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Framer: A Personal Design Tool for 3D Picture Frames

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I hereby declare that I have created this work completely on my own and used no other sources or tools than the ones listed, and that I have marked any citations accordingly.

$\overline{Aachen, March 2013}$
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Abstract

This thesis introduces existing software for 3D object construction in a 2D environment as a result of the development of personal fabrication. With CAD software like OpenSCAD, the user creates new 3D objects. With 3D object creators like Makerbot Customizer, the user changes shapes and details of already existing objects. With 3D object libraries like Thingiverse, the user can upload and share his design with other people. The benefits and limitations of existing software are discussed, upon which a new software *Framer* is proposed.

The motivation to invent such a program like *Framer* and determined requirements are considered in a survey. The system and several iterations of the design are described, containing a user study with a paper prototype, all resulting in a usable program. The usability of *Framer* is outlined in a user study, which was conducted with a software containing the elements relevant to designing a 3D frame. The results indicate that *Framer* supports personal fabrication to be more common in humans everyday life and simplifies creating 3D frames together with printing them. This is evidence which supports the idea of designing such a program.

Überblick

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Thank you,

– Verena Kuhr.

Chapter 1

Introduction

In my bachelor thesis, I will discuss the rise of personal fabrication and the necessity of good software to make these factories affordable and desirable for mainstream people. In chapter 1.1—"The Development of Personal Fabrication", different kinds of 3D printers and new factories are presented. This is combined with the topic in chapter 1.2—"Digital Photos", where personal printing is discussed. These two chapters result in chapter 1.3—"Thesis Overview", where I render the context of my thesis. There, I introduce my program Framer as a personal design tool for 3D picture frames.

1.1 The Development of Personal Fabrication

Currently, a new digital revolution is taking place, where individuals can design goods on their own (Mota [2011]). This Do-It-Youself (DIY) movement yields public access to digital fabricators like 3D printers, which fabricate 3D objects from a digitally designed model. To obtain such a model, different kinds of software, as well as blueprint-databases exist. These are explained in chapter 2.

Mass production and consumption is peaking more than ever. However, a growing number of people have the

Printing objects with a 3D printer started the developement of personal fabrication.

knowledge to create digital designs for artistic, personal, and commercial purposes and the opportunity to turn these designs into materialized objects with the aid of 3D printers. A 3D printer constructs an object by plotting it layer by layer. These layers accumulate to the desired 3D object. In chapter 1.1.1—"Different Kinds of 3D Printers", different possibilities to construct a 3D object are explained. While in 2001 a 3D printer was very expensive and not in an acceptable price range for the normal working class, it become cheaper over time. With today's technology, the 3D printers can make objects out of materials such as thermoplastics, ceramics, and out of metals like steel or titanium in powder. It is possible to produce many different 3D objects, or just a few unique parts. Therefore, digital fabrication plays an important role in the expansion of micro production and mass customization. Another advantage is the chance to print an object in one single piece which otherwise has to be manufactured in several parts and assembled afterwards. However, the technology is not elaborated yet and therefore there are some disadvantages. The speed is not comparable to traditional mass production techniques like injection molding. Furthermore, most digital fabricators only make parts out of one material type at a time. This limits the the number of products that can be manufactured with a 3D printer.

1.1.1 Different Kinds of 3D Printers

FDM technology for rapid prototyping, where melted material is formed to a 3D object.

Different processing techniques have been developed to fabricate 3D objects. Today, one rapid prototyping technology is **Fused Deposition Modeling (FDM)** (Hutmacher and Tan [2001]). FDM[1] was developed by S. Scott Crump in 1980. In 1990, it was commercialized. A plastic filament is wrapped around a coil. This material (polymer, polycarbonate, polycaprolactone, polyphenylsulfones or waxes) is then forwarded to an extrusion nozzle via drive wheels. The heated nozzle melts the material to extrude it. This part of the construction is moved in horizontal and vertical directions to form layers. The layers harden immediately

[1] http://rpworld.net/cms/index.php/additive-manufacturing/rp-rapid-prototyping/fdm-fused-deposition-modeling-.html

after extrusion because of the cooled platform. A representation of the important parts of the machine is shown in figure 1.1. The support material of a 3D Printer[2] fills the areas which are hollow in the final object. The support material is dissolved in a base after printing.

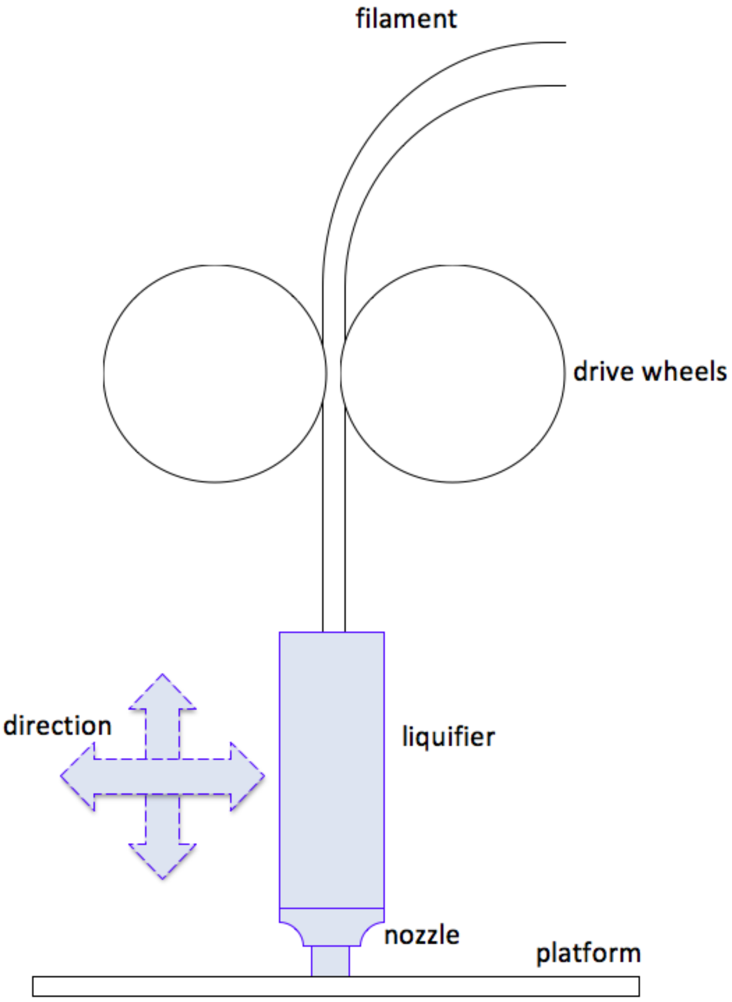

Figure 1.1: Representation of an FDM extrusion head.

SLS technology for complex structure prototyping, where 3D objects are formed with powder.

To make complex structure parts for prototyping, the **Selective Laser Sintering (SLS)** is used. SLS[3] was developed

[2]http://hci.rwth-aachen.de/3dprinter
[3]http://rpworld.net/cms/index.php/additive-manufacturing/rp-rapid-prototyping/sls-selective-laser-sintering.html

and patented by Dr. Carl Deckard in 1989. With this machine, a high power laser fuses small particles of plastic, metal (steel, titanium, alloy mixtures, or composites), ceramic, or glass powders into 3D objects. This process is called sintering. The objects are created layer by layer, the same as with FDM technology. Unlike FDM, SLS does not require support structures because the 3D objects are surrounded by unsintered powder at all times. Figure 1.2 shows the important parts of the SLS machine. Powder moves from one magazine, over the work area to the other magazine. The laser traces out the layer. The laser does not move in vertical direction, because the work platform moves down by the thickness of the layers. Layer by layer the 3D object takes shape.

1.1.2 New Factories

Since 2007, a wider distribution of digital fabrication technologies permits a growing number of creators to produce goods on their own and circulate them outside of the manufacturing model (Mota [2011]). In the following the different ventures will be annotated.

Online Fabrication

With online fabrication the user can create a 3D object, share it, and let it be printed to receive it at home.

With online fabrication services, hobbyists can produce prototypes and parts, designers can get a small scale production, and consumers can create and edit a consumer product. Services such as Shapeways[4] contain upload-to-make conditions, where customers can upload their digital design and get the physical object in the mail a few days later. They also offer a community marketplace, where people can sell their design, web-based platforms for product customization, and databases of licensed designs. A closer look to this topic is given in chapter 2.2—"How to Create 3D Objects".

[4] http://www.shapeways.com/

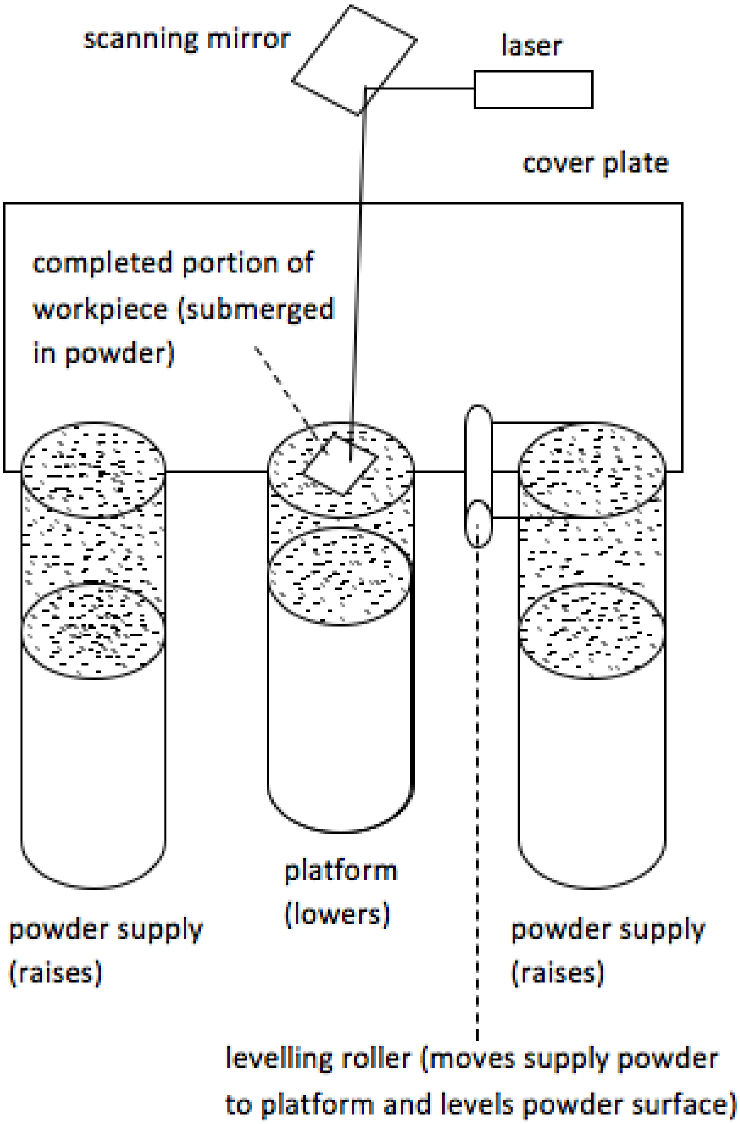

Figure 1.2: Representation of an SLS machine.

Distributed Manufactoring

Distributed manufactoring networks help users find local shops and equipment operators to print out their designs. Manufactures of open source personal fabricators, like MakerBot Industries,[5] setting up their first BotFarm, a

Distributed manufactoring supports finding a 3D printer.

[5] http://www.makerbot.com/

cluster of networked 3D printers. Soon 3D printers might be located in several points of the globe and people can choose the nearest place to print out their design.

Local Production

Fab labs are places that support local production.

Local production shops are at the beginning of their development. Fab labs[6] support local production with essential fabrication tools. Workshops help people work with these tools. Anyone can arrange an appointment and then create smart devices for themselves. More than 120 fab labs exist in the whole world and even more are planned (http://fab.cba.mit.edu/about/labs/).

Personal 3D Printers

Printers like RepRap are cheap and simple enough to build them and consequently have a personal printer at home.

3D printers have been getting smaller and cheaper over time, so the average individual consumer can have a personal 3D printer at home. These personal 3D printers are simple enough so that also someone with no technical skills can handle them. In 2004, RepRap[7] as a selfreplicating, highly affordable personal 3D printer accrued using the FDM technique for printing. It started open source, so all products' source material and blueprints were available for everyone. However, finding the material required for building a RepRap was very difficult. So in 2008, developers had the idea to create kits including instructions. These were developed by MakerBot and Bits from Bytes, and cost between 950 and 3900 dollar. This was the start for other industries to develope personal 3D printers, like UP! (2010, 2990 $) or Ultimaker (2011, 1700$). In the fab lab in Aachen, people are able to build a personal 3D printer[8] on their own for only 400 euro (534.60 $) material costs. As a direct successor of RepRap from Josef Prusa, this 3D printer was first built in 2011. It was the first workshop in Europe, where people could build their own 3D printer and therefore Josef Prusa came from Prague to help them.

[6] http://fab.cba.mit.edu/about/faq/
[7] http://www.reprap.org/wiki
[8] http://hci.rwth-aachen.de/meisterklasse

Large professional machines are now available for everyone through online fabrication services (Mota [2011]). However, there are still differences between professional machines and personal 3D printers. While professional 3D printers can produce complex objects with a lot of different materials, personal 3D printers are limited by the size of the object, cost, speed, resolution, overall quality, and the number of materials. Personal 3D printers can print a variety of plastics, but the majority of products in homes and offices are made out of a combination of different materials. At the moment, personal 3D printers cannot combine diverse materials. Until this problem is solved, there will be no large propagation of these printers. 3D printers are flexible in objects they print, but they are not very fast. Printing a plastic whistle takes 10 minutes, for example. The 3D printer can be unattended while printing, but operators have to wait until the object is finished.

Professional printers can print more complex objects in different materials.

Although there are these limitations, the current state of personal 3D printers can be compared with the early days of personal computers. Personal 3D printers are rapidly transitioning from a tech hobby to a functional technology for everyone.

1.1.3 DIY Movement

Professional computer aided design (CAD) software is complex (Mota [2011]). A lot of time is needed to become a skilled CAD user, which decreases the number of people, who would work with such software. However, like it happened with digital imaging applications, which were very complex at its beginning, simple and free modeling applications for 3D modeling are becoming available. These software products advance the DIY movement. DIY is the act of creating, producing, modifying, or repairing by non-professionals. It is influenced by social computing and online sharing tools. All in all, technology that allows us to design complex objects will soon become as widespread and customary as the technology we use to manage data.

CAD software advances the DIY movement.

1.1.4 Factories at Home

A new user group and a new motivation for printing 3D objects could help to get a mass adoption of personal pabrication.

Digital and physical tools are available to the public and a small number of people already use these technologies for personal and micro production (Mota [2011]). To get a mass adoption of personal fabrication, we have to know what people want to fabricate themselves. With this motivation, the technology used by pioneers and hobbyists can be changed to an everyday tool for mainstream consumers and businesses. In a few years, there will be personal manufactoring technologies, which will be located in schools and small businesses and after that they also will be in offices and households. At the moment, there are two different groups of users who work with personal fabricators. On the one hand, there are the technical hobbyists, who are exited about the technology. On the other hand, there are the artists, designers, and makers, who are interested in what they can create. So the question is which other self-motivating, self-educating, and self-organizing group would own and use a digital fabricator. In addition to the group of users with the right motivation, there are two other important points that might influence a widespread adoption of personal fabricators. First, there is the advantage of creative remixes and mashups, where the users have the chance to combine different models like it is already a common practice with photos. Second, there is also the advantage of turnaround time which is less than waiting two or more days for the product to arrive in the mail. When personal fabrication tools get more efficient, this becomes an increasingly important motivation to have a fabricator at home or at the office.

In general personal fabrication has a lot of advantages, which will be enhanced, when personal fabricators become more popular. A whistle designed in Germany can be used by someone in New York in as little as 15 minutes. A replacement part can be fabricated for a few cents, avoiding the repair of the whole item which can cost hundreds of dollars.

Fab@Home

The Fab@Home project is an example of how factories could be invented at home (Malone and Lipson [2007]). Even though this project yielded an aparat for laser cutting in 2007, it shows the possibility to cut or print a 3D object at home. One big advantage of this project is the simple software (a PC application for Microsoft Windows, using Microsoft Visual Studio.Net for developement environment and OpenGL for graphics rendering) so that people, who have no technical background, can learn to exploit these design tools. This aspect is not yet mentioned by personal 3D printers.

Fab@Home project includes a lasercutter and a 3D printer with a software to design 3D objects.

1.2 Digital Photos

These days, digital cameras are widely available and as a result, people have large personal collections of digital photographs (Rodden and Wood [2003]). While photos used to be printed out and put in albums, now they are stored on the computer. With a better possibility to browse the photos and a simpler way of reordering them, albums become less important. Even though people photograph more often since they have a digital camera, they still want to have printouts of their photos, or at least the most recent ones in order to show them to familiy and friends. The photos will be printed out at the highest possible quality, so they can be added to their existing collection of special photos.

Digital photos are printed to show to family and friends.

These printed photos can decorate homes in photo frames or be given as a gift (Kim and Zimmerman [2006]). Sharing narratives of events and experiences, and preserving legacy are the key motivations for families to make photos and display them at home. Photos can be divided into two groups. On the one hand, there are the formal photos, taken professionally or by a family member and gather a theme. These are placed in living rooms, entryways, and bathrooms. On the other hand, there are informal photos, which are personal and capture the moment. These photos are placed in bedrooms, family rooms, and in the kitchen.

There are formal and informal photos which are put in different places.

In general, formal photos are more up to date than informal photos and are often used to start a conversation. All these photos are in photo frames and therefore are seen more often than digital ones.

