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Tuomas Puttonen

Design of an Elevator Button Assembly for Additive Manufacturing

Master's Thesis
Espoo, October 16, 2017

Supervisor:	Professor Jouni Partanen, Aalto University
Advisor:	Sergei Chekurov, Aalto University

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ABSTRACT OF
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Additive manufacturing, with its recent technological developments, has increasingly disrupted how products are designed and manufactured. Within additive manufacturing, there has been a shift from the production of visual models and rapid prototyping applications to direct digital manufacturing of end products. Additive manufacturing provides intriguing possibilities in the design of new and existing products. These radical, pioneering designs have already redefined whole industries.

This thesis provides a practical case study for an additive manufacturing redesign together with a literature review of the current additive manufacturing technologies and applications. The target of the redesign was a low volume elevator button assembly. Concepts were prototyped and tested in contrast to the current industry specification.

As a result of the thesis, a functional button assembly was produced and tested. The part count, material usage, and costs were reduced compared to the original. However, all industry requirements were not met. A need for a more systematic material and process selection was identified. Nevertheless, additive manufacturing was proven to be a serious alternative in the production of low volume plastic products and should be researched further.

Keywords: Additive Manufacturing, 3D Printing, Design for Additive Manufacturing, Product Development, Product Design

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Lisäävien valmistusmenetelmien teknologinen kehitys vaikuttaa enenevissä määrin siihen, miten fyysisiä tuotteita valmistetaan. Visuaalisten- sekä pikamallien tulostuksesta ollaan siirtymässä lopputuotteiden suoraan valmistukseen. Geometristen rajoitusten vähyys luo kiinnostavia mahdollisuuksia uusien ja olemassa olevien tuotteiden suunnittelussa. Uudet radikaalit ja uraauurtavat tuotteet ovat jo määrittäneet uudelleen kokonaisia toimialoja.

Tämän diplomityön käytännön osuudessa suunnittellaan hissin nappikonstruktio täysin uusiksi lisäävien valmistusmenetelmien näkökulmasta. Työ tarjoaa myös kirjallisen läpileikkauksen lisääviin valmistusteknologioihin sekä käyttökohteisiin. Käytännön työssä etsittiin lisäävien valmistusmenetelmien etuja hyödyntäviä konsepteja, prototypoitiin, sekä testattiin kehiteltyjä ratkaisuja suhteessa toimialan vaatimuksiin.

Työn tuloksena valmistettiin ja testattiin toiminnallinen nappikonstruktio. Kokoonpanon osamäärää, materiaalinkäyttöä sekä hintaa saatiin vähennettyä suhteessa alkuperäiseen. Kaikkia vaatimuksia ei kuitenkaan saatu täytettyä. Prosessin aikana tunnistettiin tarve systemaattisemmalle materiaali- sekä valmistusprosessivalinnalle. Tästä huolimatta lisäävät valmistusmenetelmät todettiin vakavasti otettavaksi vaihtoehdoksi matalan volyymin muovituotteiden valmistuksessa.

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Espoo, October 16, 2017

Tuomas Puttonen

Abbreviations and Acronyms

2D	Two-dimensional
3DP	3D Printing
ABS	Acrylonitrile Butadiene Styrene
ADA	Americans with Disabilities Act
AI	Artificial Intelligence
AM	Additive Manufacturing
.AMF	Additive Manufacturing File Format
AMUG	Additive Manufacturing Users Group
ASA	Acrylonitrile Styrene Acrylate
ASTM	American Society for Testing and Materials
CAE	Computer Aided Engineering
CAD	Computer Aided Design
CNC	Computer Numerical Control
CDLP	Continuous Digital Light Processing
CT	Computer Tomography
DDM	Direct Digital Manufacturing
DED	Directed Energy Deposition
DfMA	Design for Manufacturing and Assembly
DfAM	Design for Additive Manufacturing
DMLS	Direct Metal Laser Sintering
DIY	Do It Yourself
DMD	Digital Micromirror Device
EBM	Electron Beam Melting
EMC	Electromagnetic Compability
FDM	Fused Deposition Modeling
FEM	Finite Element Method
JIT	Just in Time, customer demand driven production
ISO	International Organization for Standardization
LED	Light Emitting Diode
LOM	Laminated Object Manufacturing

MIT	Massachusetts Institute of Technology
MRI	Magnetic Resonance Imaging
PA	Polyamide (Nylon)
PC	Polycarbonate
PCB	Printed Circuit Board
PLA	Polyactid Acid
RM	Rapid Manufacturing
RP	Rapid Prototyping
RT	Rapid Tooling
SLA	Stereolithography
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
.STL	Polygonized 3D file format
UV	Ultraviolet light
VTT	Technical Research Centre of Finland

Contents

Chapter 1

Introduction

Since the emergence of additive manufacturing in the 1980s, the technology has gradually evolved to a point where direct manufacturing of end products has become possible. This evolution started with rapid prototyping and marketing applications. In the turn of the century, customized plastic hearing aids were the first products directly manufactured with additive methods. Other medical, and especially, dental applications followed. At the time, rapid tooling applications were also experimented with to reduce tooling lead times. Starting from the 2010's direct manufacturing of metal parts with additive manufacturing have been used increasingly in the aerospace, automotive, and medical industries. As of 2016, the additive manufacturing field was valued at 5.165 billion dollars with a growth rate of 25.9 percent [33]. Both, the technological and the economic development of additive manufacturing have made it an attractive alternative to, or a companion with, traditional manufacturing methods.

Manufacturers and companies producing physical products have recognized this potential but have, in most cases, been unsuccessful to implement a feasible process to support it [10]. Additive manufacturing has been mostly implemented with high value or niche market products, such as hearing aids, dental guides, or jet engine components [29]. Additive methods have not been able to compete with traditional methods in cost-effectiveness when production volumes are high. Value with additive manufacturing is added either by increasing the performance of a product, or the ease of user customization. Products, that would merit an additive manufacturing adoption, are hard to identify [20] and they often require significant design modifications before competitive solutions are achieved. However, when the identification and the following product development work is successful, superior products can potentially redefine whole market segments. This effect was first demonstrated in the production of hearing aids by Siemens and Phonak [12].

This thesis provides a practical case example of a product conceptualization and development process for additive manufacturing. A special, low volume elevator button assembly was identified as a case example. To date, the plastic components in elevator buttons are mostly injection molded. Thus, new customized button designs always require a new mold tooling as well. Design and manufacturing of the molds take resources, is costly, and accounts for longer lead times. The use of additive manufacturing, instead of traditional manufacturing methods, could radically simplify the overall process and reduce costs. An equivalent functionality could be achieved with less material, a simplified assembly, and a vast range of customization options.

The case study and the literature survey gather information about the current state, and feasibility, of additive manufacturing. The main objective of the thesis was to benchmark different additive manufacturing technologies in the direct production of an elevator button assembly. The interest is in the attainable functionality and quality of the manufactured end products. As a result of the thesis, an elevator button assembly designed for additive manufacturing was conceptualized, prototyped, and tested for functionality.

The structure of the thesis is organized into two distinct parts, *the literature part* and *the design part.* The literature part provides the context for the practical product development work presented in the design part.

The literature part is divided into two: technology and design. The first chapter, *Additive Manufacturing*, is the general background of the whole field. It is a look into the current technologies and how their specific characteristics must be taken into account in the manufacturing of products. The second chapter, *Design for Additive Manufacturing*, provides an overview of the additive manufacturing possibilities for product design and how it is changing the way product development is done.

The design part of the thesis starts with the chapter: *Elevator Button Conceptualization.* This part presents the design process, elevator industry requirements and all the practical steps that were taken in the design of the new button assembly. The *Testing* chapter provides an overview of the implemented mechanical tests and their results.

The final design for the button assembly is presented and evaluated in the *Results* chapter. Finally, everything is concluded in the *Summary and*

Discussion chapter which briefly summarizes the different AM technologies and design considerations and then discusses the results of this thesis in the context of the whole additive manufacturing field.

Chapter 2

Additive Manufacturing

Manufacturing is essentially a process where raw material is transformed into a functional object. In the process, raw material is the input, and the functional object is the output. This transformation in geometry and properties is achieved via *material shaping.* Three different basic principles of material shaping exist that can be either utilized separately or in combination with each other. [16]

The first of these shaping methods is called *subtractive shaping* which means that material is selectively removed in order to achieve a desired geometry. A historical example of subtractive shaping is the making of a knife by hitting two rocks of different hardnesses together. In modern manufacturing, methods such as milling, turning, and drilling belong to this group.

In contrast, the second shaping method, *formative shaping*, transforms the shape of the material with external energy. With formative shaping, the amount of material is preserved. Manufacturing methods such as forging, bending, casting and injection molding belong to this group.

This thesis is focused on the third principle called *additive shaping.* It is defined as the successive addition of material to form the desired shape [16]. Traditional joining methods such as welding, soldering, adhesives, and fasteners can be included in this principle. *Additive manufacturing (AM)* refers specifically to the successive addition of raw material, layer-by-layer, to manufacture *an entire three-dimensional object.*

This chapter provides the necessary background of additive manufacturing and its different technologies in order to understand what factors are to be taken into account in the design of products for additive manufacturing. The *Introduction* chapter briefly presents the history and the current terminology of the field. Next, the general principle of additive manufacturing is introduced. *Technologies and Materials*section collects the different technologies, which implement this principle, and gives a general overview of what materials can be used with them. Finally, the most common industrial applications and the current economic status of additive manufacturing is discussed.

2.1 Introduction

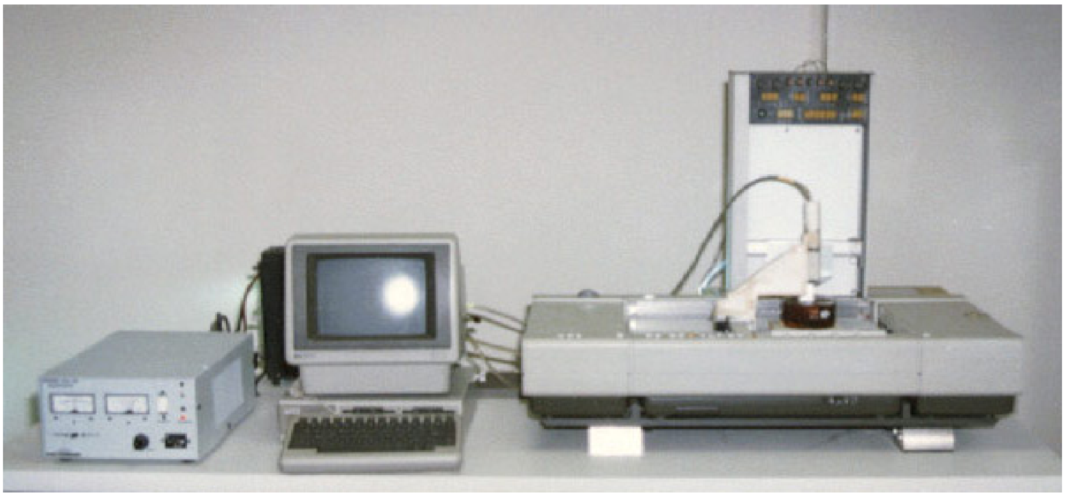


Figure 2.1: The first 3D printer. A stereolithography machine invented by Chuck Hull in 1983. The machine solidified layers of liquid photopolymer to form 3-dimensional objects [12].

The concept of building objects with 2D layers is not entirely new. Similar applications have existed over a hundred years for example in the generation of topographical maps and photosculptures [29]. However, it was not until the 1980s that the concept was brought to an industrial level with an automated machine. The discovery of photopolymers and the developments in laser-, computer- and controller technology all led to the creation of the first AM machine shown in Figure 2.1. Similar patents for 3D fabrication were filed almost simultaneously in Japan, France and in the US. After the initial break, different technologies emerged very quickly and new companies were established on the patents already during the 1980s. The initial use of additive manufacturing was mainly for *rapid prototyping* and marketing purposes. [12]

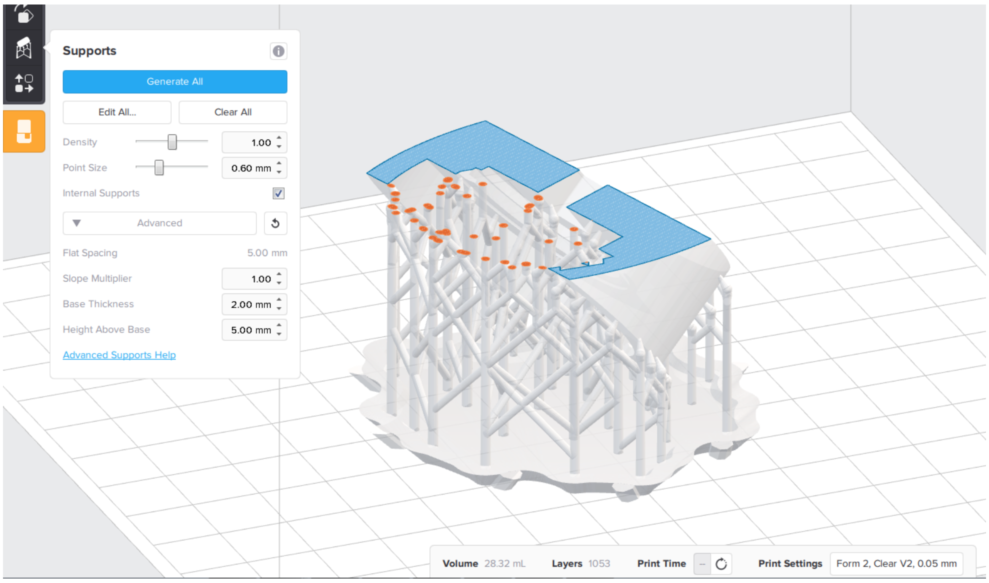
Additive manufacturing (AM) has now gained the popular momentum as the field-defining term. From this point on, this thesis will use the acronym AM to refer to additive manufacturing. *3D printing (3DP)* is used as a synonym to AM, mostly by the press and the general public. Originally, it referred only to the binder jetting AM technology developed in MIT that bears a resemblance to the classic 2D inkjet printing on paper. 3D printing is a term used more often with the cheaper machines whereas AM and rapid prototyping are used as labels for the more expensive machinery and professional applications [6]. Terms such as *additive fabrication*, *freeform fabrication*, *layer manufacturing* and *solid freeform fabrication* are all outdated terms that all point to AM [16].

During its 40 years of existence, the AM technology has steadily improved to a point where a sense of a broader industrial implementation is in the air. Some even speak of an industrial revolution of our time [6]. Existing technologies have continued to mature in terms of reliability and quality. The most recent developments have concentrated on structures supporting the design, software, and applications. This includes the standardization efforts by ISO/ASTM and the emergence of *Design for AM (DfAM)* thinking that has entered the engineering regime. Design software providers are implementing new features to facilitate and simplify the AM design process. At the same time, companies are increasingly investing on AM [11, 25] and starting projects to tests its maturity. Rapid prototyping with AM has long been an integral part of product development, but more recently rapid manufacturing applications have been explored as well. Medical, dental and aerospace industries have gone the furthest and have, in some applications, already adopted AM for direct manufacturing of products [22].

At the same time, the field has expanded for hobbyists as the machine costs have come down. A very viral *maker movement* has emerged spawning active forums as well as physical maker spaces to use for DIY projects. These spaces not only provide the hardware for common use but spread the necessary knowledge of AM as well. The establishment of multiple *3D Hub*-companies and services have facilitated the work of DIY-hobbyists and companies alike. Service platforms such as Shapeways, iMaterialize and 3D Hubs provide affordable 3D printing services and have implemented online services for direct quotation of 3D models.

2.2 Principle

Additive manufacturing (AM) is defined by the ISO/ASTM as ”a process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive and formative manufacturing methodologies” [16]. The principle is well illustrated in a screenshot from the Formlabs 3D printer pre-processing software (Figure 2.2). Most additive manufacturing technologies build objects one layer at a time. This means that the digital 3D object is first *sliced* to thin 2D sections. Raw material is first deposited and then joined or bonded one thin layer at a time. Different technologies mainly differ on how the raw material is distributed and bonded.



Density 1.00
Point Size 0.60 mm
Internal Supports ☑
Flat Spacing 5.00 mm
Slope Multiplier 1.00
Base Thickness 2.00 mm
Height Above Base 5.00 mm

Volume 28.32 mL
Layers 1053
Print Time --
Print Settings Form 2, Clear V2, 0.05 mm

Figure 2.2: The main idea of additive manufacturing illustrated through the set-up software Preform for the Formlabs stereolithography printers. The current 2D section of the part is shown in blue. Sections of the tree-like support structures are shown in orange.

The most visible physical aspect of AM objects is the *layer thickness*. If the layer thickness is too high the object appears pixelated much like in a low-resolution image. Layer thickness defines the Z-direction resolution of the printed objects. There are also machine dependent limitations for the resolution on the X-Y surface. When combined these resolutions produce the overall *print resolution* and account for the accuracy of the finished object in comparison to the original 3D model file.

When objects are manufactured with AM and sliced to 2D sections the *print orientation* can be freely defined by the designer. Only limiting factor is that the consecutive layers in AM need to adhere to the underlying layers. Very often in freeform designs, overhangs and internal cavities demand additional *support structures* to provide the necessary point to adhere to. In addition supporting structures are used to improve adhesion to the build plate, minimize bending or warping and to provide additional heat transfer. The realization and need for support structures vary between different technologies.

2.3 Digital Workflow

Gibson et al. [12] categorize the different phases of digital and physical AM process chain in 8 steps. The purely digital phases include *1. Conceptualization and CAD, 2. Conversion to STL, 3. Transfer and Manipulation of STL and 4. Machine Setup.*

The product ideation and conceptualization is the initial step in every product development process. In order for the concept product to be printable, it needs to be translated into a 3D model in some way or another. 3D CAD modeling software is the most obvious way but also existing objects can be scanned or reverse-engineered to form the initial 3D shape. In medical applications the use of CT scans or MRIs is common. Photogrammetric algorithms can transform multiple 2D photos of a single object taken from different angles to form a 3D representation [29]. The scanned objects often demand digital post-processing before being exported as STL files for the actual print process.

The 3D model data, regardless of how it was obtained, is converted to a format understandable by the specific manufacturing machine. The industry standard at the moment is the STL-format created by 3D Systems. The STL-format is a triangulated representation of the input model surface geometry. This STL model data is manipulated in a machine dependant software. This step defines the layout of the object(s), print orientation and scale of the object(s). Standardization work is underway for a replacement file format. The new AMF format would have native support for color, materials, and lattice structures [29].

Finally, the machine setup generates the parameters needed for the actual print process. The slicing height, support material creation, support placement, tool path control, temperature, material flow and numerous other aspects all depend on the technology used. They often require a tailored set-up software to function [29]. The same software normally handles the manipulation of STL and the machine setup. The resulting file is now transferred to the printer and the physical phases of the process can begin.

2.4 Technologies and Materials

The physical workflow of AM begins after the 3D design file has gone through the digital process specific steps to prepare it for a print. Gibson et al. [12] categorize the remaining phases of the process chain as *5. Build, 6. Part Removal and Cleanup, 7. Post-processing and 8. Application.*

The build phase includes a repetitive automated process where the material is laid and bonded layer-by-layer. For layer-based systems, the AM machine consists of a height adjustable build platform, a material deposition system and a way to form the 2D sections.

For accurate manufacturing, the part needs to be supported by the build platform in some way. After the build is finished, the object is detached from the build platform. Depending on the used technology the created support structures must either be removed manually, chemically, or by machining. Some of the technologies are self-supporting and do not require any additional structures to hold the parts.

Some AM methods produce so-called *green parts* that require further steps after the actual print process to finalize the object. As an example, the binder jetting technology uses a binder to bond material particles together but an additional sintering step in an oven is necessary to achieve a solid material structure for the object [12]. Finalized 3D printed parts can be further post-processed, before the part is ready for application, by machining, sanding, and heat treatment. These operations can improve the dimensional accuracy, material properties, surface finish, and aesthetics of the part.

The main difference between different technologies is how the deposition and joining of material occurs. At this time there are seven AM categories (Figure 2.3) identified by the American Society for Testing and Materials (ASTM) additive manufacturing group: *material extrusion*, *vat polymeriza-*

tion, *powder bed fusion*, *material jetting*, *binder jetting*, *direct energy deposition*, and *sheet lamination* [15].

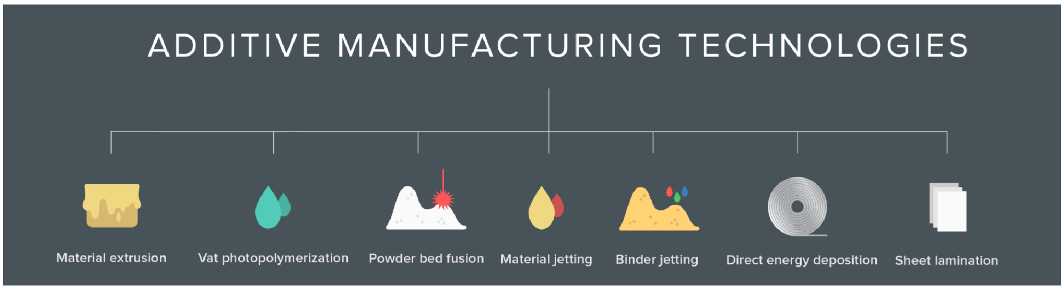


Figure 2.3: The 7 different AM technology categories. Image modified from [1].

The following chapters will present these seven categories. Introduction to each of these categories will follow the same template. First, the principle of the technology is briefly introduced. Then the focus is shifted on its advantages and challenges. Finally, the practical design implications are elaborated. The different technologies involve effects depending on the principle of function that need to be taken into account in the design of products.

Increased emphasis is put on technologies that will be utilized in the design part of this thesis. These technologies include *material extrusion, vat polymerization, powder bed fusion and material jetting*. They were identified as the most promising ones for the direct production of an elevator button assembly. Technologies that have less relevance for the thesis will be presented on a more general level.

The main interest, from the product design point-of-view, is on the opportunities and restrictions the different technologies pose. An elevator button has features and design areas with very different requirements. The face of the button must be aesthetically pleasing. Also, the fine surface quality of the face contributes to an enjoyable touch experience. There are contrast requirements for the button markings and the face as well as the face and the elevator panel. On the other hand, accurate and durable mechanical properties are also critical. The button needs to withstand press cycles from hundreds of thousands to millions without losing functionality. The tolerances for fastening mechanisms are strict. In addition, elevator buttons are treated with harsh cleaning chemicals and can undergo cyclic temperature changes up to 50 degrees celsius.

The manufacturing technologies and the materials should be able to address all of these requirements. Some AM processes might be eliminated because of a limited and lacking material selection or not being able to fulfill the requirements due to a weak print resolution or strong discretization of material layers. The necessary post-processing steps might hinder a technology unfeasible. The unit cost of production is one of the biggest requirements if direct AM production would be considered as an alternative to traditional manufacturing methods. The next sections will go through the AM technologies while keeping these considerations in mind.

2.4.1 Material Extrusion

Although not the newest technology, *material extrusion* has still taken the lead as the most widely used AM process. The principle is to deposit heated thermoplastic material at a constant rate on the build platform while plotting one xy-layer at a time. Filament from a material spool is fed with rollers through heated extrusion nozzles. The material solidifies after cooling or through a chemical reaction and bonds to the underlying layer of material. The working principle is illustrated in Figure 2.4. The most popular branch of material extrusion is called *Fused Deposition Modeling (FDM).* This technology was initially patented by Scott Crump in 1992 and since the has been further developed by the company Stratasys. A listing of biggest machine manufacturers is presented in the leftmost column of Figure 2.5. [12]

Many smaller companies have adopted the technology as well as it is well suited for the design of lower price range desktop 3D printers. A fairly simple belt drive mechanism suffices for the plotter in combination with a z-direction screw for the movement of the build platform. The nozzle usually doubles as a liquefier chamber (heating element). A screw or a pinch roller system is responsible for producing the necessary pressure to push the constant material flow through the nozzle. More professional systems keep a constant atmosphere and an elevated temperature in the build space to ensure stable material solidification. Printers targeted for home use are mostly open systems that only heat the build bed and use overhead fans for sufficient heat transfer.

Due to inexpensive machine options, FDM is in extensive use by the everyday hobbyists and the maker movement. The material selection is wide.

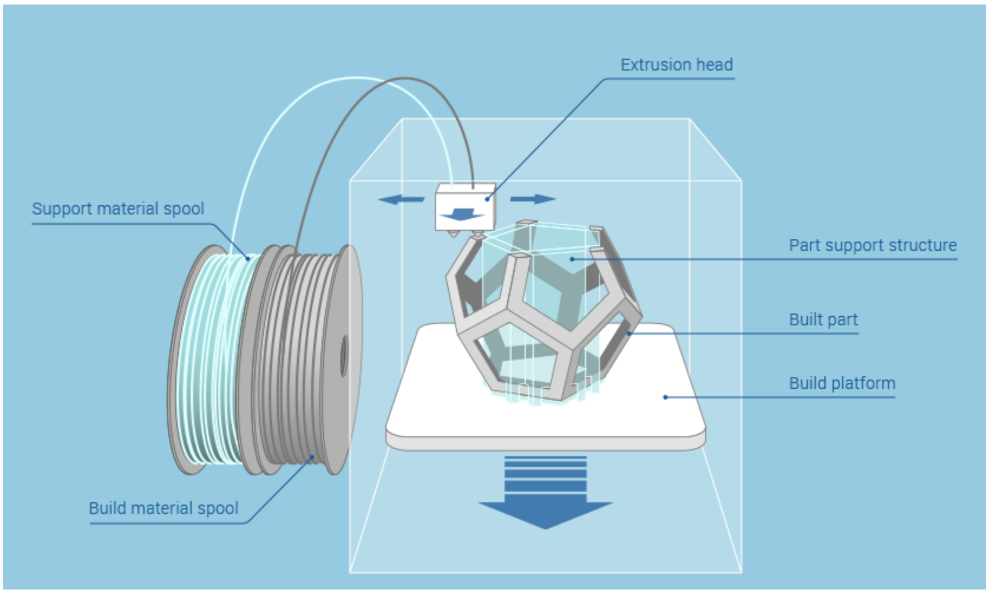


Figure 2.4: Fused deposition modeling process [2].

The technology allows the use of standard thermoplastics used in injection molding processes such as ABS, PLA, PC, ASA, and Nylon. The properties of these materials are well known and they can be customized for example improved ductility, biocompatibility, heat-resistance, or medical compatibility. Adding color to the filaments is also possible.

The layer thickness of material extrusion methods is generally around 0.1mm or slightly finer which, for design features smaller than a few millimeters, is already too coarse. Button features such as snap-fits or springs fall under this size group. Depending on the print direction slightly concave or convex topologies suffer the layering- or *stair stepping*-effect. Layers can be seen by naked eye and the line path direction is also visible in the parts without any post-processing steps or chemical treatment. For this reason the surface finish of extruded parts is generally not sufficient for end-products. The weakness of the parts perpendicular to the print direction affect the design as well. The part features experiencing shear stresses will need to be carefully designed and printed in the right orientation. However, it is not always possible to choose a print orientation beneficial for all of the mechanical and visual requirements.

