

---

[92] Python is a high-level programming language, emphasizes code readability and is often used as scripting language.

10 CONCLUSION AND NEXT STEPS

Firstly, the technology comparison was quite illuminating, since it has been discovered that low-cost systems in combination with a 3D-customization tool offer competitive advantages. If this research result had been the opposite, a further research would not have been worthwhile in success concerns.

Also, the testing period of the low-cost system Makerbot Replicator was quite informative. Findings revealed that the angle-limit of overhangs was better than expected, which was great in order to continue with a printing concept that does not need any support structures. As a result, CAD developers have to design their models for the printing-process especially, which seems to be at first glance a vast disadvantage. But, when there are no support-structures needed, the post-procedure of the printing-process is becoming considerably easier and effortless. Moreover, the additional printing of support structures would be more time-consuming. As a result, there are also time-saving advantages within the chosen concept.

The software 3DCustomizer performs satisfyingly in initial tests and experiments with 3D models. The current customization features cover the main customization purposes and desires. Especially, the powerful customization features (design and smartphone assistant) show the big potential of the 3DCustomizer. Of course, several software errors are occurring in first experiments, but this is very usual within new developments.

In addition, the rules for CAD developers are comprehensible and clear. So, there are not that many boundary conditions for CAD developers. Basically, CAD developers can design their models in the way they are used to. Of course, they should know how to use external references within CAD assemblies in order to be able to design complex customizable 3D models, but it is not absolutely necessary.

Also, the concept of the configuration files has already been established in initial experiments. Switching between different configurations runs very effortlessly. As a programmer, it is also quite easy and time-saving to add customization features or feature blocks, since everything is coded array-based and modular.

However, several improvements and new experiments in near future have to be done as well. Unfortunately, in the converting process from gcode-files into X3G- or S3G-files are minor errors occurring currently. Moreover, several experiments with gcode initialization files have to be done in the next months, since certain gcode-settings must be adjusted as well as possible in order to get best printing results.

Nevertheless, through the integration of new customization features, especially the powerful and focused ones, like smartphone assistant, the improvement of this tool will not stop in the future.

If the first testing and coding period is over, a handful of CAD developers will be invited to use 3DCustomizer for customization of their models. With their input and help, improvements can be realized as well as new features added. Thus, this next stage will be the first step towards crowdsourced customizable personal manufacturing.

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LIST OF ILLUSTRATIONS

LIST OF TABLES

LIST OF ABBREVIATIONS

3DP	3D Printing
ABS	Acrylonitrile Butadiene Styrene
ALI	American Language Institute
AM	Additive Manufacturing
API	Application Programming Interface
B-Rep	Boundary Representation
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CNC	Computerized Numerical Control
CRC	Cyclic Redundancy Check
CSG	Constructive Solid Geometry
CSU	California State University
DOF	Degree of Freedom
FDM	Fused Deposition Modeling
IGES	Initial Graphics Exchange Specification
MCU	Microcontroller Unit
NC	Numerical Control
NURBS	Non-uniform Rational Basis-Splines
PLA	Polylactic Acid
PLY	Polygon File
PVA	Polyvinylalcohol
R&D	Research and Development
RP	Rapid Prototyping
S3G	Sanguino3 G-Code
SD	Secure Digital
SDSU	San Diego State University
SLA	Stereolithography
SLDASM	Solid Assembly
SLDDRW	Solid Drawing

SLDPRT	Solid Part
SLS	Selective Laser Sintering
STEP	Standard for the Exchange of Product Model Data
STL	Stereolithography Language
UAS	University of Applied Sciences
VRML	Virtual Reality Modeling Language
XML	Extensible Markup Language

APPENDIX 1: AM TECHNOLOGY COMPARISON DETAILS

Categories	**Evaluation type**		**Polyjet**		**SLS**	
			from	*to*	*from*	*to*
Price of first investment for commissioning	**Price ranges / €**		70.000,00	Objet Connex350T 110.000,00	150.000,00	EOS Formiga P110 190.000,00
Follow-up costs	**Price ranges / € kg^{-1}**		VeroWhite material 250,00	300,00	35,00	75,00
Market prices for 3D models Cf. 3ddruckpreisvergleich.de	**Price ranges / € cm^{-3}**		1,60	2,40	0,75	2,80
Velocity	**Pre- and rework**	Prework 6…little 1…much	6		6	
		Rework 6…little 1…much	3		3	
	Printing speed	Printing speed	appr. 20 mm of building height per hour		appr. 20 mm of building height per hour	
		Explanations	velocity is nearly independent of the volumina of the object		velocity is nearly independent of the volumina of the object	
		Rank evaluation	5		5	
	Whole rank evaluation		4,7		4,7	
Overall Accuracy			standard deviation from target object	0,093 mm	standard deviation from target object	0,157 mm
Surface quality			with reference to experiences and printed benchmark model	with reference to measurment results	with reference to experiences and printed benchmark model	with reference to measurment results
Multi-colour			1. two colours per model 2. several colors available, but not many 3. no material from other suppliers		1. only one color per model 2. not many different materials/colors available, changing is difficult and time intensive 3. little material from other suppliers - risky	
Multi-material			1. two materials per model 2. several materials available 3. no material from other suppliers		1. only one material per model 2. not many different materials available, changing is difficult and time-intensive 3. little material from other suppliers - risky	
3D-model customization integration			no 3DCustomizer integration		no 3DCustomizer integration	
Prework			QUITE EASY 1. designing or downloading of model 2. starting AM-system-based software tool 3. alignment of models 4. printing		QUITE EASY 1. designing or downloading of model 2. starting AM-system-based software tool 3. alignment of models 4. printing	
Rework			1. putting out of printer 2. removing the support material with special liquid 3. no office room possible		1. removing loose powder 2. putting out of printer 3. removing rest of powder 4. surface finishing 5. no office room possible	
Complexity of 3D models			1. **high complexity possible** due to generated and removable support structures		1. **high complexity possible** due to loose powder which acts like support structures	

