Design Methodology for Additive Manufacturing
Supporting Designers in the Exploitation of Additive Manufacturing Affordances

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E.L. Doubrovski

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Introduction

Related publication

Doubrovski, E. L., Verlinden, J. C., & Geraedts, J. M. P. (2011). From Factory to Replicator: Towards Design Methods for On-Demand Additive Manufacturing. In N. F. M. Roozenburg, L. L. Chen, & P. J. Stappers (Eds.), *Proceedings of IASDR 2011, 4th World Conference on Design Research*. Delft, The Netherlands.

Drawing, designing, and building things have been personal interests of mine for as long as I can remember. The advent of digital tools for drawing and design sparked my interest for the digital domain, while the making of things appeared to remain an analog skill. It was not until 2000, reading an eye-opening article on 3D printing by Bolt (2000), that I realized that the tools for making were now also entering the digital world.

Although the first Additive Manufacturing (AM) technologies are almost 30 years old, it was only in recent years that the application of AM as a means of product manufacturing started to grow significantly, impacting products and the daily life of companies, designers, and consumers. When used as a manufacturing method, what are the important novel aspects of AM? What changes could it introduce to the discipline of design?

As a designer, these questions fascinated me. Doing the research presented in this thesis proved to be a unique opportunity to be part of an exciting new field.

1 Introduction

Additive Manufacturing (AM), or 3D Printing, is a relatively young group of manufacturing technologies. These technologies were initially mainly used for rapid prototyping. Currently, AM technologies are increasingly used as a production method in product manufacturing. Although there are various reasons why using AM as a means of manufacturing could be beneficial, it is because of recent developments that this has become possible. Among the factors contributing to this development are advances in build quality, improved material properties, and total cost of ownership of AM solutions. Examples where AM is used as a production method include parts for the aviation industry, automotive industry, medical implants and prostheses (Wohlers & Caffrey, 2014). Figure 1 illustrates a customized consumer product that is manufactured using AM as the primary production method.

Figure 1 Example of commercial AM use: Custom Ankle Sprain Protection (Molenbroek, Fleuren, & Rensink, 2013).

Considering these developments, if AM is used as a production method in manufacturing, it is expected to have an increasing impact on the products being manufactured, their designers, and their users. This research project was initiated to investigate these changes and understand what design support is required in this new design landscape. Being an open-ended undertaking, the initial step was to set a more specific goal for this research project.

Prior to the implementation of the research, the following questions were formulated;

- *What are the novel aspects of AM compared to traditional manufacturing?*
- *What are the indicators that AM could introduce changes to design, and why is it an important topic for design?*
- *How can a research project be formulated that aims to investigate these questions and aims to provide designers with a methodology that supports the application of the new possibilities of AM?*

In this first chapter, the findings regarding these questions are discussed, which include an introduction to AM technologies and the formulation of objectives that were set for this research project.

Before discussing what the novel aspects of AM are, a brief overview is sketched regarding traditional manufacturing and current design practices. Then, by discussing what aspects of AM make it a novel technology compared to traditional fabrication technologies, I discuss why I believe the environment of design will change significantly when AM is used as the primary production method in the manufacturing of consumer durables. This chapter concludes with the formulation of the objective and the research approach.

1.1 Traditional design and manufacturing

1.1.1 Products and manufacturing today

Most of the consumer products around us today are manufactured in large series. These products usually contain components that are produced using industrial processes like casting, extrusion, and injection molding. These processes all require part-specific tools, such as molds and dies, which are created specifically for each part. Usually, some parts of the products are standard off-the-shelf components, like screws, motors, and sensors. To finalize the product, the produced parts and components need to be assembled.

1.1.2 Roles of designers in traditional manufacturing

1.1.2.1 Balanced comprehension

During the development of a product, designers need to take into account many aspects of a product including ergonomics, aesthetics, sustainability, cost, and manufacturing. Such aspects interact with and influence each other, while the importance of each aspect varies. The understanding of the relationship between these aspects has been labeled "balanced comprehension" and is considered an important characteristic of industrial design engineering (Knoop, Van Breemen, Horváth, Vergeest, & Pham, 1998).