The material extrusion process, in general, is a process that does not scale

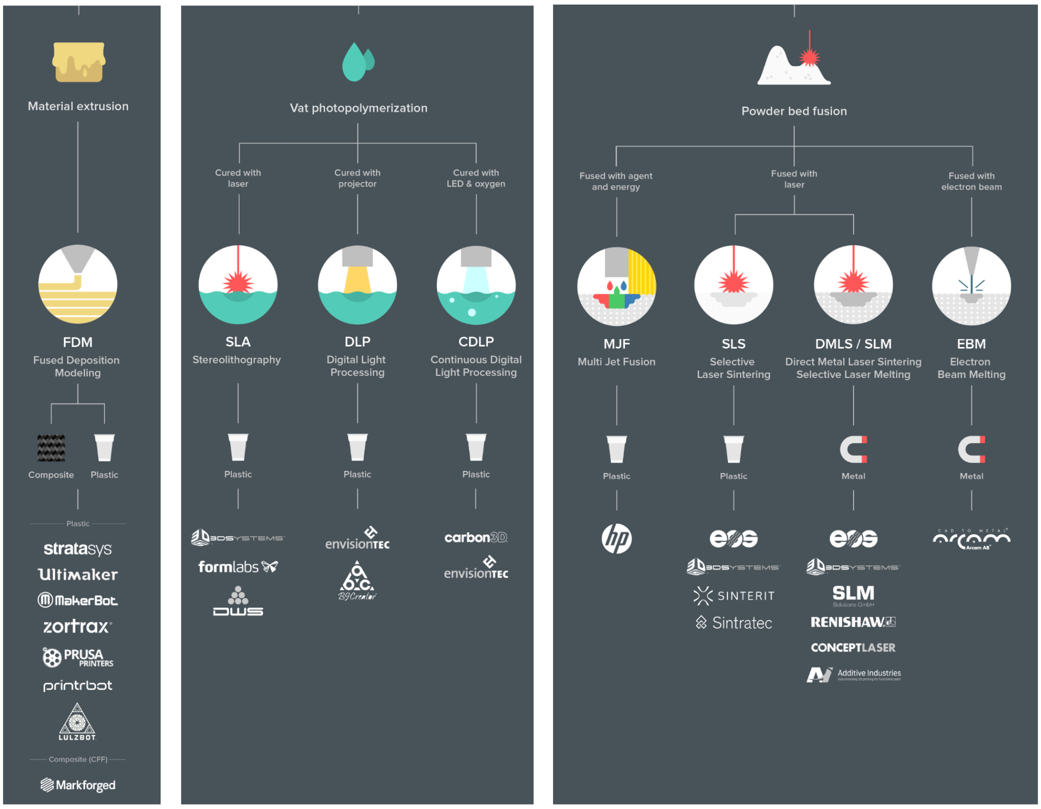


Figure 2.5: Different technologies, materials, and machine manufacturers available within material extrusion, vat polymerization, and powder bed fusion technologies. Image modified from [1].

very well in terms of build speed. Adding more nozzles is hard due to the space requirements of the heating chambers and systems that push the liquid material out. Multi-material processes exist but the build time is increased two- or even fourfold. [12] Given these restrictions it is hard to see material extrusion-based methods to be used in the production of end-use parts, at least without any post-processing phases.

2.4.2 Vat Polymerization

The development of photopolymer materials in the 1960s was the original trigger for all of the additive manufacturing technologies. Liquid photopolymer can be cured (or solidified) with radiation most often in the ultraviolet

(UV) wavelength range. Experimentation with these materials led to the invention of *Stereolithography (SLA)* and the establishment of the company 3D Systems in the mid-1980s. The SLA machines were first marketed for rapid prototyping use in companies. [12]

The principle of stereolithography is illustrated in Figure 2.6. A build platform is immersed in liquid photopolymer resin and a distance of one layer height is kept between the build platform and the surface of the liquid. A UV laser plots the area where material is to be solidified. The platform is lowered for new resin to cover the solid surface and the process repeats for a new layer. Most often the build platform is upside down and the laser cures the resin from below through a transparent window as the object is raised up layer-by-layer. Leveling of the liquid is necessary between each cycle which reduces the overall speed of printing. Polymerization processes require support structures which have to be manually removed after the print process. Also, depending on the material, *a post-cure* in an UV oven is needed [12].

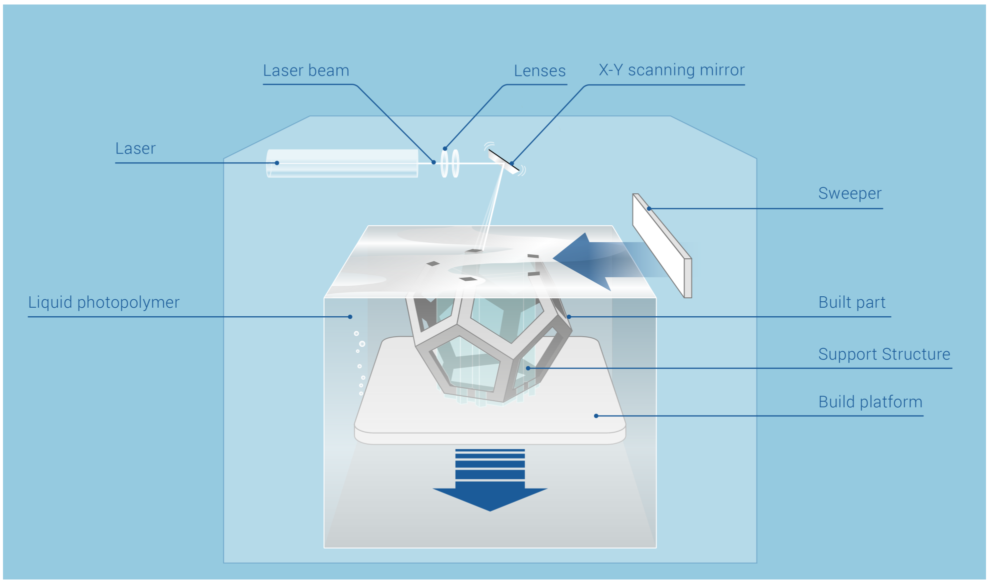


Figure 2.6: Stereolithography process [2].

Three different approaches for the polymerization exist (Figure 2.5 middle column). The main difference is how the curing laser is administered on the surface. *Stereolithography (SLA)* methods cure a path in the liquid with a laser. In comparison, the *mask projection* method cures a complete layer at a time. This is achieved with a Digital Micromirror Device (DMD) that projects a "UV mask" on the surface of the resin. Curing the whole layer at a time instead of discrete points increase the speed of the process [12]. The *continuous digital light processing* method utilizes an oxygen inhibitor layer to prevent material solidification in the interface between the resin tank and the liquid. This approach avoids the need for liquid leveling steps between layers [30]. The continuous process is marketed as 10-100 times faster than traditional stereolithography by the US startup Carbon 3D who owns the original patents for this method.

Compared to the 0.1 mm layer thickness of material extrusion, polymerization processes offer a considerable improvement. The layer thickness with these processes can be as low as 0.002 mm and the precision in xy-direction around 0.004 mm. This jump in resolution is enough to remove the discrete look and feel of the finished models. The printed objects are of more uniform quality both aesthetically and in terms of material properties. To such a degree that even some transparent materials with higher refractive indexes can be used as optical structures [32]. Some industries, such as the jewelry industry, use stereolithography to print precise models for metal investment casting [29]. As an easily scalable process in terms of print speed SLA could be the one to succeed in the future.

Although the quality of SLA prints is good, there are some major restrictions to it as well, the biggest being the materials. The material selection and properties of photopolymers are fairly limited. The final parts do not remain stable in natural light because of constant UV exposure. This is why SLA manufactured products are most often visual models or used as the alpha models for further processes such as investment casting. The SLA process itself is messy and photopolymers are often mildly toxic and thus require protective gloves to handle. The built object must be immersed into the resin vat and some liquid resin always stays on the surfaces. This makes it hard to design a machine that would allow the use of multiple materials. The removal of support material leaves visible markings on the surface of the object and post-processing steps are needed to smoothen these out.

Despite the fact that vat polymerization processes have drawbacks, the part quality is very good and with technological innovations, the print speeds have increased considerably. Material manufacturers have been able to research and customize photopolymers to mimic the properties of standard injection molding plastics. SLA examples in the industry include the production of hearing aids, patient-specific dental products and cast patterns for jewelry [29]. The fast print speeds of CDLP processes are promising but more work should still be done in the automation of post-processing and material research.

2.4.3 Powder Bed Fusion

One of the AM technology branches extensively used in the industry is *powder bed fusion.* These technologies are used in the production of end products and in conjunction with other manufacturing applications. Common for all powder bed fusion approaches is the use of raw material in a fine powder form. The material is selectively fused using a thermal source such as a laser or an electron beam to build the final object as illustrated in the Figure 2.7. The build space is filled with the powder and spread evenly with a counter-rotating roller after every layer to ensure even distribution of material. Plastic parts done with this technique do not require any support structures as the excess powder supports the parts. Supports are however used when printing on metal due to higher weight and temperature related effects. Technologies such as *Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Direct Metal Laser Sintering (DMLS) and Electron Beam Melting (EBM)* fall under this category (Figure 2.5 rightmost column). They mostly differ on how the fusion is induced. In commercial products mainly liquid-phase sintering and melting are used to fuse material particles. Solid-state sintering and chemically-induced binding are the remaining options but not widely used.

The main advantage of plastic SLS is that as no support structures are required the whole build volume can be filled with printable parts not just the base of the build platform. Optimization of print volume and unit cost is possible through deliberate stacking or *nesting* of parts. SLS is at the moment the most suitable method for production volumes of up to thousands of parts. With more complex products and especially when products are customized, it competes with injection molding. Part quality is good even though SLS leaves a slightly porous surface on the parts without finishing. Mechanical properties are not fully isotropic with SLS and some directional differences exist but the effect is much less pronounced than with FDM. In addition, the self-supporting powder makes it easier to vary print orientation for the best functional performance.

The fusion of material particles demands a lot of energy and use of high energy lasers or electron beams is necessary in order to achieve adequate

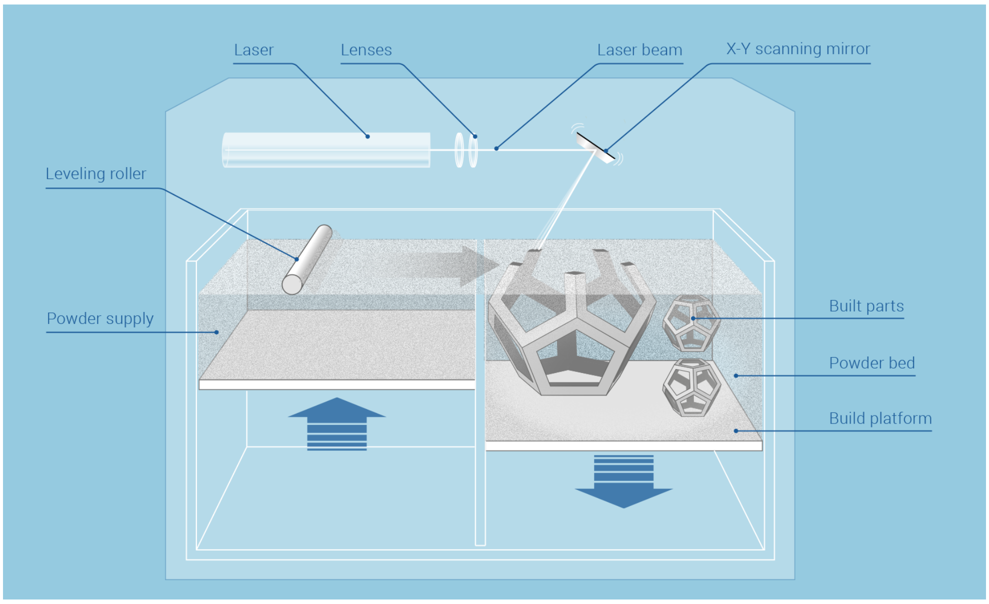


Figure 2.7: Selective laser sintering process [2].

fusion. This is especially the case with metal powders. For plastics, the energy consumption is, of course, more moderate. In general, a wide range of materials, from plastics to ceramics and metals, can be used with powder bed fusion. However, the sintering properties of some metal alloys or grades of plastic are not suitable for the process. In plastic sintering, the material selection is currently limited to different grades and mixtures of polyamide (nylon). Different additives such as aluminum, glass or mineral fiber can be added to modify material properties. The possibility of a big print volume in powder bed fusion is both an advantage and a challenge. For economic reasons, a maximal amount of nesting is beneficial but sometimes printing just a few parts fast is desirable. The machines have a warm-up as well as a cool down phase which decreases the efficiency of smaller batches. Printed parts have to be manually excavated and sorted from within the powder. Completely enclosed features are not possible with SLS and escape holes have to be designed in order to remove the excess powder after printing.

Despite all the challenges with powder bed fusion processes they are extensively used in numerous applications. The advantages are still outweighed. Production of metal parts for end products with powder bed fusion processes has been proved in the most demanding setting. Sintering of high-performance titanium and steel alloys have found their applications in the aerospace- and the medical industry. In these applications, superior functionality and weight reductions are desired. The same has not yet happened with parts produced with plastic SLS printing. As a method with a truly scaleable print volume, the future for plastic SLS printing looks promising.

2.4.4 Material Jetting

Material Jetting is similar to vat polymerization in the sense that UV light is also used to cure photopolymer resin to form the 3D object. The difference is that in material jetting the material does not reside in the build space but is jetted to the surface as small liquid droplets (Figure 2.8). A constant UV illumination follows the print heads and solidifies the small droplets instantly after they have fallen onto the surface. Additives or pigments can be added to these material droplets to dynamically modify material properties or color. AM allowing such gradually changing material properties is referred to as *functionally graded additive manufacturing* [29]. With material jetting very small details can be realized. It is one of the most precise AM technologies and can produce layer thicknesses down to 16 microns, approximately the thickness of human hair. [1]

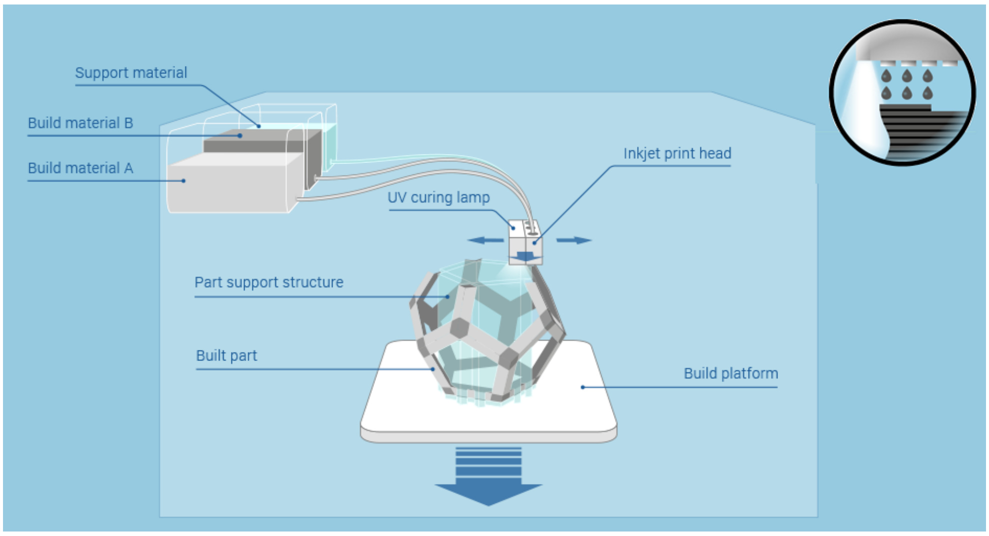


Figure 2.8: Material jetting process [2].

The material has to be deposited as very small, viscous droplets. This reduces the material selection considerably. At the moment it consists of

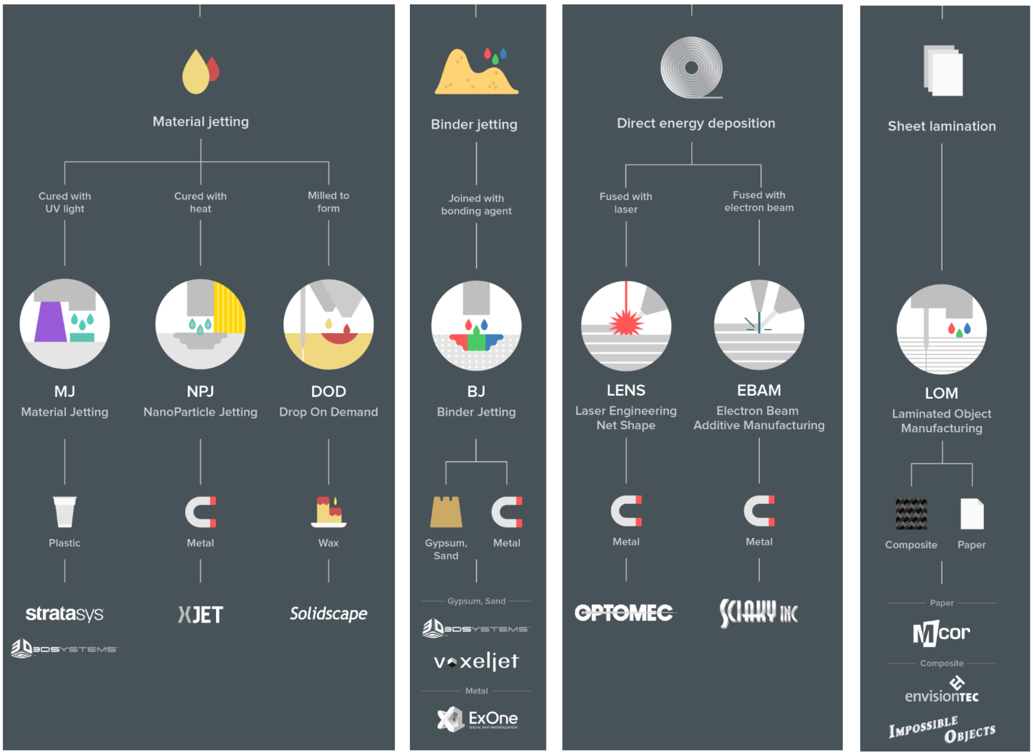


Figure 2.9: Different technologies, materials, and machine manufacturers available within material jetting, binder jetting, direct energy deposition, and sheet lamination technologies. Image modified from [1].

different polymers and waxes that can be produced in a viscous enough state for the jetting process. An Israeli company XJET have made advances with solid material jetting. In this technology metal nanoparticles are jetted inside a special liquid formula and heat is used to fuse the particles. An additional advantage together with the high precision is that the process can be easily scaled up by increasing the number of nozzles. The material selection is not limited by the process but rather by chemistry and adhesion to the surrounding material. Current high-end systems can combine up to three different materials and in some cases dynamic blends are possible. Current combinations make it possible to dynamically alter part translucency, stiffness, hardness, and color. As with other UV curable resins, the parts do not stay stable in prolonged UV exposure. The models are mainly used for visual prototyping, educational use, and marketing. Different material jetting technologies and machine manufacturers are shown in the leftmost column of Figure 2.9.

2.4.5 Binder Jetting

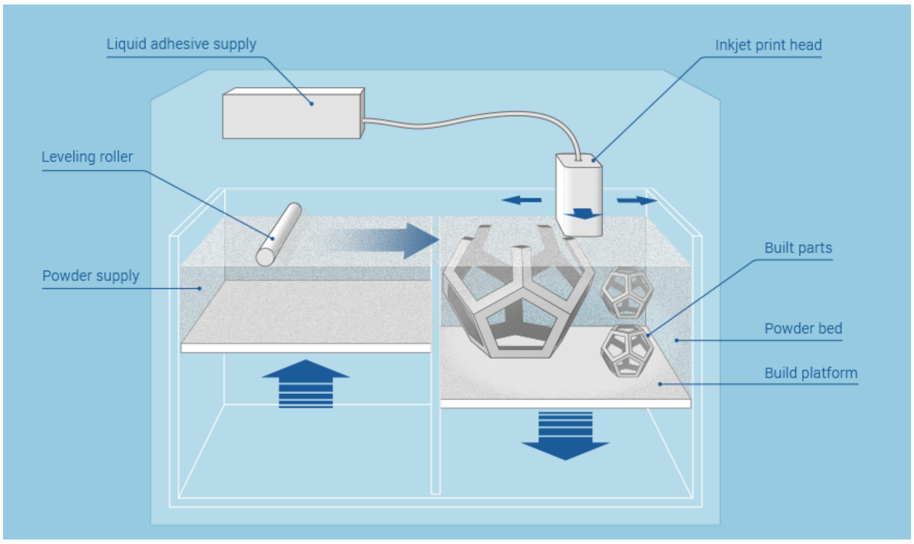


Figure 2.10: Binder jetting process [2].

The principle of *binder jetting* was invented at MIT and has since been licensed forward for commercial use. The idea is fairly similar to *powder bed fusion* where a pool of material powder is selectively sintered layer-by-layer to form the final object. In binder jetting instead of a sintering laser, a liquid binding agent is administered through multiple ejection nozzles or print heads to bind the material together. New powder is then spread evenly with a leveling roller and the process repeats until the object is finished. In addition to the binder agent, pigment can be added to dynamically color the object. The working principle is illustrated in Figure 2.10. Due to the similarities with inkjet printing, this process has been the one originally referred to as 3D printing. [12]

The binder jetting process can produce fully colored parts and be implemented to almost any material in a powder format. As plastic powder bed fusion, binder jetting is also self-supporting, no heating is needed and multiple printer heads can be added making the technology very fast. However, the mechanical properties and surface finish of the green parts, taken directly from the printer, are poor. Post-processing steps are necessary for the products to achieve any functionality. Metal and ceramic parts, for example, can be sintered in an oven to obtain functional parts. Typically parts made with the binder jetting process are visual prototypes, cast patterns or casting sand molds.

2.4.6 Directed Energy Deposition

Directed energy deposition (DED) covers multiple technologies such as *laser engineered net shaping*, *direct metal deposition*, *directed light fabrication* and *3D laser cladding.* The technology borrows elements from CNC milling, turning, and welding. A laser, an electron beam or a plasma arc melts material that is deposited through a nozzle either as a powder or a wire. The nozzle, together with the heat source, can be mounted on a 5-axis industrial robot. Even the build platform can have multiple degrees of freedom or rotational axes. The working principle is illustrated in Figure 2.11. Thus, compared to other AM methods, DED can be used to print directly on existing surfaces. DED is mostly used to repair or add functionality to existing parts.

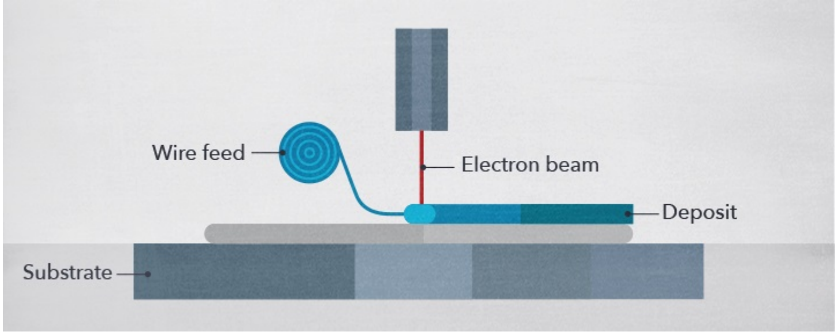


Figure 2.11: Electron beam freeform fabrication [1].

2.4.7 Sheet Lamination

A *sheet lamination* method called *Laminated Object Manufacturing (LOM)* was commercialized fairly early (1991) in the history of AM. The method is not purely additive although the resulting excess raw material can be recycled for further use. The principle is to cut the outlines of a 2D section from material sheets and then bind together subsequent layers as illustrated

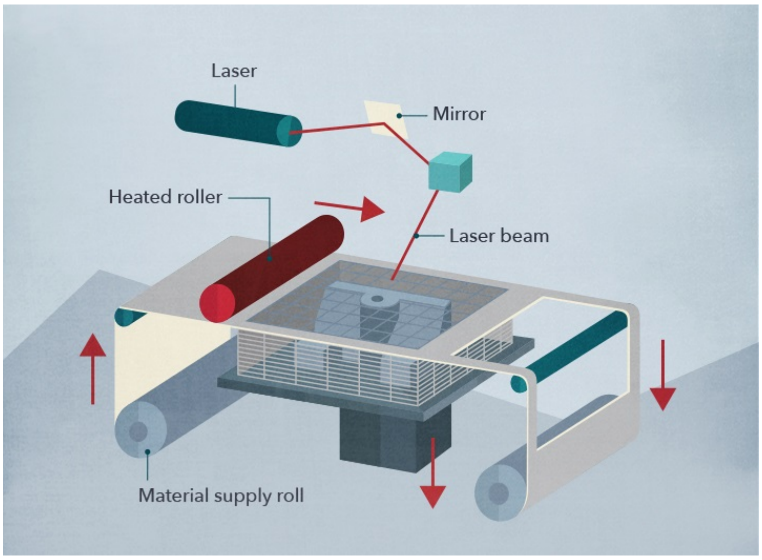


Figure 2.12: Sheet lamination process [1].

in Figure 2.12. The first edition of LOM utilized a CO_2 laser to cut 2D cross-sections from paper sheets. Different approaches of sheet lamination may differ in the sequence of cutting and stacking the material sheets as these phases can be done independently. Materials that can be used with LOM include paper, aluminum, copper, and steel. Bonding of layers can be done with adhesive, thermal bonding, clamping or ultrasonic welding. Paper models are mostly used as visual models. Metal sheets can be used for functional parts but the resolution of the final parts is generally poor. Different LOM machine manufacturers are listed in the rightmost column of Figure 2.9.

2.5 Applications

Objects manufactured with AM and 3D printing most often involve prototypes and mockups, proof of concept models and replacement parts. The products are either directly manufactured with AM or the AM phase can be a link of a longer process chain [6]. Prototyping is still by far the most common use of 3D printing as can be seen in the the results of a survey done by the company Sculpteo in 2016 (Figure 2.13). The survey included 1,118 respondents from a wide field of professions and was geographically concentrated in Europe and America. [25]

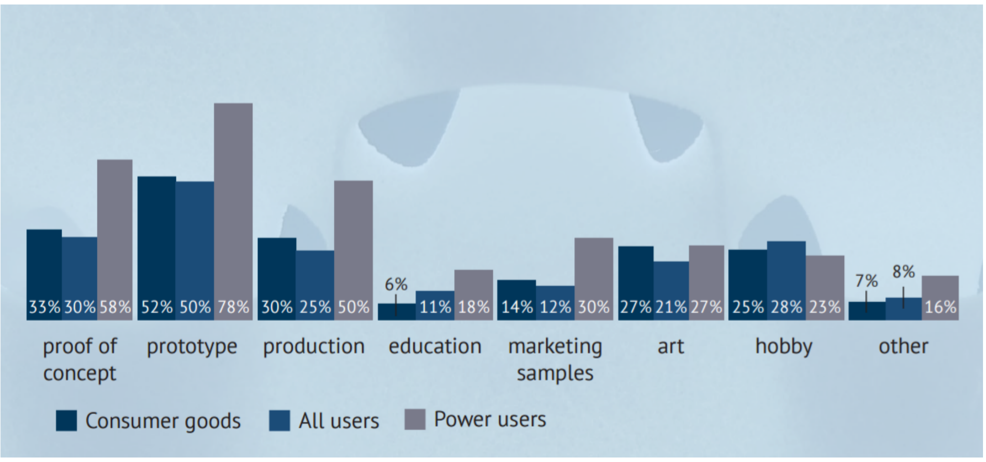


Figure 2.13: Applications of 3D Printing from a 2016 survey *State of 3D Printing* by Sculpteo [25]. Selection of multiple categories was possible for the participants of the survey.