Table 5: AM technology comparison details part 1, Reference: Own table.

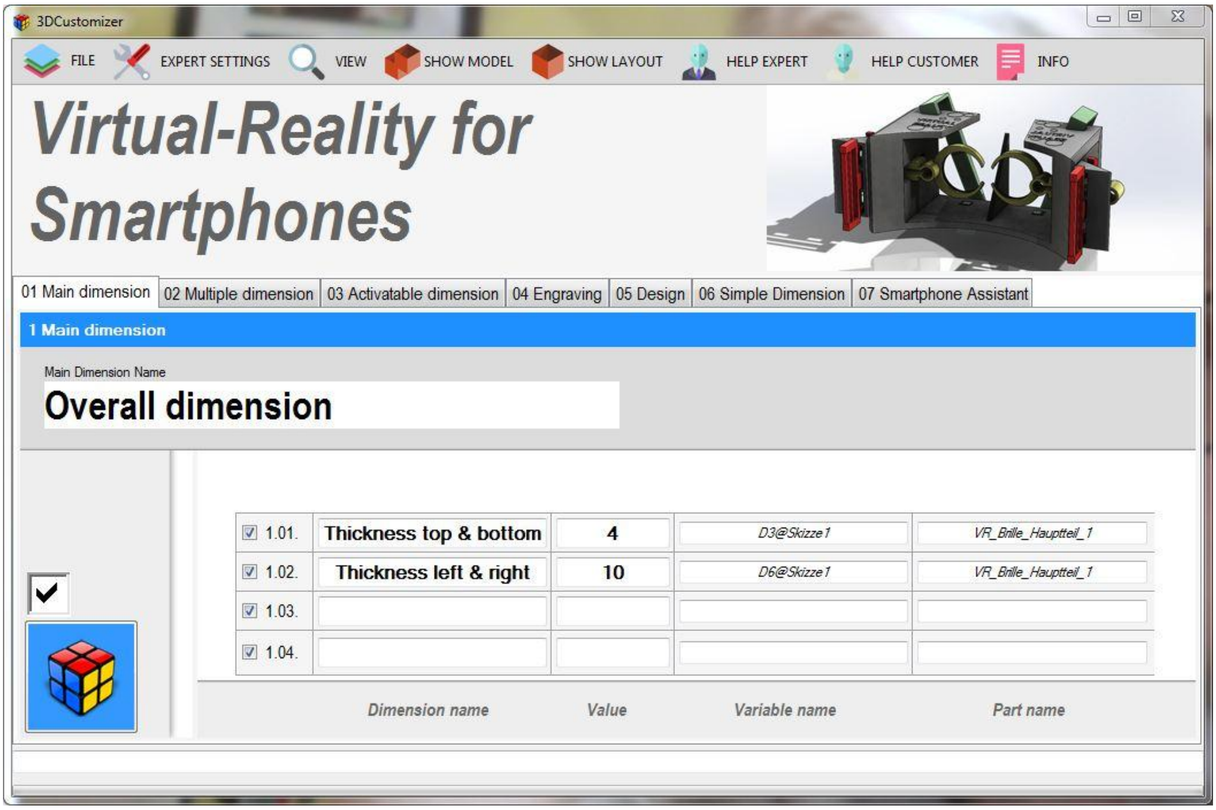
Categories	Evaluation type		Profess. FDM		Low-cost FDM	
			from	*to*	*from*	*to*
Price of first investment for commissioning	**Price ranges / €**		5.000,00	Mojo 10.000,00	1500,00	2500,00
Follow-up costs	**Price ranges / € kg^{-1}**		Stratasys retail price 90,00	110,00	20,00	50,00
Market prices for 3D models Cf. 3ddruckpreisvergleich.de	**Price ranges / € cm^{-3}**		0,20	0,40	0,10	0,30
Velocity	**Pre- and rework**	Prework 6…little 1…much	4		1	
		Rework 6…little 1…much	5		6	
	Printing speed	Printing speed	faster than low-cost systems, slower than all other systems		appr. 30 min to print ab object with 25x25x25 mm	
		Explanations	velocity is absolutely dependent of the volumina of the object		velocity is absolutely dependent of the volumina of the object	
		Rank evaluation	3		2	
	Whole rank evaluation		4,0		3,0	
Overall Accuracy			standard deviation from target object	0,215 mm	standard deviation from target object	0,201 mm
Surface quality			with reference to experiences and printed benchmark model	with reference to measurment results	with reference to experiences and printed benchmark model	with reference to measurment results
Multi-colour			1. one color per model 2. several colors available 3. little material from other suppliers		1. two colors per model 2. several colors available 3. many kinds of material from other suppliers	
Multi-material			1. one material per model (second material is support material, printed everytime) 2. several materials available 3. little material from other suppliers		1. two materials per model, experimental stage, difficult 2. a few materials available (PVA, ABS, PLA) 3. many kinds of material from other suppliers	
3D-model customization integration			no 3DCustomizer integration		no 3DCustomizer integration	
Prework			QUITE EASY 1. designing or downloading of model 2. starting AM-system-based software tool 3. alignment of models 4. printing		NOT EASY 1. Designing or Downloading of model 2. Choosing of Software-platform of Printer 3. Alignment of single-parts of models 4. Finding of appropriate Gcode-settings 5. Printing	
Rework			1. putting out of printer 2. removing the support material with water or with hand		1. putting out of printer 2. if support material used: removing the support material with water or with hand	
Complexity of 3D models			1. **high complexity possible** due to generated and removable support structures		1. **high-complex models not easily possible to print** 2. support structures with same material leads to quality issues 3. support structures with other material (soluble) in experimenting-stadium	