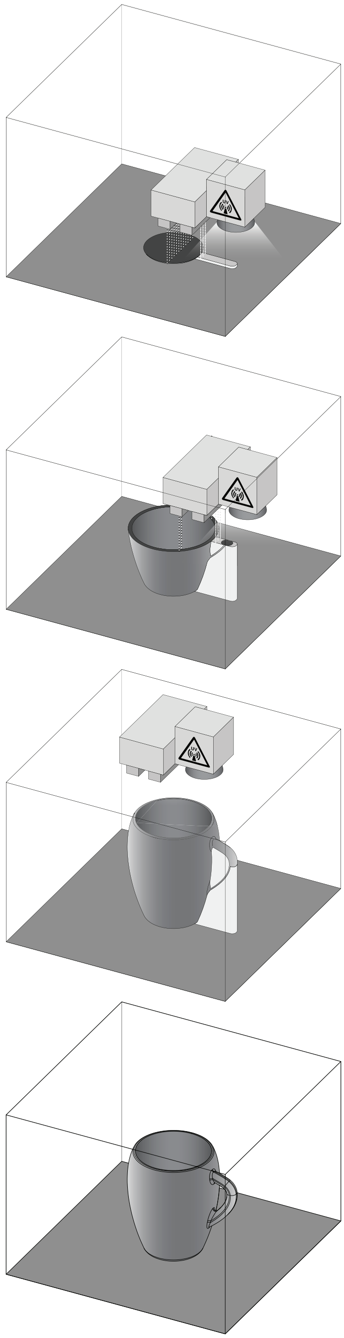
1.1.2.2 Design for manufacturing

In order to develop products that can effectively and efficiently be manufactured and assembled, designers are taught to develop products in an iterative process that includes selection of materials and selection of manufacturing technologies given a set of design criteria and optimization of the designs for the selected technology. This requires a good understanding of the manufacturing technology and principles of assembly (Tempelman, Shercliff, & van Eyben, 2014). The collection of design principles, analysis techniques, guidelines, and design rules that are used in this process are referred to as "Design for Manufacturing and Assembly". These principles were systematically developed in the early 1980s (Boothroyd, 1994). It was quickly observed that applying the principles of Design for Manufacturing and Assembly often have coinciding benefits such as a shorter time to market of a newly developed product (Boothroyd, 1994).

1.1.2.3 Designing for series and mass manufacturing

Given the current manufacturing environment, where many of the tools and the assembly need to be developed for each specific product or part at relatively high cost, it is economical to manufacture products in large series. Many of Ikea's products, like the lamp illustrated in Figure 2, are prototypical examples of products manufactured in large volumes. The product innovation processes that designers use are tailored to facilitate manufacturing for series. Elements in these processes include market research, choice of the exact product features, such as functions and dimensions, and user validation. Accurate consideration of these aspects is required to make the mass-manufactured product suitable and desirable for the large intended group of users.

Figure 2 Typical mass manufactured product (Ikea).



a

b

c

d

Figure 3 Overview of an AM process within the category Material Jetting. a) First layer of the model and support material are deposited using inkjet technology, while a UV lamp cures the deposited material. b) Further build-up of model and support structure. c) AM process is finished. d) Finished model with support material removed.

It has been attempted to describe product innovation processes in logical linear models. However, the observed chaotic nature of such processes in real-life situations has now been accepted and considered as a complementary model to the logical approach (Buijs, 2003).

1.2 Introduction to Additive Manufacturing

1.2.1 Principles of Additive Manufacturing

Additive Manufacturing is a collection of digital manufacturing technologies. Although different processes apply a variety of technological principles for adding material and applying energy, all AM technologies share the ability of manufacturing objects based on 3D model data by adding material.

The standards organization ASTM International has developed a standard terminology for AM technologies. This terminology classifies the existing AM processes into 7 categories ("Standard Terminology for Additive Manufacturing Technologies," 2012). These categories are briefly discussed below. While it is not within the scope of this work to provide an extensive description of all AM technologies, two categories of AM processes that were used extensively in this work are discussed in more detail: Material Jetting and Material Extrusion. Complete and detailed overviews of all AM processes can be found in a number of books written on this topic (Gebhardt, 2011; Gibson, Rosen, & Stucker, 2010; Tempelman et al., 2014). Currently, the categories can be described using features of existing AM processes. It is likely that new AM processes will be developed that apply new principles. Also, these categories will likely need to be adjusted, as processes that appear not to fit in one of the categories exclusively have recently been presented ("HP 3D Printers and Printing Solution," n.d.).