However in general, people do not often change the photos they display in frames at home because of the effort involved. They have different kinds of photos for different places at home to represent their family and stimulate social interactions. Having such individual photos leads to the motivation of designing picture frames on their own.

1.3 Thesis Overview

The main contribution of this thesis will be the design of a usable program called Framer, that enables non-professional designers to generate an individual picture frame on their own.

The following chapter provides an overview of the already existing software for designing 3D objects and different file formats to store them in. Tables compare the different kinds of software and show which characteristics will be adopted by Framer. In chapter 3, the research questions and the resulting requirements are listed and a survey is performed to show the motivation of this project. Additionally, this chapter elaborates the system implementation and its outer appearance including a first user study with a paper prototype and the description of a second user study with the finished software. The results and the analysis of the second user study are explained in chapter 4. The last chapter provides a summary of the whole work and describes possible future development.

Chapter 2

Related Work

In chapter 2.1—"How to Print in 3D" a short overview of the printing process with its techique is given. Furthermore the standard format STL and the new advanced format AMF to save 3D objects is described. After this, different types of software to design 3D objects are presented in chapter 2.2—"How to Create 3D Objects" to invent practices that I can assume in my work.

2.1 How to Print in 3D

To print a 3D object, the digital object must be a volume model (Fastermann [2012]). A volume model is closed on all sides and has to be solid. In the example in figure 2.1, a volume model is shown on the left side. With this volume model, it is clear where to print the material. On the right side of the figure some sides are not closed. This is called a shell model and can be used for figures in computer games. It is not possible to print this model because it is unclear where the printer has to stop printing. Good software is important to create these volume models. This software can be expensive and for special needs, or cheaper and for different purposes.

Create a volume model with CAD software to have a printable object.

CAD programs like Netfabb[1] have reparation routines to

[1] http://www.netfabb.com/

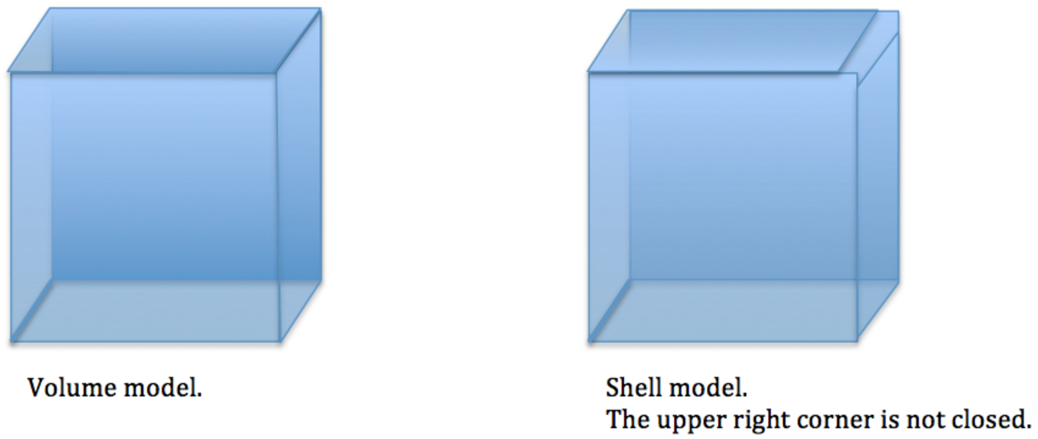

Figure 2.1: Example of a volume model (left) and a shell model (right).

Software like Netfabb contain reparation routines that detect and remove errors.

find logic failures in the designed objects (Fastermann [2012]). Another possibility is to export the object in a standard format (STEP, IGES or DWG) and then import it in the CAD software again. Furthermore this way improves the quality of the model by detecting and removing rounding errors (miscalculation of facets) and transformation errors (miscalculation of geometry).

2.1.1 STL

STL is a standard file format, which presents a 3D object in many triangle facets.

STL means Surface Tesselation Language or Standard Triangulation Language (Hiller and Lipson [2009]). STL is the industrial standard file format that is used by nearly every 3D modelling software. For the last two decades it has been used to transfer information between the program and the software that is used by 3D printers. First the object gets changed to a net of triangular areas and then exported as an STL file, which is the standard interface of current CAD systems (Fastermann [2012]). The surface of the 3D object is figured as triangle facets that have three vertices and a surface normal. The surface normal shows which side of the surface is outside and which one is inside, based on the right-hand rule. With the rigth-hand rule the points of a triangle define the orientation (Figure 2.2). Because of these facets, curved areas can only be approximated. The more facets exist, the more precise the object is, which results in a bigger file. The STL files can be saved in ASCII- or in Binary format, where the ASCII format is human readable and the binary format leads to smaller files. The maximum file size is between 40 and 80 megabyte. But files bigger than 25 megabytes in binary format have a too big resolution of the facets, so that not every detail can be printed with a 3D printer. A disadvantage of STL is the fact, that

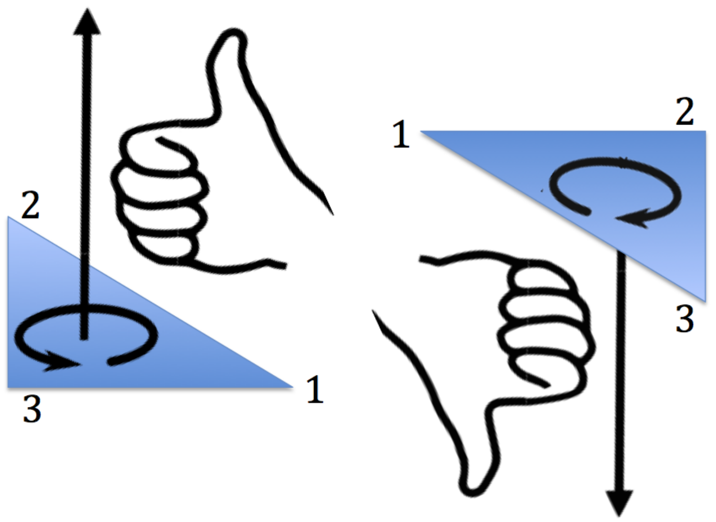

Figure 2.2: The right-hand rule defines the orientation of a triangle with the order of its points.

the files have no information of scale unit. So the export can be in inches instead of millimeters which makes the file too small. STL only has information about surface mesh but no information for representing color, texture or material (Hiller and Lipson [2009]). The STL format is simple, portable, and has sequential memory access. Even though advantages exist, the geometry leaks, no specific units, unnecessary redundancy, poor scalability, and the lack of auxiliary information leads to the need of a new file format.

2.1.2 AMF

The STL format was the industry standard for transferring files between design programs for over two decades (Hiller and Lipson [2009]). Other formats were not needed because

AMF allows resolution independent specifications of geometry and material properties.

firstly, there was no technology developed which needed functionality past what the STL format offered. Secondly, other file formats include features that were irrelevant for the Additive Manufacturing (AM) field.

With new technological developments like multiple and graded materials and surface colors there was the need of a new file format (Hiller and Lipson [2009]). The Additive Manufacturing File (AMF) format allows resolution independent specifications of geometry and material properties. It is technologically independent because of the general description of an object so that any machine can build it and the resolution and layer-thickness is independent. The simplicity allows the user to read and debug the file without any problems. Regarding the scalability, AMF handles large arrays of identical objects, complex repeated internal features, and multiple components are optimally arranged in packets. Concerning the rapidly changing industry, the systems also allows adding new featues and therefore is future compatible.

AMF stores the information in XML, which is smaller than the ASCII STL file.

The information of the files is stored in XML format, a widely accepted data format for creating, viewing, manipulating, and storing AMF files (Hiller and Lipson [2009]). This human readable ASCII XML gets compressed in a postprocessing step with optimized standardized compression routines. To compare STL and AMF files, the sample mesh geometry of a rook with 3680 triangles is given (example from Hiller et al. 2009). The XML text file is about 44% smaller than the ASCII STL file. After compression, the AMF file is 25% smaller than the binbary STL file. Compressing the binary STL file leads to a file that is 48% larger than the compressed AMF. This data is shown in figure 2.3. The AMF format is easily forwards and backwards compatible with STL files.

Top Level Tags

One top level tag covers the usefulness of an STL format.

The following top level tags show that only one single object tag is sufficient for a fully functional AMF file that covers the usefulness of the STL format. <*Object*> defines one or more regions of material having a material ID for print-

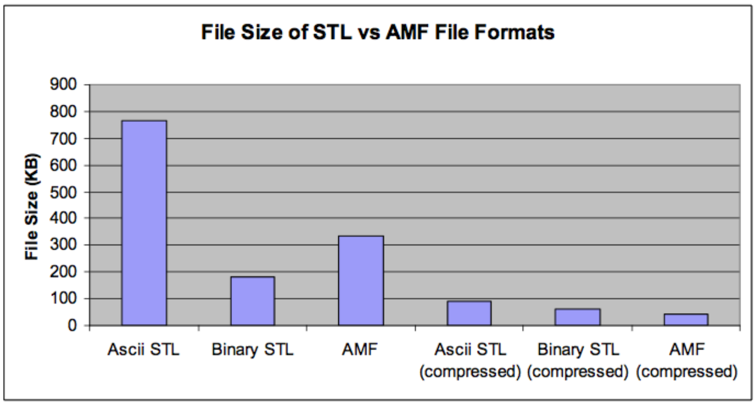

Figure 2.3: Size of STL and AFM formats in original and in compressed form [Hiller et al. 2009].

ing. A <*Color*> tag can be introduced at this level to determine the color of each region. <*Constellation*> combines objects and other constellations in one model for printing. If no constellation is given, each object will be imported without relation. <*Palette*> names one or more different materials with the material ID. If no palette tag is given, a single default material is used. <*Print*> gives the information about the objects that should be printed. The print tag is only necessary for multiple constellations.

2.1.3 The Printing Process

After the object is designed with a CAD program and exported in an STL or AMF file, it can be printed out (Fastermann [2012]). In the printing process, the heated filament is printed layer by layer on a platform (FDM in chapter 1.1.1—"Different Kinds of 3D Printers"). When there are areas that have no connection, support material is needed. Because the layers are still warm and not hard when the next layer is printed, both layers can be mixed. Therefore, a rough area is left behind when the objects are cleared from the support material.

2.2 How to Create 3D Objects

There are different kinds of software to create 3D objects. With CAD software, the user has the possibility to create new 3D objects. With 3D creators, the user can edit the shape and the details of an existing object. 3D libraries enable the users the opportunity of downloading existing 3D objects and printing or manipulating them with different software. In the following three subchapters, these different types of software will be introduced in order to show what already exists. Tables will compare several details and show which properties will be applied in Framer. These properties will be mentioned in the requirements of Framer in the next chapter.

2.2.1 3D Object Library: Thingiverse

Thingiverse contains different objects that are uploaded from users.

Today, there exist a lot of communities, where people can upload their models and share them with other users, or get inspiration by others' work. The most popular one is Thingiverse.[2] Since 2008, users can freely upload and share files that contain 3D models, so that everybody can benefit from them. In the Thingiverse Library[3] the user has several categories he can choose from to see different kinds of 3D models. Furthermore he can explore different things, different collections, and different apps other users uploaded. So the user can get inspired and download models he would like to have. "Categories", "Collections", and "Customizable Things" show the same models in different combination. In Categories, the user can distinguish between 3D printing, which shows models that can help 3D printing, art, fashion, gadgets, hobby, household, learning, models, tools, toys, and games. Collection shows different kinds of the same model like the collection lego shows different lego stones. In Customizable Things, the models are shown in no special order. To explore apps, the user is directed to a sample of different apps.

[2] http://www.thingiverse.com/
[3] http://www.thingiverse.com/categories

2.2.2 CAD Software for 3D Objects

According to A. Valero-Gomez and Salichs [2012], CAD software follows the WYSIWYG (what you see is what you get) scheme, where content is displayed on a screen exactly as it will look when it is printed out. With programs like Blender,[4] files can be enhanced with artistic orientation, animations, and textured forms (Fastermann [2012]). With its rendering engine a scene gets lighted and special camera coordinates can be specified. With these coordinates, these programs scan the scene and calculate the apperance of an object (Blain [2012]). Because of the light parameters, the shadows and the surface of the objects get defined.

CAD software like Blender generates a 3D object in a 3D environment displaying it on a 2D screen.

OpenSCAD

With OpenSCAD,[5] the user has the possibility to define the object in a script language for Linux/UNIX, MS Windows, and Mac OS X (Fastermann [2012]). It is developed for automatic and parametric model generation. With a commandline, the user can render 3D objects and export them to different file formats like STL. Because of the script language, OpenSCAD follows the WYGIWYM (what you get is what you mean) sheme (A. Valero-Gomez and Salichs [2012]). The contents are written according to their meaning and not according to their apperance. Therefore, users are forced to understand the geometry of those objects. Another advantage is the ease of sharing the designs.

With OpenSCAD the user can define an object in a script language.

TinkerCAD

TinkerCAD[6] is a browser based software and is therefore platform independent (Fastermann [2012]). The user can compose different standard objects like spheres by picking up meshes, merging them together, or removing shapes from a mesh. The user can also do linear transformations.

In TinkerCAD objects can be built by picking up meshes and merging them together.

[4] http://www.blender.org/
[5] http://www.openscad.org/
[6] https://tinkercad.com/

The resulting 3D objects can be exported as STL files and broadcasted to print contractors. To share the objects online, there is a direct link to Thingiverse from the TinkerCad web page. (B. Pettis and Shergill [2013]) On Thingiverse, the models can be reviewed and used from other users.

Google Sketchup

Google Sketchup offers different shapes that can be merged and edited with different tools.

Google Sketchup[7] was developed for modeling buildings, but can also design other objects nowadays (Fastermann [2012]). It exists for Windows and Mac OS X. The commercial software Google Sketchup Pro has the possibility to export STL files and other formats. Google Sketchup has an easy learning curve because the interface is simple and the tools are similar to other software (like Microsoft Paint) used on Windows (Singh. [2010]). Like in TinkerCAD, the user has different objects like circles, or rectangles that he can merge. With a special button these objects can be pulled from 2D to 3D objects defining its size with a ruler.

Figure 2.4 sums up the different kinds of CAD software that were described in the sections above. It also shows which ideas of the software are inherited in my program Framer.

2.2.3 3D Object Creators

3D object creators provide special objects that can be edited by the user.

With 3D object creator software, the user has a 3D object at the beginning, that can be edited and expanded with different shapes. Except Autodesk 123D, all following creators are browserbased and therefore platform independent. Most of the following software is free, only the printing costs and the costs to deliver the product have to be payed.

[7] http://www.sketchup.com/intl/en/index.html

Program	open source	free	support STL	low learning curve	WYSIWYG	Properties that will be inherited by Framer
OpenSCAD	✓	✓	✓	✗	✗	export in different file formats, use OpenSCAD to generate 3D object
TinkerCAD	✓	✓	✓	✓	✓	merge different meshes
Google Sketchup (Pro)	✓	✓	✓ Pro	✓	✓	tools similar to other programs, new panel for colors and textures

Figure 2.4: Different CAD software.

Autodesk 123D Creators

Autodesk 123D offers different creators where users can edit existing objects in different ways.

Autodesk[8] 123D is for 3D volume modeling with an easy intuitive surface, with free design files and video tutorials. (Fastermann [2012]) This software is for Windows and Mac. Autodesk 123D cooperates with companies, where the user can upload a design and has the possibility to print the model in different materials. To share different models between users, Autodesk 123D Gallery can be used. This program supports STL files. There are also enhancements shown in different decoupling programs of Autodesk 123D, called creators: **Autodesk 123D Skulpt**[9] is an iPad application, where users can push, pull und paint a model with gestures. These gestures are performed with fingers on the iPad. With **Autodesk 123D Catch**[10] the users have the possibility to create 3D objects by taking photos of an object in different angles. With cloud computation and rendering techniques, these photos get transformed to a virtual 3D model. Then this model can be enhanced like it is possible with Autodesk 123D. The **Autodesk 123D Make**[11] application allows the user to upload a 3D model which then is converted to a LOM (Learning Object Metadata) solid model (Connolly [2011]). This model is a combination of 2D cut patterns in various materials with assembly instructions to make a 3D object. The user can see with which patterns his object is created, or recombine these patterns

[8] http://www.123dapp.com/
[9] http://www.123dapp.com/sculpt
[10] http://www.123dapp.com/catch
[11] http://www.123dapp.com/make

to create a new object. **Autodesk 123D Creature**[12] gives the user the opportunity to create special characters. The user can adjust the shape of the creature by adding, repositioning, and scaling limbs. To edit the surface the user can add colors or textures (using images).

Shapeways Creators

Setting a few points in Coockie Caster creates a 3D object. Dragging points in Sake Set creates different cups.

There exist several Shapeways creators[13] for different purposes. With Cookie Caster, the user can make individual cookie cutters by setting a few points. These points then transform to a 3D object. Sake Set shows already existing 3D objects of cups and tumblers. These objects can be edited by dragging one of the five points to change the shape and pulling two sliders for the smoothness and the twist of the shape. With 2D to 3D the user can upload a simple black and white image in jpeg which than is transformed to a 3D model. Several parameters can be set to define the size. There are several more creators that work with the same scheme to provide different ideas.

Cubify Creators

With Cubify Creators the user can add several shapes in different sizes to create bracelets or rings.

Like Shapeways, Cubify[14] also offers several creators. Cubify differs its creators in "print at home" creators, which are simple and only in one color and "we print for you" creators, which are more complex and include different colors. With Cubify Bracelets the user can choose a shape and a size (XS, S, M, L, XL) and add them with different other shapes. These options are realized by pressing different buttons. Cubify Pics gives the user the possibility to get a picture as a 3D object. The user first can choose a frame, upload a picture, which can be zoomed and rotated, and define how much detail is shown and how thick the object is via two sliders. The size cannot be changed otherwise and nothing more can be edited. The other creators work with the same scheme.