Table 6: AM technology comparison details part 2, Reference: Own table.

Categories	**Evaluation type**		**Low-cost FDM with 3DCustomizer**		**3DP**	
			from	***to***	***from***	***to***
Price of first investment for commissioning	**Price ranges / €**		1500,00	2500,00	60000,00	80000,00
Follow-up costs	**Price ranges / € kg^{-1}**		20,00	60,00	100,00	120,00
Market prices for 3D models Cf. 3ddruckpreisvergleich.de	**Price ranges / € cm^{-3}**		0,10	0,30	0,90	1,50
Velocity	**Pre- and rework**	Prework 6…little 1…much	6		6	
		Rework 6…little 1…much	6		1	
	Printing speed	Printing speed	appr. 30 min to print ab object with 25x25x25 mm		appr. 28 mm of building height per hour	
		Explanations	velocity is absolutely dependent of the volumina of the object		velocity is nearly independent of the volumina of the object	
		Rank evaluation	2		6	
	Whole rank evaluation		4,7		4,3	
Overall Accuracy			standard deviation from target object	0,201 mm	standard deviation from target object	0,145 mm
Surface quality			with reference to experiences and printed benchmark model	with reference to measurment results	with reference to experiences and printed benchmark model	with reference to measurment results
Multi-colour			1. currently, one color per model possible 2. several colors available 3. many kinds of material from other suppliers		1. multiple colors per model 2. full color-range available 3. no material from other suppliers	
Multi-material			1. currently, one material per model 2. a few materials available (PVA, ABS, PLA) 3. many kinds of material from other suppliers		1. only one material per model 2. not many different materials available, switching between materials is difficult and time-intensive 3. little variety of material from other suppliers - risky	
3D-model customization integration			full integration of 3DCustomizer		no 3DCustomizer integration	
Prework			EASY 1. using 3DCustomizer 2. customizing 3D model of choice 3. generating code of customized model 4. saving on SD card 5. printing		QUITE EASY 1. designing or downloading of model 2. starting AM-system-based software tool 3. alignment of models 4. printing	
Rework			1. putting out of printer 2. finished		1. removing loose powder 2. putting out of printer 3. removing rest of powder 4. infiltration 5. drying 6. no office room possible	
Complexity of 3D models			1. **high-complex models only to a certain extent possible** (due to the lack of support structures) 2. support structures will maybe be implemented in future		1. **high complexity possible** due to loose powder which acts like support structures	

Table 7: AM technology comparison details part 3, Reference: Own table.