During the development of AM, different lines of technology have emerged to capture the principle of layer-by-layer manufacturing. The quality and material properties of the printed objects have gradually improved. Initially, the main application of AM was to quickly prototype product ideas and to produce physical models for marketing purposes, i.e. *Rapid Prototyping (RP)*. In fact to a degree that RP was considered a synonym for AM and 3D Printing. Today this is not the case anymore. For example *Rapid Manufacturing (RM)* is one of the applications of AM where end-usable parts are directly produced. AM can also be used in combination with other manufacturing methods such as machining or molding. *Rapid Tooling (RT)* is an application where a mold is created either directly or indirectly from a 3D printed model. The accuracy and durability of the mold is not yet at the same level as with traditional tooling of molds. RT is normally used to produce volumes up to a few thousand products. [23]

When compared to traditional manufacturing methods AM provides a considerable speed increase from the design to the finished product as the set-up time for a new product is minimal. Unit costs are fairly low and fixed because AM does not require any additional tooling, forms or punches. The products can be designed with minimal material consumption which further reduces costs. In addition, most of the waste material can be recycled for new use. [6]

One challenge of AM is the lack of scalability. Increase in production volume does not decrease the unit price in the same proportion. This is why at the moment AM is only cost-effective to use in the manufacturing of small to medium-sized batches [6]. Another obstacle in the implementation of AM for high volume production is the print speed. Scaling up the volume and speed with more AM machines is not cost-effective compared to injection molding. There has to be some speed advances in AM technology for the cost-effectiveness to increase.

The next chapters will introduce the most common application areas of AM along with some examples. In some cases, AM assisted production can surpass the benefits of a pure AM supply chain. Especially when production volumes are increased, traditional methods are, at the moment, the most economic. Different aspects such as the complexity of the product, customization needs, materials, lead time goals, and price all play a role in the equation. A product made with AM can be designed so that the functionality is maximized. The product improvement is not always directly valued in money or savings. When traditional methods are replaced with AM, the agility of the process chain can be improved which can provide indirect benefits.

2.5.1 Rapid Prototyping

Producing prototypes and mockups with AM is referred as *Rapid Prototyping (RP).* which was the primary use for AM technologies in the beginning. Prototypes can be produced fast, to a degree that in many industries AM has altogether replaced manual prototyping. The time span to manufacture a prototype has dropped down from weeks to days [6]. With rapid prototyping, it is possible to increase the number of design and testing cycles to discover and fix problem areas in the design. A visually and functionally accurate prototype is the best way to communicate and validate ideas with other designers and with customers.

Rapid prototyping methods enable the designers to come very close to the final product both visually and functionally. In addition, more prototyping cycles can be included into the duration of new product development. By 3D printing in color and with multiple materials in one print the design intent can be translated very well into the prototypes. A good example of this comes from the shoemaking industry. Prototyping of shoes requires the use of materials with varying elastic behaviors and appearances. Before 3D printing, Adidas had 12 technicians to manually make the prototypes. Now they only need a few AM machine operators. The prototyping cycle has shortened from four to six weeks to a few days. Nike recently used rapid prototyping to optimize its Vapor Laser Talon boot for professional American footballers. 12 rounds of rapid prototyping with SLS technology optimized the plate of the shoe for maximum surface traction. Although the final plate was manufactured with traditional methods rapid prototyping allowed the designers to test and achieve the superior performance. All major shoemakers have invested in and experimented heavily on AM and are going into the direction of a fully 3D printed shoe. [17][23]

2.5.2 Rapid Tooling

One of the most time consuming and costly phases of product development is the creation of tooling for the series manufacturing of products. When AM is used to produce molds a term *Rapid Tooling (RT)* is used. This can be achieved either with indirect (pattern-based) tooling or direct tooling. In indirect tooling, a master model is manufactured with AM and then used to create the mold. Example techniques include silicon rubber molds and investment- or sand casting. With direct tooling, the mold itself is manufactured with AM.

AM methods that use thermoplastics or photopolymers such as FDM or stereolithography can be used for the direct manufacturing of molds for urethane or silicon rubber casting. A single tool is often good for series up to 500 parts. Printing the tools in metal either with SLS or DMLS expands the material possibilities and can be used to produce molds which can withstand more use cycles.

The main drivers to use RT are the reduced lead times and costs. In product development, it is often beneficial to manufacture a smaller batch of products (less than 100) for proof-of-concept, design validation, user tests or pre-production tests. RT makes it possible to alter the designs fast and to make different versions of the same products. It is also used as the final check before approval of production in the production ramp-up phases. Generally, RT is not valid for series larger than a few hundred as the durability of the molds is not on the same level as is for traditional CNC milled molds. A good surface finish is hard to achieve without additional machining. AM as a layer based manufacturing method causes a stair-step phenomena that needs to be manually removed. On the other hand, the design of *conformal cooling* channels is possible with AM. These freeform channels can precisely follow the part surfaces to achieve uniform cooling. [9]

2.5.3 Rapid Manufacturing

Print quality and material integrity of some AM methods is on a level that the manufacturing or production of end products is possible. Terms *Rapid Manufacturing (RM) and Direct Digital Manufacturing (DDM)* are used to refer to these applications. RM has proven to be the most competitive with highly customized, complex products with a fairly low production volume. [12]

The use of AM for direct production and is on the rise as novel success stories encourage companies to invest and experiment with AM. Aerospace and the medical industry have paved the way. Individualized products such as dental crowns or hearing aids merit of the fast customization of products with AM. Weight reductions and optimized functionality are the driving forces for the aerospace industry.

AM has been compared to *Mass Customization* which is a product customization principle normally based on the modularity and interchangeability of product segments. A modifiable desktop computer is a good example of a mass customized product. Mass customization is based on the modular design and pre-assembly of a customized product. AM can achieve a similar customization effect and can often reduce the number of components in an assembly. Both principles meet the *just-in-time-* ideology where components are produced only based on demand and inventory risk is thus diminished. Even though they both share features, an even comparison cannot be made. Mass customization is a true mass production method whereas AM can only cope with low- to medium volume production. In some applications, AM can be the superior alternative to mass customization as it allows the products to be customized further. In addition, the supply chain can be simplified. [6]

Chapter 3

Design for Additive Manufacturing

Design for AM is very different when compared to design for conventional manufacturing methods. AM allows a higher degree of complexity in the design. Manufacturing cost is not as tightly influenced by the geometry of the object. This does not mean AM is rule-free. Although with AM, it is often quoted that *"complexity is free"*, AM methods still have their own restrictions that need to be taken into account. However, these restrictions differ considerably from traditional methods and offer interesting new design opportunities to be explored.

The following chapter will introduce the concept of *Design for Additive Manufacturing (DfAM)* together with different possibilities of AM for product design. The computational approach to material layout optimization, *topology optimization*, is briefly introduced. The chapter *Design Strategy and Process with AM* elaborates the different levels how AM can be adapted to product design. A few design examples are presented. Finally, the *Constraints* chapter discusses some of the issues that restrict AM from reaching its full potential.

3.1 Introduction

Every design for X philosophy tries to maximize product performance relative to X. These guidelines try to establish workflow structures that automatically steer the emerging design favorable to X. They guide the engineers towards a proven goal starting early in the product development. For example, the X could be manufacturing and assembly. The resulting design philosophy, *Design for Manufacturing and Assembly (DfMA)*, is a practice of minimizing manufacturing and assembly difficulties and cost [12].

DfMA is an umbrella architecture that includes many sublevel guidelines for more specific functions such as how an injection molded product should be designed. At the same time, it includes very broad ideas about the industry practices and the organizational structure of product development teams. A complete realization of the DfMA principle requires a considerable amount of knowledge about the manufacturing methods, materials and supply chains. Everything cannot be taken into account by individuals and the set structures and guidelines of DfMA steer the design processes automatically towards the wanted direction.

Much the same way work in the midst of AM is underway to construct structures supporting good design. The equivalent principle within AM is called *Design for Additive Manufacturing (DfAM).* This principle highlights the difference of AM to traditional manufacturing methods. Instead of evading design choices that are limited by manufacturability, the idea of DfAM is to promote designs that explore the AM *design opportunities* as much as possible. The idea is to maximize product performance given the capabilities of AM technologies. More elaborately put ”through the synthesis of shapes, sizes, hierarchical structures, and material compositions” [12].

3.2 Design Opportunities

In order to maximize product performance, different opportunity categories unique to AM have been recognized. Thompson et al. [29] divide these opportunities into three abstract levels: the part level with macroscale complexity, the material level with microscale complexity and the product level with multi-scale complexity. In many publications categorization is based on functional aspects of AM such as the possibility to *consolidate* multiple parts into one, design freeform geometry or the ability to directly manufacture assemblies. Gibson et al. centralize on complexity and divide the categories into *shape complexity, functional complexity, material complexity and hierarchial complexity* [12].

3.2.1 Shape Complexity

The category that affects all of the three abstract opportunity levels is *complexity*, or more specifically, *shape complexity.* AM makes it possible to manufacture virtually any shape or geometry. Shape complexity is often the root enabler for other opportunity categories of AM. Features such as undercuts, variable wall thicknesses, organic shapes and lattice structures are all possible and often not as punishable as is the case with traditional manufacturing methods. Generally speaking, the complexity of a design is only limited by the resolution of the AM technology and the imagination of the designer.

3.2.2 Functional Complexity

Shape complexity allows separate parts or features to be *consolidated* into a single part. Traditionally part integration has meant attaching parts together by welding, adhesives, and fasteners when the resulting structures have been too complex to manufacture as a single part. Without complexity restrictions, AM enables these parts to be integrated in one part. Not only can features be integrated but even functional assemblies can be integrated into a single print. [8]

The layer-wise manufacturing principle gives complete control over the internal features and geometry of parts. By designing clearances between separate features kinematic joints or whole assemblies can be manufactured in one print. This functional complexity allows *direct or integrated assemblies* to be made [12]. FDM, SLS and SLA technologies have all been used to manufacture prismatic, revolute, cylindrical, spherical and Hooke joints. The joint movement must be ensured after the print by removing the excess support material in some way [12]. As designers have access to the manufacturing process in every phase, external components can be embedded inside the manufactured objects. This is extremely interesting when electronic circuits and components are inserted inside printed structures (Figure 3.1).

3.2.3 Material and Hierarchical Complexity

The opportunity for *material complexity* includes the use of multiple materials and changing the material properties dynamically within a single part. For example, material extrusion and material jetting systems are capable of alternating between two or more materials and it is possible to alter the whole material composition on the fly. Using two or more functional materials allow the designer to change the functionality or appearance of the object

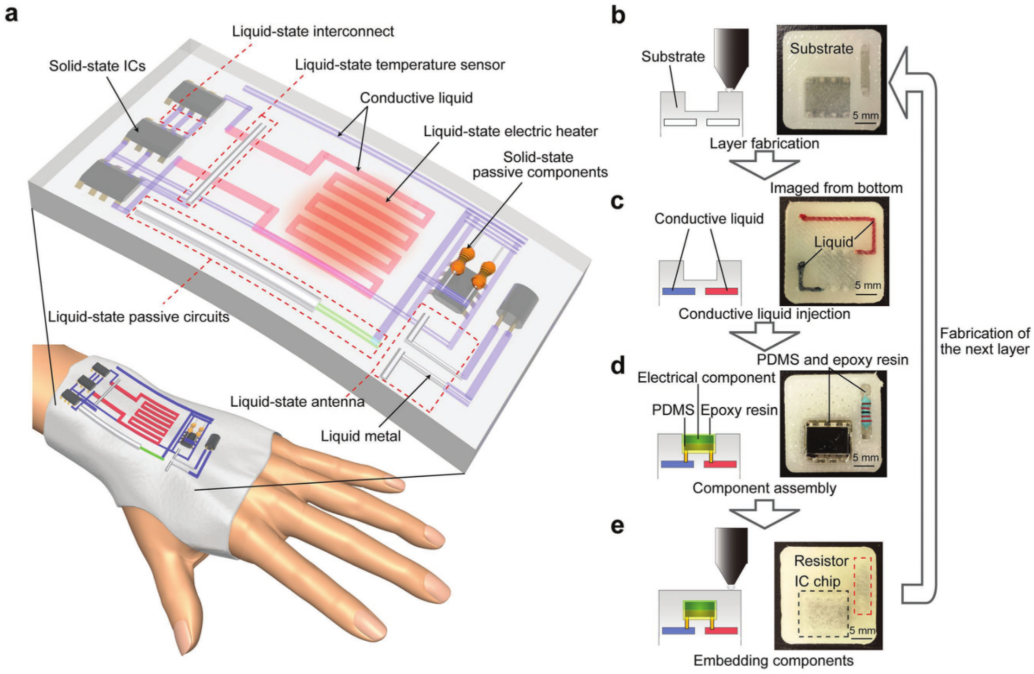


Figure 3.1: Example of embedded electronics with 3D printing [24].

in very specific regions.

The opportunity of *hierarchical complexity* makes it possible to alter the material structure of the manufactured objects on many size levels. Within the metal laser deposition and sintering technologies, the process parameters can be changed to even control the metal microstructure in specific locations. On the next size level, the mesoscale, material space can be filled by small truss structures. The repeating unit block of these small structures can be designed so that the overall material properties are changed. These so-called *metamaterials* emulate material properties depending on their layout and density [12]. One example of a said structure is the *voronoi foam* structure in Figure 3.2. The density of the foam structure in the Moomin character was defined with a heat map during 3D modeling to control the elastic behavior of the object [21]. Hollow-, lattice-, or porous structures are used more often in the design of stiff and lightweight structures. The fine texture or porosity in the material surface can have other functions. They can, for example, promote friction on the part surface or bone growth in medical implants. [29]

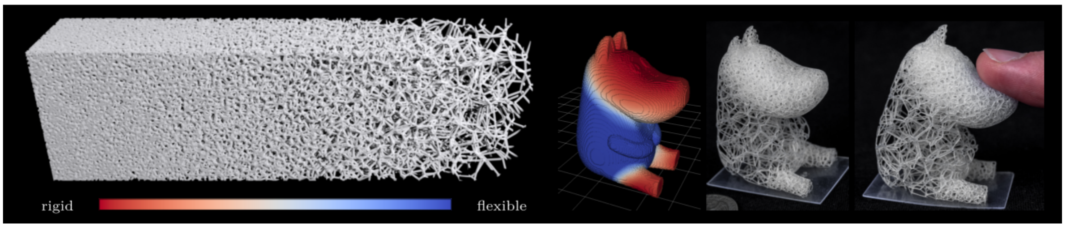


Figure 3.2: Voronoi foams and dynamic elastic behaviour [21].

3.3 Topology Optimization

AM as a manufacturing method gives designers the option to assign material only where it is necessary. Traditionally *Computer Aided Engineering (CAE)* software, as an example, have been able to optimize wall thicknesses or the locations of holes to minimize stresses. However, as there are fewer restrictions on manufacturability with AM, it is possible to optimize the structure even further. *Topology optimization* is a mathematical method that aims to calculate the optimum material layout in 3-dimensions given the design space, loads and constraints. It was first proposed by Bendsoe and Kicuchi in the late 80s [34].

Sizing, topology, and shape optimization are all *structural design problems*. In sizing problems, optimal thicknesses or cross-sections of profiles are calculated for a given load case. The thicknesses are addressed as design variables and minimized in comparison to a state variable, for example, the deflection of the structure. In topology optimization material is assigned to FEM nodes, where necessary. The node system is iteratively edited in contrast with the stiffness of the structure. Shape optimization tries to further optimize the coordinates of these existing nodes. [5]

Topology optimization has been studied and implemented in a very broad range of design applications. These include for example optimizations for weight, vibration, mechanisms, thermal conduction, multi-material integration and fluid flow to name a few [5]. Not only is topology optimization a way to optimize designs but it can equally be used to provide inspiration in the earlier phases of product conceptualization. Optimized structures are not only functionally superior. In addition, they reduce material usage, waste, and minimize energy consumption in manufacturing. [14]

3.3.1 Principle

Topology optimization determines the optimal placement of isotropic material in a design space. Each point in space can be either material or void (no material). The optimization algorithm seeks for the optimal subset of points that maximizes the global stiffness matrix of the given load case [5]. A simple 2D result of such an optimization is illustrated in Figure 3.3.

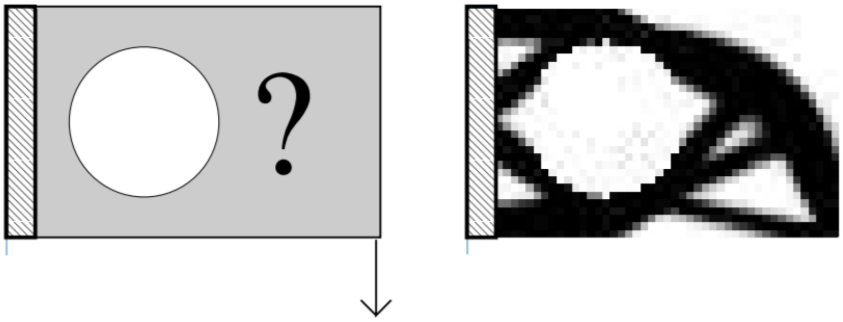


Figure 3.3: A 2D example of a topology optimization achieved by a Matlab code of only 99 lines. The illustration on the left shows the design space with supports and the load applied. The result of the calculation can be seen on the right [5].

The optimizer algorithm works on the basis of a *design space*. This space defines the allowable volumes for material addition or removal. This space also takes into account areas where fixed material or an empty space will be added. Numerical algorithms create the design space from a numerical input. Programs with a 3D user interface can use a sketched volume or an existing 3D CAD model for the definition. After the design space is set *loads, boundary conditions and constraints* are added that correspond to the actual forces and stresses for the given design case. Often in the design environments, different load combinations are possible. This ambiguity can be handled in the optimization through different *load cases* which take into account the changing directions, magnitudes, and combinations of forces.

A classic topology optimization routine aims to generate a stiff structure in the design space by minimizing compliance (*the objective function*). It is an iterative loop that first computes the displacements of the material density with the finite element method. Then it calculates the compliance of the design and how well it was affected by the design changes in the distribution. If no improvements were made the iterations stop. Otherwise, the density variables are updated and the iteration loop is continued with new values.

Loads, constraints and boundary conditions with the objective function often lead to differential equations that are solved using the finite element method. Material distribution and density at given points p(u) can be handled as discrete or continuous values. When continuous values are used the resulting material distribution needs to be penalized to achieve a discrete result. Some filtering is needed to alleviate problems arising from the computational methods. The optimization can lead to regions where solid and void spots alternate. This effect is called the *checkerboard problem.* Sometimes the optimization solutions can be highly mesh-size dependant. Both problems arise from the discretization of the continuous problem. [5]

The 99 line 2D topology optimization code written in Matlab is a good source to further understand how the algorithm works in the simplest form. The actual code, together with descriptions of the different areas of the code, is provided as an appendix. [27]

3.4 Design Strategy and Process with AM

The adoption of AM technology in the design and manufacturing of products can be realized on many levels. To fully exploit all the AM opportunities, often the whole design process has to be altered from the beginning. This does not rule out benefits from more light AM adaptations. Sometimes benefits can be achieved simply by changing the manufacturing method of an existing legacy product to AM.

Khlan et al. [18] divide the AM adoption strategy into two levels. If a *manufacturing-driven design strategy* is used only the process advantages of AM are utilized. This approach simplifies the complex manufacturing chain but the product design stays unchanged. Only when a *function-driven design strategy* is followed the products are designed to fully utilize AM design opportunities.

A presentation given by Kevin Bridge in the AMUG 2016 conference adds another level of AM adoption between these two. The levels are illustrated in Figure 3.4. Direct part replacement can be seen as a manufacturing-driven design strategy and design for AM as a function-driven design strategy. The middle ground in between is *adaptation for AM.* The design of a component is changed to benefit from AM but the interfaces to other components are kept the same. [7]

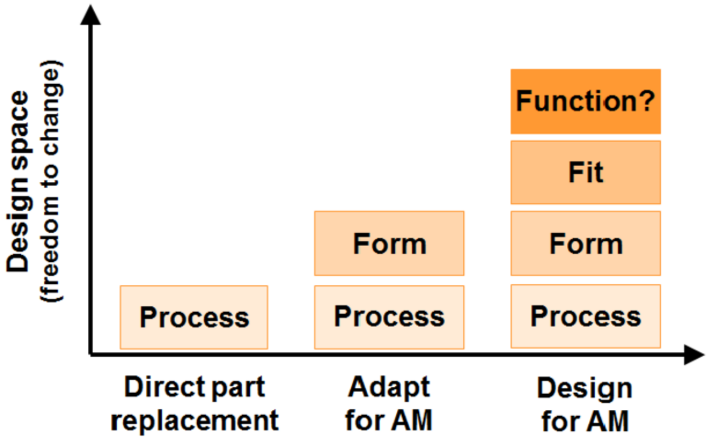


Figure 3.4: Levels of AM adoption [7].

The launch of completely new products or products with superior function gives companies the possibility to improve their position on the market. However it is not often easy to identify which products or parts would benefit from the change to AM. The original designer of a component or a product is the expert of its fit and function and thus in the best position to recognize AM potential. However, the constraints of traditional manufacturing methods are strongly embedded into the engineering mindset.

One way to identify products that would merit an AM adoption is by using case examples and by labeling benefit areas. Leutenecker et al. [20] have used four easily memorable category clusters together with industrial case studies to demonstrate AM potential. These categories are *integrated design, individualization, lightweight design and efficient design.* This makes it easier for the engineers to recognize benefit areas and to transfer working AM solutions from other fields into their own work.

Another way to identify AM cases is to use positive or negative indicators. Existing product databases, bill of materials, and assembly documentation hold a lot of information that can be used as indicators. Positive indicators for AM could be joined parts of the same material, a high number of processing steps or a complex assembly documentation. This information indicates that there might be a possibility to integrate separate features into a unified product. Negative indicators for AM include a large part size, very specific material requirements or a high production volume. These are, on the other hand, areas where AM machines are not competitive enough.

In the industry, change is often driven by necessity. Some industries have already been impacted by AM. Often when radical shifts happen in an industry, all companies will have to adapt in order to remain competitive. As an example, hearing aid inserts were traditionally investment cast based on a solidified wax model of the patient's ear canal. Through a collaboration between two competitors (Siemens and Phonak) AM was explored and proved to be a superior manufacturing method for this application [12]. In general, a similar trend in manufacturing is dominant in the highly patient specific medical industry.

The three different levels of AM adoption should be considered when considering manufacturing options for a product, be it a legacy product or a completely new product. In direct part replacement, only the manufacturing process is changed from a traditional one to AM. This change can already provide benefits as production steps can be avoided, material saved, lead times reduced or storage space released. The attainable advantage is highly dependant on the production volume, complexity, and the number of manufacturing steps of the design. The a) column of Figure 3.5 shows a traditionally manufactured hydraulic block manifold with its design interfaces. Directly changing the manufacturing method to AM, in this case, would remove the need for complex drilling. But as the block is quite massive the material need would be high and the manufacturing time long, together with the cost.

To move one step further *a single component* can be adapted to AM. The interfaces to other components still have to be taken into account and thus the fit and function of the existing part have to remain unchanged in the adapted version. Adapted designs with AM often aim for weight and cost reductions and increased performance. Topology optimization is often used to compute a better performing version of the part while maintaining the defined interfaces in an assembly. The b) column of Figure 3.5 shows an AM adapted version of the same hydraulic manifold. A 78 percent weight reduction together with improved flow characteristics was possible to achieve while still keeping the same component interfaces.

The ultimate step to take is to design *the whole product* for AM from the very beginning. The functionality of the product can be designed to exploit as many AM opportunities as possible. When surrounding interfaces can be minimized, or completely removed, radically new designs come possible. Topology optimization can be used in the starting phases as a form inspiration tool, and later to perfect product functionality. Shape-, functional-, hierarchical- and material complexity are all explored to develop novel ways to achieve functionality. The c) column of Figure 3.5 presents the manifold designed for AM.

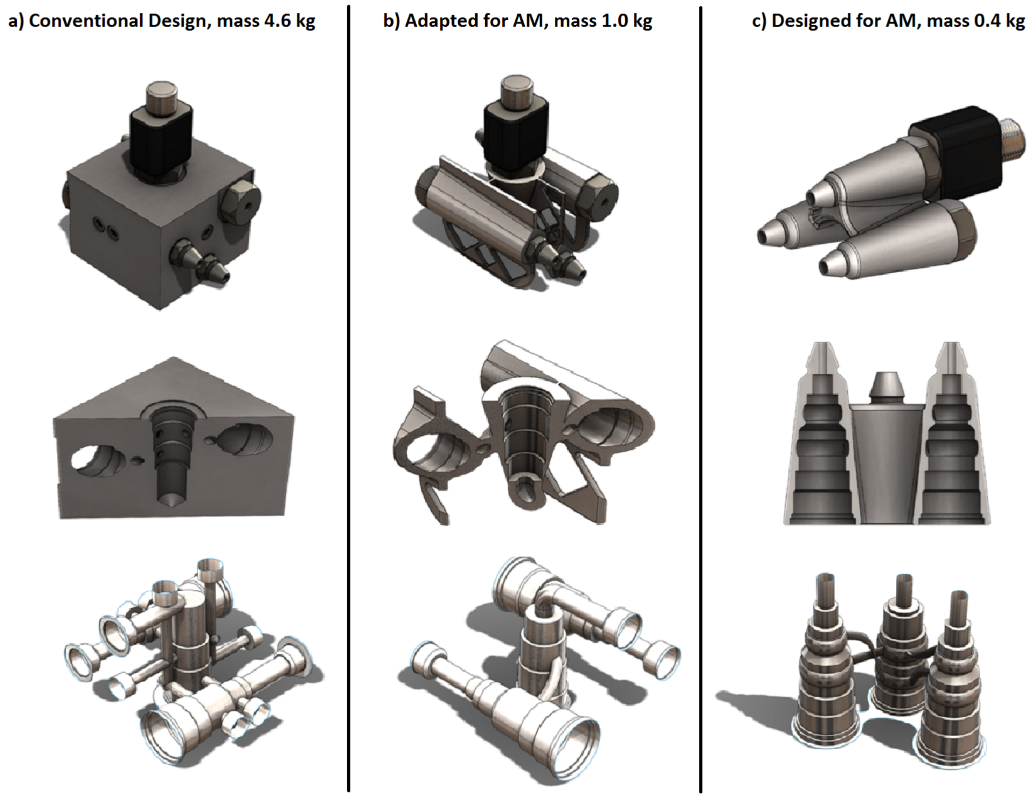


Figure 3.5: The three levels of AM adoption through an example component. a) conventional design b) design adapted for AM and c) designed for AM [7].

In the design of the AM elevator button, the interest is in the actual workflow of the design process, and in the actual solutions that will emerge. The previous paragraphs have concentrated mostly on AM design strategy: the different levels of AM adoption and how AM applications can be identified. Next, the focus is on the design process itself. How the form and function of a component or product should change to benefit from AM? What would be the ideal design process for AM?