[12] http://www.123dapp.com/creature
[13] http://www.shapeways.com/create
[14] http://cubify.com/

OmNomNom

OmNomNom[15] is a desktop application for Mac that converts an image to a 3D object like "2D to 3D" from Shapeways. Here, the image must not be black and white. The colors the image has are inherited in the 3D object. The size and the number of levels can be changed. OpenSCAD contains the template of the 3D object.

Color picture is transformed to a 3D object via OmNomNom.

Miniature Moments

Miniature Moments[16] is a web application where a photo can be uploaded and a 3D miniature will be printed out and sent to the users home. The software creates a CAD model with the size of a passport photo, where a simple frame is added. In the frame, there is the photo with material on its top having a texture like the apperance of the picture. Nothing can be edited or changed, the user can only choose a photo.

With Miniature Moments the user gets a 3D photo in passport photo size.

MakerBot Customizer

MarkerBot Customizer[17] is a browser based application released in 2013, where users can edit objects by setting parameters and inputs. The user can design an object with OpenSCAD which, when it is uploaded to MakerBot Customizer, is available for every Thingiverse user. On the right side the 3D object is shown and on the left side the parameters are editable. The view of the 3D object can be changed with arrow buttons. The parameters then can be edited by the user or the whole object downloaded and printed with MakerBot Replicator 2 Desktop 3D Printer. Furthermore, the user can create an STL file. With the creator Customisable Spirograph Vase Generator, the user can edit a vase. The height can be edited with a slider, the number of segments can be choosen via a pull down list

Edit an object by setting parameters and using sliders in Makerbot Customizer.

[15] http://www.thingiverse.com/thing:24639
[16] http://www.miniaturemoments.com/
[17] http://www.thingiverse.com/apps

Program	free	support STL	Properties that will be inherited by Framer
Autodesk 123D	✓	✓	cooperate with company (Thingiverse), object shown as a combination of patterns
Shapeways Creators	✓	✓	set parameters to define size
Cubify	✓	✓	rotate object, edit image
OmNomNom	✓	✓	use OpenSCAD, able to change size of the whole object
Miniature Moments	✗	✗	automatic generated frame
Makerbot Customizer	✓	✓	connection to Thingiverse, using OpenSCAD

Figure 2.5: Different creator software.

and other parameters like base thickness, radius, and wall width can be set via typing. The model on the right side gets updated automatically. The other creators follow the same scheme.

Figure 2.5 sums up the different kinds of 3D object creators that were described in the paragraphs above. Like it is done with different kinds of CAD software, this figure shows which ideas of the creators are inherited in my program Framer.

Chapter 3

Own Work

Having a closer overview of the development of personal fabrication, different file formats, and different software to model objects for 3D printers, I will define my work in chapter 3.1—"Requirements From Related Work". In chapter 3.2—"Survey" the motivation and the need of my work is in the center of attention. To have the right design I evaluate a paper prototype in chapter 3.4.1—"User Interface Iteration: Paperprototype Validation", show the system design in chapter 3.3—"System Design", and the resulting design of Framer in chapter 3.4.3—"Resulting Design". At least, to have a good usability, I test the software in a user study (chapter 3.5—"User Study for Usability Testing"). The results and its analysis will be constituted in chapter 4—"Results and Evaluation".

3.1 Requirements From Related Work

After related software was introduced, the research questions, which will be pursued with my work are now explained.

3.1.1 Research Questions

1. How to make personal fabrication more common in humans everyday life?
    (a) Which new user group could be motivated to design 3D objects?
    (b) How to motivate users creating a special 3D object?
        i. How to simplify the design procedure?
    (c) How to simplify the possibility to print 3D objects?

The research questions get determined in the following requirements and answered in the survey and the studies.

Framer shall give the user more reasons to fabricate personal things and therefore make personal fabrication more common in humans everyday life. Whether Framer is a benefit for personal fabrication will be tested with a survey in chapter 3.2—"Survey" and in the last user study in chapter 3.5—"User Study for Usability Testing". The survey will also determine the new user group and show if this group is motivated to use Framer. To show that this software also simplifies creating a special 3D object (picture frame), there is a need of a good design which will be iterated in several user studies. To simplify the printing process of 3D objects there must be the possibility to have several ways to print a 3D model. All these requirements will be shown in the following three subsections.

3.1.2 Representation

The representation supports the simplicity of designing objects.

Framer is a desktop application that can save different file formats. This will give the user the chance to print 3D objects at different places. At the beginning, the user already has a rectangular frame which size and shape can be changed by the user. The user is also able to add different textures and shapes, which makes the frame more individual. More details will be shown in chapter 3.4—"Framer: The Design" and the underlying system will be explained in chapter 3.3—"System Design".

3.1.3 Usability

With Framer, the user has a simple, usable program. Existing shapes of the frame can be changed by typing in boxes to change special parameters. Additional shapes can be added, edited and deleted via buttons in a special window. When the user wants to be inspired by other users, he can import other designs that are shown in an additional window. This design is tested and evaluated in several user studies, which are described in chapter 3.4.1—"User Interface Iteration: Paperprototype Validation" and chapter 3.5—"User Study for Usability Testing". How fast the user should get an individual frame will be determined in chapter 3.2—"Survey".

The usability of the design is tested and evaluated in several studies.

3.1.4 Connection to 3D Printer

Framer is connected with Thingiverse which is a distributed manufactoring network. Thingiverse supports sharing, so that everyone can quickly document and showcase the DIY projects to a large audience. Furthermore, it allows easy printing. The user has to register to Thingiverse to use all these functionalities. When he does not want to be registered on Thingiverse, the user can save the 3D model as an STL file and can print it in a fab lab or everywhere else, where a 3D printer exists.

Framer support different ways of printing.

Connection to Thingiverse

With Thingiverse, the user is able to upload the 3D model. The advantage of uploading it to Thingiverse is the point, that the user can share his design and make it available for everyone. Furthermore, it is simple for the user and doesn't take much time. Thingiverse is a website by MakerBot.[1] There, the user is able to buy a 3D printer (MakerBot Replicator 2 Desktop 3D Printer[2]) to print the downloaded designs from Thingiverse.

Thingiverse offers the possibility to share the objects.

[1] http://www.makerbot.com/
[2] http://www.makerbot.com/faq/

To appropriate these advantages, my software includes a binding to Thingiverse. Furthermore, the user has the oppotunity to upload and download files to Thingiverse directly from the software Framer. Giving the users the different possibilities to print 3D objects simplifies the printing process and causes a rising interest in designing individual 3D objects on their own. How this is realized will be shown in chapter 3.4—"Framer: The Design" and its underlying structure in chapter 3.3—"System Design".

3.2 Survey

The following survey shows the motivation of this thesis. (Kevin O'Brien [2002]) That also includes setting a special user group and determining requirements and therefore the design of my program Framer.

3.2.1 The Problem to be Investigated

The survey gives an initial answer of the reserach questions.

This study investigates the limits of photo frames, which everyone can buy in a shop, to see if there is a wish to make individual photo frames of their own. It will show whether the user is motivated to create a frame on his own, on the background of different kinds of photos (see B.1—"Background"). Furthermore, it will determine how much time the user would spend to design a frame. Consequently this survey will give us an initial answer of the reserach questions whether the new usergroup gets motivated to personal fabrication with Framer. Additionally, it will determines some of the requirements. The possibility to print out an individual 3D picture frame at home will also be mentioned, to increase the number of printed photos and therefore determine, where it makes sense to have a 3D printer.

Motivation

The storyboards in A—"Storyboards - Appendix" show why Framer could be a program to help customising personal fabrication to a widespread of users. The users can create a desirable object that is a nice individual present or that fits to the establishment of their apartments. It can also enshrine the memory of a photo by creating a desirable object. Whether the users are interested in such a possibility will be figured out in this survey.

Whether the users are motivated to use Framer will result from the survey.

Aims and Hypotheses

The main goal is to show, that people want to make more individual frames on their own. It will show, how much time they would spend to design their own frame and because of that, how simple and fast the program has to be. Furthermore, this survey will determine the group of adopters of personal digital fabrication. The inferior aim is to find out, whether printing individual frames at home can increase the number of photos printed out at home. When this result will not occur, the survey will determine where they print out the photos and because of that, where it is useful to have a 3D printer.

The hypotheses incorporate the research questions.

The following results may follow from the survey.

- People will print more photos.
- People would have more photo frames.
- People would fabricate more on their own.
- People spend fewer time to create a frame than buying one.
- New user group is interested in personal fabrication.

3.2.2 Method of Investigation

To get answers to all questions, special methods to ask questions are very important. The questions have to be clear, so that no participants misperceive them (see B.2—"Methods"). Having a circumscribed user group that will be the end users is also very helpful for that.

Subjects and Design

The new user group is comprised of students, trainees, and young professionals between 20 and 39.

The following description of the subjects will define the new user group, which differs from the already existing user groups using personal fabrication. The participants will be people around 20 to 39, they should be interested in individual designed objects and be creative. Because of the age, the participants are students, trainees or young professionals. Like it is shown in figure 3.1, the new user group intersects with the already existing user group for personal fabrication. However, there are a lot of other people that could get motivated to personal fabrication using Framer. The total number of participants will be around 60 to get an inference to the whole user group with the results.

The subjects will participate in the survey (see figure B.3), having a duration of approximately 10 minutes. They will do it online with Googledocs. The questions will be answered by writing down the right number, by answering with yes or no and by choosing a number between 1 and 5 of how often something is used (see Likert scale in appendix B.2.2—"Statistical Methods").

3.2.3 Results

63 participants would spend 30.98 minutes in average to design a frame.

After two weeks of questioning, 63 participants completed the survey. The average age was 24.48. In general, the participants have 8.38 frames at home. The participants spend 21.67 minutes in average to find a frame und would spend 30.98 minutes in average to design a frame on the computer.

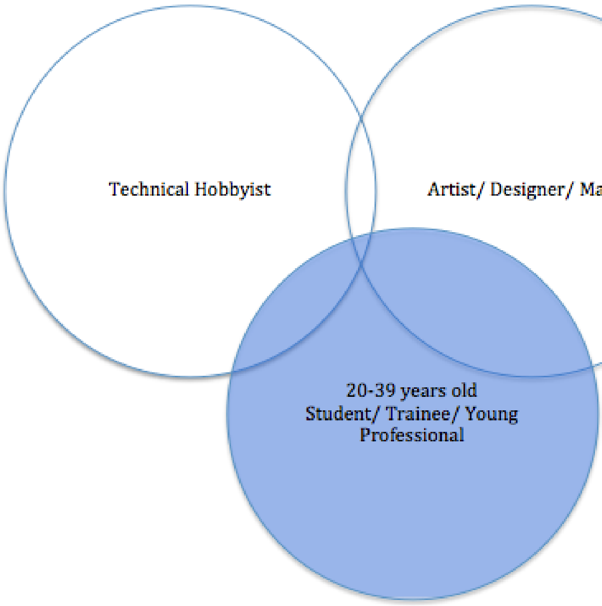

Figure 3.1: Presentation of the new user group shown in the blue circle.

Most participants print their photos at the photostation and not at home, because the quaility of their printer is not good enough. The quaility has to be good, because 66.67% of the participants gift the photos to others. Combining the photo with an individual frame could advance the gift.

66.67% of the participants gift photos.

38.46% of the participants would print more photos if they had the possibility to design picture frames. However this rate is not more than the half, there are still people, who would print more photos and therefore it makes sense to give them the possibility to do so in less time and an easier way.

38.46% of the participants would print more photos having Framer.

For more details, see B.3—"Results".

3.2.4 Results of Hypotheses and Determination of Requirements

In the following, it is listed whether the hypotheses given in chapter 3.2.1—"Aims and Hypotheses" are right or wrong.

This also contains the determination of some requirements.

People will print more photos.

38.48% of the participants will print more photos.

The survey results in 38.46% of participants that would print more photos when having the possibility to design individual frames. So there are a lot of people who would do that, which leads to the motivation of being creative and making individual frames. This verifies the first hypothesis. However, because of the bad quality of the printers, most participants would not print their photos at home. This leads to the fact that having a 3D printer at home would not make much sense. Therefore it is important to give the user other possibilities to print a 3D object like arranging an appointment with fab lab to print the STL file.

People would have more photo frames.

People would have more frames, because they are inclined to design these.

The fact, that people print pictures to put them in frames for their own or as a gift in combination with the first hypothesis shows, that there are people who will have more photo frames because of Framer. Additionally, 84.13% of the participants are inclined to design picture frames, which also raises the number of photo frames.

People would fabricate more on their own.

People would fabricate more on their own, having Framer.

The verified hypotheses above lead to the fact, that people would also fabricate more frames on their own. Therefore the design of Framer has to be very simple and usable.

People spend fewer time to create a frame than buying one.

This hypothesis is wrong. In general, the participants would spend around 31 minutes to design a frame on their own on a computer. They only spend 22 minutes on average to buy a frame. This shows, that the user would spend more time to have an individual frame. However, there were also people who would spend 5 minutes or less to design a frame on their own. Because of this fact, Framer has a rectangular frame at the beginning, which fits to normal $10x15$ cm size photo. So the user can design a simple frame in less than one minute.

People would spend more time to design a frame on the computer then buying one.

New user group is interested in personal fabrication.

According to the other hypotheses, the subjects are interested in Framer and therefore in personal fabrication. Therefore, the new user group is interested in personal fabrication and the last hypothesis is verified.

New User group is interested in personal fabrication

Comparing the results with the hypotheses shows, that each requirement, which is described at the beginning of this chapter, is important to help creating a solution for the research questions. So all these requirements will yield in the design of Framer and considered in the system design.

3.3 System Design

How different applications interact with Framer to support all its functionalities is shown in figure 3.2. Framer is a desktop application using Cocoa with the Xcode IDE. Most of the application is coded in Objective-C, parts of it also in C. The 3D objects are displayed in OpenGL which is embedded in Framer. The objects shown in OpenGL are constructed with OpenSCAD and transformed to a STL file via the Terminal. This connection is also used to change the parameters of the frame and different shapes. With the connection to Thingiverse other created frames can be shown. It also provides the possibility to print the finished design with an own 3D printer, in a fab lab, or in another printing shop, containing a 3D printer.

The desktop application displayes OpenSCAD constructed objects with OpenGL and supports a connection to Thingiverse.

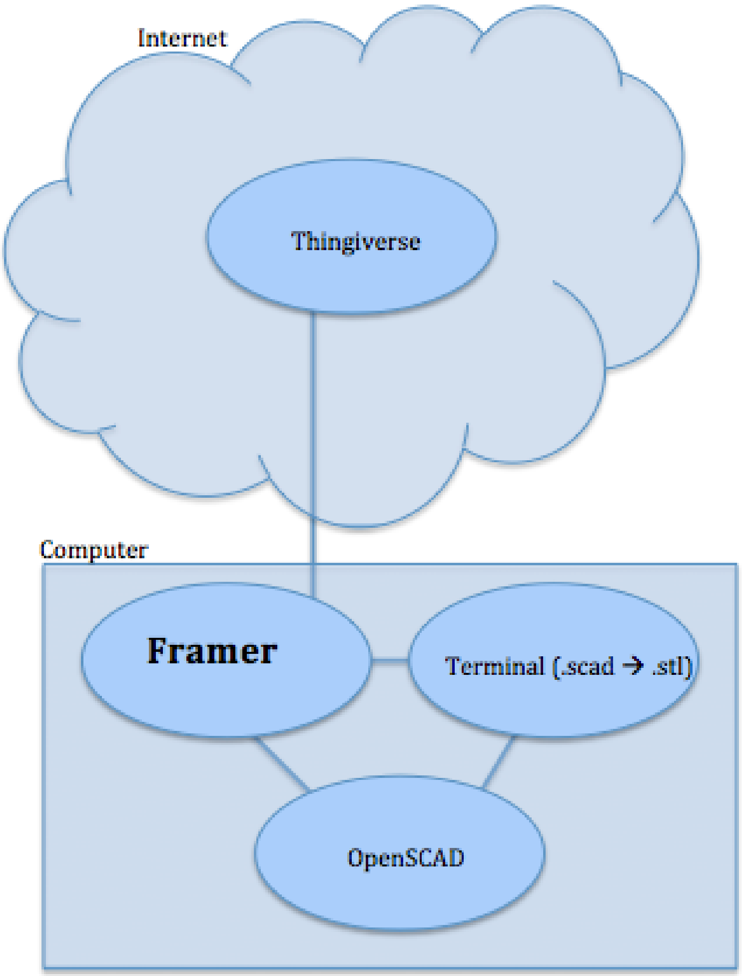

Figure 3.2: Interaction design of the system.

3.4 Framer: The Design

Framer went through three design iterations to resolve its user interface and its functionality.

3.4.1 User Interface Iteration: Paperprototype Validation

When people work with programs, mistakes and slips occur (Norman [1983]). An error in the desired action is called a mistake. A slip is an error in carrying out the desired action. However, people will make errors. Therefore it is important to give feedback to all their actions, to avoid similarity of response sequences for different actions, to make actions reversible, and to make the system consistent in its structure and design.

To avoid slips and errors or make them reversible, special design choices are important.

Procedure and Statistical Methods

To avoid these problems in my software, I firstly designed a paper prototype and evaluated it with 6 people. The prototype and its constellation is shown in appendix C.1—"Constellation". No connection to Thingiverse is shown yet, because at this time of evaluation, FabCenter contained all the functionalities. During the design process the connection to FabCenter was deleted and the connection to Thingiverse as a better sharing system was established.