APPENDIX 2: SCREENSHOTS OF 3DCUSTOMIZER



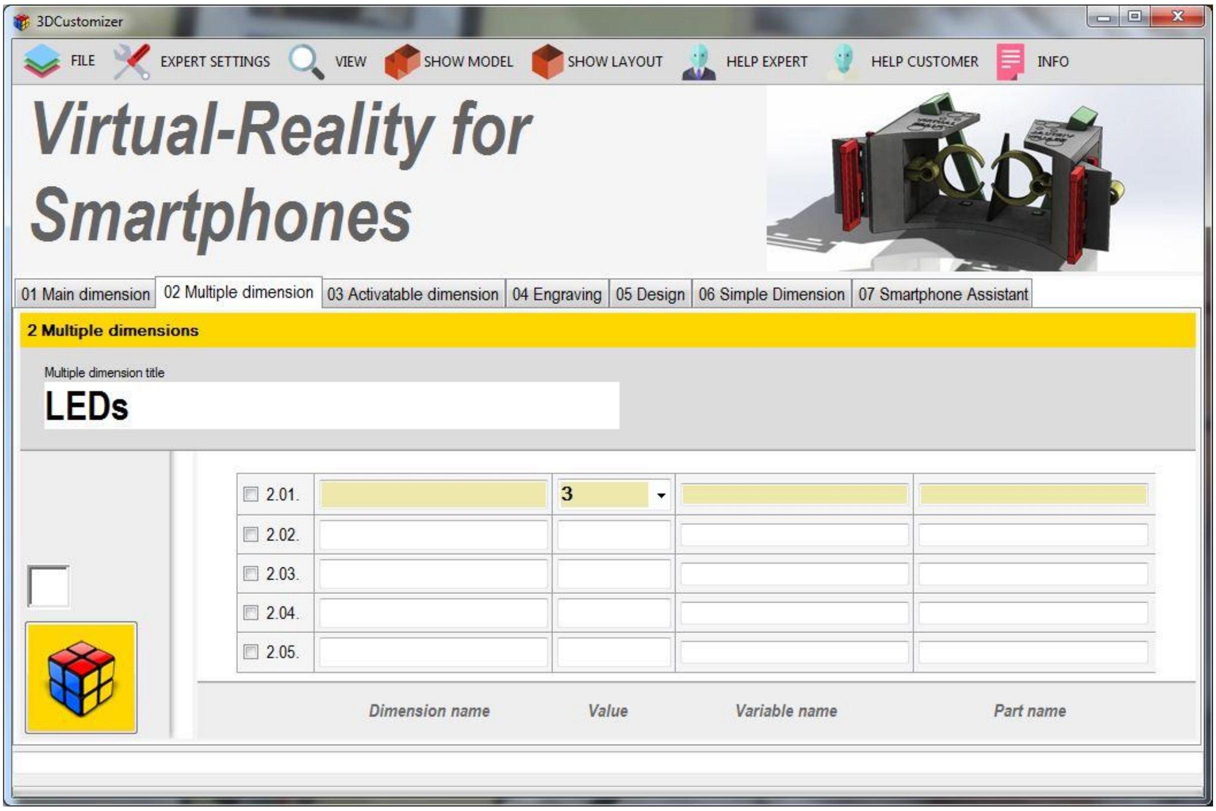
1 Main dimension

Main Dimension Name: Overall dimension

☑

	Dimension name	Value	Variable name	Part name
☑ 1.01.	Thickness top & bottom	4	D3@Skizze1	VR_Brille_Hauptteil_1
☑ 1.02.	Thickness left & right	10	D6@Skizze1	VR_Brille_Hauptteil_1
☑ 1.03.				
☑ 1.04.				

Fig. 62: Customization feature main dimension, Reference: Own illustration.