A few research papers have attempted to answer these questions through case studies. Hällgren et al. [13] differentiate a *designer driven* and a *process driven* design process for AM adaptation. Vayre et al. [31] focus on the design process itself and recommend a specific workflow. Atzeni et al. [3] have taken a small airplane landing gear assembly as an AM redesign case. This study together with [4] have also evaluated costs related to AM in comparison to traditional methods.

On the abstract level, all of these studies follow and highlight the DfAM principle of identifying and using as many AM benefits as possible. Design processes have variation depending on the level of AM adaption, the case, and the design focus. Nevertheless, every process commonly starts with the identification of the shape, interfaces, and functionality of the *design space.* This space constitutes the volume where material can be added. Interfaces of the design space with the surrounding parts and environment are called *interface volumes.* This division is the *initial specification* of the product. For AM adaption the geometrical interfaces include the restricting interfaces with other components. For AM designed products these include for example the interfaces with the user or where two or more bodies of different function integrate. As an example, the interface volumes with other assembly components in the case of an airplane landing gear are highlighted orange in Figure 3.6 [3].

The next step of the design process is to explore AM possibilities for the given specification and its subproblems. In addition to shape- and function restrictions the initial specification has to take into account the operating and environmental forces, stresses and vibration. The designer needs to ask the question: *Which geometry and features would fulfill the given specification in that environment?* At this point, the design opportunities discussed earlier are relevant and might help in the identification of possible solutions. The use of shape complexity, consolidation of parts, internal mechanisms or material complexity could be the answer to a certain subproblem. The exploration phase requires some level of ingenuity and liberality from the designer. The openness of the requirements often leads to a very high if not infinite number of different viable solutions. The "best" AM solution to any subproblem might be very different in terms of geometry and function compared to traditional solutions. The number of options and the lack of prior reference makes the job of the designer rather hard. The process is ambiguous at best. For this reason, the use of topology optimization software or

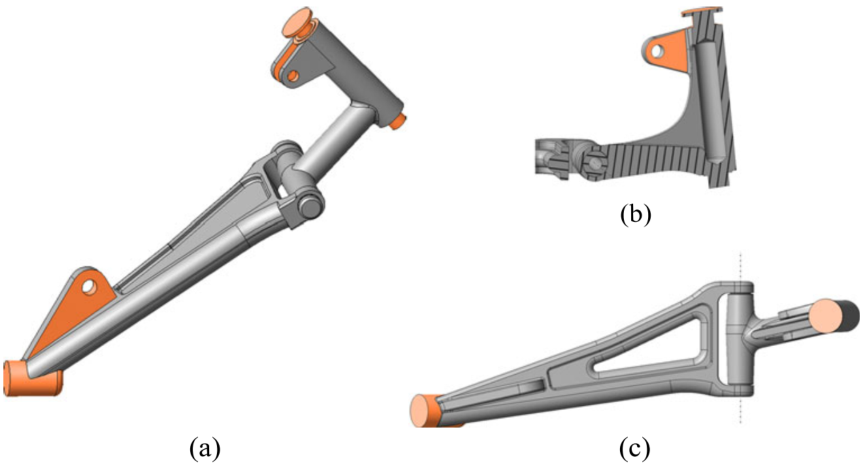


Figure 3.6: Recognition of *locked or unchangeable* design interfaces for an airplane landing gear AM adaption [3].

other generative methods to compute *a pool of* viable geometries is advisable.

Hällgren et al. [13] divide the AM possibility exploration phase to two classes: *process-driven* and *designer-driven*. The process-driven approach utilizes the previously mentioned way of using topology optimization or simulations to come up with viable shapes and geometries. The designer-driven approach leans on the the knowledge and experience of the designer instead. The geometry is manually created by the designer. The use of this approach requires that the designer knows about the effects of the AM method in question. For example what implications does the design have on the build orientation, support structures, internal stresses during printing, or surface quality? The designer-driven approach is more labor-intensive and requires multiple rounds of iteration and validation. The process-driven approach is based on computational FEM simulations and is thus faster and more accurate by default. On the other, hand the designer-driven approach can result in solutions that no algorithm could have ”thought of”. The development of AI-assisted design software will eventually reduce the gap between human designers and computational designers.

3.5 Constraints

Even though AM is marketed with clauses, such as *complexity is free* or *the next industrial revolution*, it certainly is not free from design or manufacturing constraints. The constraints still exist but affect new areas. The principles behind different technologies produce effects that need to be taken into account for the products to succeed.

The design and manufacturing constraints are often dependent on the technology and even the characteristics of a specific AM machine. In addition, material availability and properties have their effect on constraints as well. As with any other manufacturing method, the designer needs to be familiar with the technology to attain desirable results. A level of familiarity can be achieved by studying the technology, but most often it happens via trial and error. This is why it is not unusual for machine manufacturers and service providers to have introduced design guidelines or rules to support design work for AM. Most often these rules define minimum wall thicknesses, detail resolutions, clearances, print orientations, and ways to minimize support structures of the components.

Following the aforementioned design rules normally guarantees a successful print. However, producing components to strict specification has higher requirements. The resolution and accuracy of the machine could limit the implementation of some features and design solutions. For direct digital manufacturing, the repeatability of the machine is crucial, especially where tight functional tolerances apply. The standardized material and test data is often insufficient or not available. In addition, there are not enough industry examples to assure designers for AM implementation.

In addition to physical design constraints, digital constraints exist as well. The design process for AM is heavily software-oriented. Different cases and objectives require a specific program for realization. There are numerous interfaces where the 3D geometry needs to be converted into another format and passed for the next software. At these intersections, the parametricity of a design is normally lost. The amount of import-export steps is significant and accounts for a fair slice of the designers time. This is well visible in a process chart (Figure 3.7) for a topology or lattice optimized AM design. If the design space or interfaces for the design change, the whole process has to start from the beginning. Similarly, the design cycle between different optimization options always requires a new analysis to be run. Standardization and implementation work is in progress for design guidelines and a file format that would better support the needs of AM. The replacement candidate for STL, the *Additive Manufacturing File Format (AMF)* would have native support for color, materials, textures, and lattices structures.

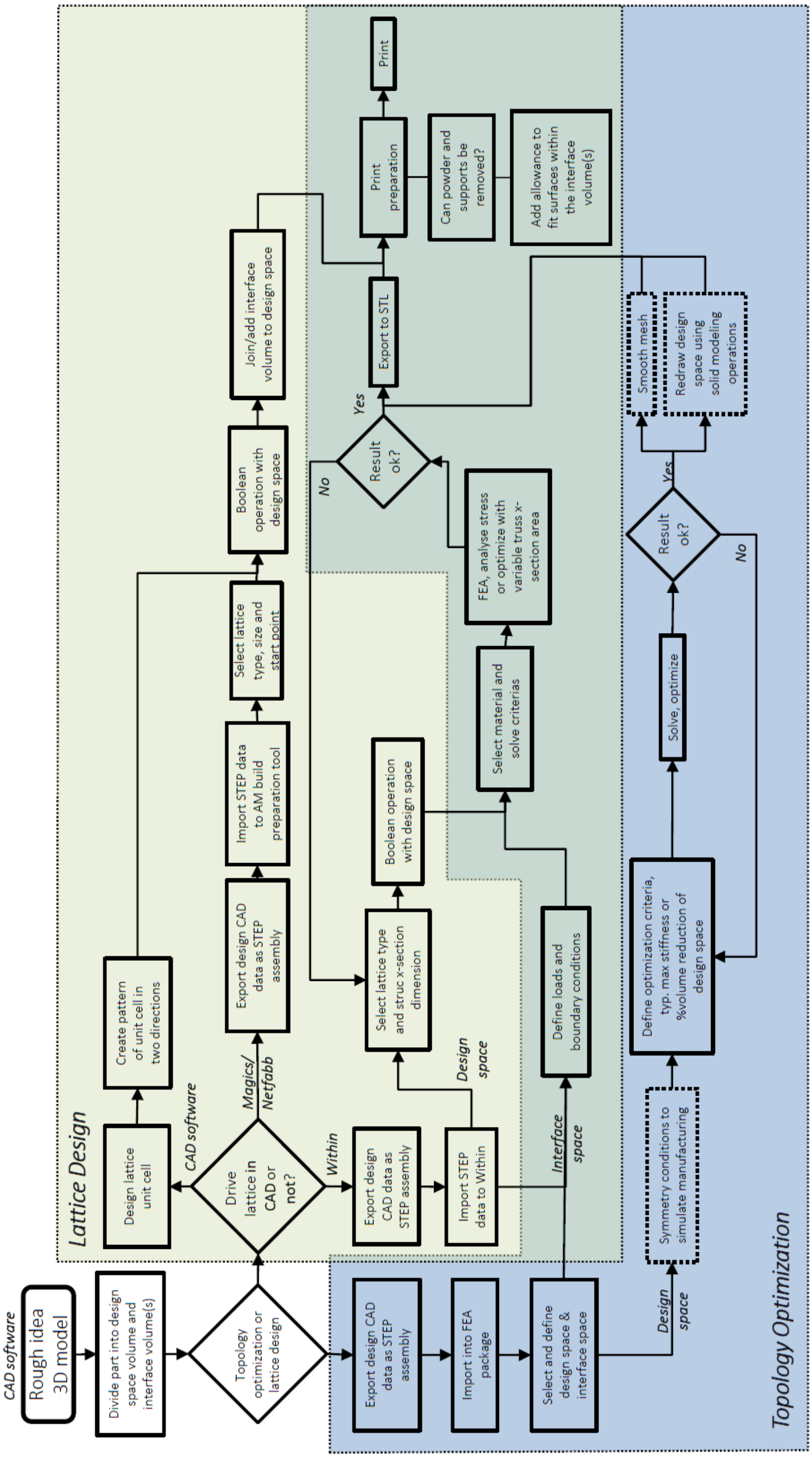


Figure 3.7: The digital workflow of a topology or lattice optimized AM design process. Flowchart adapted from [13].

Chapter 4

Elevator Button Conceptualization

This chapter marks the beginning of the *design part* of the thesis. The practical objective of the design part is to conceptualize, prototype and test an elevator button assembly optimized for, and made with AM. The status of AM technology is investigated to find out if it is currently possible to manufacture an elevator button that would satisfy the industry specification together with mechanical, chemical and aesthetic requirements. A higher objective is to find solutions that would surpass the traditionally manufactured button in functionality and cost.

The actual case for the design part is a so-called *Jumbo button.* It is a larger, duplicate button in the elevator car. The normal vertical button layout with small buttons can be hard to operate for people with limited reach, visual impairment or a wheelchair. To increase elevator accessibility, an additional button panel with larger buttons can be installed in the elevator car. The layout of this extra panel is horizontal instead of vertical and slightly inclined from the wall. A traditionally manufactured disassembled Jumbo button design is shown in Figure 4.1.

The visible part of the button consists of the *active part* and the frame, or *button base*, which is installed through a hole in a panel and fastened in place. The floor number and braille markings for the visually impaired are located in the active part. The active part is required to move slightly inwards and back out when operated to give the user tactile feedback. A light ring is illuminated upon activation. A small microchip with a push switch and LEDs is fastened into the button base. A cable is connected to the microchip that relays the activation information forward to the upper logic. Buttons inside

Figure 4.1: A traditionally manufactured elevator button disassembled. Components from left to right: a faceplate and spring package glued on the backside, an externally threaded base with the circuit board glued, an offset collar, and the fastening nut.

elevator cars are called *car control devices.* Buttons in floors to call elevators are referred as *landing control devices.*

A traditional button design consists of several, most often injection molded, plastic parts that are sourced from multiple manufacturers. Most of the parts are standard bulk parts but the button markings change. There are thousands of customized surface markings differentiated by applications, target countries, and region-specific requirements. This causes the first problem for traditional manufacturing. Every time a new button face is introduced a custom injection molding tool is needed for production. Thus the one-time cost, as well as the lead time, is high because the manufacturing of the tool can often take weeks.

The second problem or a challenge arises from the fact that in the elevator maintenance business the lead time from a spare part order to delivery needs to happen in a 24-hour window. The volumes of more specialized buttons range in only hundreds per year. To meet the 24-hour service requirement, in a fluctuating demand, an excess stock has to be constantly kept in the warehouse.

Direct AM production could solve both of these problems. Introducing new customized parts into the catalog would not cause any extra expenses or lead times as no new tooling is needed. The production volumes ranging in a few hundred could be easily realized with AM. The required stock in the warehouse could be scaled down considerably for the 24-hour spare part service, in the best case scenario to zero if the printing speed would allow a perfect on-demand service pipeline. This would greatly simplify the sourcing networks involved, reduce logistics and provide material and energy savings.

However, before all of these benefits are acquired, the AM part quality must first meet the industry-, regulative- and user standards. Mechanical, chemical and aesthetic properties of the 3D printed products have not yet reached their traditionally manufactured equivalents. This is especially true with plastic parts and their attainable surface finish.

The first section of this chapter, the *Design Process*, will abstract and generalize the elevator button and its requirements. The design process itself is briefly presented. The industry specifications and regulations for elevator buttons are introduced in the next section: *Requirements and Standards*. The following *Concepts* section is divided into subsections. These subsections present the conceptualization of the different button functionality areas. The different subconcepts are combined as the final concept in the *Concept Assembly* section.

4.1 Design Process

Traditional design work, as well as design for AM, are both processes that pursue a goal immersed in an environment of requirements and limitations. To be able to design an elevator button it first needs to be defined. In fact, a physical button is just one solution to the design case that the elevator environment presents. It acts as a control interface between the user and the elevator. The textual *design abstraction* for this case could be for example:

> *There exists a user-operable element that controls the elevator actions, is self-explanatory, gives feedback on activation and reports the activation forward for the upper logic.*

The goal is to come up with a solution to this abstracted sentence. The abstraction can be further divided into sub-categories such as user element, activation or system architecture. In the ideation phase, existing solutions and all the requirements and limitations should be consciously forgotten. It is favorable to be as imaginative as possible and to come up with a wide variety of solution candidates.

The interface with the user could be based on voice instead, it could be a touchscreen instead of buttons or gesture-based. The elevator could be controlled via a cell phone, augmented reality glasses, or even a brain implant. The operation of the elevator could be continuous so that there would not be a need to choose a floor in the first place.

The ideation phase is followed by *idea screening* where the bulk of ideas are further filtered into concept candidates through requirements and limitations. The design of an elevator and its accessories is highly standardized. For the development of this thesis, the user element (button), activation style (tactile) and the elevator system architecture were all pre-defined. The design is thus idealistically and physically restricted. In addition, this thesis explores the use of AM for the manufacturing of this product. This all sounds rather discouraging from the innovation point-of-view. Luckily AM, as a manufacturing method gives a high degree of freedom in combining resourceful features into a unified final design. With shape complexity, the physical volume can be still explored freely for innovative solutions. AM possibilities should be maximized in this design space.

The following concept evaluation and testing cycles are essentially problem-solving processes. Concept candidates are evaluated against the requirements and tested for adequate functionality. The design work follows *the designer-driven approach* presented earlier in chapter 3. This method was evaluated more suitable for the initial identification of design possibilities with AM. Computer generated solutions would be an option but these are, at the moment, only capable of producing solutions for alternative shapes and topologies. The design goals for the button are more complex than that. Due to time limitations, only one assembled button concept candidate was taken further for mechanical testing. Further product development would include ranking multiple concepts for final selection. The selected concept would go forward to the *detailed design* phase, iterative optimization, and eventually ramp-up for production.

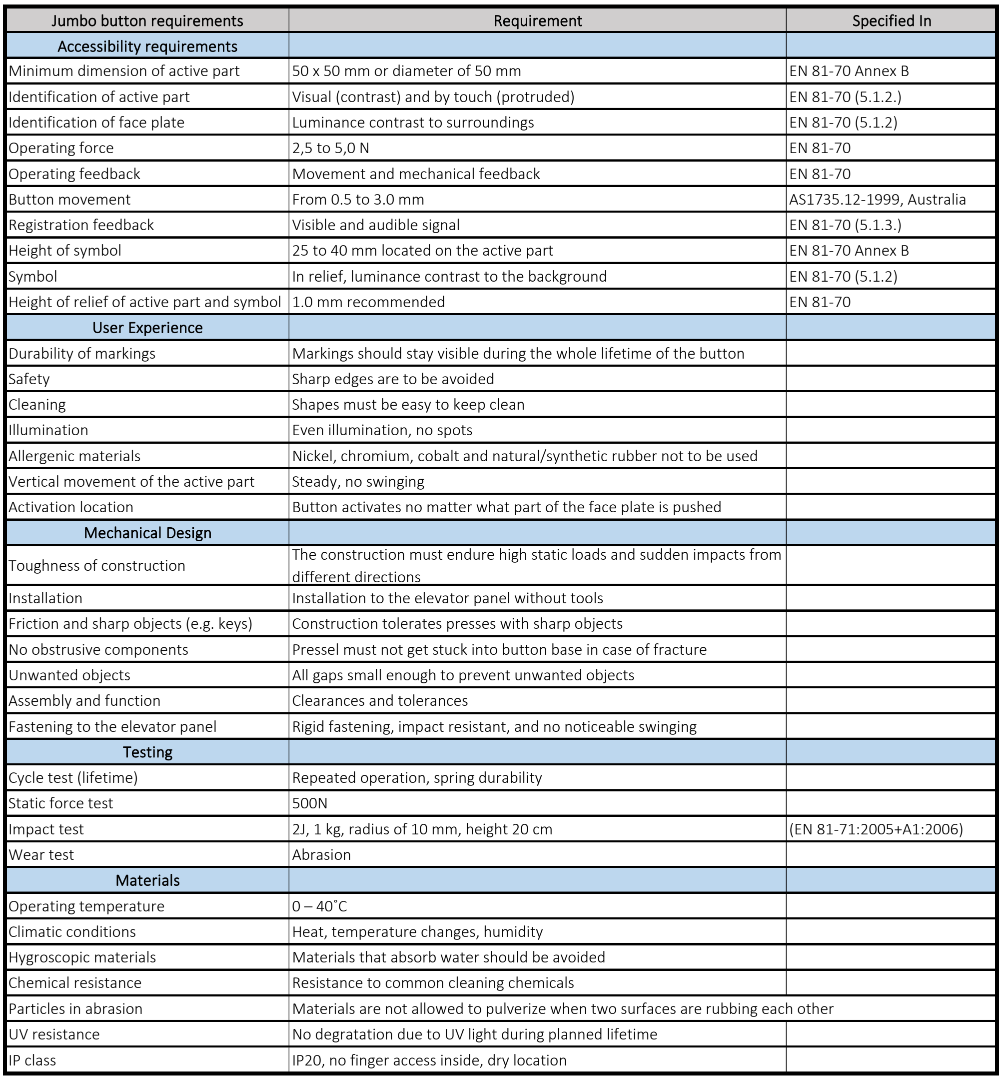
The interfaces of the traditional button design, in this design case, were not altered. These include the interfaces caused by the physical human interaction and the mechanical surroundings of the button and the PCB board. In addition to these form and function requirements, there are several specifications and industry-specific requirements that the elevator buttons must meet. These requirements are presented in the following chapter.

4.2 Requirements and Standards

An elevator is, at the moment, a vertical transport vehicle that facilitates floor to floor movement in buildings. The end user spectrum of elevators is very broad. For elderly, people with reduced mobility, wheelchairs or other disabilities an elevator might be the only way to access parts of a multi-story building. *Accessibility* is defined as a design of products, services or environments for people with disabilities. For an elevator, this is not an option but a requirement. For that reason, it is not surprising that the design of elevators and control devices is globally and regionally standardized by different accessibility codes and standards.

In Europe, the accessibility standard EN81-70 defines the requirements but is often replaced with regional standards. In the US, ADA 1996 (Americans with Disabilities Act) and elevator safety code A17.1 created by the industry provide the necessary documentation for elevator design. Regional differences are high. The newer ADA code (2004) exists but is not officially approved. Even cities can have their own codes and the final authority is given to regional inspectors who can interpret the codes differently. Some

Australian and Asian standards stand out with higher requirements than the European and US standards. A collection of requirements for the Jumbo button are listed in Figure 4.2. The accessibility standards determine the dimensions and functional operation of the button. A rigid operation and a clear visual appearance ensure a good user experience. In addition, the button must be mechanically stable in the planned use environment.



Jumbo button requirements	Requirement	Specified In
Accessibility requirements		
Minimum dimension of active part	50 x 50 mm or diameter of 50 mm	EN 81-70 Annex B
Identification of active part	Visual (contrast) and by touch (protruded)	EN 81-70 (5.1.2.)
Identification of face plate	Luminance contrast to surroundings	EN 81-70 (5.1.2)
Operating force	2,5 to 5,0 N	EN 81-70
Operating feedback	Movement and mechanical feedback	EN 81-70
Button movement	From 0.5 to 3.0 mm	AS1735.12-1999, Australia
Registration feedback	Visible and audible signal	EN 81-70 (5.1.3.)
Height of symbol	25 to 40 mm located on the active part	EN 81-70 Annex B
Symbol	In relief, luminance contrast to the background	EN 81-70 (5.1.2)
Height of relief of active part and symbol	1.0 mm recommended	EN 81-70
User Experience		
Durability of markings	Markings should stay visible during the whole lifetime of the button	
Safety	Sharp edges are to be avoided	
Cleaning	Shapes must be easy to keep clean	
Illumination	Even illumination, no spots	
Allergenic materials	Nickel, chromium, cobalt and natural/synthetic rubber not to be used	
Vertical movement of the active part	Steady, no swinging	
Activation location	Button activates no matter what part of the face plate is pushed	
Mechanical Design		
Toughness of construction	The construction must endure high static loads and sudden impacts from different directions	
Installation	Installation to the elevator panel without tools	
Friction and sharp objects (e.g. keys)	Construction tolerates presses with sharp objects	
No obstrusive components	Pressel must not get stuck into button base in case of fracture	
Unwanted objects	All gaps small enough to prevent unwanted objects	
Assembly and function	Clearances and tolerances	
Fastening to the elevator panel	Rigid fastening, impact resistant, and no noticeable swinging	
Testing		
Cycle test (lifetime)	Repeated operation, spring durability	
Static force test	500N	
Impact test	2J, 1 kg, radius of 10 mm, height 20 cm	(EN 81-71:2005+A1:2006)
Wear test	Abrasion	
Materials		
Operating temperature	0 – 40˚C	
Climatic conditions	Heat, temperature changes, humidity	
Hygroscopic materials	Materials that absorb water should be avoided	
Chemical resistance	Resistance to common cleaning chemicals	
Particles in abrasion	Materials are not allowed to pulverize when two surfaces are rubbing each other	
UV resistance	No degratation due to UV light during planned lifetime	
IP class	IP20, no finger access inside, dry location	

Figure 4.2: Requirements for button design based on different standards and user experience targets.

The button action should be self-explanatory through the symbol and the arrangement on the panel. In the case of Jumbo buttons, symbols have to protrude at least 1 mm. People with visual impairment should be able to locate the buttons by touch and distinguish the markings. If braille markings are added, they should comply with the ISO 17049 standard. The codes require a good contrast between the symbols, the button face, and between the button and its surroundings. Further and more detailed requirements are embedded into the following chapters where different concept areas will be explored.

4.3 Concepts

This chapter presents the practical design work done for the thesis. The elevator button was first divided into different subconcept areas. Solutions to these areas were conceptualized to fill the requirements presented in Figure 4.2. These are based on the current industry specifications and user experience targets. The visualization in Figure 4.3 was implemented to help the conceptualization process. It attempts to gather the requirements as a visual package. The idea is to provide *only the necessary interfaces* and requirements that the final concept must satisfy. The surrounding physical interfaces of the elevator panel and the PCB board are illustrated.

AM as a manufacturing method presents some novel opportunities in terms of attainable shape complexity. The possibility of shape complexity is transmitted to *hierarchical-, material-, and functional complexities.* These opportunity categories were presented earlier in chapter *3.2 Design Opportunities.* The objective of the design part is to explore these AM opportunities within the button design space (Figure 4.3) and to maximize product functionality. Due to the increased design freedom with AM, different shapes and features of the whole design can be explored separately. This enabled the conceptualization process to be divided into smaller, more manageable subconcepts. The division of subconcepts was based on functional similarity. In addition, dimensional and user experience requirements were considered simultaneously.

The practical design work was partly inspired by the research papers and thoughts presented in the Chapter: *Design Strategy and Process with AM.* The design part of the thesis is mainly focused on the early concept generation phase of product development. Within each subconcept area, solutions

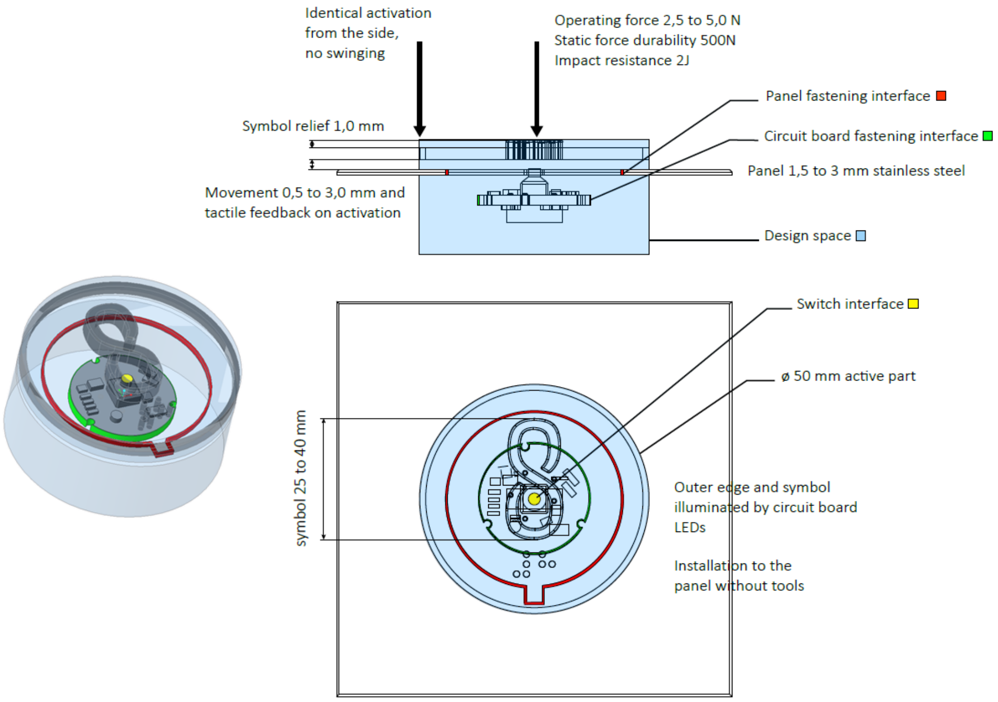


Figure 4.3: The microchip, switch and the panel installation hole provide the physical limits for the design. The protruded symbol on the active part is required to move 0.5 to 3.0 mm relative to the microchip and activate the switch. The switch interface is colored in yellow, the PCB interface in green and the panel interface in red. The blue volume denotes the available design space.

to the given requirements are explored. The main focus is on design opportunities with AM. The design workflow was highly empiric. Functionality of features and feasibility of AM processes were tested with various prototypes and experiments.

The following sections will present the different subconcept areas that were experimented with and iterated during the design process. These are *Contrast and Illumination*, *Fastening*, and *Spring Functionality*. Each chapter will start by introducing the requirements and physical interfaces that affect the conceptualization of that specific area. Different opportunity areas of AM are discussed. Finally, the subconcepts are unified into an assembled button concept introduced in the chapter *Concept Assembly*.