A paper prototype is evaluated to avoid most of the slips and errors.

The participants were in the same user group like in the survey and at first had to follow eleven small tasks that I assigned appendix C.2—"Tasks". After they followed the tasks step by step thinking aloud, they had to state which tasks were difficult to fulfill and what they would like to have changed in the program.

It is tested with the new user group using the thinking aloud method.

Results

The following changes were implemented:

- To continue to the main window, where the user can design a frame, the user now presses the "Design your Frame" button instead of the "Continue" button.
- In the main window the buttons "Texture" and "Shape" are renamed in "Add Texture", "Add Shape".

Now there is a popup button to change the frame instead of the and "Add Frame" button. It is labeled with "Shape:" that now is in a box called "Frame". At the beginning a rectangular frame exists around the photo.

- To avoid misunderstanding by editing the frame and the photo, there is a new button "Edit Image". When the user presses this button a new window appears where the user can perform the tasks to edit the photo like he did in the paper prototype design.
- To load a photo in the program, the user now clicks "Open Image" in the image window.
- The user can press the "Add Image" button in the main window to add the image in the 3D frame.
- The task of the button to change the size of the frame is changed. The user can change the size by writing down the width, height, and depth of a frame and press the "Change Size" button. These textfields and the button are inside of the frame box, where the shape of the frame is defined.

Different windows for editing the image and the frame to avoid mode errors

To avoid mode errors the actions to edit a photo and the actions to edit a frame must suggest good feedback. Therefore the configuration of the system must be very good which contains the description of the different actions (to avoid description errors) like it is done with different windows for editing the photo and the frame.

The user can not upload a design when he is not logged in to avoid loss-of-activation.

To avoid a loss-of-activation error, where people forget what they intend to do, the system needs reminders. In this software a user should know, whether he is already logged in to FabCenter or not to avoid failures (uploading a design to FabCenter, although he is not logged in). When the user is not logged in, he has no possibility to upload or download a frame.

Windows user had problems with the menubar.

There were other problems that occurred by people who were not familiar with a Mac. Windows users had problems with the menubar and searched for buttons in the main window to perform each task. However these problems did not occur by participants who use a Mac. To make this program usable for every user, buttons like "Add Image" are added to support the main functionalities in buttons.

3.4.2 Iteration Caused by Design Challenges

During the implementation, several reasons caused a renewed change in design. With MakerBot Customizer, a big new field is opened in Thingiverse, where users have a better possibility to design things and upload and share it to learn from others. Therefore, also FabCenter is replaced with Thingiverse, which causes a change of design according to FabCenter. Now the tasks according to FabCenter are deleted.

FabCenter is replaced with Thingiverse, which causes a change in design.

Additionally, the user has the opportunity to operate with Thingiverse. In a new window, the user now can see different designs of frames from other users that are downloaded from Thingiverse. To see these designs, the user first has to be registered and logged into Thingiverse. Therefore he can press the "Login/ Register" button that opens a new webview window. The user also has the possibility to visit Thingiverse and to upload an own designed frame to Thingiverse by pressing buttons.

Now, the user can download frame designs from Thingiverse after he is logged in.

3.4.3 Resulting Design

The changes of the two iterations above and thoughts during the implementation process causes the final design. The interface in detail is shown in appendix D—“Resulted Design - Appendix”.

When the user adds a shape, he can define the size in the "Shapes" panel. There, the user can also define the position of the added shapes in the "Shape coordinate" box. The size of the frame in the main window can be defined in special ranges. The frame cannot be smaller than $100x150$ mm which is the size of a picture. When the size of the frame or the coordinates of the added shapes are not in a special range, a warning message appears and the change is not

The user can define the size and the position of the added shapes.

fulfilled. With the texture panel, the frame can get different textures and colors. Both panels are presented in figure 3.3.

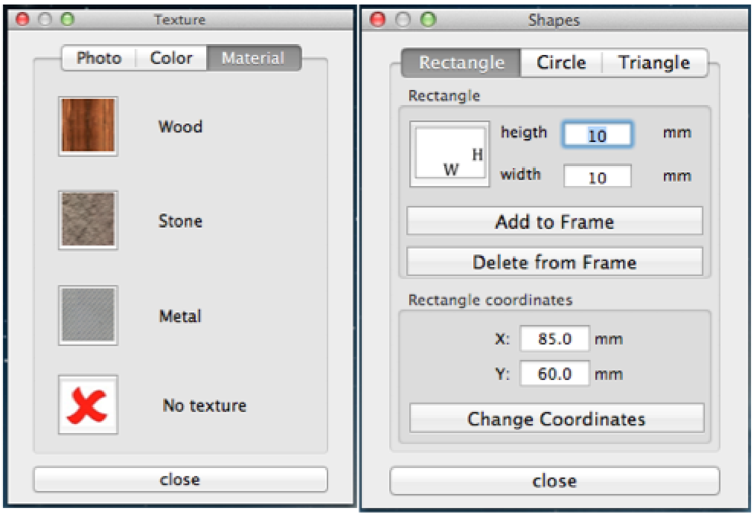

Figure 3.3: The texture panel on the left side shows three different textures. The shapes panel offers three different shapes.

The viewpoint of the frame can be edited by the user to simplify the design process.

The OpenGL view can be changed by editing the dimensions and the center (see figure 3.4). The object can be centered in the view with a button. This allows the user a detailed view of the frame. Beside the rotation by dragging the object with a mouse, the user can rotate the object by clicking $+90°$ buttons or writing down a number. It helps the user to make more precise rotation. The object can also be autorotated and the composition of triangles of the STL file can be shown by clicking the checkbox "wireframe". So the user can see the constellation of his design. The user also has the opportunity to reset the perspective.

3.5 User Study for Usability Testing

The usability, the visibility, the learnability, the creativity, and the adoption of Framer is tested in a user study. The study will also show, whether the changes taken from the

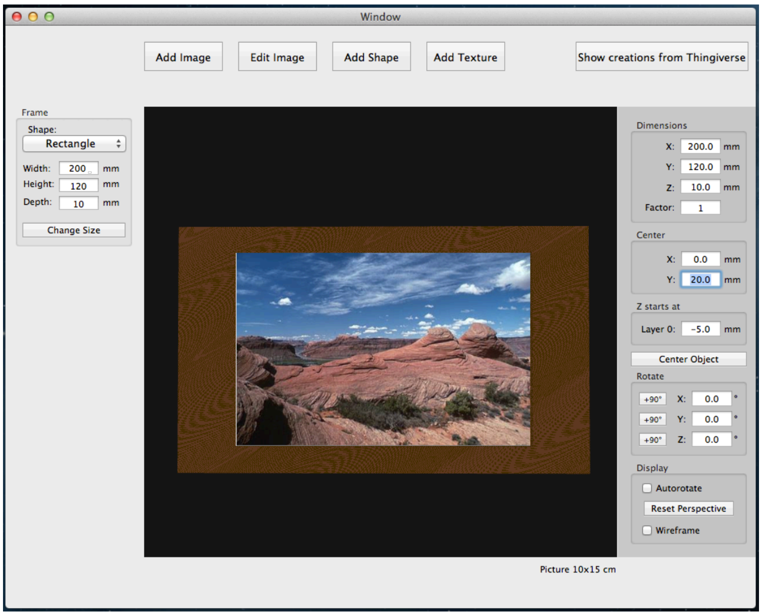

Figure 3.4: Presentation of the main window of Framer. The frame has a wooden texture and in the middel is a picture.

study with the paper prototype will help the user performing the tasks.

3.5.1 Subjects

Like in the prototype validation the new user group participated. 12 participants performed the tasks shown in appendix E.1—"Tasks". To show, whether Framer supports learnability, the results are divided into results of users, who already tested the prototype and users, who used Framer the first time.

12 participants of the new usergroup.

3.5.2 Procedure and Statistical Methods

Additionally to video-recording their interaction with Framer for closer inspection at a later date, they had the chance to discuss their thoughts and actions. The following

The study was video recorded.

methods were used:

1. Usability Inspection Method
    (a) Formal action analysis method
2. Usability Test Method
    (a) Thinking aloud method
    (b) Questionnaires (appendix E.2—"Questions")
        i. SUS questions
        ii. NPS question
        iii. CSI questions

Stop time of each task.

The formal action analysis method requires close inspection of the action sequences the user has to perform (Hol [2005]). The tasks are divided into smaller subtasks to calculate the time of some steps.

Thinking aloud reveal visibility.

The thinking aloud method was used after the method above to determine the visibility of the UI. The method shows, why users do something. Therefore preference and performance information can be collected simultaneously.

SUS reveals usability, NSP reveals adoption.

At the end, some questionnaires help to get a better overview of the user preferences. The System Usability Score (SUS) assesses the usability of Framer with eleven questions using the Likert Scale (Bangor and Miller [2009]). With one additional question, the Net Promoter Score (NPS) can be calculated to know how well Framer might be adopted (Rechheld [2003]).

CSI reveals creativity.

Finally, the Creativity Support Index (CSI) can be estimated to show how creative the user can be with Framer (Carroll and Terry [2009]). Therefore the user has to rate six orthogonal factors related to creativity support, that were generated with the PCA (Principle Components Analysis) test. Secondly, the user performes a pairwise factor ranking. Combining these two actions results in the CSI between 0 and 100.

In the following chapter, the results and its analysis will be presented.

Chapter 4

Results and Evaluation

4.1 Results of the User Study

The following section will describe the results and the analysis of the user study from the perspective of the methods described at the end of the last chapter.

4.1.1 Time

Participants needed 1.5 minutes in average to design a frame.

In average, the participants needed 1.5 minutes to edit the size of the frame, to add a new shape, and to add a wooden texture. Differences can be seen by participants that participated the prototype study. Like figure 4.1 reveals, participants who already worked with the prototype are on average 31.84 seconds faster then participants who worked with Framer for the first time. This faster processing time states the learnability of Framer. However, although this difference is relatively high, it could be much higher if the participants worked a second time with Framer. In consequence of the big difference between the prototype and the final design, the participants did not have indications regarding the first study. Particulars to the different tasks are shown in appendix E.3—“Time to Perform each Task”.

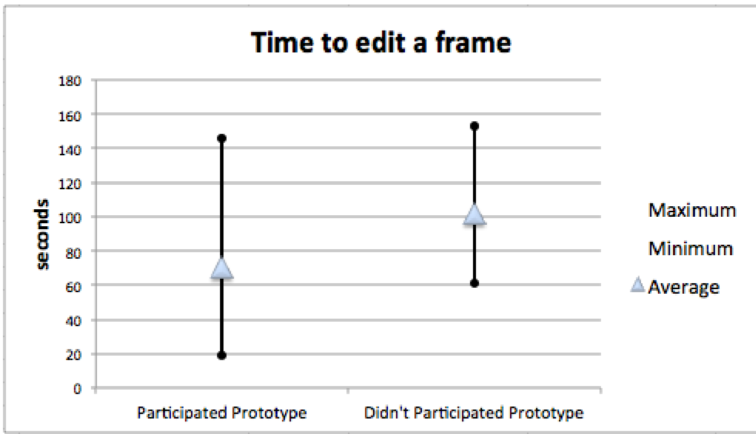

Figure 4.1: Time of participants to edit the frame.

4.1.2 Think aloud

The participants used all three possibilities to rotate the object.

Framer offers different ways to solve several tasks. To rotate the object, the user can move it with the mouse, push the $+90°$ button or insert the degree in a textfield. While the first method offers direct feedback, the other two methods provide precise rotation. During the tasks, the user detected the direct rotation and one of the precise ones. The users had different preferences, but there was no difference between first time users und users who had already participated with the paperptototype. To reset the rotation, most people used the textfield. Some participants used the $+90°$ button instead. They noticed the textfield but preferred using the button.

To center the object, most participants used the center coordinates box.

To center the object, most participants used the x and y coordinates in the "Center box". To reset the rotation most users resetted the textfield, because they were focused in the box. Some also used the center button, after they had a short overview over the program and its functionalities. A few people dragged the frame by clicking the right mouse button und dragging it to the desired place. With this method, the user has to fulfil the same steps to center the frame again.

To get a textured frame the users need more time.

To get a texture on the frame the user had to choose a texture and then doubleclick on the frame. This presented the most problems. Most people tried to click only on the texture, drag and drop the texture or doubleclick on the tecture button. After these steps, they also tried to doubleclick on the frame and get the results. To avoid this problem several changes can be made. The program can be changed, so that a simple click on the button adds the texture. Another possibility would be a popup-text that appears, when the user moves the curser over the texture button. As a third possibility, the user could drag the texture onto the frame.

To see different designs from Thingiverse, two ways were used.

To see different frames on Thingiverse, all participants switched directly to the Thingiverse window. Some participants then noticed the text in the empty box and tried to login. Others directly switched to the webside of Thingiverse via the "Visit Thingiverse" button. Both ways offers different designs. With the first possibility, the pictures of different frames from Thingiverse users get directly downloaded in Framer.

4.1.3 SUS and NPS

SUS is 87.5%.

To calculate the SUS of Framer, several steps are important. The ten questions at the beginning are devided into positive-worded items (question $1, 3, 5, 7, 9$) and negative-worded items (question $2, 4, 6, 8, 10$). To calculate the score contribution take the scale position and perform:

$$positive-wordeditems : scorecontribution = scaleposition-1$$

$$negative-wordeditems : scorecontribution = 5-scaleposition$$

The calculation

$$(\sum scorecontribution) * 2.5$$

results in the SUS. The average SUS of Framer is 87.5%. The adjective rating results from the eleventh question. The values are ranged in the following score in figure 4.2. The usability is in an acceptable range and Framer gets the grade B. This is a good result for Framer, which offers basic techniques. To get a better usability score, the problems shown in chapter 4.1.2—"Think aloud" have to be addressed and special additions should be made. These additions are explained in the next chapter.

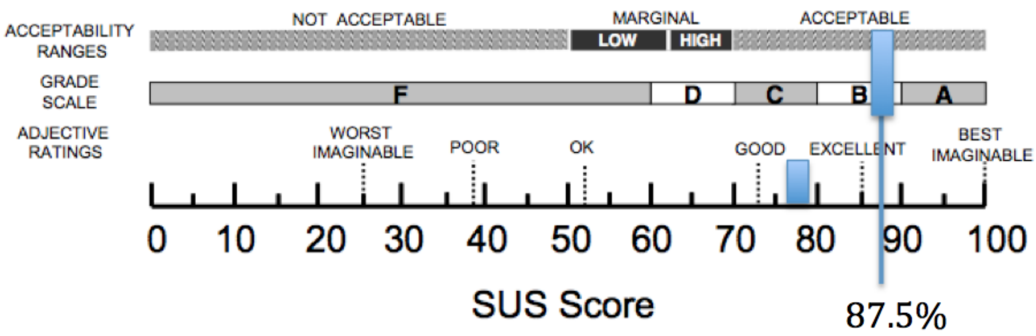

Figure 4.2: Classification of Framer in SUS score. The left marker shows the adjective rating and the right marker the result of the SUS. [Bangor et al. 2009]

NPS is 100%.

The NPS results from the last question. Detractors are people who answered the question in the range of 0 to 6. Promoters answered the question in the range of 9 to 10. To calculate NPS the following calculation is needed.

$$NPS = \%promoters - \%detractors$$

The calculation containing the outcomes of the study results in a NPS of 100%. Not all rated the scale 9 or 10, but there where 33% who rated 7 or 8. This shows, that all participants would recommend Framer to a friend or colleague, when it is available or when it will appear on the market. This result is understandable because the survey stated, that the new usergroup is motivated to use and therefore also adopt Framer.

4.1.4 CSI

CSI is 82.15%.

To get the CSI, the following calculation is necessary:

$$CSI = (Exploration * ExplorationCount+$$

$$Expressiveness * ExpressivenessCount+$$

$$Immersion * ImmersionCount+$$

$$EffortResults * EffortResultsCount+$$

$$Enjoyment * EnjoymentCount+$$

$$Collaboration * CollaborationCount)/1.5$$

The outcome of the study result in an average CSI of 82.15% for Framer. This creativity support afforded by Framer is already a good value at this point of time. Because of a high CSI, the time becomes distorted. Having the possibility to be creative leads to longer times and therefore the time to prepare a design becomes less important. To support more creativity, different additions can be done. This is shown in chapter 5.2—"Future work".

4.2 Discussion

The following conclusion regarding the research questions can be made:

Students, trainees, and young professionals between 20 *and* 39 *are interested in using Framer.* Like the survey presented, the new user group is motivated to use this program. The user studies with the paper prototype and the final version additionally supported that. The NPS was 100%, which supports the positive feedback of the usergroup. Whether this user group will really be integrated in the group of personal fabricators, can be investigated in future work.

The new user group is motivated to design picture frames.

With Framer, users are motivated to design picture frames. This was already shown in the survey. 84.13% of the participants are creative and would design 3D picture frames on the computer. These can be used as individual gifts or individual frames fitting to the establishment, like it was shown in the storyboards. The user study results in a CSI value of 82.15%, which shows, that Framer supports creativity and therefore motivates the user to use Framer. Additionally, giving the user time to play with the program after the user study showed great interest. Like the integration of the new user group, the motivation can also be stated in future long term studies.

Framer motivates people to create 3D objects.

Framer is a simple, usable program to design frames. Users had no problems during the user study of the final design. Furthermore, the time of 1.5 minutes to design a frame was smaller than the average time users would spend to design a frame (30 minutes), determined in the survey. All the re-

Framer simplifies the design procedure.

quirements that were invented to support Framer were implemented and the benefits tested in the studies. The connection to Thingiverse to share objects and the possibility to download STL files supports different ways to print the final design. The SUS of $87,5\%$ of the user study leads to the fact that it is a usable program for the users.