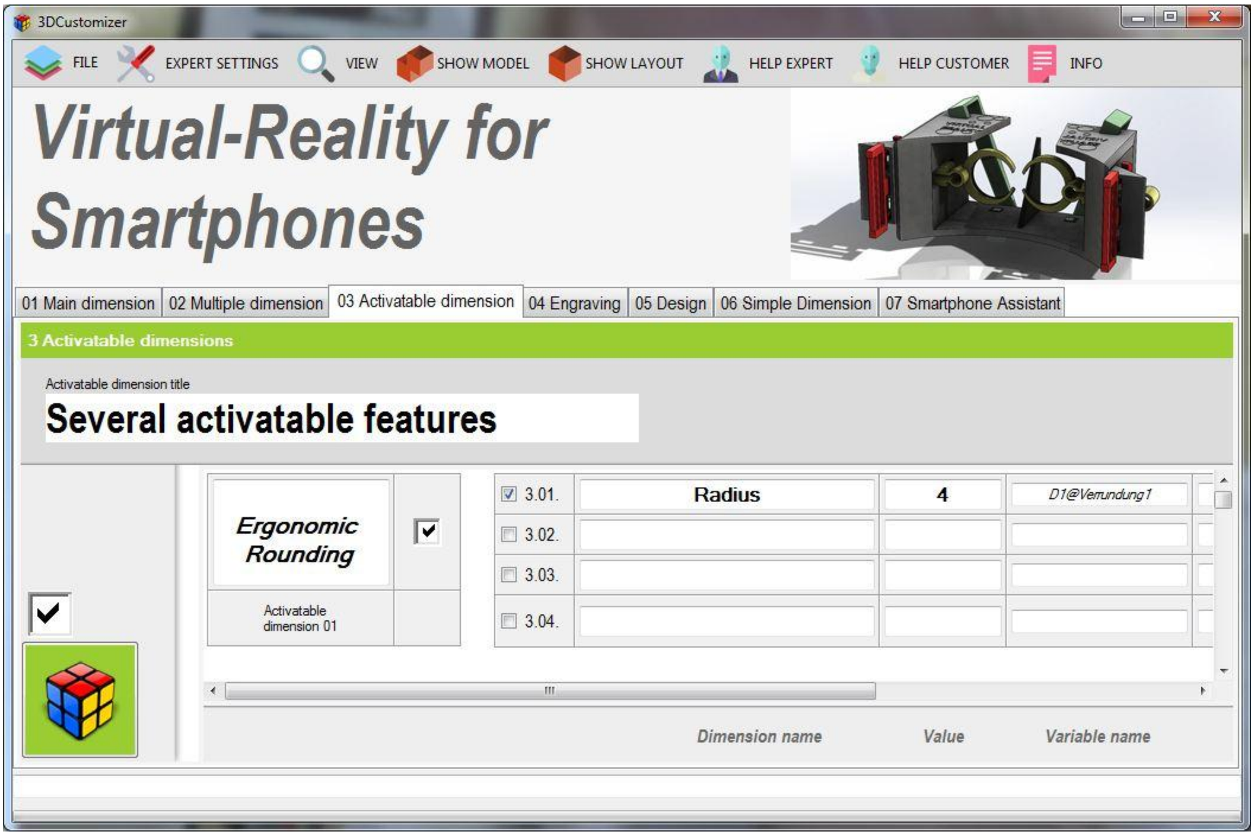
2 Multiple dimensions

Multiple dimension title: LEDs

☐

	Dimension name	Value	Variable name	Part name
☐ 2.01.		3		
☐ 2.02.				
☐ 2.03.				
☐ 2.04.				
☐ 2.05.				

Fig. 63: Customization feature multiple dimension, Reference: Own illustration.

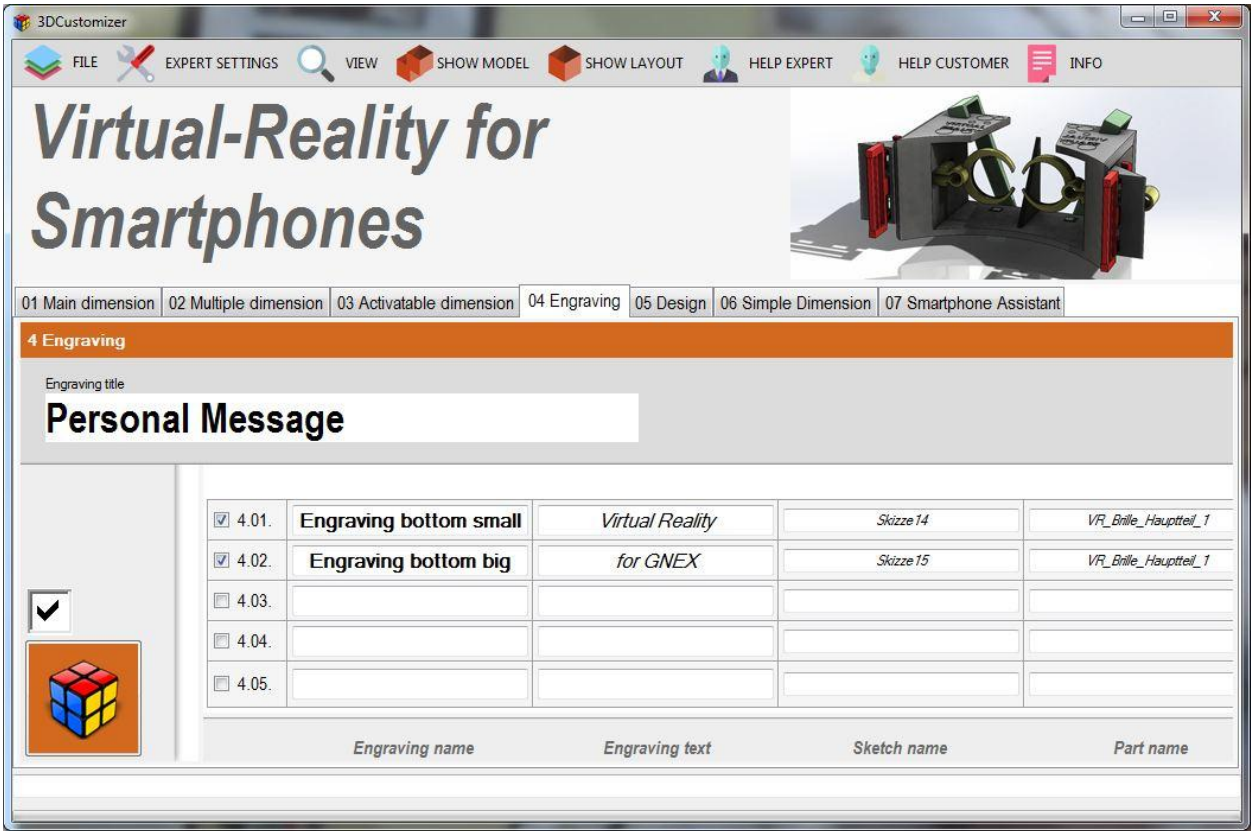


Activatable dimension title: Several activatable features

☑ Ergonomic Rounding ☑
Activatable dimension 01

	Dimension name	Value	Variable name
☑ 3.01.	Radius	4	D1@Verrundung1
☐ 3.02.			
☐ 3.03.			
☐ 3.04.			

Fig. 64: Customization feature activatable dimension, Reference: Own illustration.