4.3.1 Contrast and Illumination

The accessibility standard requires that buttons are easily recognized by persons with visual impairment. The button has to stand out from the elevator panel and the symbol from the button face. The standard defines a greyscale contrast difference for these boundaries when the setup is non-illuminated. The circuit board placed under the faceplate has LEDs to provide the visual feedback signal when the button is activated. Light from these LEDs has to propagate and illuminate a part of the button that is visible to the user. The standards do not specify the location of the light feedback in more detail. Traditionally, the ring surrounding the active part of the button has illuminated.

The contrast requirement may sound trivial but it is one of the most restricting requirements for the button in terms of the whole construction. The contrast and illumination requirements are essentially requirements for the materials. In an optimal design, the whole button would be printed as a single process. The contrast difference, on the other hand, either requires multiple parts, multiple materials, or multiple surface finishes. Similarly, the illumination can be controlled with multiple parts, multiple materials, or selective placement of thinner walls in the design.

The following experiments aim for an understanding of the optical properties of certain AM processes and materials. The propagation, diffraction, and scattering of light between boundary layers were studied. Small internal and external features were experimented with to see how they affect light propagation. The underlying objective of these experiments was to find non-traditional solutions for the contrast and illumination requirements and to provide new opportunities for product design.

Both the contrast and illumination requirements can be achieved by combining two parts with different properties. First, AM technologies able to print on transparent or translucent plastic were identified. SLA and material jetting technologies can provide near transparent objects on a very high resolution. These technologies even permit the manufacturing of lenses. FDM and SLS have material options that are translucent with thin wall thicknesses. Material jetting is the only technology that can provide a multi-material print as a single process.

To get familiar with the light propagation and scattering properties, samples were printed on Formlabs Form 2 printer and their clear photopolymer material. The layer thickness was kept at 0.05 mm. Initial prints included a hemicylinder and a light pipe structure shown in Figure 4.4 **a)** and **b)**. Refractive properties of the material were found to be surprisingly good. A near total internal reflection occurred on the flat surface of the hemicylinder. Irregularities and voids in the structure caused the light to scatter slightly. In this design, light propagation was found to be good, on a short distance, if the angle of the light pipe was less than 45 degrees and the length of the edge was more than or equal to 5 mm.

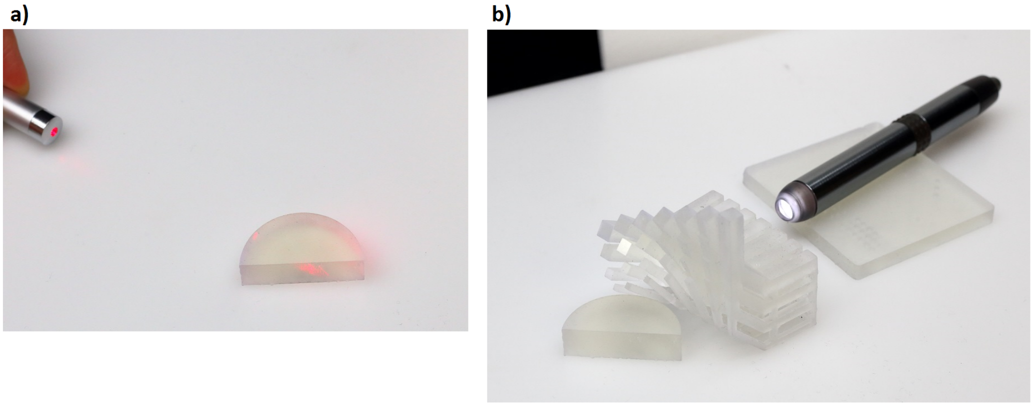


Figure 4.4: **a)** A hemicylinder for refractive index experiments and **b)** a sample with differing cross sectional areas and angles to test light propagation.

Next, a 0.5 mm laser cut stainless steel plate was placed on top of a translucent 3D printed faceplate (Figure 4.5 **a)**). A clearance of 0.2 mm on each side allowed the plate to fit on top of the embossed symbols. Small snap-fit structures in the rims turned out to be too small to print. Instead, instant adhesive was used to secure the parts. A clear print material allowed symbols as well as the base to illuminate on activation (Figure 4.5 **b)**). The problem was that individual LED spots were clearly visible through the symbol. An internal structure or a less permeable material would be necessary to diffuse light evenly. A miniature sample of a car rear light cover (Figure 4.5 **c)**) provided inspiration for printed structures that could diffuse light. This was initially tested by covering a surface with small 2 mm diameter hemispheres (Figure 4.5 **d)**). Improved diffusion was achieved by stacking these surfaces and increasing the distance between them. A structure, such as this,

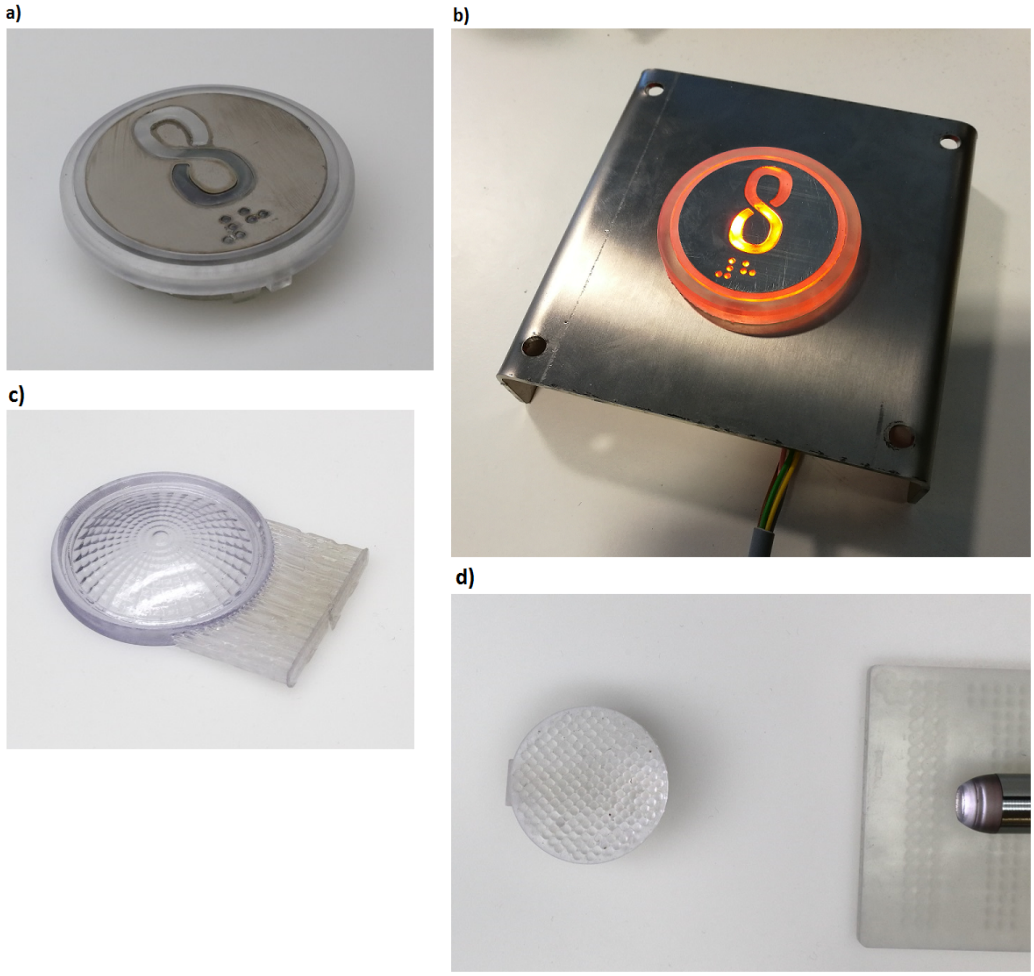


Figure 4.5: **a)** A button assembly printed with Form 2 translucent photopolymer, **b)** the same assembly installed and illuminated, **c)** a varnish coated stereolithography sample for increased translucency and UV resistance (with supports attached), and **d)** a plate covered with small hemispheres to increase light diffusion.

could be embedded inside the faceplate structure.

One possibility to achieve the required contrast and illumination is through a solidification of a liquid material that is impermeable to light. The recess on the faceplate provides a pool for the liquid to level. As the liquid solidifies the embossed symbols stick out from the solid surface. The liquid material could be a colored two component epoxy. This trick would fill contrast requirements and achieve a hard, smooth and chemically resistant surface. A common problem with translucent AM materials at the moment is their poor mechanical properties and brittleness. By minimizing the translucent material the structure could be optimized for rough impacts while the clear cavities would still create the optical features.

Internal light scattering was experimented with to test if it is possible to produce numbers or symbols inside a translucent material using only light. Numbers from one to three were inserted inside a stack of translucent plates (Figure 4.6 **a)**). Rhinoceros and Grasshopper were utilized to sample fonts into a grid of modifiable 3D shapes. Example implementation and the resulting shapes are shown in Figure 4.6 **c) and d)**. With boolean cut, these shapes were turned to void volumes inside the plates in Creo. The first void structures in the samples were spheres with a diameter of 1 mm. These failed to print with SLA. Liquid resin got caught inside the spheres and the structure turned out completely solid. No scattering could be recognized. In a further trial bigger dimensions and different shape geometries were experimented with. The number one was printed with void shapes of spheres, oblique cylinders, and cones. This time a small clearance was inserted between two plates for liquid resin to escape (Figure 4.6 **b)**) providing a slightly improved result.

4.3.2 Fastening

The design case includes three different fastening interfaces. The buttons are installed through openings on elevator panels. This interface will be referred to as *the panel interface*. The panels are usually 1.5 to 3 mm thick stainless steel. The button function requires two entities that move relative to one and other to operate the switch. This interface is referred to as *the faceplate interface*. These entities must be fastened or somehow geometrically locked but allow motion in one direction. Design of the spring functionality has to be taken into account in the design of this fastening solution. The third interface is the *circuit board interface* between these two entities. The dimensions and installation surfaces of the circuit board are fixed. Empty space is required for components, a switch, and a connector. The circuit board will have to be installed into the assembly. This requires either an opening, to slide the board on place, separate parts that will be fastened around the circuit board, or a pick and place process during 3D printing.

From the functionality point-of-view, the fastening solutions should be

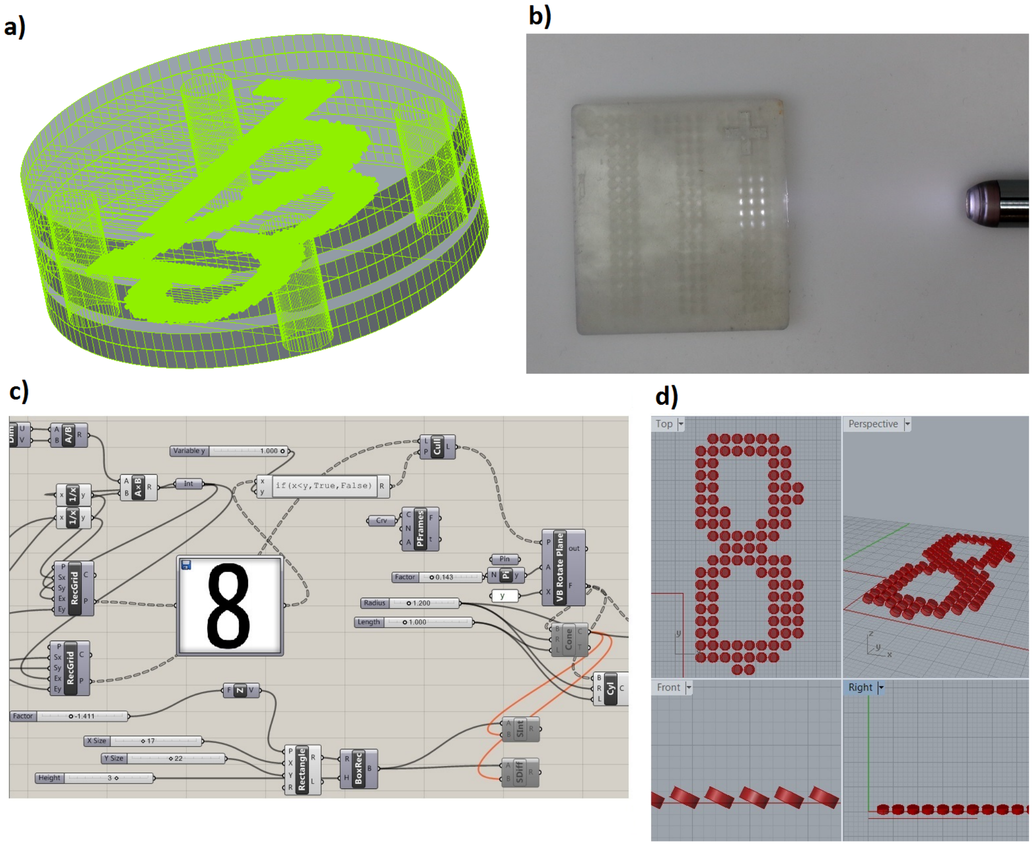


Figure 4.6: Tests for internal light scattering: **a)** numbers 1,2, and 3 embedded into a stack of disks as small sphere cavities and **b)** internal illumination with different cavity geometries. These modifiable structures were made with Rhinoceros and the Grasshopper plugin. **c)** A number was routed through an image sampler and and equivalently spaced grid was created and filled with modifiable 3D shapes depending on the contrast of the image. **d)** Tilted cylinders as a result of a sampled number "8".

mechanically rigid, free of play, and enable both installation and disassembly without tools. This chapter studied these design goals in combination with the AM opportunities. AM allows functional features to be embedded more easily into the surrounding structures and multiple functional features to be combined as a single part. Complex features and even mechanisms can be embedded into the same print. Objective of the following experiments was to find a solution to all of the different fastening requirements, preferably within a single part.

The conceptualization of the different fastening solutions started with *the circuit board interface.* The board has three slots on the perimeter to fix the axial orientation. The leftmost part in Figure 4.7 was the initial idea for an overhead installation. Small guide pins align with the slots on the circuit board. A recess and a hole were provided for the components and the connector on the underside of the board. This arrangement, however, leaves one degree of freedom. The board can still buckle upwards. A locking feature is necessary for a rigid installation. Snap-fit structures, a rotational bayonet, or an internal locking mechanism would be the solutions to lock the board in place. In addition, with the overhead installation, the faceplate would have to be either a separate part or include some kind of a mechanism to allow the circuit board installation.

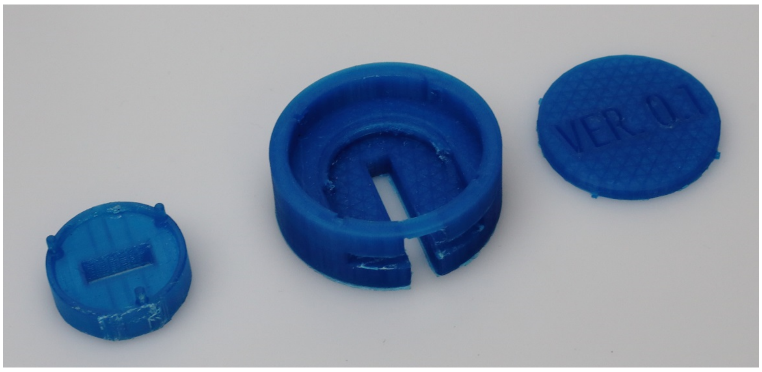


Figure 4.7: First prototypes for circuit board and faceplate installation. **On the left:** A circuit board bed with installation guides and an opening for the connector. **In the middle:** A concept for a side installation with and internal groove for the circuit board. **On the right:** A faceplate with small radial installation guides.

A second option for the board installation is from the side, through an opening on the button base as can be seen in the middle of Figure 4.7. A side installation would allow the faceplate and the base of the button to be printed in a single part. Similarly to the overhead option, a groove with alignment pins would fix the board in place. The space requirements for this setup were considerably higher. To a degree that would interfere with the design of other features. For this reason, the concept was not taken further.

A third option exists but was not prototyped: a rear installation. This direction provides some advantages over the other options and should have been prototyped in the beginning. There are no obtrusive structures or components on the back side. This way the whole button assembly could be printed as a single piece and the space reservation for the circuit board would be minimal. This would require a mechanism to reduce clearances when installed.

The panel interface is usually an opening through which buttons are installed, although some surface mounted solutions exist. The button assembly will have to fit through the opening from one side and tightly lock in place after the installation procedure. Both the geometry of the opening and the fastening mechanism can be freely explored. The geometry of the opening should allow the installation of the button only in the correct orientation. Possibilities for the fastening mechanism include threads and a nut, a rotational bayonet, snap-fit structures, flexible material, and an embedded mechanism. A general objective for the fastening solutions is to integrate fastening features to other components, and ease the installation. The installation, in the best case scenario, would be tool free in both directions.

A laser cut 2 mm stainless steel installation plate was ordered to verify the operation of concept prototypes for the panel fastening (Figure 4.8 **a)**). A radial snap-fit structure was chosen as a candidate for this fastening interface. 8 snap-fit arms lock the button base in place. A section view of the snap-fit geometry is shown in Figure 4.8 **d)**. The installed button is shown in Figure 4.8 **e)**. Disassembly of the button is possible with a disassembly tool shown in Figure 4.8 **c)**. The geometry should be altered so that no tools are needed.

The requirement for *the faceplate interface* is that the movement between the two entities activates the switch on the circuit board. Only translation in this direction is allowed. Other degrees of freedom should be eliminated. When pushed the faceplate is dampened and reverted back to original position by spring elements of some kind. The spring functionality concepts will be explored in the next section.

The switch activation movement requires the surrounding geometry to enclose the faceplate. Possibilities include a bayonet style groove, openings for snap-fits, an internal mechanism, or directly exploiting flexible material properties. After installation, the rotation of the plate and the symbol cannot change. Clearances are necessary for smooth movement but should be minimized to prevent play and users from pushing sharp objects between

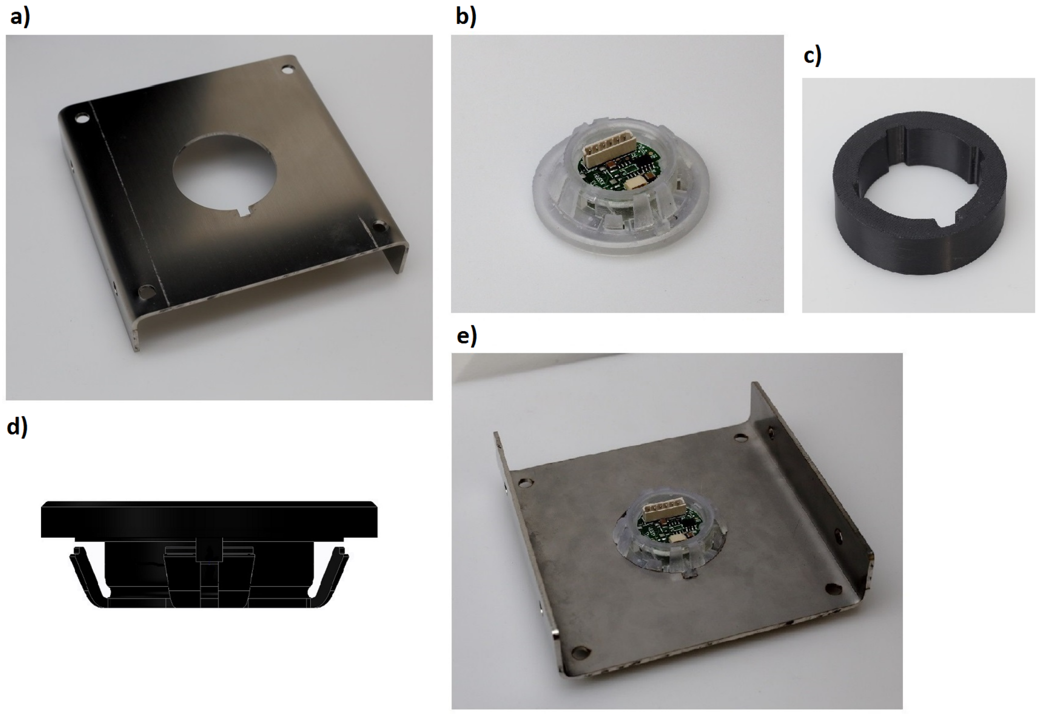


Figure 4.8: Prototypes for the *panel fastening interface*: **a)** a stainless steel installation plate, **b)** an assembled button from the rear, **c)** a disassembly tool, **d)** a side view of the radial snap-fits, and **e)** an installed button.

parts.

Snap-fits were again used for fastening. Four snap-fit arms in the faceplate extend through openings in the button base, as seen in Figure 4.9 **a)** and **b)**. Compressed lever arms expand after the openings and secure the faceplate in place. The spring elements hold the assembly static. This solution works well but leaves less space for the spring elements. In addition, as the lever arms extend through the structure but cannot cross with the circuit board, the installation hole on the panel needs to be wider. The lever arms also obstruct free propagation of light inside the structure. The openings cause some rotational play in the assembly but with small enough clearances the effects are negligible in use.

Inspired by the even activation of keyboard buttons an internal scissor mechanism was sketched but never prototyped. For future consideration,

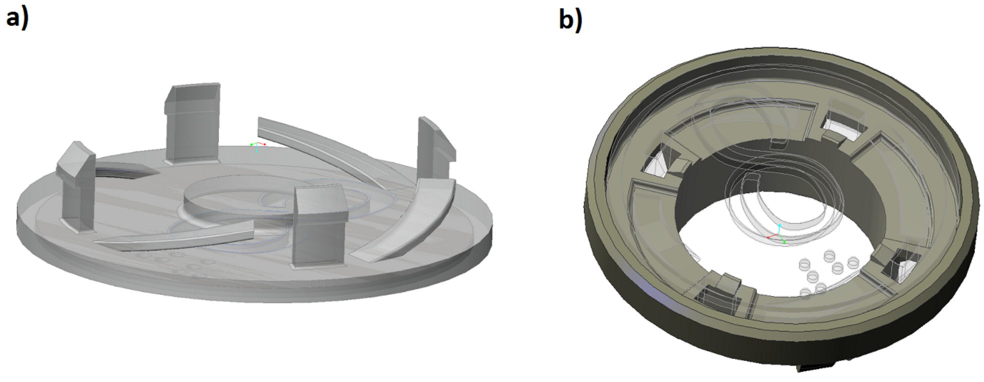


Figure 4.9: **a)** The faceplate is installed through the openings in **b)** the button base part.

the idea would be worth looking into. If a mechanism behaving similarly was possible to print as a single piece, it would enhance the touch of the button significantly. The faceplate in previously mentioned concepts had a tendency to swing from side to side if a push was not centered.

4.3.3 Spring Functionality

For the operation of the button, the standards require an operating force between 2.5 to 5.0N, button movement between 0.5 and 3.0mm and a clear tactile feedback. Movement is required to be uniform despite eccentric activation. The active part should return to initial position after activation. Most of the operating force of a button is generated by the stiffness of the electronic switch itself but springs are necessary to revert the faceplate back to original position. They also contribute in suspension of sudden impacts and excessive force. The springs need to retain these properties for millions of press cycles, throughout the lifetime of the component.

These requirements limit the choice of material of the *spring element(s)*. The material has to be highly elastic, durable and impact resistant. The design, location and working principle of the spring element(s) however can be freely explored. Based on the function of the product, there are certainly two entities that move relative to one and other. The spring element(s) can be integrated to either one of these entities or be independent. The entities can consists of the same part and material if the material itself allows a partial relative movement in the structure.

The following experiments and prototypes explore the structural and material properties of 3D printed springs. The main objective is to fulfill the button specification requirements. The secondary objective is to explore new AM possibilities. The desired spring functionality could be achieved in many ways. For example by using flexible metastructures, embedded mechanisms, or carefully selected material thicknesses to flex the material itself. From the user experience perspective, a uniform activation together with a constant activation force is desirable and the side-to-side swinging of the faceplate should be minimized. The prototyped solutions succeeded in functionality and managed to consolidate multiple features into a single part. However, these solutions were still fairly traditional and to meet the user experience targets, more resourceful solutions should be explored.

Different spring geometries were first explored and modeled with Creo (Figure 4.10 **a), b), c), and d)**). Springs with different parameters were printed with Fortus 450mc, 0.127 mm layer height, and M30-ABS. Printing springs with FDM is problematic because of the stair stepping effect and the need for support structures under overhangs. Fortus 450mc utilizes a soluble support material which makes it possible to print the springs in the first place (Figure 4.11 **a)**). In comparison Figure 4.11 **b)** shows wave springs printed with Ultimaker 3, 0.06 mm layer thickness, and flexible material. The standard setting on Ultimaker is that support structures are printed with the same base material but with a hatched pattern. The removal of support structures has left the surface very rough and fractured some of the samples. Printing on a different orientation would help but with flexible parts the flex direction will have to be perpendicular to the print orientation for maximum durability. Figure 4.10 **d)** shows a faceplate where the flex direction of the springs is perpendicular to the radial snap-fit lever arms. Parts, such as this, do not perform well in all directions when printed with FDM.

A faceplate with integrated sinusoidal springs and snap-fits in Figure 4.11 **c)** was printed with a SLA printer Form 2, 0.05 layer thickness, and clear material. The integrity of the material is better compared to FDM and layer boundaries are not easily visible to the naked eye. The brittleness and non-elasticity of the material turned out to be the problem. One of the springs in the forefront has fractured. In addition, the springs did not revert fully to their original position after numerous activation cycles.

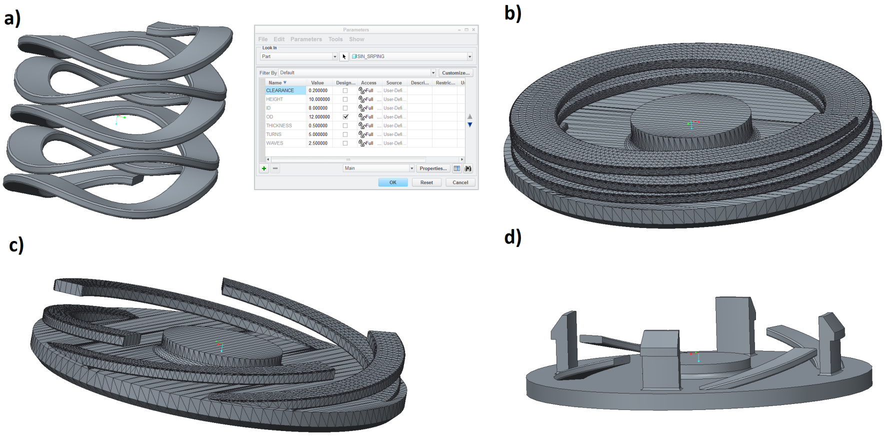


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Figure 4.10: Different spring geometries: **a)** a parametric wave spring model on Creo to test different geometry configurations, **b)** a wave spring embedded onto the faceplate, **c)** embedded radial sinusoidal springs, **d)** sinusoidal radial springs together with the faceplate installation snap-fits.