1.2.1.1 Vat photopolymerization

A solid model is built by selectively curing a liquid photopolymer using light. This light source is usually a UV laser that scans in two dimensions to cure a layer. Sometimes a projector is used that instantly illuminates a full 2D image. Illumination and curing is repeated for each layer until the entire model is completed.

1.2.1.2 Powder bed fusion

A layer of powder is selectively fused using thermal energy, usually a laser. After fusion of one layer, a new layer of powder is deposited on top of the previous layer and the process is repeated. Currently available materials include various plastics and metals.

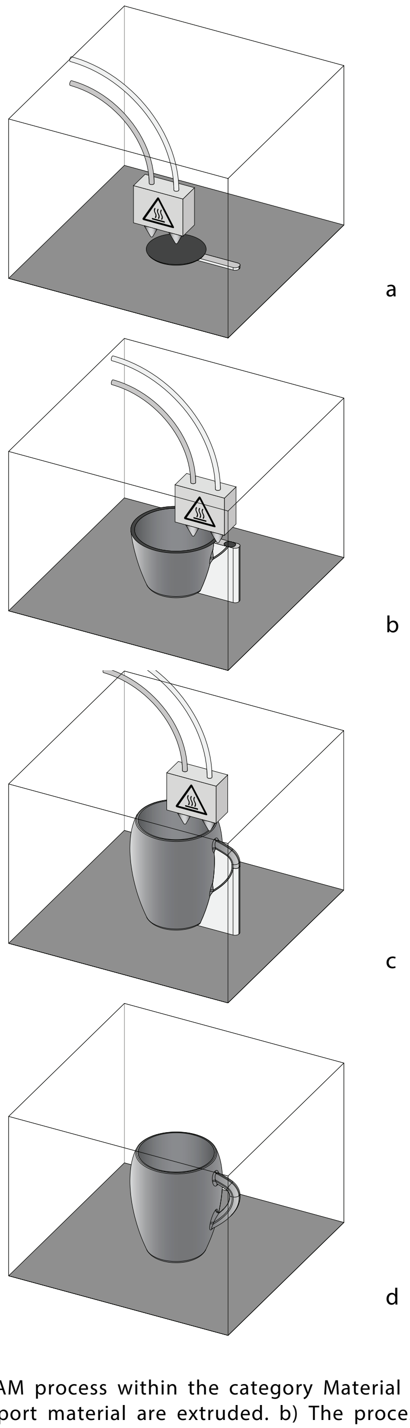


Figure 4 Overview of an AM process within the category Material Extrusion. a) The first layer of building material and support material are extruded. b) The process is repeated for consecutive layers c) AM process finished d) Final model after removal of support material.

1.2.1.3 Binder jetting

Using inkjet heads, a bonding liquid is selectively deposited onto a thin layer of powder. Once a layer is completed, a new layer of powder is added and the process is repeated.

1.2.1.4 Sheet lamination

In this category, sheets of material are cut and stacked onto each other. An adhesive is used to join the sheets. The materials are usually paper or plastics. The cutting of the sheets is usually done using a knife or a laser.

1.2.1.5 Directed energy deposition

Thermal energy and powder material are focused in order to locally fuse material. Often, the deposition and fusion is done using an articulated robotic arm.

1.2.1.6 Material jetting

Small droplets of material are selectively deposited, layer upon layer. Examples of this technology are the PolyJet technology by Stratasys, the MultiJet technology by 3D Systems, and Project Eiger by Océ – A Canon Company ("Project Eiger," n.d., "Stratasys: PolyJet Technology," n.d., "What is MJP (MultiJet Printing)?," n.d.). These technologies resemble the process of 2D inkjet printing; one or more inkjet heads, each with an array of nozzles, move over a platform and build up an object layer after layer by depositing small droplets of material from the nozzles. The material used is usually a UV curing liquid (photopolymer), which is cured by a UV light that is attached to the printing head. A secondary inkjet head simultaneously deposits the support material, which has to be removed after the printing. Figure 3 illustrates this process in 4 steps.

1.2.1.7 Material extrusion

A heated nozzle extrudes a bead of material, usually a thermoplastic. The nozzle moves in two axes, parallel to the build platform to build a layer with the extruded material. After completion of each layer, the distance between the nozzle and build platform is increased to allow the deposition of the next layer on top of the previous layer. 3D files that have overhanging geometry require a support structure in order to be manufactured. Some systems use a soluble material for the support, which is extruded through a secondary nozzle, while simpler systems use the build material itself for the support. The relative simplicity of this technology made it a popular choice for home-built systems and low-end AM machines. The development of such low-end systems was sparked by the development of the open-source project RepRap (RepRap.org, n.d.). 4 steps of this process are illustrated in Figure 4.