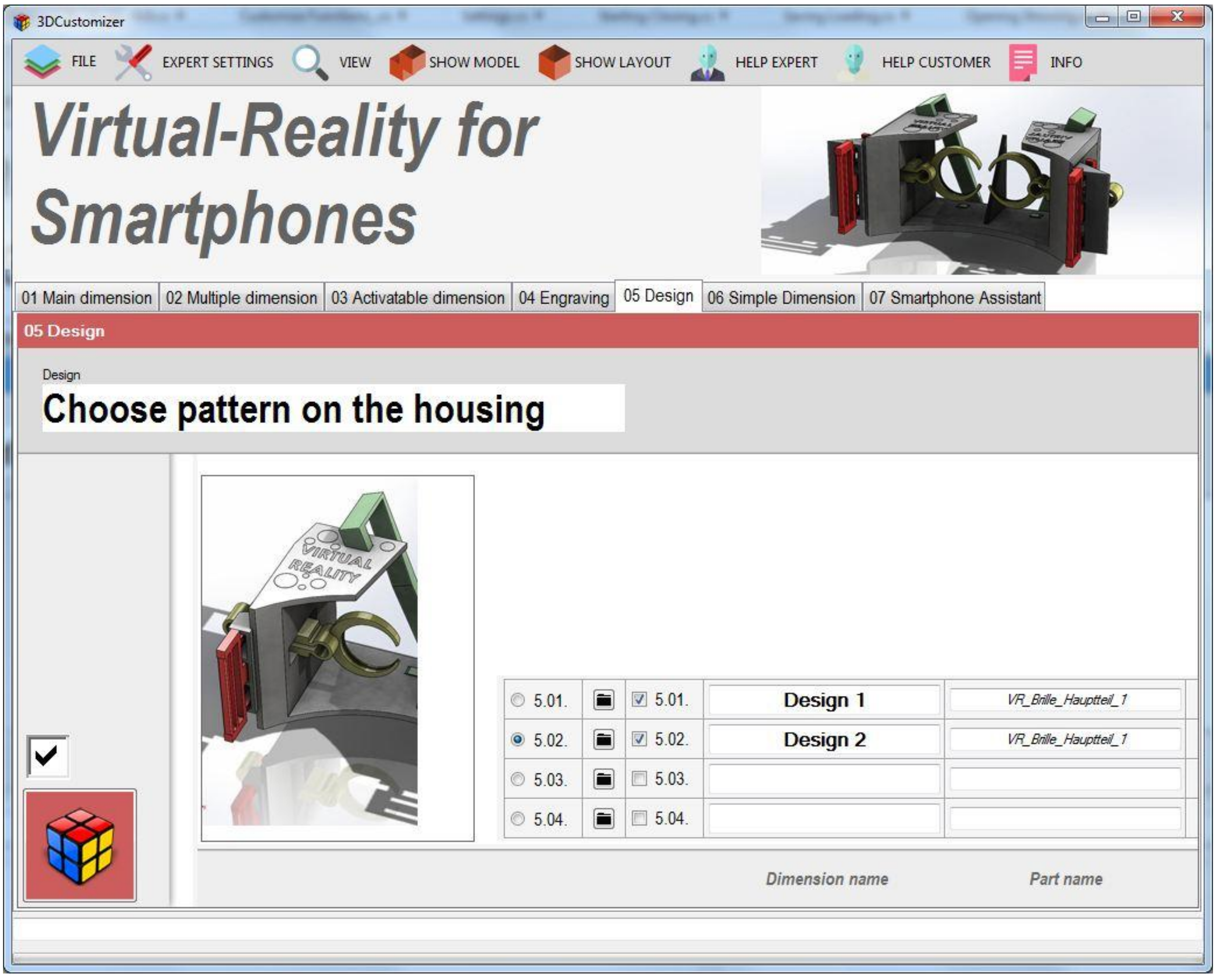


Engraving title: Personal Message

☑

	Engraving name	Engraving text	Sketch name	Part name
☑ 4.01.	Engraving bottom small	Virtual Reality	Skizze14	VR_Brille_Hauptteil_1
☑ 4.02.	Engraving bottom big	for GNEX	Skizze15	VR_Brille_Hauptteil_1
☐ 4.03.				
☐ 4.04.				
☐ 4.05.				

Fig. 65: Customization feature engraving, Reference: Own illustration.