Framer simplifies printing 3D objects, supporting different ways.

The connection to Thingiverse, as well as the storage in different file formats simplifies the possibility to print 3D objects. The user then has the possibility to get different designs via Thingiverse that can be printed. If the user can be present during the printing process, he can arrange an appointment with a fab lab. Because of the connection to Thingiverse, the user has its file online for printing. However the users also have the possibility to print it on another place because of the file formats that can be saved on the computer. Therefore the user does not need to register on other sides. All different possibilities to let the picture frame be printed are enabled. This ensures flexibility and therefore simplicity in printing.

Framer can make personal fabrication more common in humans everyday life.

Framer makes personal fabrication more common in humans everyday life. All the statements above cause this last assertion. The new user group, the motivation, the simplicity, and the easy way to print the 3D models sums up to an everyday usable program.

In general it can be said, that this thesis presented all these research questions and showed ways to answer them. Whether Framer will really improve personal fabrication must be analysed in future steps with longterm user studies.

Chapter 5

Summary and Future Work

The main goal of this thesis was to determine whether a program like Framer makes personal fabrication more common in humans everyday life. Whether my thesis contains this is sumed up in the first section. This also determines what can be done in future work.

5.1 Summary

Creativity is important for the generation of innovative ideas and therefore motivated the development of personal fabrication. This work presented a review of different software to work on 3D objects. Therefore, the software was classified in *CAD software* to create objects, *Software Creators* to edit objects, and *Libraries* to upload and share objects. Bearing in mind that I want to create a new software to design and edit picture frames, I decided to implement a creator with a connection to the Thingiverse library.

Based on related work, Framer is a creator to edit 3D picture frames.

Research questions were identified that focused on how personal fabrication can get more common in humans everyday life. Therefore, special requirements were determined. The following survey fathomed the motivation and special requirements. Storyboards were created to analyse

The survey clarified the requirements and showed the motivation of the new usergroup.

the usage of Framer and a special new user group was clarified that opens the personal fabrication field to a wider field of users.

Several iterations resulted in the final system.

Afterwards the representation of the system and the design as well as several iterations and design challenges were discussed. Resulting from these iterations, Framer is a local desktop application containing OpenGL to display 3D objects and allowing users to edit the shape, the color or the texture of a frame, and adding other shapes. The final picture frame then can be saved as STL. Furthermore the user can login to Thingiverse, so that different 3D frames of other users can be displayed in a second window in the desktop.

The user study answers research questions.

This system then was tested in a user study. The user study was conducted in order to evaluate the system and answer the research questions. The time to design a frame was much smaller than the user would spend to design a frame. The high SUS of 87.5% shows how usable Framer is to the new usergroup. The great creativity of 82.15% (CSI) that is supported by Framer causes an adoption value of 100% (NPS). The users would recommend Framer to friends and colleagues because it supports creativity and therefore enjoyment. It also provided feedback and recommendations for further improvements, which are presented in the following section.

5.2 Future work

There are different tasks to be done in future work, which on the one hand accrued during the working process and on the other hand resulted from the user study.

5.2.1 Long Term User Studies

Additionaly, long term studies can ensure the main research question.

I already showed that the new user group is interested in Framer during the survey. Furthermore, the design offers the possibility to create an individual frame in fast processing work. However, whether the new system really improves personal fabrication can only be shown in long term user studies. This can be done by observing the Thingiverse library on different frame designs created with Framer. There, Framer is available to a big already existing user group.

To test the system with the new user group, Framer could be forwarded to students, trainees, and young professionals for a few month. This can show whether the users really use Framer to design frames. Furthermore, it can really determine the research questions.

To increase the creativity and the usability of Framer, the system improvements and system additions, described in the following sections, can be done and tested with the user groups.

5.2.2 System Improvements

Framer offers already basic functions that can be extended to improve the functions. This could increase the creativity of Framer.

AMF

However the program is already able to show one texture or color, the program can be improved by saving a model having more than one material and more than one color.

Support more than one color or texture.

Different Textures

A few textures are already given in Framer. However there could be several more textures. Additionally, Framer could allow the user to set own textures by uploading different pictures.

User shall choose own textures.

5.2.3 System Additions

There are several possibilities to make this project available and more interesting for a larger amount of people. Two main additions can be done in future to reinforce the individuality of designing frames and therefore the creativity and usability.

Design Frame on Paper

Draw frame that is transformed into 3D on the computer.

One possilbility to intensify the design process of a frame is to let the user draw a 2D frame on paper. This drawing then can be held in front of the laptop camera to display the design on the screen. Framer then can create a 3D object, like it is done with "2D to 3D" from Shapeways. The user edits the design via sliders and buttons on Framer. At the end of the last userstudy, the user had to draw a frame on paper. On average, they needed 27 seconds to draw a frame they would like to have. With this addition, the user would not need more time to design a frame but the creativity is even higher. Therefore it makes sense to implement this addition.

Design Frame With Gestures

Use gestures to design frames.

Another possibility that precipitates the design process, can be gestures made in the air. Systems like the Vicon[1] can gather the gestures that will then be transformed in a shape with Framer. These models can be edited with the Framer interface or with other gestures. However this will lead to fast and intuitively created models, the stress of making the gestures must be taken into account.

5.2.4 Further Thoughts

Copyright gets important in personal design.

In a few years, people will be able to produce objects on

[1] www.vicon.com

their own with the decision at what time and at which place (Mota [2011]). However, there are a few scenarios, that are not solved at the moment: When people fabricate objects on their own, what will happen, if someone gets injured by these home-made objects? Having the possibility to design objects on their own can decrease the product's life cycle and increase the amount of waste. So what can we do against this? While we have copyright court battles over music, movies, and book file sharing, how can we handle this with personal designs which are now given away for free?

Appendix A

Storyboards - Appendix

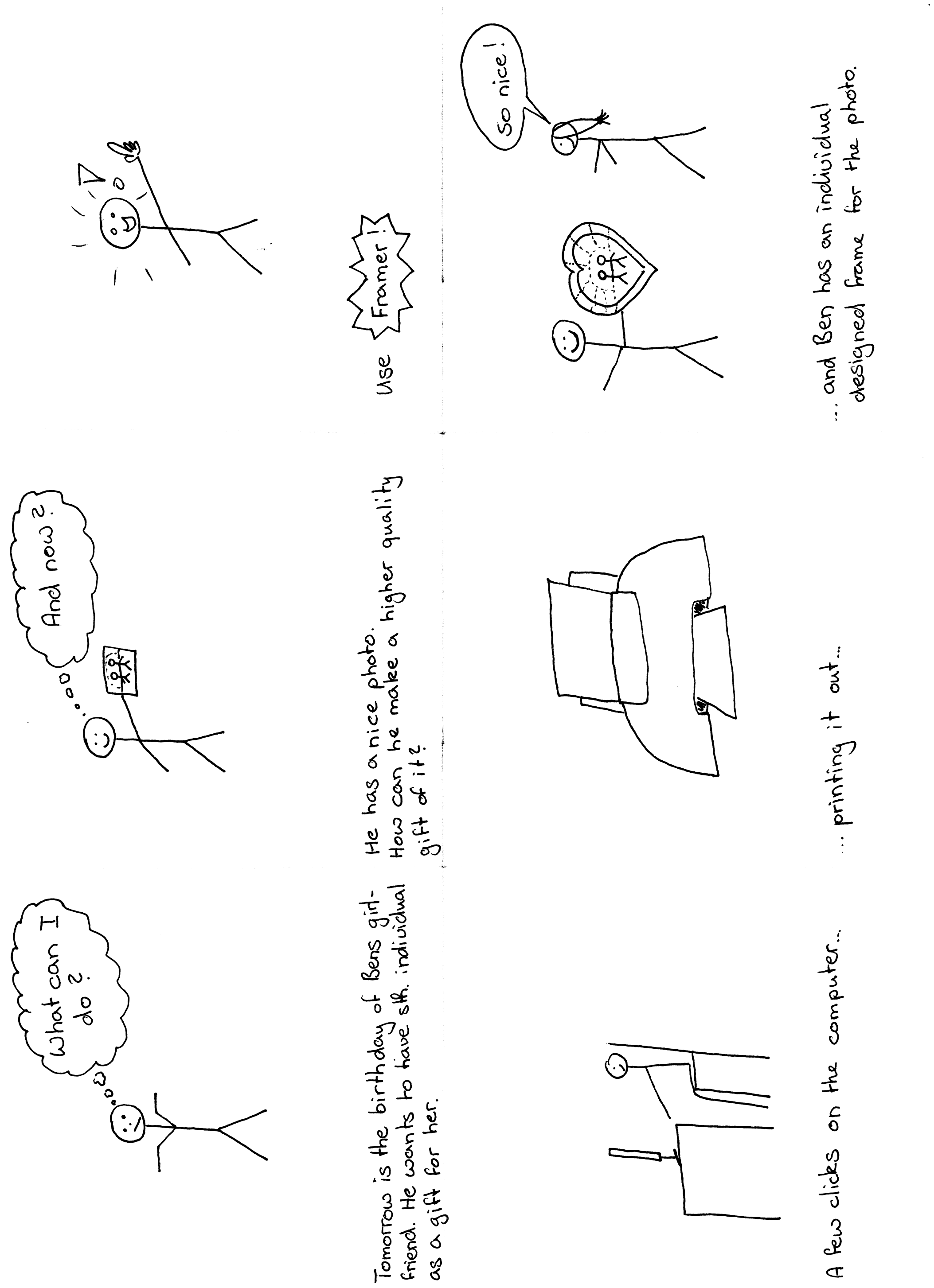

Figure A.1: This Storyboard shows a 22 year old student designing an individual frame as a present for his girlfriend.

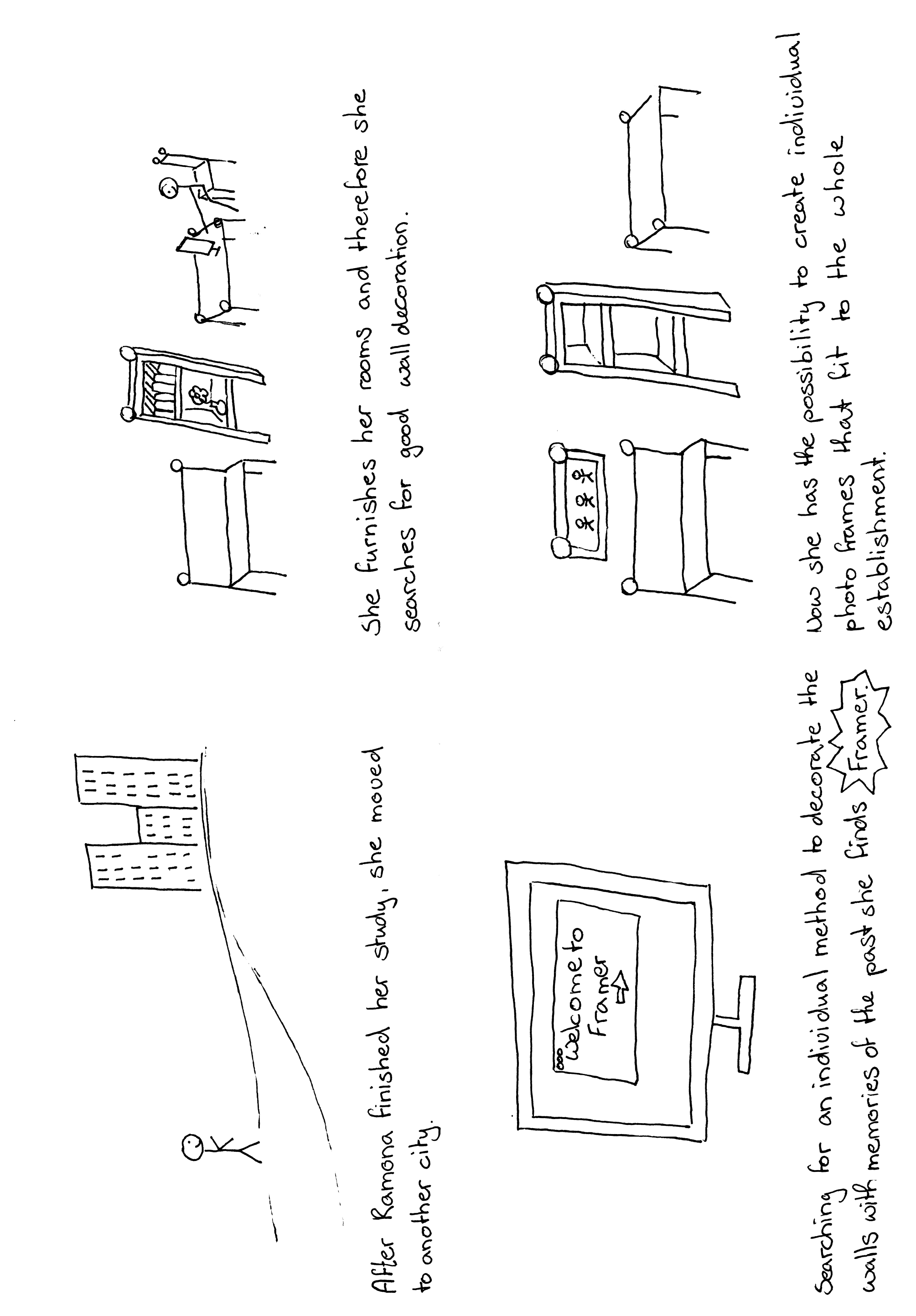

Figure A.2: This storyboard shows a career entrant, who creates an individual frame that fits to her whole esablishment.

Appendix B

Survey - Appendix

B.1 Background

Digital photos are printed to present them to others in formal and informal spaces.

With the development of digital cameras, people have the possibility to make more photos without printing all of them out and therefore are much more prolific in taking photos (Rodden and Wood [2003]). However, people want to have prints of their photos for certain purposes, e.g. to look at the photo without switching to a computer or a television, or to show these photos to friends. Usually, they only wanted to have selected photos printed out, at the highest possible quality, to be added to their existing permanent collection of special photos. Most of the modern printers have the capability to guarantee this. Additionally, products from camera manufacturers support users ability to print individual photos or make albums through a service (Kim and Zimmerman [2006]). These products deal with presentation of digital photos but almost all of these photos need to be printed then. Like it is shown in figure B.1 making albums and printing photos to do them in photo frames are the biggest components in analog photo sharing. Having albums are a bigger part than photo frames. However this changed till now, like the trend of the survey in chapter 3.2.3—"Results" reveals. The maps in figure B.2 reveal that families have formal and informal spaces for displaying photos. Formal spaces are living rooms, entryways, and bathrooms. These photos are posed, taken

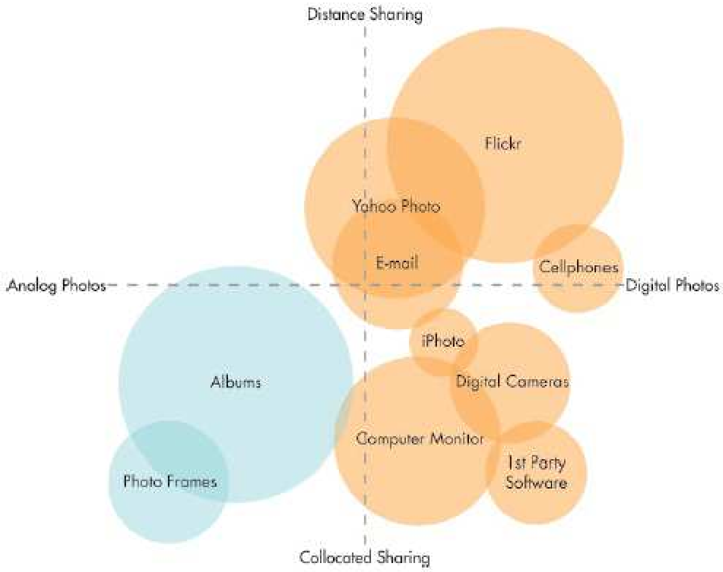

Figure B.1: Sharing of analog and digital photos. [Kim et al. 2006]

professionally, or taken by a family member and follow a theme. Informal spaces are bedrooms, family rooms, and the kitchen. Here, photos are candid, personal, and captured the moment. In summary, it can be stated that many different kinds of photos, individually edited by the owner, need an individual designed frame. This is also shown in chapter 3.2.3—"Results" of the survey.

B.2 Methods

B.2.1 Procedure and Measurement used

Different kinds of questions will accure in the survey.

The user will get three different kinds of questions. In the first step, there are questions about the person himself. In the second step, there are questions about frames. And in the last step, there are questions about photo printing and the usage of the printer at home (see figure B.3). The outcome measure for this study will be the percent of the questions presented above. At the end, a couple of bar diagrams

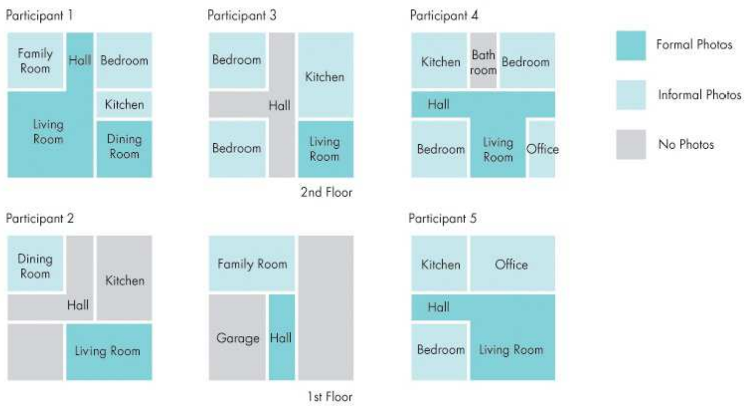

Figure B.2: Formal and informal spaces for displaying photos. [Kim et al. 2006]

show the result in percent (y-axis) of each occupational category (x-axis).