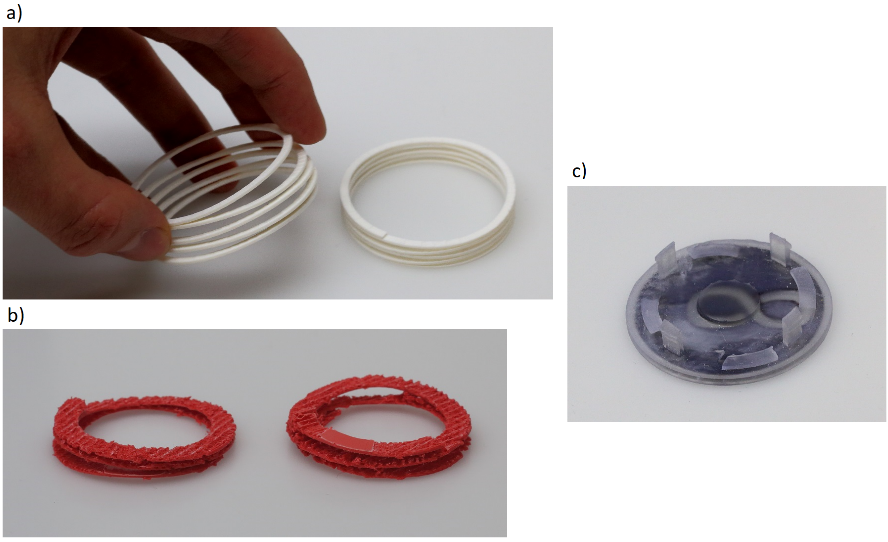


Figure 4.11: **a)** loose wave springs printed on FDM ABS-M30, **b)** wave springs printed on Ultimaker 3, 0.06 mm layer thickness, and flexible PLA, and **c)** a translucent faceplate with a broken spring element due to material brittleness.

Figure 4.12 **a)** demonstrates the flexibility of a part printed with PA2200 (nylon). In addition, the cyclic performance of nylon was found to be good in testing. With thin walls and a flexible material, the movement of the faceplate could be achieved in a single part. Together with a rear installation of the circuit board one part could be eliminated from the assembly. A spring functionality such as this was prototyped with a faceplate in Figure 4.12 **b)**. The material thickness was only 0.5 mm. Solid and relieved designs were tested. Although the faceplate is a separate part the base could be easily integrated to form a continuous structure. This solution could even enable a highly IP protected button design. With higher resolution printers and improved materials, it will become possible to affect material properties by affecting the microscopic structures of the print as illustrated before in Figure 3.2.

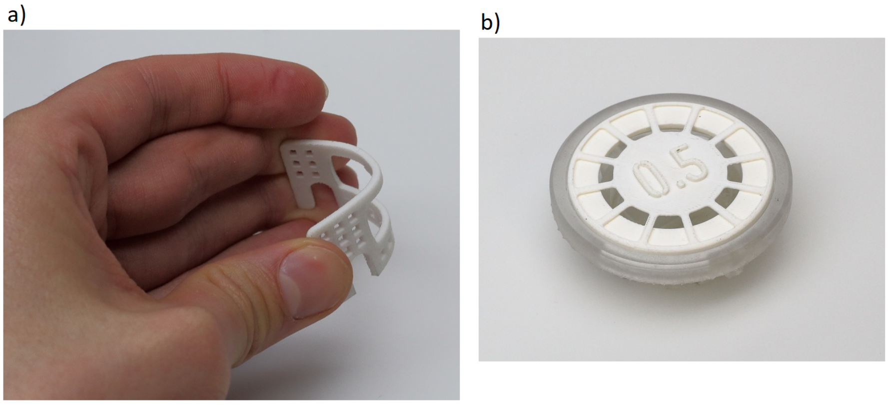


Figure 4.12: **a)** A flexible PA2200 (nylon) sample printed with EOS P395 and 0.1 mm layer height. **b)** a spring based on thin material thickness printed on Fortus 450mc and M30-ABS.

4.4 Concept Assembly

The best performing subconcepts were unified into a final assembly presented in Figure 4.13. The assembly comprises of 4 parts. The base part with radial snap-fits for fastening to the signalization panel. The circuit board which attaches to the base from the top. The faceplate that is pushed through openings in the base and equally locks in place with snap-fits. Finally, a 0.5

mm laser cut stainless steel plate is glued on top.

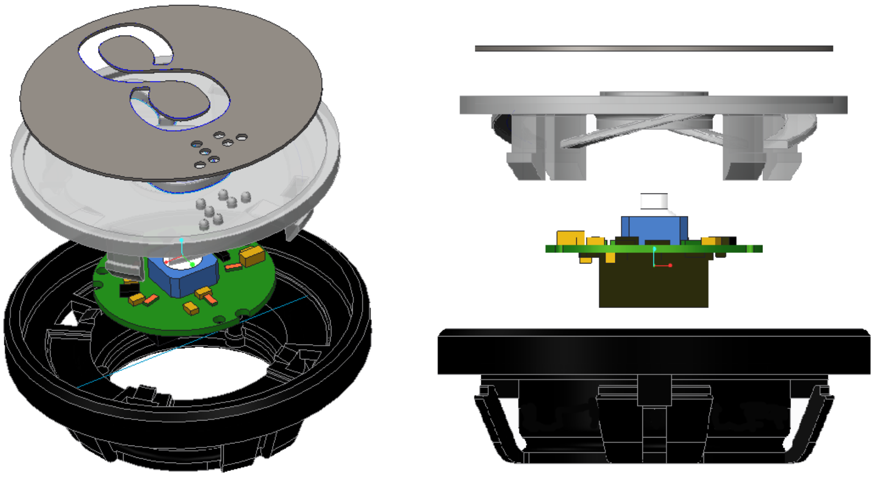


Figure 4.13: The exploded button assembly.

The assembly was found fully functional and it passed the activation and the cycle tests which are presented in the next chapter. However, the assembly failed to address some requirements. The contrast between the symbols and the faceplate was not sufficient. Also, fastening of the PCB was not rigid enough and a tool was needed to remove the button from the panel. The response to pushes from the button edges was not satisfactory and the impact durability of the construction was also found to be poor.

The concept assembly mainly addressed mechanical functionality and stability. The industrial design possibilities were, at this point, mostly left unexplored. Once the mechanical requirements have been fulfilled, attention should be diverted to visual design. Possibility for shape complexity with AM can be utilized for design features that can affect the appearance and user experience of the button. Very small production batches could be completely customized for user needs. This includes for example customized shapes, fonts and surface textures. The haptic touch and feel of the button activation can be optimized for a superior user experience. Also, the illumination of the button could be controlled with light pipes and internal structures that affect light propagation and intensity.

4.5 Process and Material Selection

Selecting a suitable AM process for manufacturing starts with an *evaluation for technical feasibility.* Product-dependent properties and requirements can oftentimes be translated to data and evaluated against machine specifications. Obviously, the part will need to fit the printing area and the resolution of the machine should be able to print the finest details of the design. Dimensional accuracy of the machine in XY- and Z-direction is reviewed to maintain product tolerances. For consumer products or parts with mechanical contact, a fine surface quality is necessary. [12]

In addition to dimensional requirements, material suitability is considered when choosing an AM process. Material options are often machine dependent and limitations exist depending on the AM process. Mechanical properties such as tensile strength and modulus, impact strength, strain at break, hardness and flexural strength are evaluated in contrast with the load cases for the product. Other considerations include thermal and environmental properties and chemical resistance. For design purposes properties like appearance, color and surface texture might be relevant.

The technical feasibility check is followed by *production and cost analysis.* That is, the ability of the AM processes to reach needed production volumes, lead times and unit costs. These attributes are compared between AM methods and traditional manufacturing. The production can be organized in-house or ordered from a subcontractor. AM processes include phases that are often overlooked in decision making. Preparation of raw material, machine warm-up and cool down, post-curing, support removal and post-processing are phases that can significantly add up on cost and lead times.

4.5.1 Material Suitability

The material selection within AM technologies is still very limited. The elevator button assembly is a fairly low-cost product and one of the main objectives in the design is to minimize cost. Thus, the material should fulfill the functional and design requirements while keeping the cost down. This somewhat restricts the material options. As the material cost with metal AM is high, different grades of plastic were explored. Two candidate materials were selected for further testing and evaluation. Some of the functional and design requirements of the elevator button can be derived into material requirements. These are presented in the following paragraphs.

The specifications and standards only advice against the use of allergenic materials, such as nickel, cobalt, chromium and natural or synthetic rubber on the button surface. No requirements for overall mechanical or chemical durability are stated other than for the durability of the braille markings. However, manufacturers have compiled their own internal guidelines for the design and testing of buttons. This empirical collection of good practice guarantees the quality, appearance, and operation of the buttons for their planned lifetime. The following material requirements originate from these guidelines.

The button testing routines define the load cases the construction must endure without damage nor disruption of functionality. These tests are presented in the following chapter in more detail. Briefly, the button must withstand low cyclic loads, high static loads and sudden impacts. Elasticity, sufficient strength, and impact resistance are required.

In general, all the button materials need to be environmentally stable. Meaning that they retain dimensions and properties in changing temperatures and humidity. For example, some plastics have a tendency to absorb water and swell in humid conditions. This can result in excessive stress or jamming of the active part into the button base. Mechanical properties might be altered due to a higher water content.

The operable surfaces of buttons are pushed millions of times during the lifetime of the product and this cyclic operation together with a changing environment can cause micro fractures and eventually a fatigue failure. An elastic material behavior is desirable and all structures that flex on operation should fully revert to the original state after a force is removed.

The amount of abrasive wear on the button markings is high. A hard, wear-resistand surface is important that the markings stay visible for the lifetime of the button. Grease and dirt is transferred onto the surfaces from fingers and the buttons are regularly cleaned with harsh cleaning chemicals. This combination places high requirements on the design as well as the material and rules out many low penetration surface finishes such as painting or anodization.

Operating environment of an elevator button is not often in direct sunlight. However, such instances are possible if the car walls or the door are made of glass. As material requirements always come from the most demanding situation, the selected material has to be highly resistant to UV light. The appearance and material properties cannot be changed by any amount of exposure.

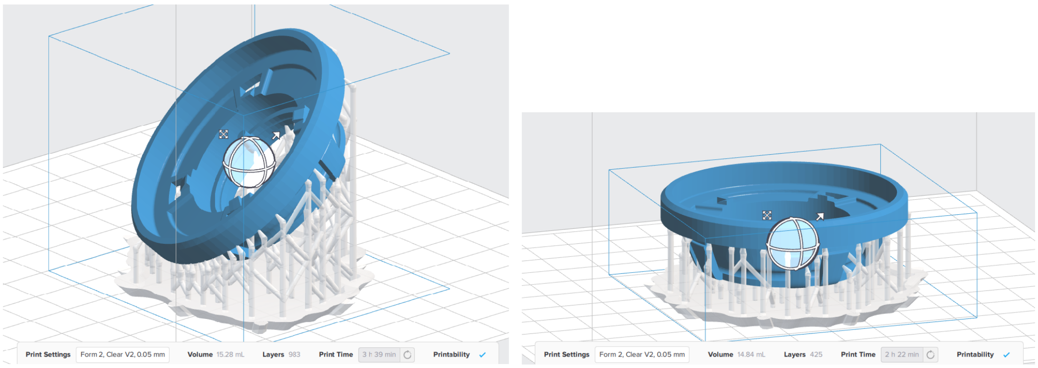
The feedback signal via illumination is a functional requirement that transfers to either a material or a design requirement. Preferably the product would be at least in part of a translucent material. The illumination effect might be possible to achieve through careful optimization of wall thicknesses.

4.5.2 Optimization

Optimization procedures can be divided in two segments, *product optimization* and *process optimization.* Product optimization is an iterative process that aims to improve product performance, functionality, and appearance. Process optimization aims for maximum efficiency in manufacturing. The latter category includes optimization for build time, packing or nesting of build volume, support structure minimization, and maximizing printability. This chapter will showcase some practical examples that were implemented in the design and discuss noteworthy areas of optimization that should be acknowledged in all phases of product design.

The most important design driver for the button was functionality. This proof-of-concept button assembly was iterated for dozens of rounds and tested in between for functionality. Mainly this work included adjusting clearances between moving parts and modifying geometry. The touch interface and the snap-fits required constant adjustments. The geometry was highly experimental. In addition, every AM technology has its own characteristics for part clearances and printable geometries to be learned. With hindsight, a more systematic and analytical way to design geometry should be used. Simulations could be used to predict elasticity, stiffness, and impact resistance of the structures.

The second design driver after functionality was cost. The manufacturing cost with AM is determined by material costs, machine time, operator cost, and the post-processing needs. These are mainly process optimization considerations but they can be addressed with clever design as well. The amount of material was iteratively reduced throughout the design process. Another way to reduce material and cost is to minimize support structures and hence post-processing needs. This varies with different AM technologies. Machine time can be minimized by a favorable print orientation as shown in



Print Settings: Form 2, Clear V2, 0.05 mm — Volume 15.28 mL — Layers 983 — Print Time 3 h 39 min — Printability ✓

Print Settings: Form 2, Clear V2, 0.05 mm — Volume 14.84 mL — Layers 425 — Print Time 2 h 22 min — Printability ✓

Figure 4.14: The effect of print orientation on the build time and support material with SLA. On the left: A build orientation optimized by the PreForm software, volume: 15.28 ml, layers: 983, Print Time: 3 h 39 min. On the right: volume: 14.84 ml, Layers: 425, Print Time: 2 h 22 min.

Figure 4.14. In general, the fewer the layers, the faster the build. However, the build orientation affects the mechanical properties and surface finish of the parts as well. Figure 4.14 shows two different print orientations for the same part. The one on the right prints over an hour faster. However, the orientation causes all underside flat surfaces to print with a poor surface quality.

With delicate design, support structures can be eliminated throughout the part. A part structure that follows *an organic growth* can be printed as a completely self-supporting structure. In practice, each AM technology that prints with supports has a specific threshold angle which should be followed in the design to minimize the need for supports. Often designs have mandatory features that can not be fully optimized. SLS, on the other hand, is a self-supporting method with plastic and allows parts to be nested in the whole print volume. Some AM technologies, such as FDM, produce very anisotropic macrostructures and the build orientation can have serious implications on mechanical properties and performance. With all technologies, the best compromise between mechanical properties, surface finish, support structures, and build time should be used.

Topology optimization is one way to increase the functional efficiency of the product and reduce material costs. Figure 4.15 shows the resulting organic structure from a simulation done in SolidThinking Inspire that maximized stiffness and minimized material usage. In the load case, a vertical

Figure 4.15: Topology optimized versions of the traditional face plates printed with Ultimaker 3, PLA (on the left) and Form 2, clear photopolymer (on the right). An organic structure is a result of a simulation to support a static load of 500N.

force of 500N was placed on the faceplate. The design volumes for the optimization were copied from the example button shown in Figure 4.1. These designs were printed on FDM (left) and SLA (right). Some fractures occurred in the SLA print due to thin walls in the faceplate. This thickness was increased for the FDM model. Taking into account all possible load cases in a simulation is an art on itself and a subject for another thesis. The real world is complex and load cases are rarely presented separately. A public research report by VTT [19] gives a nice overview and practical examples of the topology optimization process for metal components. Similar principals can be transferred to plastic designs as well.

The printability of designs can change between technologies. SLA with a 0.05 layer thickness can cope with features where FDM on 0.1 mm could fail completely. A distinct difference between technologies is the way how internal cavities can be printed. In powder bed technologies, removal of excess powder is often desired and big enough escape holes have to be designed. Some FDM machines have soluble support structures which allow more freedom. SLA prints should be designed so that internal cavities are self-supporting. The tree branch support structure (Figure 4.14) is near impossible to remove from inside the part. In addition, small and tubular cavities might get clogged with uncurable resin due to capillary effect and liquid cohesion.

Chapter 5

Testing

Some of the button specifications in the accessibility standard EN81-70 require testing for verification. Dimensional and design requirements are easily verified by hand or by visual inspection but the operation feedback, mechanical durability, and environmental aspects must be measured with specialized instruments. Two different materials were tested for operation, cyclic activation, static load, and impact performance. This chapter presents the test setup for each of these tests together with the results.

The material options were restricted to different grades of plastic due to product cost requirements. Technologies that print on plastic include material extrusion, powder bed fusion, vat polymerization and material jetting. Two different AM technologies were selected, powder bed fusion and vat polymerization. The powder bed fusion parts were ordered from a service provider using an EOS EOSINT P395 (SLS) machine. The material was PA2200 (Nylon). Vat polymerization parts were prepared with a Formlabs Form2 printer and their clear photopolymer material. These two technologies give a nice overview of the design implications and the suitability of these materials for end products. Material jetting was compensated with vat polymerization due to the similarity of the material properties. The spring structures for cyclic operation were not possible to produce with current material extrusion methods.

5.1 Operating Force and Static Load Test

The operating force, movement and static load of the buttons were tested with Lloyd Instruments LRX Plus materials testing machine. An activation force between 2.5 and 5 N is required with movement in a range from 0.5 mm to 3 mm. The standard also requires a tangible feedback when the switch has been activated. The static load test verifies if a button is suited for elevator use and will remain intact for example if a heavy object leaned against it.

Three tests were conducted. The first test was a single activation test where the force was increased to 30 N and then decreased back to zero. The speed of movement was kept constant at 10 mm/min. The activation piece was a metal shaft with a rubber tip of 15 mm diameter.

The following test was with 5 cycles, 0 to 10 N and the same 10 mm/min speed. The idea was to see if a repeated activation changed the feedback of the button.

The third test was a static force test. A centered force was increased to 500 N and kept for 2 seconds. Due to some buckling with a soft rubber head, the activation piece was changed to a solid metal shaft with a convex tip of 15 mm diameter. The results of the tests are shown in Figure 5.1.

5.2 Cycle Test

The cycle test studies material fatigue, wear, and operation success for a number of activations that corresponds to the whole estimated lifetime of a button. A pneumatic test setup which continuously operates the buttons was used together with a custom sheet metal installation plate for the buttons. The piece that activates the buttons simulates a finger. On given intervals a visual check and an operating force test was conducted to verify the functionality of the button. At the same time it was also verified that there are no structural changes due to fatigue or wear.

The first cycle test was implemented on 5 button assemblies printed with Form 2 and on clear material. The spring structures under the face plates were inspected at 80 000 cycles. Already after the first inspection, it was clear that the material was not suitable for extensive cyclic use and the test was terminated. Significant creep had occurred and the button touch was already nonexistent. The results of the test together with a reference faceplate can be seen in Figure 5.2.

The second test included 4 samples made with selective laser sintering

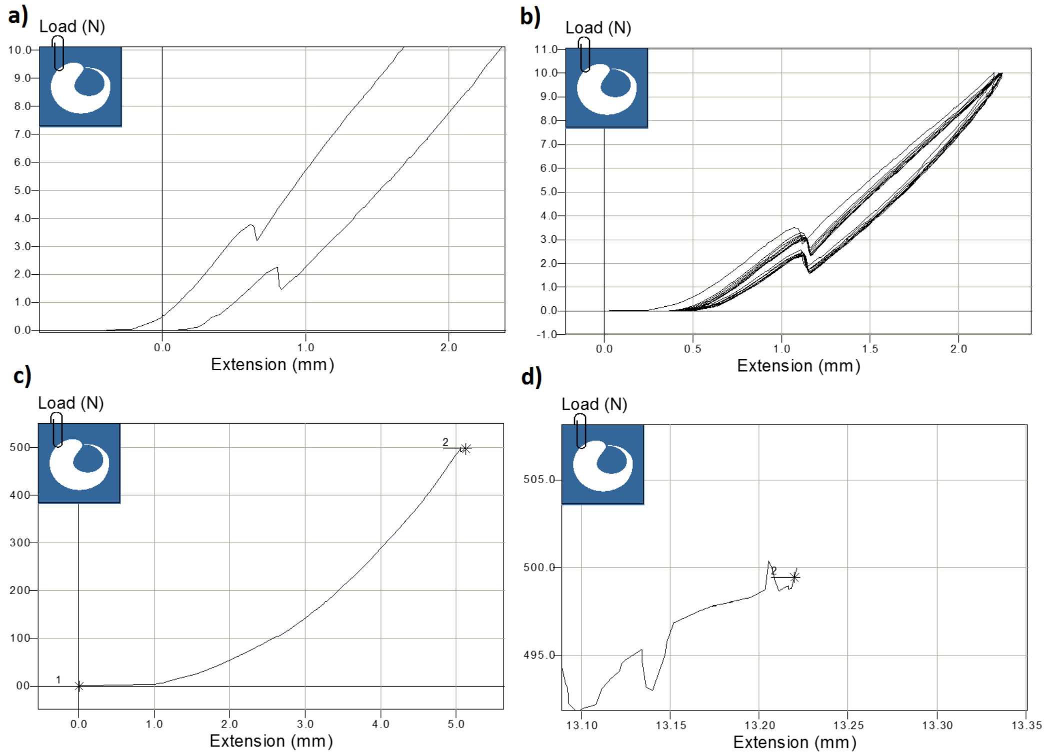


Figure 5.1: Operating force test with a) one cycle and b) 5 cycles. Static load tests with a maximum load of 500 N. c) with a circular steel shaft and d) with a soft rubber cap.

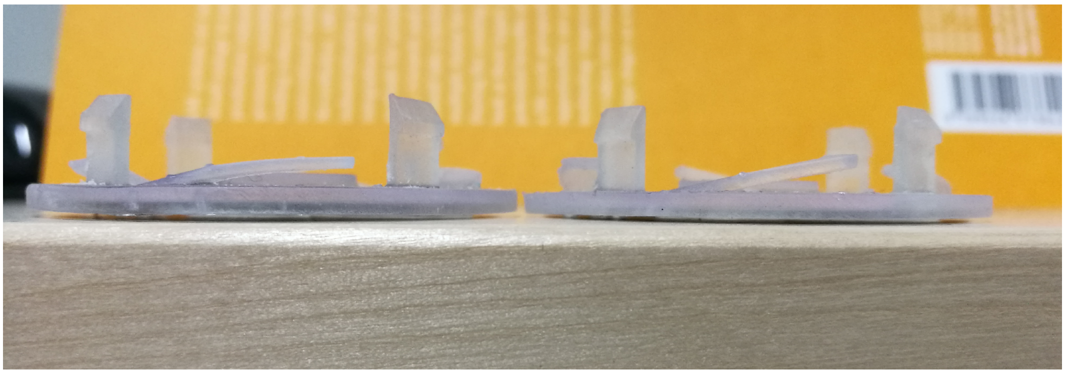


Figure 5.2: Cycle test with Clear V2 and SLA

and PA2200. This test ran for 1 000 000 cycles. The springs were inspected and found intact at 100 000, 200 000, 500 000, and 1 000 000 cycles. A test sample together with a reference faceplate can be seen in Figure 5.3 **a)** and **c)**. Creep of the springs was measured with a caliper and compared to an average measured from untested samples. On average a reduction of 4.75 percent was found. Similarly, the height of the markings was measured to see if abrasive wear had occurred. No clear indication of this could be derived from the results. The movement of the faceplate had generated some wear which could be seen in the snap-fit structures extending through the base. The rear of the base was partly covered in fine polymer dust as seen in Figure 5.3 **b)**.

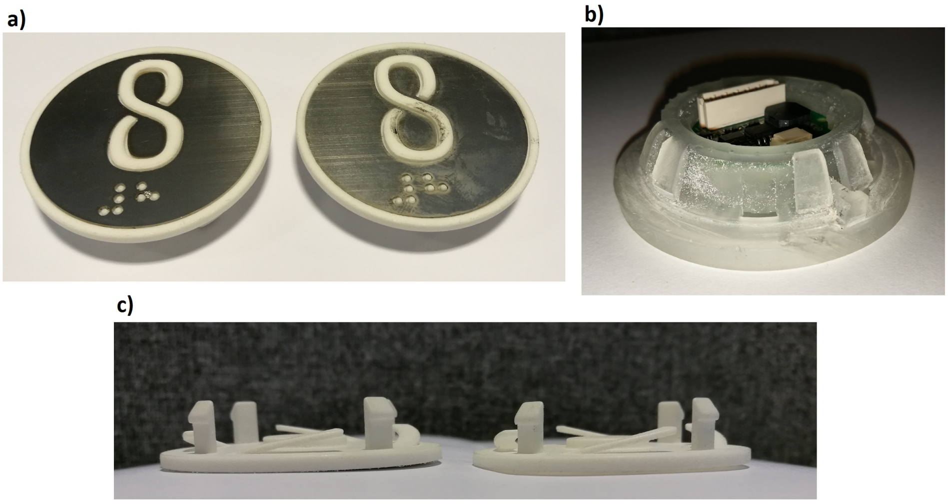


Figure 5.3: Cycle test results on PA2200 after one million cycles. **a)** Reference on the left and test sample on the right **b)** Fine nylon dust on the rear side of the base **c)** Test sample on the left and the reference on the right

5.3 Impact Test

The impact test together with the static load test gives a good estimation of the overall mechanical durability of the button construction. The test setup for the impact test is very simple. A 1kg steel cylinder is dropped from an elevation of 20 cm onto the button face and the kinetic energy transferred on impact is roughly 2 joules. The sample button should resist the impact with no damage and endure a normal operation after the test.

The SLA test subject shattered on impact. The result can be seen in Figure 5.4. The fracture on the faceplate seems to have originated from the lower right edge of the numbering. The base part remained intact. This button was designed with radial shelves that would relay the energy to the button base and the panel instead of the underlying switch on the circuit board. This particular sample, however, had close to zero extension downwards which made the impact time shorter. The Formlabs clear material is brittle and shatters easily on impact. Designing an impact resistant button with this material is challenging. Extended button face movement together with additional springs could solve the design problem. These additional springs could be placed so that they damp movement only after the face is pressed further from the normal operational limit. The circuit board switch is a silicone nib that can slightly extend the normal limits without damage.

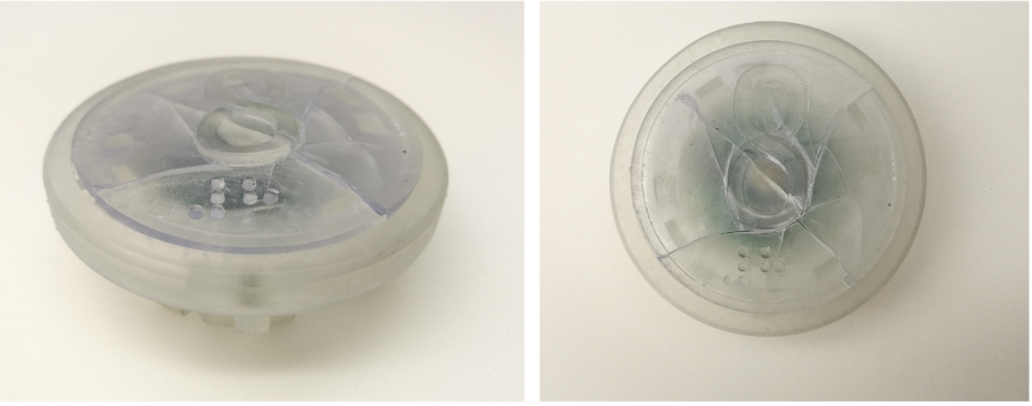


Figure 5.4: Impact test on Formlabs Clear

The second impact test was done on a selective laser sintered PA2200 sample. The design of the button base was slightly modified. The radial shelves, that would transfer the impact energy to the button base instead of the circuit board, were moved from the outer edge towards the centre. The reason for this change was that the button activation was not possible from the outer edges in the original design. Moving the shelves closer to the center allowed the plate to swing slightly and improved the touch. However, due to the new location of the shelves and thin walls in the central areas of the button base, the impact pierced through the base. The faceplate was also fractured even though not as violently as with the SLA sample. Both fractures occurred around sharp boundaries. The results can be seen in Figure 5.5.