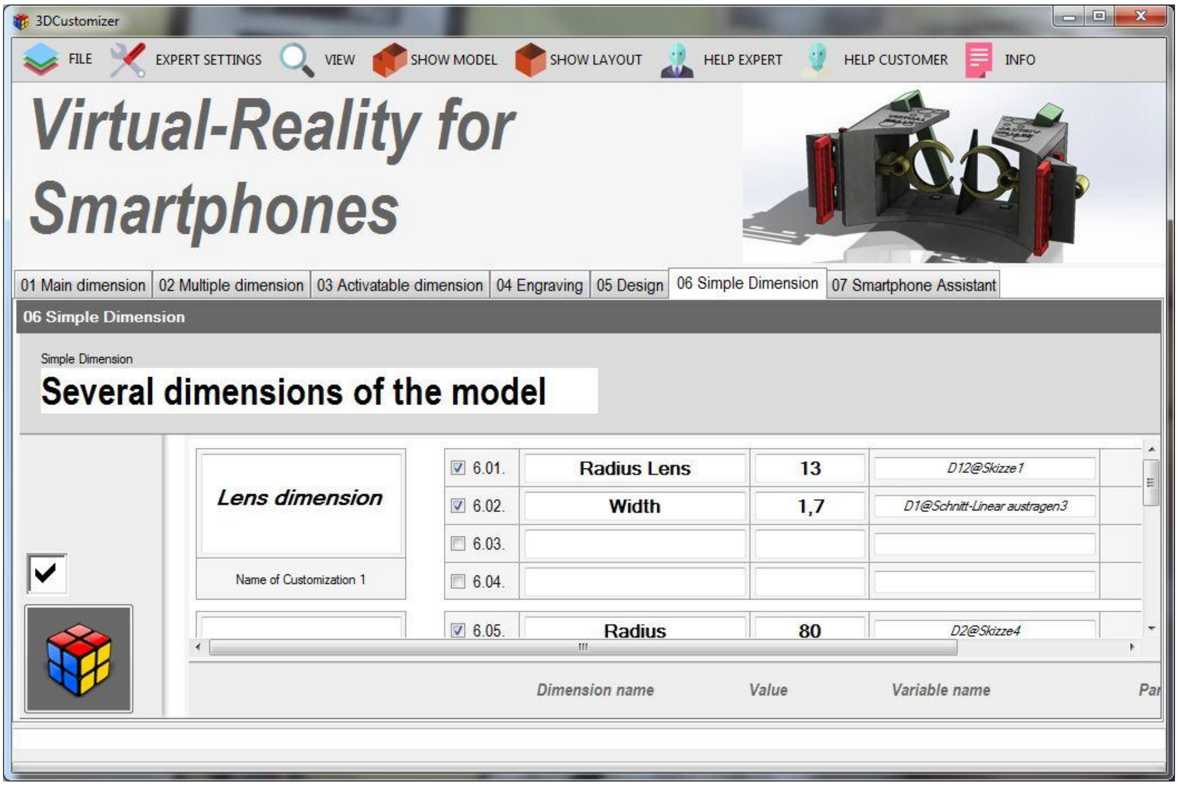


Design

Choose pattern on the housing

○ 5.01.		☑ 5.01.	Design 1	*VR_Brille_Hauptteil_1*
● 5.02.		☑ 5.02.	Design 2	*VR_Brille_Hauptteil_1*
○ 5.03.		☐ 5.03.		
○ 5.04.		☐ 5.04.		
			Dimension name	*Part name*

Fig. 66: Customization feature design, Reference: Own illustration.