B.2.2 Statistical Methods

Using the Likert scale with 5 numbers to get good weighted answers.

To answer the different questions, the subjects have to answer the questions, like it is explained in chapter 3.2.2—"Subjects and Design". In the third part, the subjects mark a number in the Likert scale. There will be 5 numbers, because a good Likert scale is balanced on both sides of a neutral option. Having 5 instead of 3 numbers increases the emphasis of the statement for each question. Then, the volition to print more photos when having a 3D printer to create individual frames can be compared to the location of the 3D printer.

B.3 Results

Most people bought a frame from Ikea.

29.85% of the people bought them from Ikea, but there are also a lot of people (26.87%), who got the frames as a gift (Figure B.4). 1.5% bought materials in a handcraft store and 4.48% bought them in a hardwarestore. This shows, that there are already a few people, who are interessted in

The effect of the availability of individual photo frames.

Gender: male ☐ female ☐
Age: __________ years
Job: ________________

How many photo frames I have at home (rounded number): ________________
Where I got the frame: ________________
How much time did I spend to find the right frame: ____________
I made a frame on my own. yes ☐ no ☐
I did handcraft in the past. yes ☐ no ☐
I would make a frame on my own, when I have the possibility. yes☐ no☐
How much time I would spend to make an individual picture frame on my own: ____________
How much time I would spend to make an individual picture frame on the computer: ____________

I have a colour printer: yes ☐ no ☐
Which kind of printer: inkjet printer ☐ laser printer☐ LED-printer ☐
LCD/LCS-printer ☐ don’t know ☐ other ________________

Mark the appropriate number:

I print photos for:	never		sometimes		often
photo album	1	2	3	4	5
picture frame	1	2	3	4	5
collage	1	2	3	4	5
as a present	1	2	3	4	5

Where I print photos:					
online printservice	1	2	3	4	5
photostation (e.g. DM)	1	2	3	4	5
at home with printer	1	2	3	4	5

Why I do or don't print photos at home:

	not correct		neutral		correct
quality of the printer is not good enough	1	2	3	4	5
paper too expensive	1	2	3	4	5
ink too expensive	1	2	3	4	5
no usage of photos	1	2	3	4	5
no space for photos	1	2	3	4	5
no individual frames for pictures	1	2	3	4	5
costs too much time to find the right frame	1	2	3	4	5

If I had the chance to create an individual picture frame, I would print more photos.
1 2 3 4 5
If I had the chance to create an individual picture frame, I would print more photos with my printer at home. 1 2 3 4 5

The outcome will be treated confidentally.

Figure B.3: Final survey only shown in textform.

creating and designing an individual frame. However, this is only a small part, because it causes lot of time.

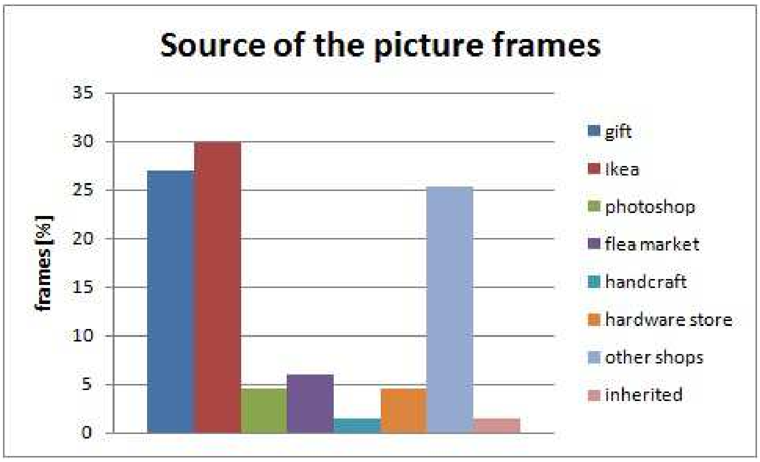

Figure B.4: Places, where the participants bought the frame.

In average, the participants spend 21.67 minutes to find a frame. However, the participants vary very much in the time, they would spend (Figure B.5). 22.22% only spend 5 minutes, $19,44\%$ of the participants spend 20 minutes. There are also people (11.12%), who would spend 60 minutes and more to find the right frame. Added to this, there is also the time, to go to the shop. However, the time to find a frame on this way is smaller than to make a frame. Because of this 76.19% of the participants made no frame on their own in the past (Figure B.12).

Participants spend 21.67 minutes in average to find a frame.

This result is also shown in the following figure B.6. 84.13% of the participants are inclined to design picture frames. In average, participants would spend 83.24 minutes to make a frame and 30.98 minutes to design a frame on the computer. The second value is the benchmark, the program Framer in average should need to make an individual frame. Because of figure B.5, it should also be possible, to get a simple frame in 5 minutes, or to have the possibility to change details, so that the user also can spend more time designing a frame.

Participants would spend 30.98 minutes in average to design a frame.

68.25% of the participants have a printer (Figure B.13) and

Most participants print their photos at the photo station.

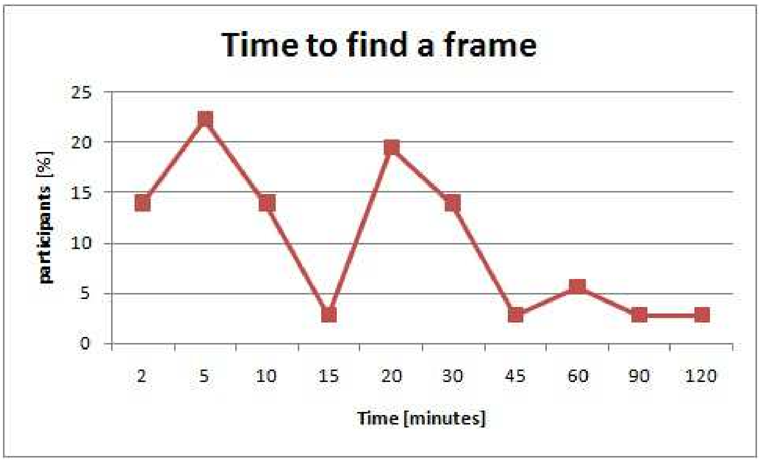

Figure B.5: Time the user spent to find a frame.

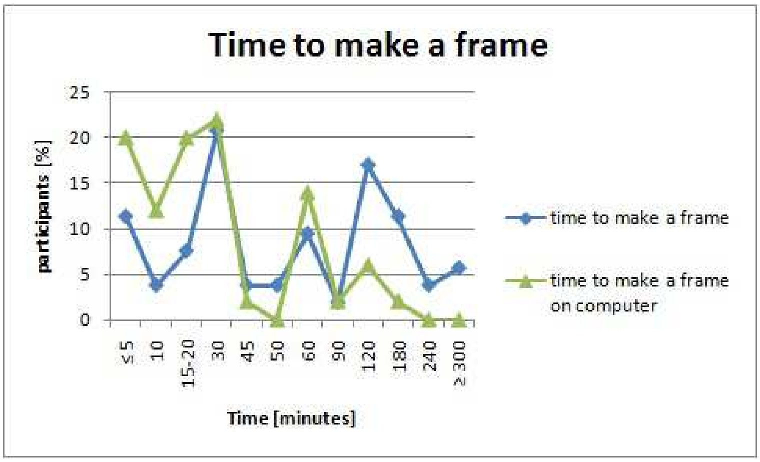

Figure B.6: Time the user would spend to create a frame.

in 81.39% of the falls it is an inkjet printer (Figure B.14). Although a huge group of the participants have an own printer, most of the people do not print their photos at home. Figure B.7 shows, that most people print their photos at a photo station, followed by the possibility to send the photos to an online print service.

Participants do not print their photos at home because the quality of the printer is not good enough.

The reason, why people do not print their photos at home is shown in figure B.8. 57.14% of the participants say, that the bad quality of their printer is the main reason not to print at home. For 55.55% the good ink for quality printing is too

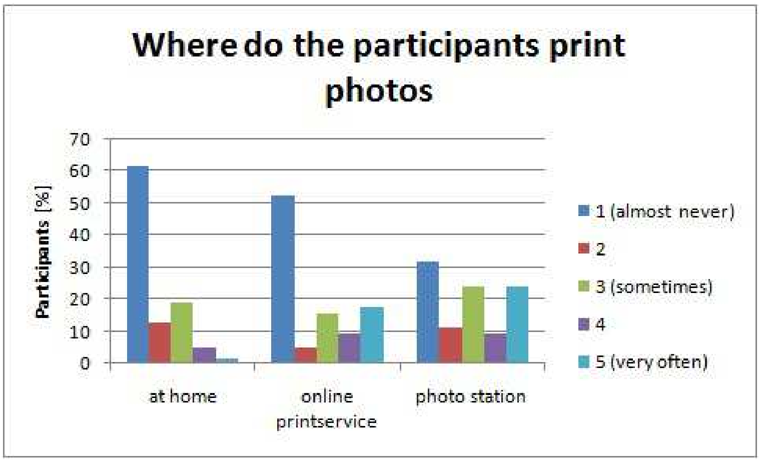

Figure B.7: Places, where participants normally print photos.

expensive and for 41.27% the photopaper is too expensive. Only 9.52% have no place for more photos, which is only a small number.

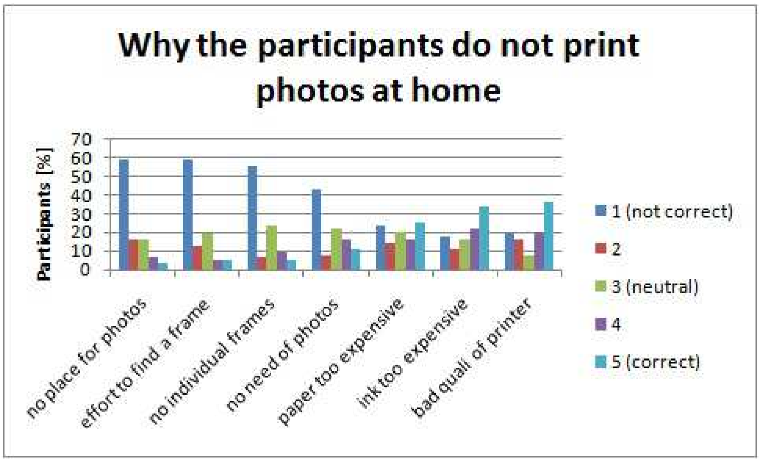

Figure B.8: Reasons why the participants don't print photos with their printer.

The number of participants, who do not print photos, because they have no place at home get even less relevant, showing the next figure (Figure B.9). 66.67% of the people print photos as a gift (7.94% very often, 23.81% often and

66.67% of the participants gift photos to others.

34.92% sometimes). Having the possibility to create individual picture frames could reduce the number of participants, who gift the photos sometimes and raise the number of participants, who print the photos to gift them very often. 41.26% print photos to do them in a picture frame. Also this number can grow with the possibility to design individual frames. Another important result of this diagramm is the fact, that more participants print pictures to do them in a frame, than put them in albums. So this changed compared with the first figure in appendix B.1—"Background".

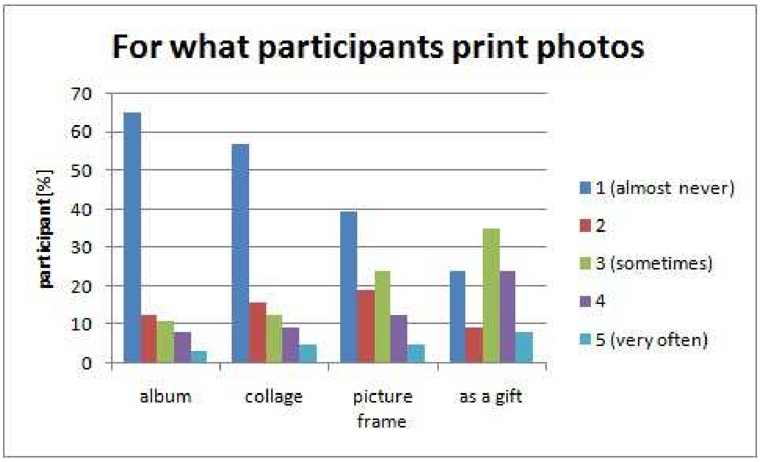

Figure B.9: Why participants print photos.

38.46% of the participants would print more photos having the possibility to design picture frames.

The last figures B.10 and B.11 show the results of the question, whether the participants would print more photos, when they have the possibility to design individual picture frames. In both figures, only participants with the will to design such frames were mentioned. In figure B.10 the general trend shows, that people would rather print more photos at places like a photo station (31.7%) than at home (17.5%). In figure B.11, additionally to the people, who have no will to design frames, also people, who have no printer at home were taken out of the results. 23.08% now would print more photos at home and 38.46% would print more photos anywhere else. However this rate is not more than the half, there are still people, who would print more photos and therefore it makes sense to give them the possibility to do so in less time and easier way.

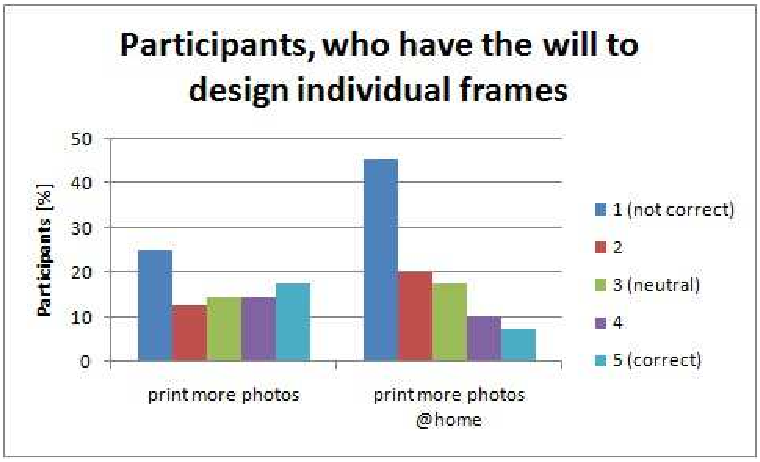

Figure B.10: How many participants have the will to print more photos. (including only participants who want to design frames)

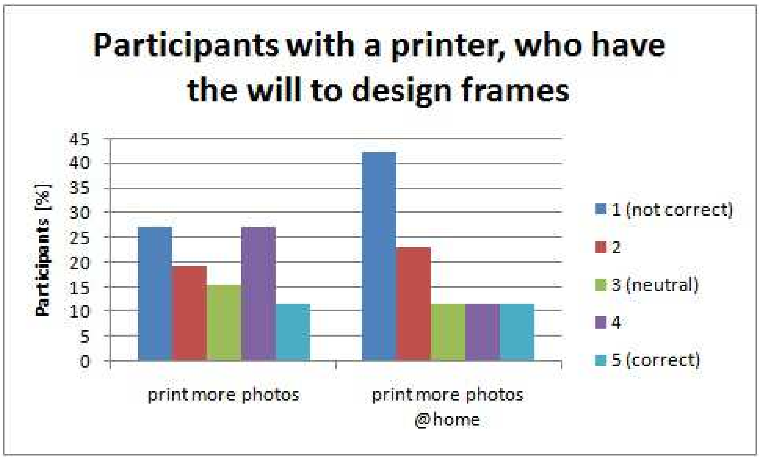

Figure B.11: How many participants have the will to print more photos. (including only participants who have a printer and who want to design frames)

B.4 Additional diagrams:

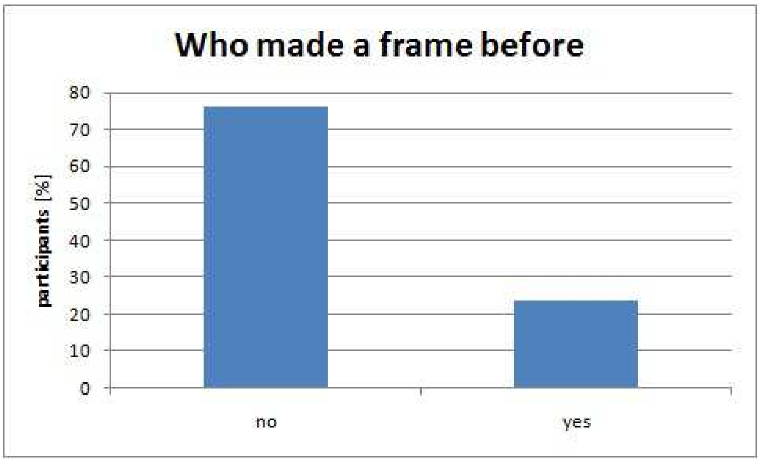

Figure B.12: Participants, who made a frame.