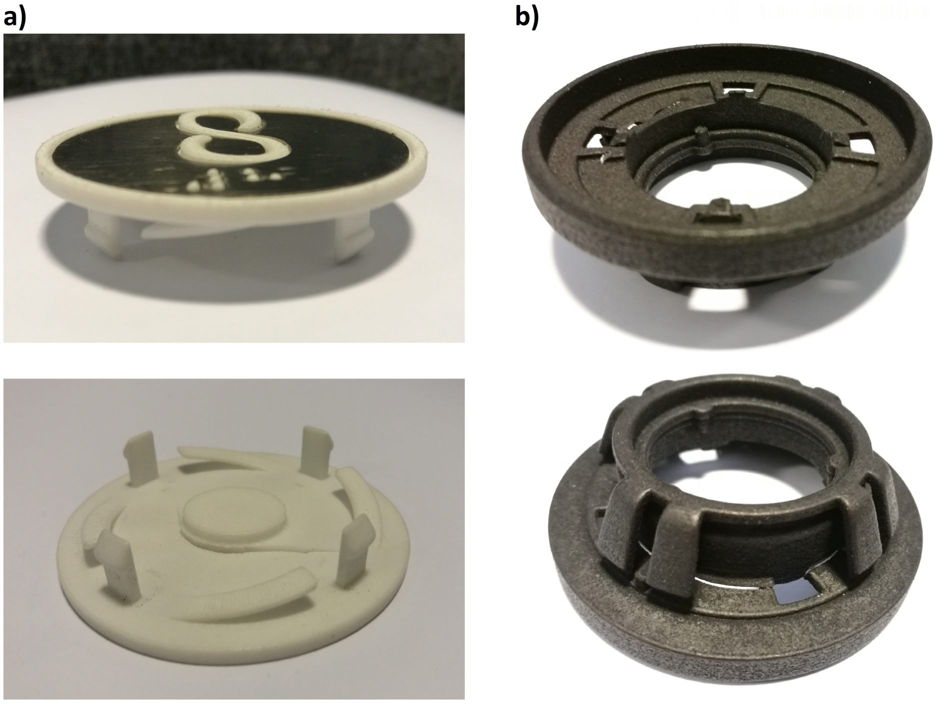


Figure 5.5: Impact test results on PA2200. Column **a)**: a fractured faceplate, front and back. Column **b)**: a fractured base, front and back

Chapter 6

Results

The final button assembly was compiled from the best performing subconcepts presented in Chapter 4. Different material combinations of the final assemblies are collected in Figure 6.1. With the clear photopolymer, a vivid illumination through the markings and the collar was achieved. A white PA2200 faceplate is slightly translucent and produces a gradient illumination effect together with a clear base. Both, the contrast and illumination requirements, were satisfied only with a clear base and a colored faceplate. Clear faceplate together with the stainless steel pressel did not provide a sufficient contrast.

A combination of a clear base with a PA2200 faceplate satisfied all design requirements shown in Figure 4.2. In addition, almost all functional requirements were met. Operating force was found between 2.5 and 5.0 N with a clear tactile feedback. Static load test passed. The cycle endurance of PA2200 was satisfactory with only a 4.75 percent reduction in suspension travel after one million cycles. Impact test failed but was due to flaws in the design. These test results were presented in the preceding chapter.

Further testing for the assembly would include environmental, chemical, and UV tests. Some of this data is already available. In the case of nylon, humidity and temperature changes should not have a significant effect on the mechanical properties. Equivalent knowledge for the clear photopolymer is not yet available. Generally, UV resistance of SLA prints is known to be poor. A protective surface treatment would be necessary if these parts would be utilized in the final product. The Formlabs Form 2 printer and its standard materials are not designed for rapid manufacturing applications. Better machine and material options exist and those should be systematically analyzed.

Figure 6.1: The final elevator button assembly in different material combinations. **a)** a PA2200 base colored black with a clear faceplate, **b)** a PA2200 base colored black with an untreated white PA2200 faceplate, **c)** a clear base with an untreated white PA2200 faceplate, **d)**, **e)**, **f)** forementioned assemblies illuminated in the same order.

As a proof-of-concept product for AM, the assembly fulfilled its objective. The functional performance of the product gives confidence that direct plastic manufacturing with AM is a feasible option. The resulting design managed to consolidate parts and the button functionality into a smaller envelope at a very competitive overall cost. For a more refined solution, the product would still require further optimization to achieve better overall performance and quality. Problems in the current design include the swinging of the active part with eccentric pushes, clearances between the springs and the base and the unintended play between component interfaces. Also, users could easily pry open or break the assembly if they so desired. A more detailed account on the AM material suitability remains to be tested. There will certainly be challenges related to the materials and their resistance to abrasion, cleaning chemicals, and impacts.

The lack of an extensive design exploration and prototyping was identified as one of the design flaws in the process as the resulting solutions were very traditional. The increased geometrical freedom of AM should be exploited further and more ingenious ways of designing the same functionality should be prototyped and tested. The button functionality, when manufactured with AM methods, can potentially outperform traditional products if more time and resources are put into the design.

Chapter 7

Summary and Discussion

The main practical objective of the thesis was to explore novel design possibilities with AM for an elevator button assembly. Ideas were prototyped and a concept assembly was produced and tested for functionality. The design for the elevator button assembly was evaluated in the preceding chapter. Based on this brief case study, the utilization of AM in the direct manufacturing of an elevator button assembly is indeed possible and it could potentially simplify the overall assembly, installation, maintenance and supply chain operations. Even the price was found competitive and the expenses of AM are estimated to decrease in the future. Another goal was to evaluate the suitability of different AM processes for end-use production of the button. Fused deposition modeling, stereolithography, selective laser sintering, and material jetting were initially selected as promising AM processes because of their cost-effective material options.

This chapter commences with a brief summary of these AM processes, their available materials, and the different design considerations that were identified in the practical design work. Next, different constraint areas, that currently complicate the design process for AM, are collected together. The thesis is concluded with a more general discussion on the whole AM field and its direction in the future.

The *fused deposition modeling (FDM)* process is mainly used in the rapid manufacturing of jigs and fixtures. A good collection of production-grade material options exists and the process is easy to integrate into production environments. However, print quality and surface finish, without costly post-processing, restrict the use of the technology for functional products because of the stair-stepping effects and material anisotropy. Without any technological innovations, it is hard to see FDM to take further flight in rapid manufacturing applications.

With the *stereolithography (SLA)* process a high level of geometrical complexity is possible. Both, detail resolution and surface finish of the printed objects are on a very good level. Material selection is currently limited to engineered photopolymers, so-called *simulated materials* which often have inferior material properties compared to their simulated counterparts, and deteriorate in prolonged UV exposure. Still, this technology has some promising advancements with the continuous processes that can provide tenfold improvements in print speed together with a better material microstructure. Work is underway to modify the chemical structure of resins for a wider material catalog and to improve their mechanical properties [30]. Machine and material providers are in a healthy technological competition which will advance the technology and bring both, machine and material costs down.

The *selective laser sintering (SLS)* is a process that scales well with volume. For plastic materials the process is self-supporting and, in contrast to other technologies, the whole build volume of the machine can be nested with parts. Currently, plastic material options are restricted to polyamide, polyamide mixtures and polystyrene. Mechanical properties of the components are very good although the process generates a slightly porous structure. Resolution and surface finish of the parts are inferior to SLA. The process is best for producing small, customized parts in masses. Despite the manual work in excavation and cleaning of the finished products, SLS is currently the most cost-effective way to produce parts in higher volumes.

The *material jetting* process has emerged as an interesting technology for functionally graded components. The nature of the process limits the material selection to a handful of polymers and waxes. Multiple materials and pigments can be blended to achieve dynamic coloring and varying material properties within a single print. In addition, material jetting provides the best detail resolution of the considered technologies. The same problem exists as with stereolithography, however, that parts do not remain stable in prolonged UV exposure. Nonetheless, material jetting is a technology which has intriguing possibilities. Combining alternating material properties with electronic conductivity would allow fully functional electromechanical products to be printed as a single process. In addition, some experiments have been made where structures have been printed on top of existing components [28]. However, extensive research will still have to be done before commercial applications are possible.

The design and development work for an AM version of an elevator button assembly was not found to be streamlined. Multiple areas were identified that restrict the design work. These areas can be broadly categorized under *availability of data*, *experience*, and *software*.

AM technology is new and the knowledge and available engineering data on the machines and materials have not yet accumulated. Material data and functional test results are often lacking. Reliable information, to base decisions on, is the backbone of engineering. New experiments and pilot products are often driven by inspiration from existing examples. Currently the industrial cases, where AM has been adopted for end-product manufacturing, are very scattered, case-specific, and interdisciplinary. It takes courage from the management, and the engineers, to start novel projects with no guarantee of end results.

This brings us to the second restricting area, *experience*. The design process for AM is somewhat different compared to the traditional design pipeline. Before, manufacturing restrictions have provided a natural limitation for the designs. Suddenly these well-known restrictions have changed completely. The increased geometrical freedom with AM provides countless possibilities, none of which have been evaluated or tested before. Traditional design work in companies is supported by the vast heritage of design in the form of design guidelines, training, collaborations, and silent knowledge. For AM, however, this heritage is just starting to build up.

The final problematic area of AM is the *software*. The AM design pipeline is very demanding on the software and often different design areas require a specific program. Engineering accuracy and modeling of complex freeform geometries are not, in general, found in the same software package. File types are not standardized and model parametricity is usually lost between export-import steps. As the AM design process itself is more open, it would merit some software automation to support the designer. Virtual testing of mechanical structures through FEM simulation works very well, but only if the material is homogeneous and the load cases and material interactions are simple enough. Even though progress has been made, computational simulation tools are not yet capable of predicting accurately the behavior of AM produced, layered structures. Combining design interfaces, generative shape creation, product restrictions, and FEM simulation in the same software would streamline the design process considerably.

These three constraint areas together, are amplified in a vicious cycle.

Inadequate information combined with a lack of practical experience on a myriad of software refusing to discuss with each other. Luckily all of the mentioned problems are resolved by technological developments and by the passage of time. As the AM technology continues to mature, the amount of information and experience is also accumulated. The user interfaces and features of the software are modified to fit the new practicalities in the design work.

Currently, the AM field is driven forward by aerospace, medical, and automotive industries that utilize mainly metal AM for the production of end-use components. Medical AM adaptations include some plastic manufacturing applications, such as hearing aids and dental guides. The justification for an AM adoption with these industries is most often only indirectly cost-driven. The whole supply chain is considered. AM adoption achieves functional superiority, and in turn a competitive edge for the company. The improvement in functionality, compared to traditionally manufactured products, is achieved via a weight reduction, customer customization, or increased product performance. The technological advancements in print speed, print quality, materials, and design software will increase the performance and cost-effectiveness of both metal and plastic AM technologies in the near future. Design processes are simplified with the emergence of AI-assisted design software. The number of AM applications increases constantly and accumulates knowledge within research organizations and companies.

The Gartner hype cycle for emerging technologies is one way to get insight how new technologies are entering the mainstream and what technologies and trends are currently emphasized in the media. The most recent publicly available hype cycle for 3D printing is presented in Figure 7.1. As of 2015, 3D printing for prototyping, hearing devices, and 3D printing service providers, among the others, were advancing into mainstream adoption. 3D printing in manufacturing, consumer 3D printing, and industrial 3D printing were still labeled as 5 to 10 years from mainstream adoption.

As of 2016, the additive manufacturing field was valued at 5.165 billion dollars with a growth rate of 25.9 percent [33] yearly. Both, the technological and the economic development of additive manufacturing have made it an attractive alternative to, or a companion with, traditional manufacturing methods. Cost of AM production will be reduced every year due to increased demand, supply, and competition. At the moment many materials are machine-specific and thus material prices can be freely adjusted by their providers. This will likely change as the number of third-party material

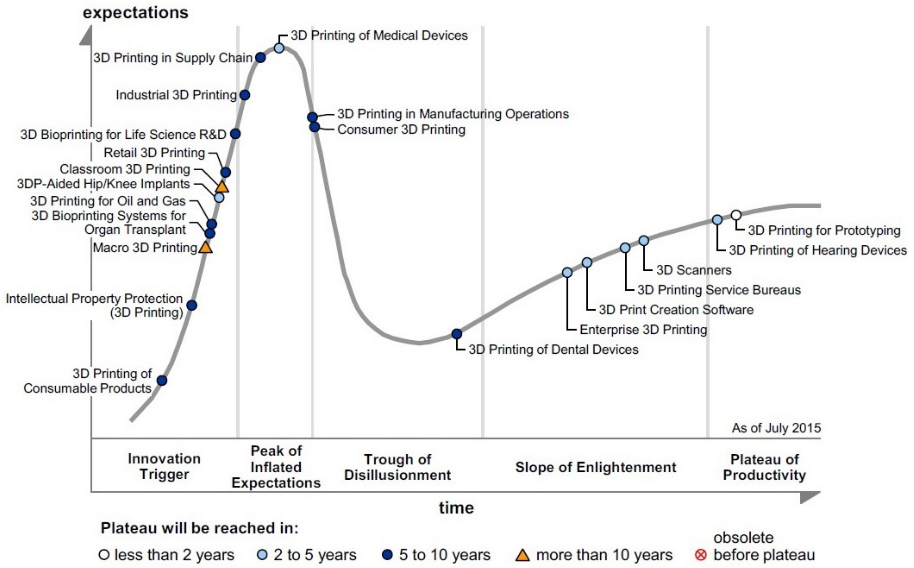


Figure 7.1: Gartner's hype cycle for 3D printing from 2015 [26].

providers is growing, as is the customer demand for more tailored materials.

Figure 7.2 categorizes the different areas that affect and are affected by the AM implementation in companies. The thesis focused mainly on AM technologies and Design for AM. To study the AM supply chain- and systems of operation- categories further, a larger case study, possibly with a pilot product, would be beneficial. Finally, the AM strategy- and organizational change- categories are goals to be set on a higher level. If AM is agreed upon as an implementation area, changes in the strategy, budgeting, and organizational structure might be necessary. This can be achieved with small steps. For example by incorporating a small and flexible *AM task force* inside the company to identify AM applications together with different teams, help with the design process and to provide information related to AM. It is left decided on the higher level what competencies are relevant to keep inside the company and what can be outsourced.

Some companies have chosen a more aggressive and active approach with their AM strategy. The American multi-industry company GE has invested billions of dollars in AM. In addition, they have acquired two AM machine manufacturers, Arcam and Concept Laser. This is an ambitious endeavor to set up an in-house AM manufacturing environment to support the produc-

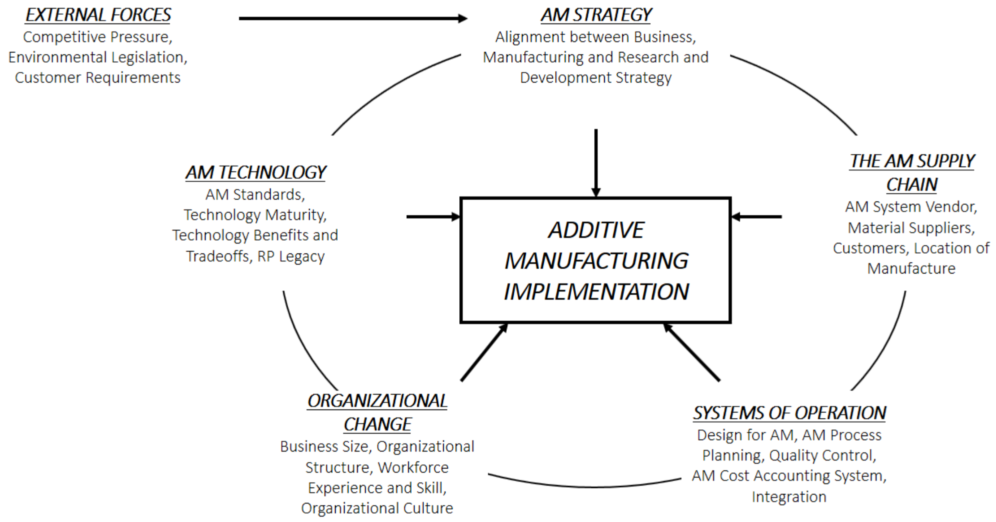


Figure 7.2: Different areas that affect and are to be taken into account in the implementation of AM [22].

tion of airplane components in higher volumes [11].

The results of this brief case study and the movement in the manufacturing sector support the argument that AM will have to be taken seriously as a direct manufacturing method, even with low-cost plastic products. However, the product suitability for an AM redesign has to be evaluated case by case based on product volumes, AM opportunities, and interpolated business benefits.

Companies, at this point, should act accordingly and start the preparations to adapt their company structure and internal competencies to support AM. Insufficient understanding of AM and design principles is said to limit the penetration of the whole field and preventing the use of AM for end-use parts [29]. Possibilities are not only linked to new products. A countless number of potential AM business cases can be found in the legacy products, maintenance, and spare parts businesses.

Bibliography

[1] 3DHubs. What is 3D Printing? The definitive guide. URL `https://www.3dhubs.com/what-is-3d-printing`. Accessed on 15.3.2017.

[2] Additively. Overview over 3D printing technologies. URL `https://www.additively.com/en/learn-about/3d-printing-technologies`. Accessed 10.6.2017.

[3] Eleonora Atzeni and Alessandro Salmi. Economics of additive manufacturing for end-usable metal parts. *International Journal of Advanced Manufacturing Technology*, 62(9-12):1147–1155, 2012. ISSN 0268-3768.

[4] Eleonora Atzeni, Luca Iuliano, Paolo Minetola, and Alessandro Salmi. Redesign and cost estimation of rapid manufactured plastic parts. *Rapid Prototyping Journal*, 16(5):308–317, 2010. ISSN 1355-2546.

[5] Martin Philip Bendsoe and Ole Sigmund. *Topology optimization: theory, methods, and applications*. Springer Science & Business Media, 2013. ISBN 978-3-662-05086-6.

[6] Barry Berman. 3-D printing: The new industrial revolution. *Business Horizons*, 55(2):155–162, 2012. ISSN 0007-6813.

[7] Kevin Bridgen. Adaptation for AM versus Design for AM. Presentation at the annual AMUG Conference 2016, St. Louis, May 2016.

[8] Brett P. Conner, Guha P Manogharan, Ashley N Martof, Lauren M Rodomsky, Caitlyn M Rodomsky, Dakesha C Jordan, and James W Limperos. Making sense of 3-D printing: Creating a map of additive manufacturing products and services. *Additive Manufacturing*, 1:64–76, 2014. ISSN 2214-8604.

[9] Azhar Equbal, Anoop Kumar Sood, and Mohammad Shamim. Rapid tooling: A major shift in tooling practice. *Manufacturing and Industrial Engineering*, 14(3-4):1–9, 2015. ISSN 1339-2972.

[10] Iñigo Flores Ituarte et al. *From rapid prototyping to digitalization: Steps on industrializing additive manufacturing.* PhD thesis, Aalto University, 2017.

[11] GE. GE Agrees to Purchase Controlling Shares of Arcam AB. Nov 2016. URL `http://www.geadditive.com/press-releases/ge-agrees-to-purchase-controlling-shares-arcam-ab`. Accessed on 6.9.2017.

[12] Ian Gibson, D.W. David W Rosen, and Brent Stucker. *Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing.* Springer, New York, 2009. ISBN 9781441911193.

[13] Sebastian Hällgren, Lars Pejryd, and Jens Ekengren. (Re)Design for Additive Manufacturing. *Procedia CIRP*, 50:246–251, 2016. ISSN 2212-8271.

[14] Samuel H Huang, Peng Liu, Abhiram Mokasdar, and Liang Hou. Additive manufacturing and its societal impact: a literature review. *The International Journal of Advanced Manufacturing Technology*, 67(5–8): 1191–1203, 2013. ISSN 0268-3768.

[15] ISO 17296-2:2015. Additive manufacturing – General principles – Part 2: Overview of process categories and feedstock. Standard, The International Organization for Standardization, Geneva, CH, 2015.

[16] ISO/ASTM 52900:2015. Additive manufacturing – General principles – Terminology. Standard, The International Organization for Standardization, Geneva, CH, 2015.

[17] Barney Jopson. New stamping ground for Nike and Adidas as 3D shoes kick off. *Financial Times*, June 2013. URL `https://www.ft.com/content/1d09a66e-d097-11e2-a050-00144feab7de`. Accessed on 5.8.2017.

[18] Christoph Klahn, Bastian Leutenecker, and Mirko Meboldt. Design strategies for the process of additive manufacturing. *Procedia CIRP*, 36: 230–235, 2015. ISSN 2212-8271.

[19] Erin Komi. Design for Additive Manufacturing. Research Report VTT-R-03159-16, VTT Technical Research Centre of Finland, 2016.

[20] Bastian Leutenecker, Christoph Klahn, and Mirko Meboldt. Indicators and design strategies for direct part production by additive manufacturing. In *Proceedings of the 20th International Conference on Engineering Design ICED*, pages 27–31, 2015.

[21] Jonàs Martínez, Jérémie Dumas, and Sylvain Lefebvre. Procedural voronoi foams for additive manufacturing. *ACM Transactions on Graphics (TOG)*, 35(4):44, 2016. ISSN 0730-0301.

[22] Stephen Mellor, Liang Hao, and David Zhang. Additive manufacturing: A framework for implementation. *International Journal of Production Economics*, 149:194–201, 2014. ISSN 0925-5273.

[23] Michael Molitch-Hou. Adidas Uses Carbon's 3D Printing to Mass-Produce Futurecraft 4D Shoes. Apr 2017. URL `http://www.engineering.com/3DPrinting/3DPrintingArticles/ArticleID/14691/Adidas-Uses-Carbons-3D-Printing-to-Mass-Produce-Futurecraft.-4D-Shoes.aspx`. Accessed on 27.7.2017.

[24] Hiroki Ota, Sam Emaminejad, Yuji Gao, Allan Zhao, Eric Wu, Samyuktha Challa, Kevin Chen, Hossain M Fahad, Amit K Jha, Daisuke Kiriya, et al. Application of 3D printing for smart objects with embedded electronic sensors and systems. *Advanced Materials Technologies*, 1(1), 2016. ISSN 2365-709X.

[25] Sculpteo. The State of 3D Printing. May 2016. URL `https://www.sculpteo.com/media/ebook/Sculpteo_State_of_3D_Printing_2016.pdf`. Accessed 20.6.2017.

[26] Michael Shanler and Pete Basiliere. Hype Cycle for 3D Printing, 2015. *Gartner*, July 2015.

[27] Ole Sigmund. A 99 line topology optimization code written in matlab. *Structural and multidisciplinary optimization*, 21(2):120–127, 2001. ISSN 1615-147X.

[28] Pitchaya Sitthi-Amorn, Javier E Ramos, Yuwang Wangy, Joyce Kwan, Justin Lan, Wenshou Wang, and Wojciech Matusik. MultiFab: a machine vision assisted platform for multi-material 3D printing. *ACM Transactions on Graphics (TOG)*, 34(4):129, 2015. ISSN 0730-0301.

[29] Mary Kathryn Thompson, Giovanni Moroni, Tom Vaneker, Georges Fadel, R. Ian Campbell, Ian Gibson, Alain Bernard, Joachim Schulz, Patricia Graf, Bhrigu Ahuja, and Filomeno Martina. Design for Additive

Manufacturing: Trends, opportunities, considerations, and constraints. *CIRP Annals - Manufacturing Technology*, 65(2):737–760, 2016. ISSN 1726-0604.

[30] John R Tumbleston, David Shirvanyants, Nikita Ermoshkin, Rima Janusziewicz, Ashley R Johnson, David Kelly, Kai Chen, Robert Pinschmidt, Jason P Rolland, Alexander Ermoshkin, et al. Continuous liquid interface production of 3D objects. *Science*, 347(6228):1349–1352, 2015. ISSN 1095-9203.

[31] B. Vayre, F. Vignat, and F. Villeneuve. Designing for additive manufacturing. In *Procedia CIRP*, volume 3, pages 632–637, 2012. ISBN 2212-8271.

[32] Karl Willis, Eric Brockmeyer, Scott Hudson, and Ivan Poupyrev. Printed Optics: 3D Printing of Embedded Optical Elements for Interactive Devices. In *Proceedings of the 25th annual ACM symposium on User interface software and technology - UIST '12*, page 589, 2012. ISBN 9781450315807.

[33] Wohlers, T.T., Wohlers Associates, Campbell, R.I. and Caffrey, T. *Wohlers Report 2016: 3D Printing and Additive Manufacturing State of the Industry : Annual Worldwide Progress Report*. Wohlers Associates, Inc, 2016. ISBN 9780991333226.

[34] Kyeong-Soo Yun and Sung-Kie Youn. Multi-material topology optimization of viscoelastically damped structures under time-dependent loading. *Finite Elements in Analysis and Design*, 123:9–18, 2017. ISSN 0168-874X.

Appendix A

Appendix

Educational article

Struct Multidisc Optim 21, 120–127 © Springer-Verlag 2001

A 99 line topology optimization code written in Matlab

O. Sigmund

Abstract The paper presents a compact Matlab implementation of a topology optimization code for compliance minimization of statically loaded structures. The total number of Matlab input lines is 99 including optimizer and Finite Element subroutine. The 99 lines are divided into 36 lines for the main program, 12 lines for the Optimality Criteria based optimizer, 16 lines for a mesh-independency filter and 35 lines for the finite element code. In fact, excluding comment lines and lines associated with output and finite element analysis, it is shown that only 49 Matlab input lines are required for solving a well-posed topology optimization problem. By adding three additional lines, the program can solve problems with multiple load cases. The code is intended for educational purposes. The complete Matlab code is given in the Appendix and can be down-loaded from the web-site `http://www.topopt.dtu.dk`.

Key words topology optimization, education, optimality criteria, world-wide web, Matlab code

1
Introduction

The Matlab code presented in this paper is intended for engineering education. Students and newcomers to the field of topology optimization can down-load the code from the web-page `http://www.topopt.dtu.dk`. The code may be used in courses in structural optimization where students may be assigned to do extensions such as multiple load-cases, alternative mesh-independency schemes, passive areas, etc. Another possibility is to use the program to develop students' intuition for optimal design. Advanced students may be asked to guess the optimal topology for given boundary condition and volume fraction and then the program shows the correct optimal topology for comparison.

In the literature, one can find a multitude of approaches for the solving of topology optimization problems. In the original paper Bendsøe and Kikuchi (1988) a so-called microstructure or homogenization based approach was used, based on studies of existence of solutions.

The homogenization based approach has been adopted in many papers but has the disadvantage that the determination and evaluation of optimal microstructures and their orientations is cumbersome if not unresolved (for noncompliance problems) and furthermore, the resulting structures cannot be built since no definite length-scale is associated with the microstructures. However, the homogenization approach to topology optimization is still important in the sense that it can provide bounds on the theoretical performance of structures.

An alternative approach to topology optimization is the so-called "power-law approach" or SIMP approach (Solid Isotropic Material with Penalization) (Bendsøe 1989; Zhou and Rozvany 1991; Mlejnek 1992). Here, material properties are assumed constant within each element used to discretize the design domain and the variables are the element relative densities. The material properties are modelled as the relative material density raised to some power times the material properties of solid material. This approach has been criticized since it was argued that no physical material exists with properties described by the power-law interpolation. However, a recent paper by Bendsøe and Sigmund (1999) proved that the power-law approach is physically permissible as long as simple conditions on the power are satisfied (e.g. $p \geq 3$ for Poisson's ratio equal to $\frac{1}{3}$). To ensure existence of solutions, the power-law approach must be combined with a perimeter constraint, a gradient constraint or with filtering techniques (see Sigmund and Petersson 1998, for an overview). The power-law approach to topology optimization has been applied to problems with multiple constraints, multiple physics and multiple materials.