Simple Dimension

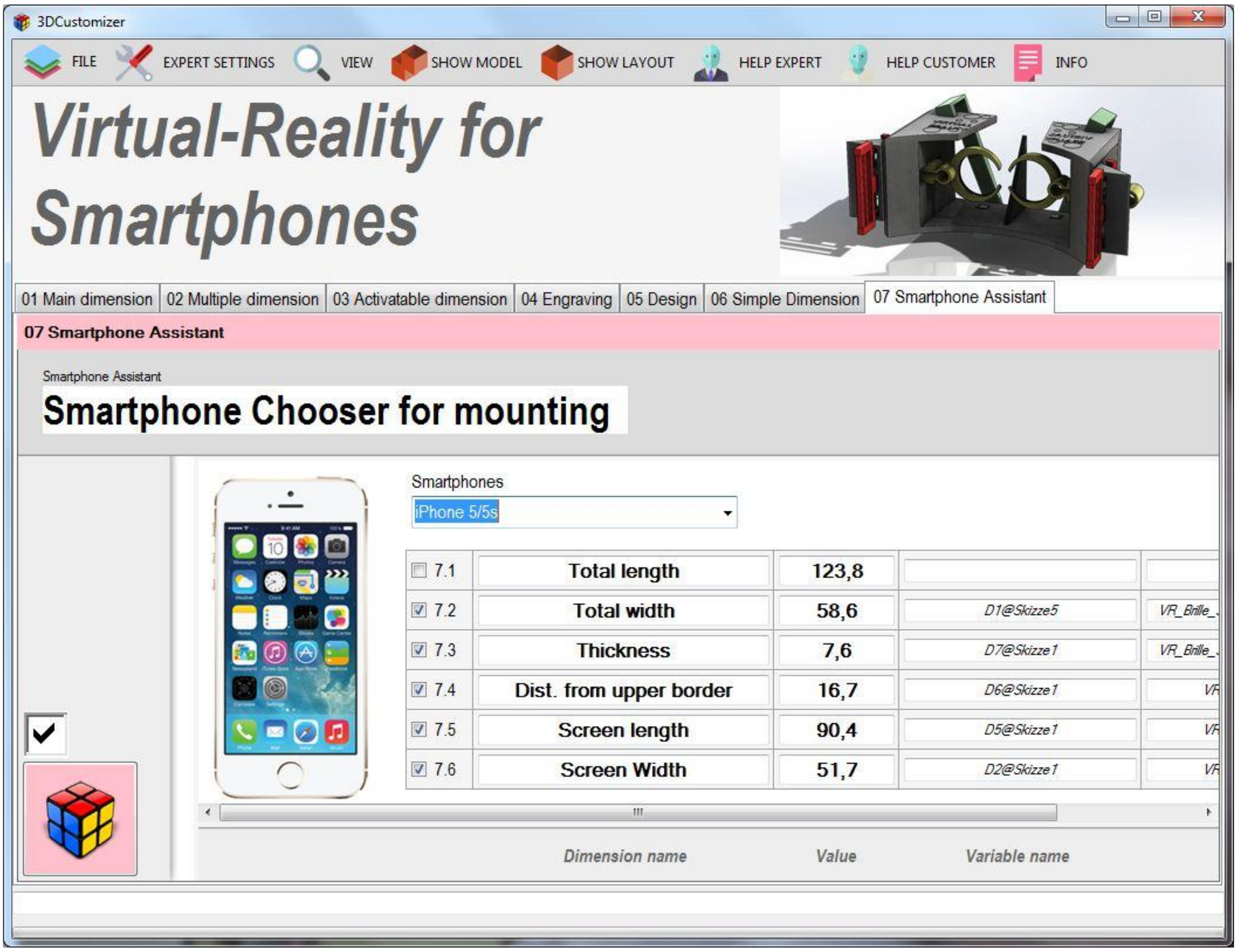
Several dimensions of the model

Lens dimension

Name of Customization 1

☑ 6.01.	Radius Lens	13	*D12@Skizze1*	
☑ 6.02.	Width	1,7	*D1@Schnitt-Linear austragen3*	
☐ 6.03.				
☐ 6.04.				
☑ 6.05.	Radius	80	*D2@Skizze4*	
	Dimension name	*Value*	*Variable name*	*Par*

Fig. 67: Customization feature simple dimension, Reference: Own illustration.



07 Smartphone Assistant

Smartphone Assistant

Smartphone Chooser for mounting

Smartphones: iPhone 5/5s

	Dimension name	Value	Variable name	
☐ 7.1	Total length	123,8		
☑ 7.2	Total width	58,6	D1@Skizze5	VR_Brille_
☑ 7.3	Thickness	7,6	D7@Skizze1	VR_Brille_
☑ 7.4	Dist. from upper border	16,7	D6@Skizze1	VR
☑ 7.5	Screen length	90,4	D5@Skizze1	VR
☑ 7.6	Screen Width	51,7	D2@Skizze1	VR

Fig. 68: Customization feature Smartphone assistant, Reference: Own illustration.

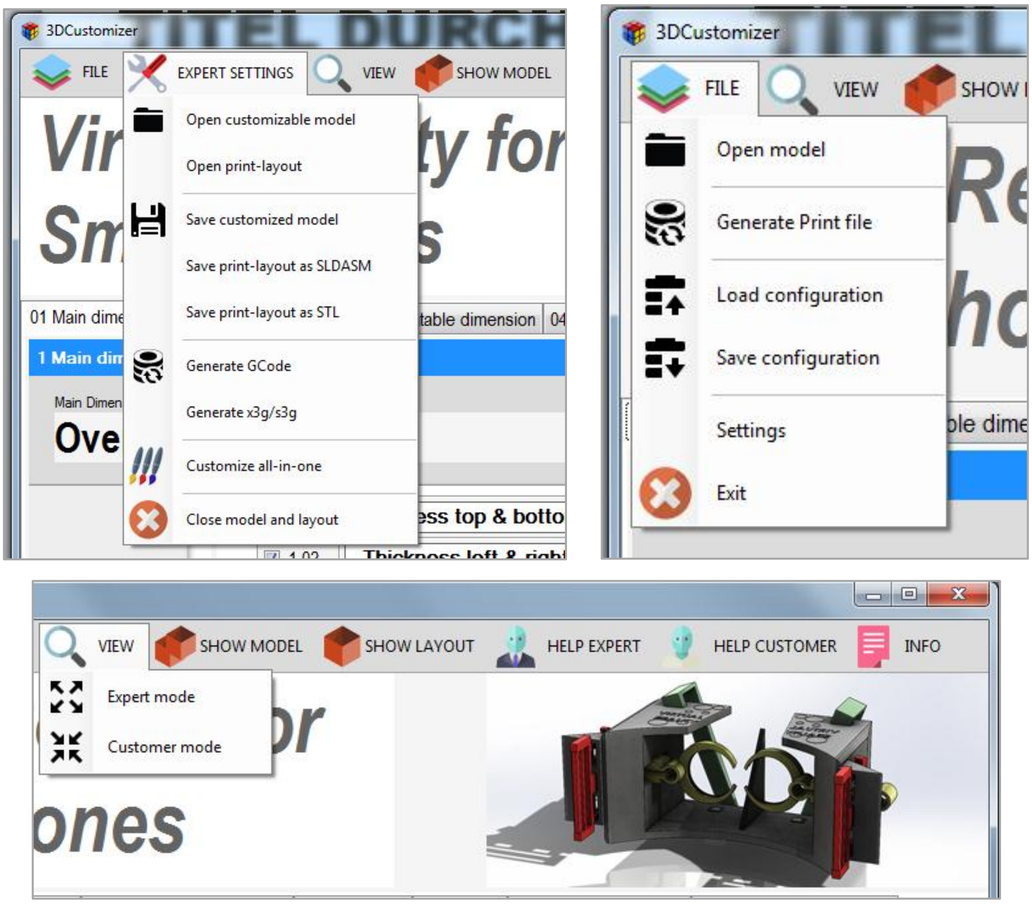


Fig. 69: Example of action bar menus, Reference: Own illustration.