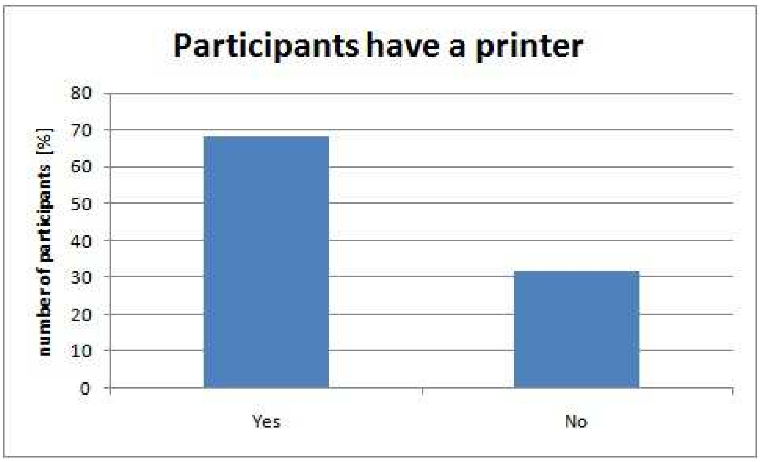

Figure B.13: Who has a printer

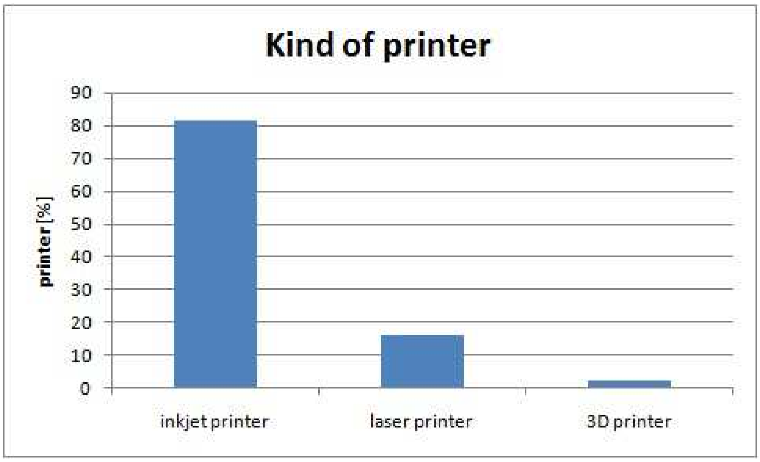

Figure B.14: Which kind of printer

Appendix C

Paperprototype - Appendix

C.1 Constellation

C.2 Tasks

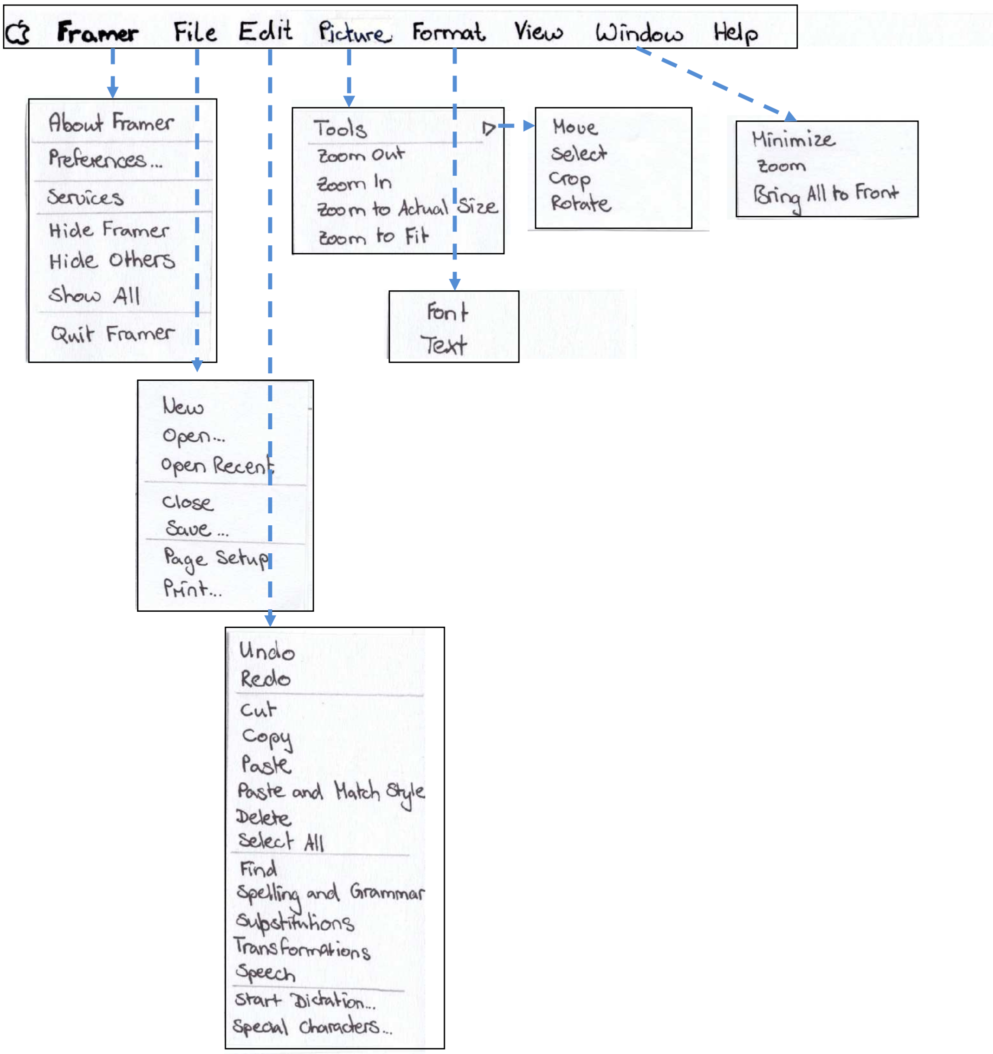

Figure C.1: Menubar of Framer.

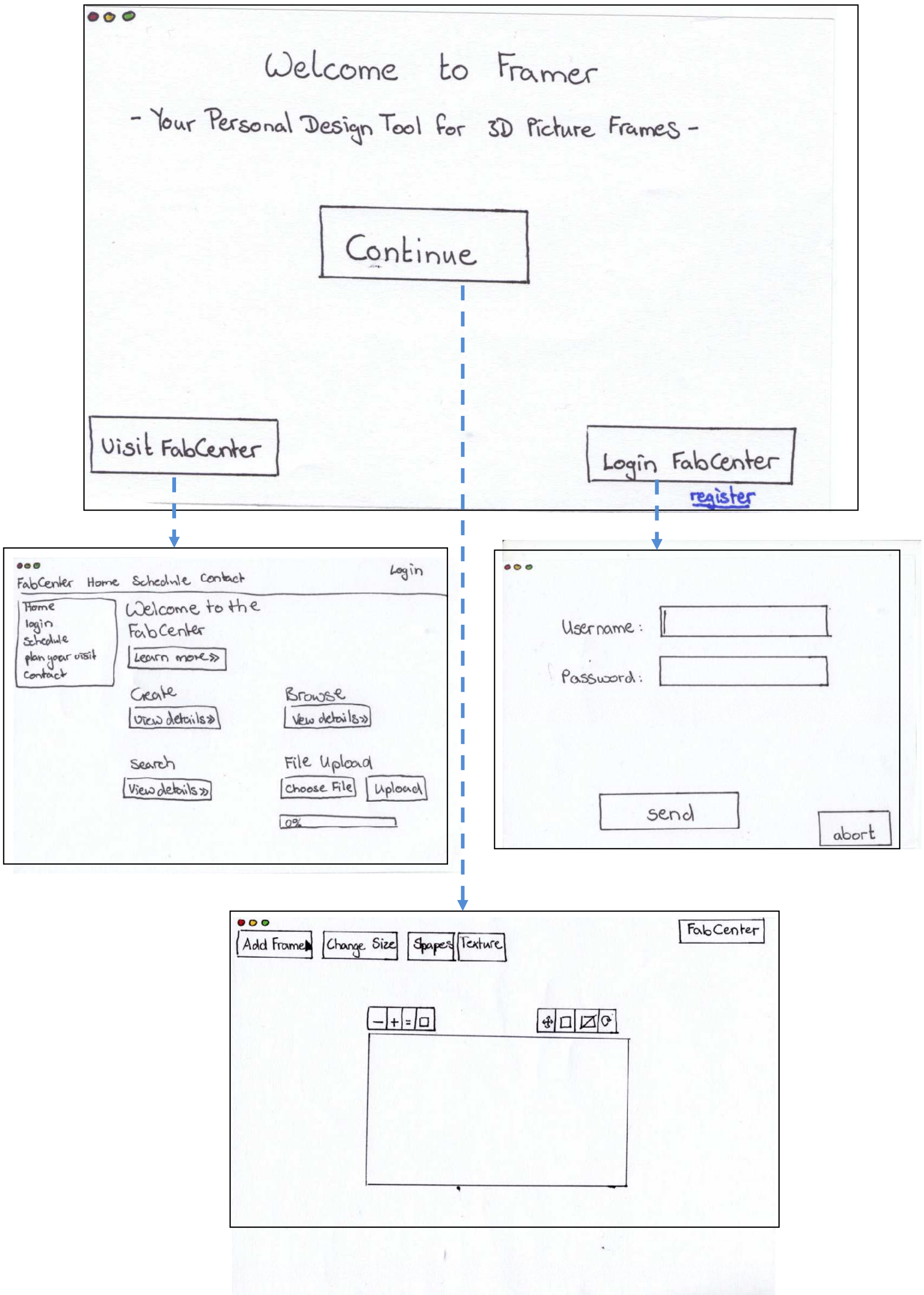

Figure C.2: Constellation of the Welcome window.

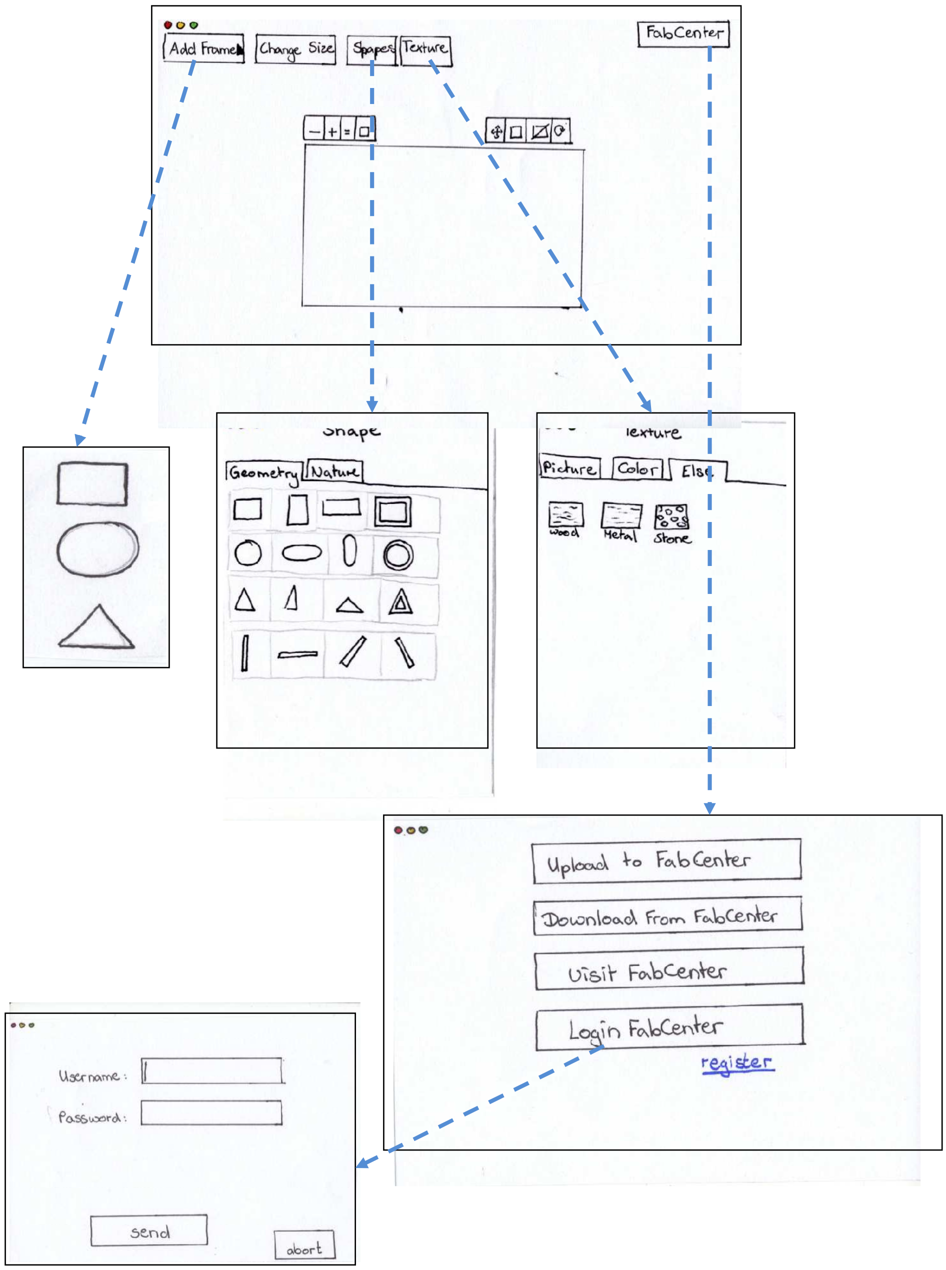

Figure C.3: Constellation of the Main window.

Tasks to perform with the paperprototype

1. Visit FabCenter*[1]
2. Go to Framer*[2]
3. Load Picture
4. Make it smaller
5. Rotate it
6. Add round frame
7. Add stone texture
8. Add shape (rectangle)
9. Login to FabCenter
10. Upload frame to FabCenter
11. Save

---

zu *[1] FabCenter is a webpage where people can upload their design to be reviewed and scored and where they can reserve a termin on a fab lab to print the model.

zu *[2] Main window where people can load and edit a picture before they can design an individual frame.

How to solve tasks

1. Click button "Visit FabCenter"
2. Click button "Continue"
3. Click "File" in menu bar then "Open…"
4. Click button "-"
5. Click rotate button
6. Click button "Add Frame" then on circle
7. Click button "texture" then stone
8. Click button "shape" then rectangle
9. Click button "FabCenter" then button "Login"
10. Click button "FabCenter" then button "Upload to FabCenter"
11. Click "File" in menu bar then "Save"

Figure C.4: Tasks to perform.

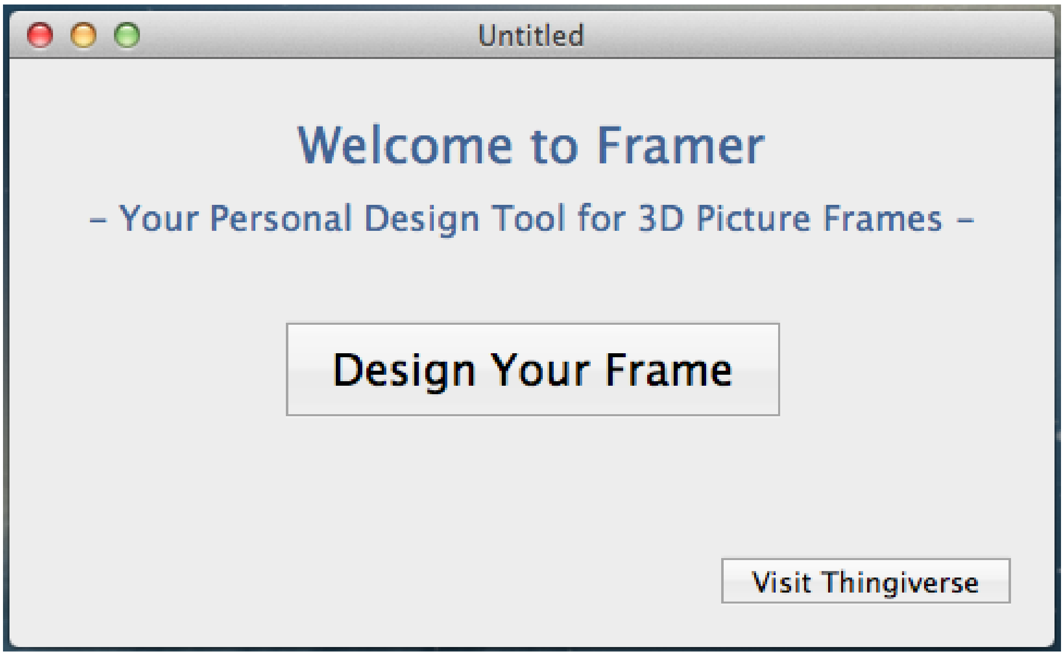

Figure D.1: Initial window, where the user can visit the webpage of Thingiverse and continue to the main window.

Appendix D

Resulted Design - Appendix

D.1 Design

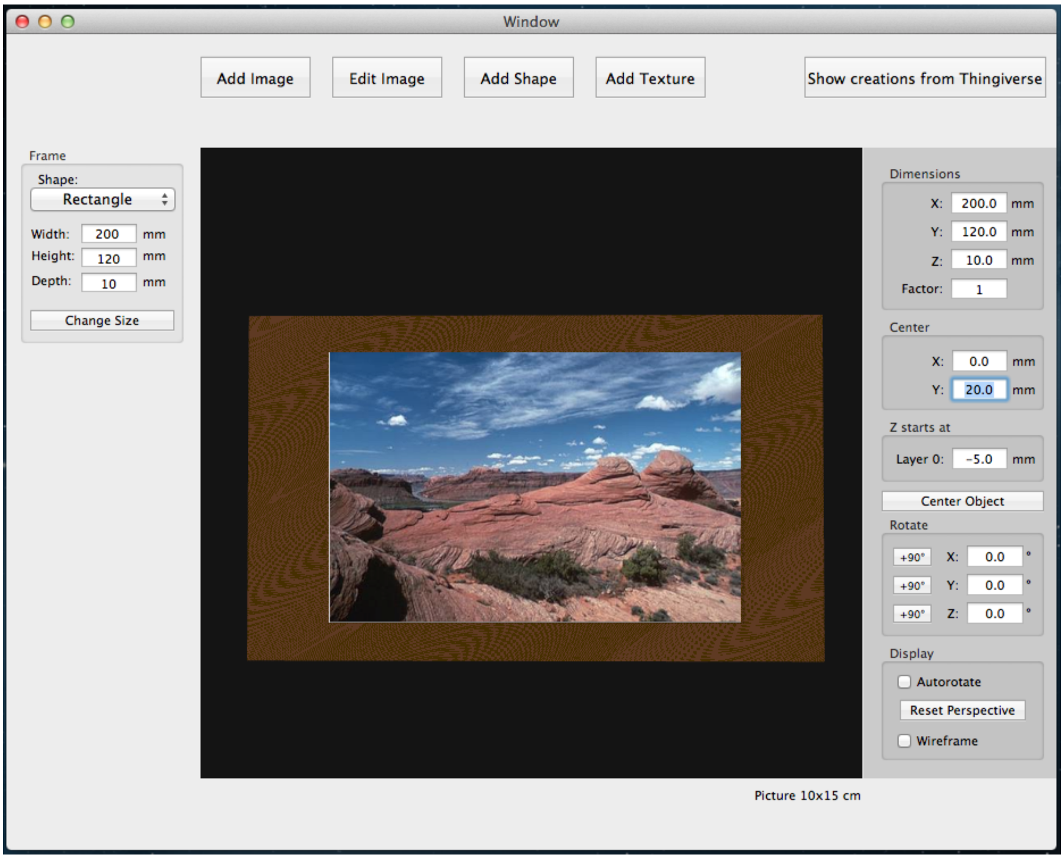

Figure D.2: The main window shows the frame. Buttons open the shape panel, the texture panel and the window to the creations of Thingiverse.