1.2.2 Definitions of Additive Manufacturing

1.2.2.1 Existing definitions of AM

The term *3-Dimensional printing*, or *3D Printing* was already used in 1985 to describe the first commercial rapid prototyping system. Given the large number of proprietary technologies that have emerged since, the naming of AM processes has been rather inconsistent. More recently, the term *Additive Manufacturing* has been chosen as the industry's standard term and is defined as:

> *the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies ("Standard Terminology for Additive Manufacturing Technologies," 2012).*

However, in the media and in colloquial speech, *3D Printing* has become the widely used term for AM technologies. Initially, this was a point of debate and confusion, as *3D Printing* was used to describe a specific class of inkjet-based AM processes. Currently there seems to be a growing consensus that the term *3D Printing* is synonymous to *Additive Manufacturing*. Evidence for this can be found in the terminology used in media, book titles (Lipson & Kurman, 2013; Wohlers & Caffrey, 2014), and academic literature. Also, in 2012, the Wikipedia entries for the two terms were merged into one article covering nearly all technologies that fit the AM definition.

1.2.2.2 Definitions of AM used in this research

Considering the observed consensus described above, in this research, *3D Printing* and *Additive Manufacturing* were considered synonymous. Consequently, *AM machine* and *3D printer* were considered synonymous and an *AM machine* combined with dedicated preparation, management, and control software is referred to as an *AM system*.

The ASTM definition of AM states that 3D model data is used as a source in order to make objects. Although not explicitly mentioned, the context of the definition implies that the 3D model data is a digital file. Also, the building process is digitally controlled. Apart from the fact that AM describes a process of joining materials, as opposed to subtracting or forming materials, in the scope of this research it is emphasized that the digital aspect is an essential differentiation between a traditional (analog) manufacturing technologies and AM and places AM in the realm of digital manufacturing.

To illustrate the essence of the digital aspect, the example of the 3D pen is discussed. Amid the hype around 3D printing ("Gartner Says Consumer 3D Printing Is More Than Five Years Away," n.d.), many products have been marketed as a 3D Printing process, including laser cutters and handheld 3D pens ("3Doodler," n.d., "Glowforge - the 3D laser printer," n.d.). The mentioned 3D pens build up objects by adding material (layer by layer). However, no digital file is used as an input and no digital control is used during the building process. Instead, a person actually *crafts* the object. Therefore, the building process cannot be considered to be digital and stating that such machines are 3D printers is similar to categorizing a pencil as a 2D printer. However, this distinction is not always completely clear. For example, a project that seems to blur the boundary between craft and a digital process is the freehand digital sculpting tool developed by Zoran and Paradiso (2013).

1.3 Trends of digitalization

Over the past decades, many everyday products and services transitioned from analog to digital. These include digital recording, storage and distribution of music, digital photography, but also (2D) desktop printing and the digital high-resolution printing press. This had a significant impact on the related industries, the (graphic) design discipline, the products themselves, and how the products are being used. Since this research focuses on how the widespread use of AM can change the field of design and manufacturing, it is meaningful to evaluate changes in domains that have made the shift to digital.

1.3.1 Digital products

Often digitalization can improve the quality of the product. Digital television broadcast currently has superior image quality compared to common analog television. However, improved quality seldom seems to be the main driver towards digitalization (Negroponte, 1995). Considering the ease of storing and shipping bits of data compared to physical goods, digitalization provides opportunities to rethink how and which products are created, stored, and distributed. For example, customers of music services like Spotify ("Spotify," n.d.) enjoy an unprecedented vast collection of songs, which can be streamed instantly to a connected device. Physical stores are simply unable to economically house such a large assortment, let alone deliver the music to the users with such ease. Similar developments are happening for television content and books ("Amazon.com: Kindle eBooks," n.d., "Apple iBooks," n.d., "Netflix," n.d.).

In addition to the changes in supply and logistics, changes in the functionality of the products themselves also become possible, as the digital domain allows product features that are otherwise impossible to achieve. For example, e-books can be expanded with search functions, enriched media, or interactive and dynamic elements. The development of high-volume production digital (2D) printing presses allowed business models that apply the benefits of digital creation, storage, and distribution to physical products; on-demand printed books.