Whereas the solution of the above mentioned approaches is based on mathematical programming techniques and continuous design variables, a number of papers have appeared on solving the topology optimization problem as an integer problem. Beckers (1999) success-

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O. Sigmund

Department of Solid Mechanics, Building 404, Technical University of Denmark, DK-2800 Lyngby, Denmark
e-mail: `sigmund@fam.dtu.dk`

fully solved large-scale compliance minimization problems using a dual-approach but other approaches based on genetic algorithms or other semi-random approaches require thousands of function evaluations even for small number of elements and must be considered impractical.

Apart from above mentioned approaches, which all solve well defined problems (e.g. minimization of compliance) a number of heuristic or intuition based approaches have been shown to decrease compliance or other objective functions. Among these methods are so-called evolutionary design methods (see e.g. Xie and Steven 1997; Baumgartner *et al.* 1992). Apart from being very easy to understand and implement (at least for the compliance minimization case), the main motivation for the evolutionary approaches seems to be that mathematically based or continuous variable approaches "involve some complex calculus operations and mathematical programming" (citation from Li *et al.* 1999) and they contain "mathematical methods of some complexity" (citation from Zhao *et al.* 1998) whereas the evolutionary approach "takes advantage of powerful computing technology and intuitive concepts of evolution processes in nature" (citation from Li *et al.* 1999). Two things can be argued against this. First, the evolutionary approaches become complicated themselves, once more complex objectives than compliance minimization are considered and second, as shown in this paper, the "mathematically based" approaches for compliance minimization are simple to implement as well and are computationally equally efficient. Furthermore, mathematical programming based methods can easily be extended to other non-compliance objectives such as non-self-adjoint and multiphysics problems and to problems with multiple constraints (e.g. Sigmund 1999). Extensions of the evolutionary approach to such cases seem more questionable.

The complete Matlab code is given in the Appendix. The remainder of the paper consists of definition and discussion of the optimization problem (Sect. 2), comments about the Matlab implementation (Sect. 3) followed by a discussion of extensions (Sect. 4) and a conclusion (Sect. 5).

2
The topology optimization problem

A number of simplifications are introduced to simplify the Matlab code. First, the design domain is assumed to be rectangular and discretized by square finite elements. In this way, the numbering of elements and nodes is simple (column by column starting in the upper left corner) and the aspect ratio of the structure is given by the ratio of elements in the horizontal (`nelx`) and the vertical direction (`nely`).[1]

A topology optimization problem based on the power-law approach, where the objective is to minimize compliance can be written as

$$\left.\begin{array}{rl} \min\limits_{\mathbf{x}}: & c(\mathbf{x}) = \mathbf{U}^T\mathbf{K}\mathbf{U} = \displaystyle\sum_{e=1}^{N} (x_e)^p\ \mathbf{u}_e^T\ \mathbf{k}_0\ \mathbf{u}_e \\ \text{subject to}: & \dfrac{V(\mathbf{x})}{V_0} = f \\ : & \mathbf{K}\mathbf{U} = \mathbf{F} \\ : & \mathbf{0} < \mathbf{x}_{\min} \leq \mathbf{x} \leq \mathbf{1} \end{array}\right\}, \tag{1}$$

where $\mathbf{U}$ and $\mathbf{F}$ are the global displacement and force vectors, respectively, $\mathbf{K}$ is the global stiffness matrix, $\mathbf{u}_e$ and $\mathbf{k}_e$ are the element displacement vector and stiffness matrix, respectively, $\mathbf{x}$ is the vector of design variables, $\mathbf{x}_{\min}$ is a vector of minimum relative densities (non-zero to avoid singularity), N (= `nelx` × `nely`) is the number of elements used to discretize the design domain, p is the penalization power (typically $p = 3$), $V(\mathbf{x})$ and V_0 is the material volume and design domain volume, respectively and f (`volfrac`) is the prescribed volume fraction.

The optimization problem (1) could be solved using several different approaches such as Optimality Criteria (OC) methods, Sequential Linear Programming (SLP) methods or the Method of Moving Asymptotes (MMA by Svanberg 1987) and others. For simplicity, we will here use a standard OC-method.

Following Bendsøe (1995) a heuristic updating scheme for the design variables can be formulated as

$$x_e^{\text{new}} = \begin{cases} \max(x_{\min}, x_e - m) \\ \quad \text{if} \quad x_e B_e^\eta \leq \max(x_{\min}, x_e - m)\,, \\ x_e B_e^\eta \\ \quad \text{if} \quad \max(x_{\min}, x_e - m) < x_e B_e^\eta < \min(1, x_e + m)\,, \\ \min(1, x_e + m) \\ \quad \text{if} \quad \min(1, x_e + m) \leq x_e B_e^\eta\,, \end{cases} \tag{2}$$

where m (`move`) is a positive move-limit, η $(= 1/2)$ is a numerical damping coefficient and B_e is found from the optimality condition as

$$B_e = \frac{-\dfrac{\partial c}{\partial x_e}}{\lambda \dfrac{\partial V}{\partial x_e}}\,, \tag{3}$$

where λ is a Lagrangian multiplier that can be found by a bi-sectioning algorithm.

The sensitivity of the objective function is found as

$$\frac{\partial c}{\partial x_e} = -p(x_e)^{p-1}\ \mathbf{u}_e^T\ \mathbf{k}_0\ \mathbf{u}_e\,. \tag{4}$$

---

[1] Names in type-writer style refer to Matlab variable names that differ from the obvious (see the Matlab code in the Appendix)

For more details on the derivation and implementation of the optimality criteria method, the reader is referred to the literature (e.g. Bendsøe 1995).

In order to ensure existence of solutions to the topology optimization problem (1), some sort of restriction on the resulting design must be introduced (see Sigmund and Petersson 1998, for an overview). Here we use a filtering technique (Sigmund 1994, 1997). It must be emphasized that this filter has not yet been proven to ensure existence of solutions, but numerous applications by the author have proven the the filter produces mesh-independent designs in practice.

The mesh-independency filter works by modifying the element sensitivities as follows:

$$\widehat{\frac{\partial c}{\partial x_e}} = \frac{1}{x_e \sum_{f=1}^{N} \hat{H}_f} \sum_{f=1}^{N} \hat{H}_f \, x_f \, \frac{\partial c}{\partial x_f} \,. \tag{5}$$

The convolution operator (weight factor) $\hat{H}_f$ is written as

$$\hat{H}_f = r_{\min} - \mathrm{dist}(e,f) \,,$$

$$\{f \in N \mid \mathrm{dist}(e,f) \le r_{\min}\}, \quad e = 1, \ldots, N \,, \tag{6}$$

where the operator $\mathrm{dist}(e,f)$ is defined as the distance between centre of element e and centre of element f. The convolution operator $\hat{H}_f$ is zero outside the filter area. The convolution operator decays linearly with the distance from element f. Instead of the original sensitivities (4), the modified sensitivities (5) are used in the Optimality Criteria update (3).

3
Matlab implementation

The Matlab code (see the Appendix), is built up as a standard topology optimization code. The main program is called from the Matlab prompt by the line

```
top(nelx,nely,volfrac,penal,rmin)
```

where `nelx` and `nely` are the number of elements in the horizontal and vertical directions, respectively, `volfrac` is the volume fraction, `penal` is the penalization power and `rmin` is the filter size (divided by element size). Other variables as well as boundary conditions are defined in the Matlab code itself and can be edited if needed. For each iteration in the topology optimization loop, the code generates a picture of the current density distribution. Figure 1 shows the resulting density distribution obtained by the code given in the Appendix called with the input line

```
top(60,20,0.5,3.0,1.5)
```

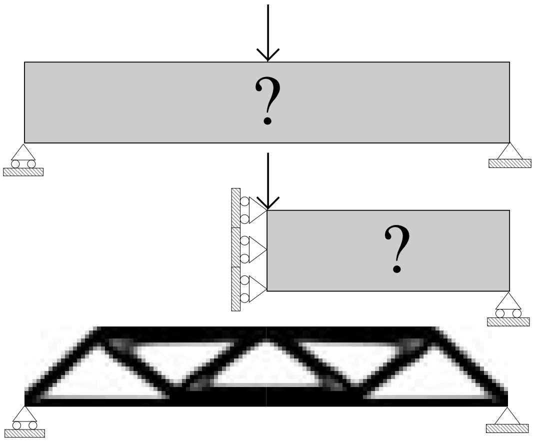

Fig. 1 Topology optimization of the MBB-beam. Top: full design domain, middle: half design domain with symmetry boundary conditions and bottom: resulting topology optimized beam (both halves)

The default boundary conditions correspond to half of the "MBB-beam" (Fig. 1). The load is applied vertically in the upper left corner and there is symmetric boundary conditions along the left edge and the structure is supported horizontally in the lower right corner.

Important details of the Matlab code are discussed in the following subsections.

3.1
Main program (lines 1–36)

The main program (lines 1–36) starts by distributing the material evenly in the design domain (line 4). After some other initializations, the main loop starts with a call to the Finite Element subroutine (line 12) which returns the displacement vector `U`. Since the element stiffness matrix for solid material is the same for all elements, the element stiffness matrix subroutine is called only once (line 14). Following this, a loop over all elements (lines 16–24) determines objective function and sensitivities (4). The variables `n1` and `n2` denote upper left and right element node numbers in global node numbers and are used to extract the element displacement vector `Ue` from the global displacement vector `U`. The sensitivity analysis is followed by a call to the mesh-independency filter (line 26) and the Optimality Criteria optimizer (line 28). The current compliance as well as other parameters are printed by lines 30–33 and the resulting density distribution is plotted (line 35). The main loop is terminated if the change in design variables (`change` determined in line 30) is less than 1 percent[2]. Otherwise above steps are repeated.

---

[2] this is a rather "sloppy" convergence criterion and could be decreased if needed

3.2
Optimality criteria based optimizer (lines 37–48)

The updated design variables are found by the optimizer (lines 37–48). Knowing that the material volume (`sum(sum(xnew))`) is a monotonously decreasing function of the Lagrange multiplier (`lag`), the value of the Lagrangian multiplier that satisfies the volume constraint can be found by a bi-sectioning algorithm (lines 40-48). The bi-sectioning algorithm is initialized by guessing a lower `l1` and an upper `l2` bound for the Lagrangian multiplier (line 39). The interval which bounds the Lagrangian multiplier is repeatedly halved until its size is less than the convergence criteria (line 40).

3.3
Mesh-independency filtering (lines 49–64)

Lines 49–64 represent the Matlab implementation of (5). Note that not all elements in the design domain are searched in order to find the elements that lie within the radius `rmin` but only those within a square with side lengths two times `round(rmin)` around the considered element. By selecting `rmin` less than one in the call of the routine, the filtered sensitivities will be equal to the original sensitivities making the filter inactive.

3.4
Finite element code (lines 65–99)

The finite element code is written in lines 65–99. Note that the solver makes use of the sparse option in Matlab. The global stiffness matrix is formed by a loop over all elements (lines 70–77). As was the case in the main program, variables `n1` and `n2` denote upper left and right element node numbers in global node numbers and are used to insert the element stiffness matrix at the right places in the global stiffness matrix.

As mentioned before, both nodes and elements are numbered column wise from left to right. Furthermore, each node has two degrees of freedom (horizontal and vertical), thus the command `F(2,1)=-1.` (line 79) applies a vertical unit force force in the upper left corner.

Supports are implemented by eliminating fixed degrees of freedom from the linear equations. Matlab can do this very elegantly with the line

```
84 U(freedofs,:) = K(freedofs,freedofs) \
                   F(freedofs,:);
```

where `freedofs` indicate the degrees of freedom which are unconstrained. Mostly, it is easier to define the degrees of freedom that are fixed (`fixeddofs`) thereafter the `freedofs` are found automatically using the Matlab operator `setdiff` which finds the free degrees of freedoms as the difference between all degrees of freedom and the fixed degrees of freedom (line 82).

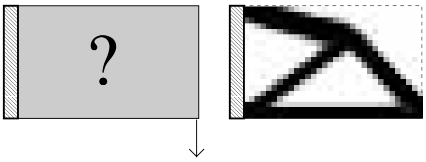

Fig. 2 Topology optimization of a cantilever beam. Left: design domain and right: topology optimized beam

The element stiffness matrix is calculated in lines 86–99. The 8 by 8 matrix for a square bi-linear 4-node element was determined analytically using a symbolic manipulation software. The Young's modulus `E` and the Poisson's ratio `nu` can be altered in lines 88 and 89.

4
Extensions

The Matlab code given in the Appendix solves the problem of optimizing the material distribution in the MBB-beam (Fig. 1) such that its compliance is minimized. A number of extensions and changes in the algorithm can be thought of, a few of which are mentioned in the following.

4.1
Other boundary conditions

It is very simple to change boundary conditions and support conditions in order to solve other optimization problems. In order to solve the short cantilever example shown in Fig. 2, only lines 79 and 80 must be changed to

```
79 F(2*(nelx+1)*(nely+1),1) = -1;
80 fixeddofs   = [1:2*(nely+1)];
```

With these changes, the input line for the case shown in Fig. 2 is

```
   top(32,20,0.4,3.0,1.2)
```

4.2
Multiple load cases

It is also very simple to extend the algorithm to account for multiple load cases. In fact, this can be done by adding only three additional lines and making minor changes to another 4 lines.

In the case of two load cases, force and displacement vectors must be defined as two-column vectors which means that line 69 is changed to

```
69 F = sparse(2*(nely+1)*(nelx+1),2);
   U = sparse(2*(nely+1)*(nelx+1),2);
```

The objective function is now the sum of two compliances, i.e.

$$c(\mathbf{x}) = \sum_{i=1}^{2} \mathbf{U}_i^T \mathbf{K} \mathbf{U}_i \tag{7}$$

thus lines 20–22 are substituted with the lines

```
19b   dc(ely,elx) = 0.;
19c   for i = 1:2
20     Ue = U([2*n1-1;2*n1; 2*n2-1;2*n2;
            2*n2+1;2*n2+2;2*n1+1;2*n1+2],i);
21     c = c + x(ely,elx)^penal*Ue'*KE*Ue;
22     dc(ely,elx) = dc(ely,elx) -
          penal*x(ely,elx)^(penal-1)*Ue'*KE*Ue;
22b   end
```

To solve the two-load problem indicated in Fig. 3, a unit upward load in the top-right corner is added to line 79, which then becomes

```
79 F(2*(nelx+1)*(nely+1),1) = -1.;
             F(2*(nelx)*(nely+1)+2,2) = 1.;
```

The input line for Fig. 3 is

```
   top(30,30,0.4,3.0,1.2).
```

4.3
Passive elements

In some cases, some of the elements may be required to take the minimum density value (e.g. a hole for a pipe).

An `nely` × `nelx` array `passive` with zeros at elements free to change and ones at elements fixed to be zero can be defined in the main program and transferred to the OC subroutine (adding `passive` to the call in lines 28 and 38). The added line

```
42b   xnew(find(passive)) = 0.001;
```

in the OC subroutine looks for passive elements and sets their density equal to the minimum density (0.001).

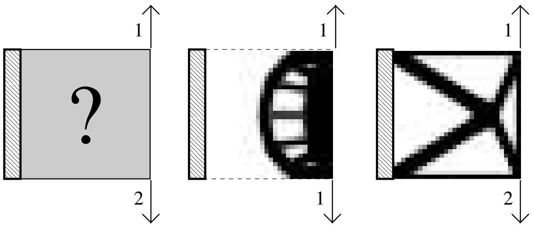

Fig. 3 Topology optimization of a cantilever beam with two load-cases. Left: design domain, middle: topology optimized beam using one load case and right: topology optimized beam using two load cases

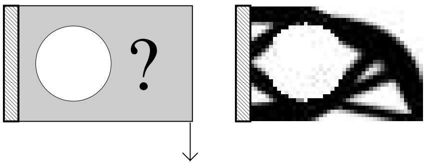

Fig. 4 Topology optimization of a cantilever beam with a fixed hole. Left: design domain and right: topology optimized beam

Figure 4 shows the resulting structure obtained with the input

```
   top(45,30,0.5,3.0,1.5),
```

when the following 10 lines were added to the main program (after line 4) in order to find passive elements within a circle with radius `nely/3.` and center (`nely/2.`,`nelx/3.`)

```
for ely = 1:nely
  for elx = 1:nelx
    if sqrt((ely-nely/2.)^2+(elx-nelx/3.)^2) <
                                           nely/3.
      passive(ely,elx) = 1;
      x(ely,elx) = 0.001;
    else
      passive(ely,elx) = 0;
    end
  end
end
```

4.4
Alternative optimizer

Admittedly, the optimality criteria based optimizer implemented here is only good for a single constraint and it is based on a heuristic fixed point type updating scheme. In order to install a better optimizer, one can obtain (free of charge for academic purposes) the Matlab version of the MMA-algorithm (Svanberg 1987) from Krister Svanberg, KTH, Sweden. The MMA code is called with the following input line

```
mmasub(INPUT-variables, ... ,
       OUTPUT-variables)
```

where the total number of input/output variables is 20, including objective function, constraints, old and new densities, etc. Implementing the MMA-optimizer is fairly simple, but requires the definition of several auxiliary variables. However, it allows for the solving of more complex design problems with more than one constraint. The Matlab optimizer will solve the standard topology optimization problem using less iterations at the cost of a slightly increased CPU-time per iteration.

4.5
Other extensions

Extensions to three dimensions should be straight forward whereas more complex problems such as compliant mechanism design (Sigmund 1997) requires the implementation of the MMA optimizer and the definition of extra constraints. The simplicity of the Matlab commands allow for easy extensions of the graphical output, interactive input etc.

5
Conclusions

This paper has presented a very simple implementation of a mathematical programming base topology optimization algorithm. The code is implemented using only 99 Matlab input lines and includes optimizer, mesh-independency filtering and Finite Element code.

The Matlab code can be down-loaded from the webpage `http://www.topopt.dtu.dk` and is intended for educational purposes. The code can easily be extended to include multi load problems and the definition of passive areas.

Running the code in Matlab is rather slow compared to a Fortran implementation of the same code which can be tested at the web-site `http://www.topopt.dtu.dk`. However, an add-on package to Matlab (MATLAB Compiler) allows for the generation of more efficient C-code that can be optimized for run-time (this option, however, has not been tested by the author). It should be noted that speed can be gained by modifying the Matlab code itself, however the speed is gained on the cost of simplicity of the program. The modification is suggested by Andreas Rietz from Linköping University who uses sparsity options in the assembly of the global stiffness matrix. The reader may down-load his code at the web-page: `http://www.mekanik.ikp.liu.se/andridiv/matlab/theory.html`.

The code was intentionally kept compact in order to keep the total number of lines below 100. If users of the code should find ways to further compactify or simplify the code, the author would be happy to receive suggested modifications that can be implemented in the public domain code (the author's e-mail address is `sigmund@fam.dtu.dk`).

Since its first publication on the World Wide Web in October 1999, the Matlab code has been down-loaded more than 500 times by different users (as of August 2000). Among other positive feedbacks, several professors reported that they have used the code in courses on structural optimization and have let their students implement alternative boundary conditions and multiple load cases.

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References

Baumgartner, A., Harzheim, L.; Mattheck, C. 1992: SKO (Soft Kill Option): The biological way to find an optimum structure topology. *Int. J. Fatigue* **14**, 387–393

Beckers, M. 1999: Topology optimization using a dual method with discrete variables. *Struct. Optim.* **17**, 14–24

Bendsøe, M.P. 1989: Optimal shape design as a material distribution problem. *Struct. Optim.* **1**, 193–202

Bendsøe, M.P. 1995: *Optimization of structural topology, shape and material*. Berlin, Heidelberg, New York: Springer

Bendsøe, M.P.; Kikuchi, N. 1988: Generating optimal topologies in optimal design using a homogenization method. *Comp. Meth. Appl. Mech. Engrg.* **71**, 197–224

Bendsøe, M.P.; Sigmund, O. 1999: Material interpolations in topology optimization. *Arch. Appl. Mech.* **69**, 635–654

Li, Q.; Steven, G.P.; Xie, Y. M. 1999: On equivalence between stress criterion and stiffness criterion in evolutionary structural optimization. *Struct. Optim.* **18**, 67–73

Mlejnek, H.P. 1992: Some aspects of the genesis of structures. *Struct. Optim.* **5**, 64–69

Sigmund, O. 1994: *Design of material structures using topology optimization*. Ph.D. Thesis, Department of Solid Mechanics, Technical University of Denmark

Sigmund, O. 1997: On the design of compliant mechanisms using topology optimization. *Mech. Struct. Mach.* **25**, 495–526

Sigmund, O. 1999: Topology optimization of multi-physics, multi-material structures. *Proc. WCSMO-3* (held in Buffalo, NY)

Sigmund, O.; Petersson, J. 1998: Numerical instabilities in topology optimization: a survey on procedures dealing with checkerboards, mesh-dependencies and local minima. *Struct. Optim.* **16**, 68–75

Svanberg, K. 1987: The method of moving asymptotes – a new method for structural optimization. *Int. J. Numer. Meth. Engrg.* **24**, 359–373

Xie, Y.M.; Steven, G.P. 1997: *Evolutionary structural optimization*. Berlin, Heidelberg, New York: Springer

Zhao, C.; Hornby, P.; Steven, G.P.; Xie, Y.M. 1998: A generalized evolutionary method for numerical topology optimization of structures under static loading conditions. *Struct. Optim.* **15**, 251–260

Zhou, M.; Rozvany, G.I.N. 1991: The COC algorithm, part II: Topological, geometry and generalized shape optimization. *Comp. Meth. Appl. Mech. Engrng.* **89**, 197–224

6
Appendix – Matlab code

```
%%%% A 99 LINE TOPOLOGY OPTIMIZATION CODE BY OLE
  SIGMUND, OCTOBER 1999 %%%
function top(nelx,nely,volfrac,penal,rmin);
% INITIALIZE
x(1:nely,1:nelx) = volfrac;
loop = 0;
change = 1.;
% START ITERATION
while change > 0.01
  loop = loop + 1;
  xold = x;
% FE-ANALYSIS
  [U]=FE(nelx,nely,x,penal);
% OBJECTIVE FUNCTION AND SENSITIVITY ANALYSIS
  [KE] = lk;
  c = 0.;
  for ely = 1:nely
    for elx = 1:nelx
      n1 = (nely+1)*(elx-1)+ely;
      n2 = (nely+1)* elx   +ely;
      Ue = U([2*n1-1;2*n1; 2*n2-1;2*n2; 2*n2+1;
           2*n2+2; 2*n1+1;2*n1+2],1);
      c = c + x(ely,elx)^penal*Ue'*KE*Ue;
      dc(ely,elx) = -penal*x(ely,elx)^(penal-1)*
                     Ue'*KE*Ue;
    end
  end
% FILTERING OF SENSITIVITIES
  [dc]   = check(nelx,nely,rmin,x,dc);
% DESIGN UPDATE BY THE OPTIMALITY CRITERIA METHOD
  [x]    = OC(nelx,nely,x,volfrac,dc);
% PRINT RESULTS
  change = max(max(abs(x-xold)));
  disp([' It.: ' sprintf('%4i',loop) ' Obj.: '
       sprintf('%10.4f',c) ...
       ' Vol.: ' sprintf('%6.3f',sum(sum(x))/
         (nelx*nely)) ...
        ' ch.: ' sprintf('%6.3f',change )])
% PLOT DENSITIES
  colormap(gray); imagesc(-x); axis equal; axis
  tight; axis off;pause(1e-6);
end
%%%%%%%%%% OPTIMALITY CRITERIA UPDATE %%%%%%%%%
function [xnew]=OC(nelx,nely,x,volfrac,dc)
l1 = 0; l2 = 100000; move = 0.2;
while (l2-l1 > 1e-4)
 lmid = 0.5*(l2+l1);
 xnew = max(0.001,max(x-move,min(1.,min(x+move,x.
        *sqrt(-dc./lmid)))));
 if sum(sum(xnew)) - volfrac*nelx*nely > 0;
   l1 = lmid;
 else
   l2 = lmid;
 end
end
%%%%%%%%%% MESH-INDEPENDENCY FILTER %%%%%%%%%%%
function [dcn]=check(nelx,nely,rmin,x,dc)
dcn=zeros(nely,nelx);
for i = 1:nelx
  for j = 1:nely
    sum=0.0;
    for k = max(i-round(rmin),1):
          min(i+round(rmin),nelx)
      for l = max(j-round(rmin),1):
      min(j+round(rmin), nely)
        fac = rmin-sqrt((i-k)^2+(j-l)^2);
        sum = sum+max(0,fac);
        dcn(j,i) = dcn(j,i) + max(0,fac)*x(l,k)
        *dc(l,k);
      end
    end
    dcn(j,i) = dcn(j,i)/(x(j,i)*sum);
  end
end
%%%%%%%%%% FE-ANALYSIS %%%%%%%%%%%%
function [U]=FE(nelx,nely,x,penal)
[KE] = lk;
K = sparse(2*(nelx+1)*(nely+1), 2*(nelx+1)*
     (nely+1));
F = sparse(2*(nely+1)*(nelx+1),1); U =
     sparse(2*(nely+1)*(nelx+1),1);
for ely = 1:nely
  for elx = 1:nelx
    n1 = (nely+1)*(elx-1)+ely;
    n2 = (nely+1)* elx   +ely;
    edof = [2*n1-1; 2*n1; 2*n2-1; 2*n2; 2*n2+1;
           2*n2+2;2*n1+1; 2*n1+2];
    K(edof,edof) = K(edof,edof) +
           x(ely,elx)^penal*KE;
  end
end
% DEFINE LOADS AND SUPPORTS (HALF MBB-BEAM)
F(2,1) = -1;
fixeddofs   = union([1:2:2*(nely+1)],
             [2*(nelx+1)*(nely+1)]);
alldofs     = [1:2*(nely+1)*(nelx+1)];
freedofs    = setdiff(alldofs,fixeddofs);
% SOLVING
```

```
U(freedofs,:) = K(freedofs,freedofs) \
                F(freedofs,:);
U(fixeddofs,:)= 0;
%%%%%%%%%% ELEMENT STIFFNESS MATRIX %%%%%%%
function [KE]=lk
E = 1.;
nu = 0.3;
k=[ 1/2-nu/6  1/8+nu/8 -1/4-nu/12 -1/8+3*nu/8 ...
   -1/4+nu/12 -1/8-nu/8  nu/6       1/8-3*nu/8];
KE = E/(1-nu^2)*
  [ k(1) k(2) k(3) k(4) k(5) k(6) k(7) k(8)
    k(2) k(1) k(8) k(7) k(6) k(5) k(4) k(3)
    k(3) k(8) k(1) k(6) k(7) k(4) k(5) k(2)
    k(4) k(7) k(6) k(1) k(8) k(3) k(2) k(5)
    k(5) k(6) k(7) k(8) k(1) k(2) k(3) k(4)
    k(6) k(5) k(4) k(3) k(2) k(1) k(8) k(7)
    k(7) k(4) k(5) k(2) k(3) k(8) k(1) k(6)
    k(8) k(3) k(2) k(5) k(4) k(7) k(6) k(1)];
```