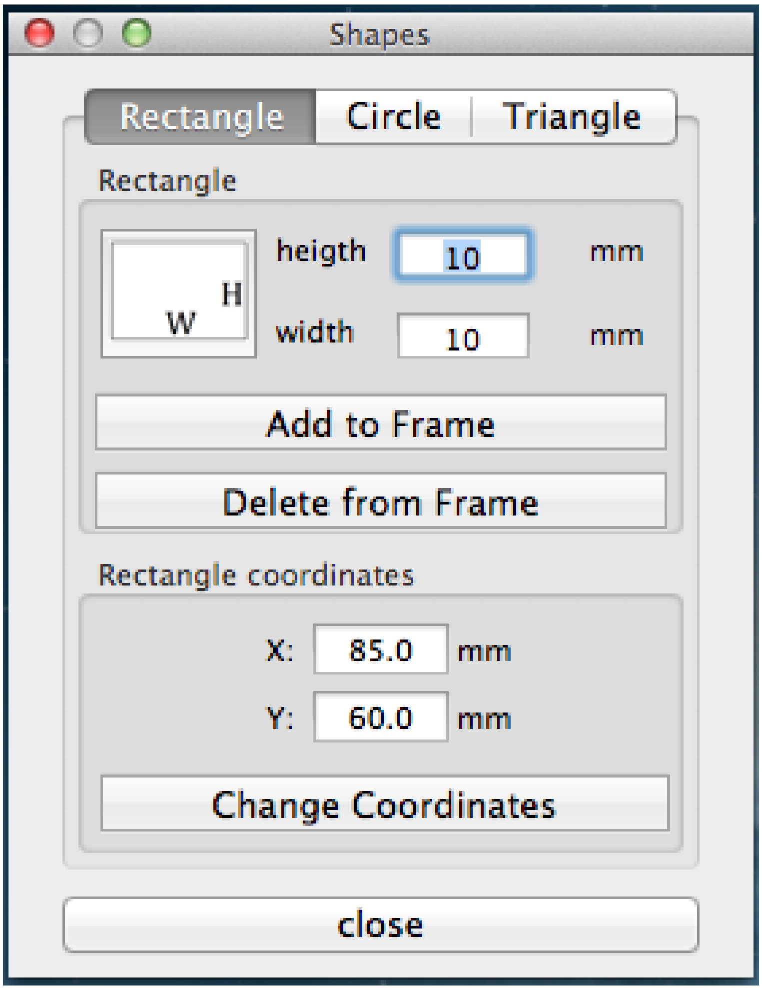

Figure D.3: The user can add a shape in different forms and sizes. Furthermore the positions on the frame can be defined by editing the x and y coordinates.

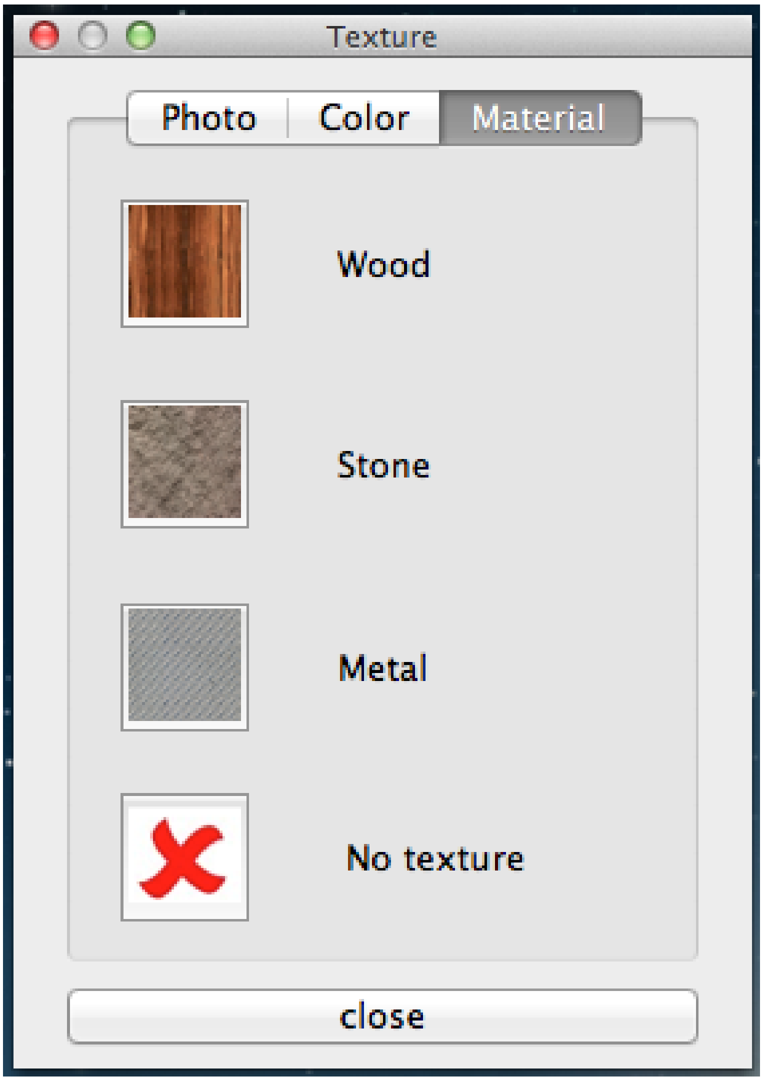

Figure D.4: The whole frame can get different textures and colors.

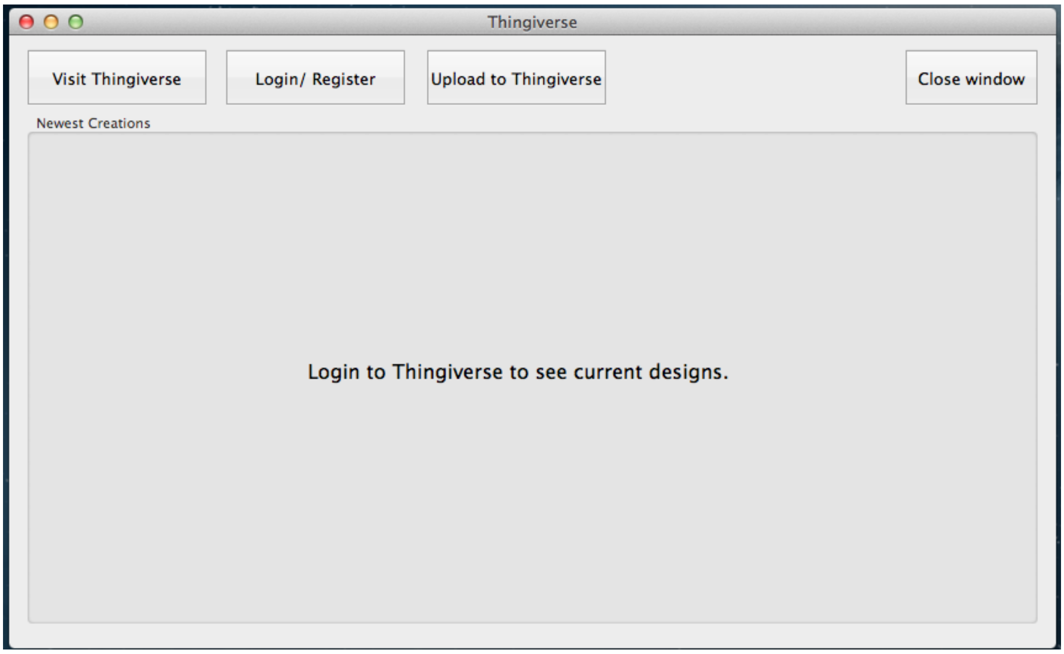

Figure D.5: The user can see different designed frames from other Thingiverse users, when he logs in.

Figure D.6: The user can edit the image in this window.

User Study – Tasks –

1. Move Object
2. Zoom in/out
3. Rotate 90° (X)
4. Reset rotation
5. Change center (right upper corner)
6. Center object
7. Change size of frame
8. Add rectangular shape (h=10mm w=20mm) on upper right corner
9. Add wooden texture
10. See other creations
11. Autorotate object
12. Save model
13. Open another design

Stop time

Think aloud

Figure E.1: Tasks of the user study.

Please check the box that reflects your immediate response to each statement. Don't think too long about each statement. Make sure you respond to every statement. If you don't know how to respond, simply check box "3".

		Strongly Disagree				Strongly Agree
1.	I think that I would like to use Framer frequently.	1	2	3	4	5
2.	I found Framer unnecessarily complex.	1	2	3	4	5
3.	I thought Framer was easy to use.	1	2	3	4	5
4.	I think I would need the support of a technical person to be able to use Framer.	1	2	3	4	5
5.	I found the various functions in Framer were well integrated.	1	2	3	4	5
6.	I thought there was too much inconsistency in this product.	1	2	3	4	5
7.	I imagine that most people would learn to use Framer very quickly.	1	2	3	4	5
8.	I found Framer very awkward to use.	1	2	3	4	5
9.	I felt very confident using Framer.	1	2	3	4	5
10.	I needed to learn a lot of things before I could get going with Framer	1	2	3	4	5

11. Overall, I would rate the user-friendliness of Framer as:

Worst Imaginable	Awful	Poor	OK	Good	Excellent	Best Imaginable

12. How likely is it that I would recommend Framer to a friend or colleague?

Extremely unlikely							Satisfied		Extremely likely
1	2	3	4	5	6	7	8	9	10

Figure E.2: Questionnaires to calculate SUS and NPS [Bangor et al. 2009] and [Reichheld et al. 2003]

Rate your agreement with the following statements:

Results Worth Effort
What I was able to produce was worth the effort I had to exert to produce it.

Strongly Disagree									Strongly Agree
1	2	3	4	5	6	7	8	9	10

Expressiveness
I was able to be very expressive and creative while doing the activity

Strongly Disagree									Strongly Agree
1	2	3	4	5	6	7	8	9	10

Exploration
It was easy for me to explore many different ideas, options, designs, or outcomes.

Strongly Disagree									Strongly Agree
1	2	3	4	5	6	7	8	9	10

Immersion
My attention was fully tuned to the activity, and I forgot about the system that I was using.

Strongly Disagree									Strongly Agree
1	2	3	4	5	6	7	8	9	10

Enjoyment
I was very engaged in this activity – I enjoyed this activity and would do it again.

Strongly Disagree									Strongly Agree
1	2	3	4	5	6	7	8	9	10

Collaboration
The system allowed other people to work with me easily.

Strongly Disagree									Strongly Agree
1	2	3	4	5	6	7	8	9	10

Figure E.3: Factor ratings to calculate CSI [Carroll et al. 2009]

For each pair below, please select which factor is more important to you when doing the activity:

Exploration	☐	☐	Collaboration
Exploration	☐	☐	Enjoyment
Exploration	☐	☐	Results Worth Effort
Exploration	☐	☐	Immersion
Exploration	☐	☐	Expressiveness
Collaboration	☐	☐	Enjoyment
Collaboration	☐	☐	Results Worth Effort
Collaboration	☐	☐	Immersion
Collaboration	☐	☐	Expressiveness
Expressiveness	☐	☐	Results Worth Effort
Expressiveness	☐	☐	Immersion
Expressiveness	☐	☐	Enjoyment
Enjoyment	☐	☐	Immersion
Enjoyment	☐	☐	Results Worth Effort
Immersion	☐	☐	Results Worth Effort

Figure E.4: Pairwise factor rankings to calculate CSI [Carroll et al. 2009]

Appendix E

Study - Appendix

E.1 Tasks

E.2 Questions

E.3 Time to Perform each Task

Here are the resulting times to perform each task:

To change the width of the frame, the first time users needed in average 38.5 seconds and the users, who already participated the prototype (second time users) needed in average 25 seconds (see Figure E.5). The maximal time was the same, but some second time users were faster then the first time users.

To add a rectangular shape there were differences of the maximal and minimal time to perfom the task (Figure E.6). The second time users already knew that the "Add Shape" button adds a new shape and therefore were faster than the first time users. However there were also second time users, who were not faster than first time users. This task is well integrated, so that first time users are nearly as fast as the second time users.

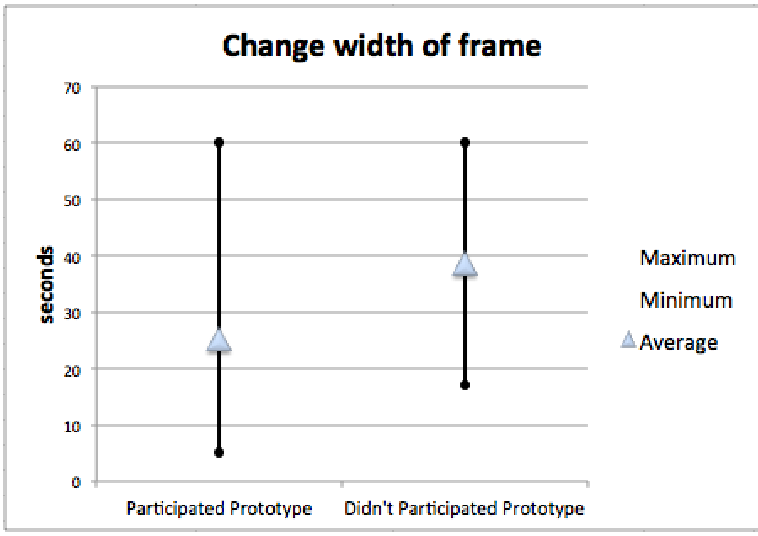

Figure E.5: Time to change the width of the frame.

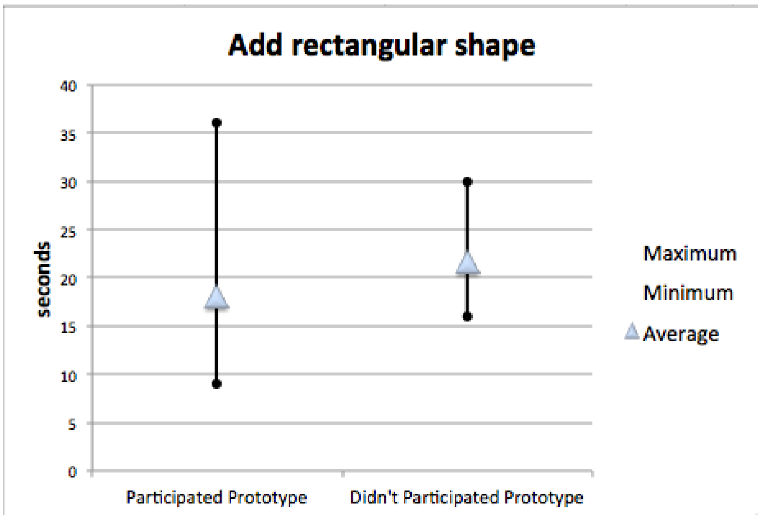

Figure E.6: Time to add an ectangular shape on the frame.

To add a wooden texture the first time users needed more time than the second time users (see figure E.7). As with the added shape, the second time users knew how to add a texture. The first time users needed 20.67 seconds more in average to perform the tasks. This result displays the good learnability of the program.

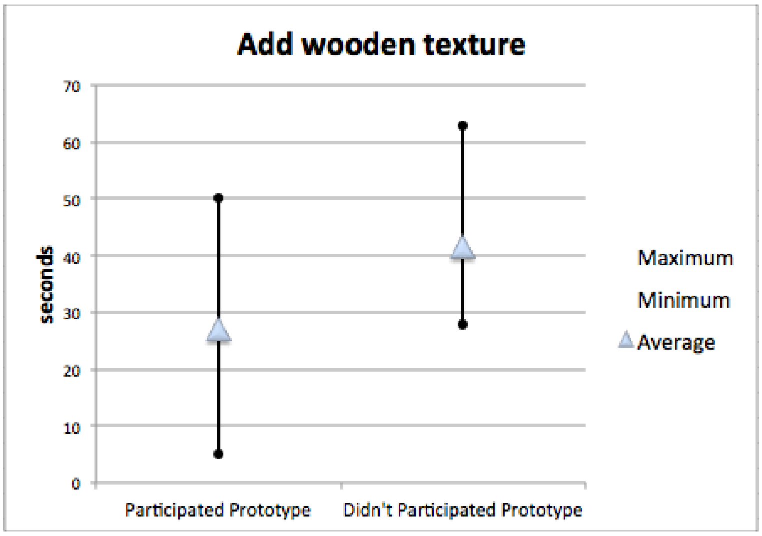

Figure E.7: Time to add a wooden texture.

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