1.3.2 Digital to physical: 2D printing

Until recently, large-volume 2D printing jobs were mainly done using analog offset printing. In offset printing, a plate needs to be made for each color channel of a page. During the printing process, ink is transported from the plate to the paper using a rubber blanket. Although the plates can be produced using a digital process, the printing itself is mainly analog (Kipphan, 2006). Developing an offset plate is a complex process and a skilled person is required to develop the plate and set up the press. This person is usually not the designer of the artwork. This process can be considered equivalent to injection molding, where the parties who are involved in making the mold and running the machine are generally not the designers of the product being produced.

The early digital laser printing process, which used electrophotography technology and toner, was significantly slower and produced poor quality monochrome prints, compared to full color offset. Further development of full color showed that high-volume production encounters too many technical problems. Also, the relatively thick layers of toner made the printing costs too high.

The first professional digital inkjet color printers were also slow and were therefore mainly used for proofing the artwork before starting the fabrication of the offset plates. In the 1990s the inkjet printers had matured to the point that users started to use these machines for small production runs. It took two decades of further development and currently digital high-volume production inkjet printing presses account for a growing portion of the graphical commercial printing industry (Diginova – Innovation for Digital Fabrication. Roadmap for Digital Fabrication, 2014).

The introduction of the digital inkjet printing press for high-volume production brought several changes to the printing industry. Since small droplets of ink are directly deposited on the medium by a computer-controlled system, an offset plate is no longer required. Therefore, the start-up costs of a print job are significantly lower. The possibility for low-volume runs has made business models that use on-demand printing conceivable. On-demand printing also contributed to making the technology available to a larger group of people, spawning new business opportunities. For example, companies like Amazon offer millions of book titles, many of which are only printed once they are bought, keeping the physical inventory significantly smaller to what would be necessary without on-demand printing (Anderson, 2006). Maintaining products in the digital domain also provides new opportunities for logistics. Products can be distributed in digital form faster and cheaper than physical products. This principle is currently used by newspaper publishers who digitally distribute their daily newspapers to digital printers worldwide for small local production runs.

Digital distribution and on-demand production allow inventories that contain millions of digital products. However, this creates new challenges for customers to find the desired product. Therefore, the development of new product browsing methods and principles of product recommendation are becoming increasingly important (Anderson, 2006; Schafer, Konstan, & Riedl, 1999).

1.3.3 Digitalization of manufacturing: what is new with AM?

Traditional manufacturing processes like injection molding, casting, and extrusion account for large portions of manufactured products. These technologies often rely on embedded digital measurement and control systems that automate the primarily analog process. Digital production processes like computer numeric control (CNC) milling, lathing, laser cutting, and water jet cutting, have also become important in manufacturing. In some cases, end products are manufactured using these digital manufacturing tools. These tools are also frequently used to support traditional manufacturing. For example, injection molds are often made with the aid of CNC milling. Being digital, these processes afford relatively short start-up and differentiation of manufactured products.

Over the past years, the capabilities of AM have been discussed by various authors (Lipson & Kurman, 2013; Rosen, 2015). In this thesis, 2D printing is used as a reference to discuss how the capabilities of AM are related to the unique aspects of the AM process. The obvious difference between AM and existing digital manufacturing is the fact that with AM material is locally added to build up an object, while in other digital processes material is deformed, cut, or removed from bulk material to leave the shape of the final part. In addition to the **digital** and **additive** aspects of AM, in this research, a third aspect was identified to be essential when discussing the novel characteristics of AM; the possibility to locally control the material deposition. To understand the possible implications of this, the analogy between 2D printing and 3D printing was drawn. A new overview was made (Figure 5) that illustrates the comparable processes in 2D and 3D printing. The distinction was made between the analog/digital and vector/raster processes.

A 2D plotter can be considered as the digital equivalent of a pen, as it uses a computer-controlled pen to draw images. Both the pen and the plotter draw an image in a line-wise fashion. Therefore, they were positioned in the *vector* domain, illustrated in the upper half of the 2D quadrant in Figure 5. As a plotter has very limited possibilities for producing different color shades, its applications are restricted to line art.

High-resolution full-color images are generally not made using plotters. Instead inkjet systems are used for this. These printers can control the composition of color on pixel level. Digital inkjet printers can be considered the digital equivalent of analog offset presses, and were therefore placed in the *raster* domain of the 2D quadrant in Figure 5.

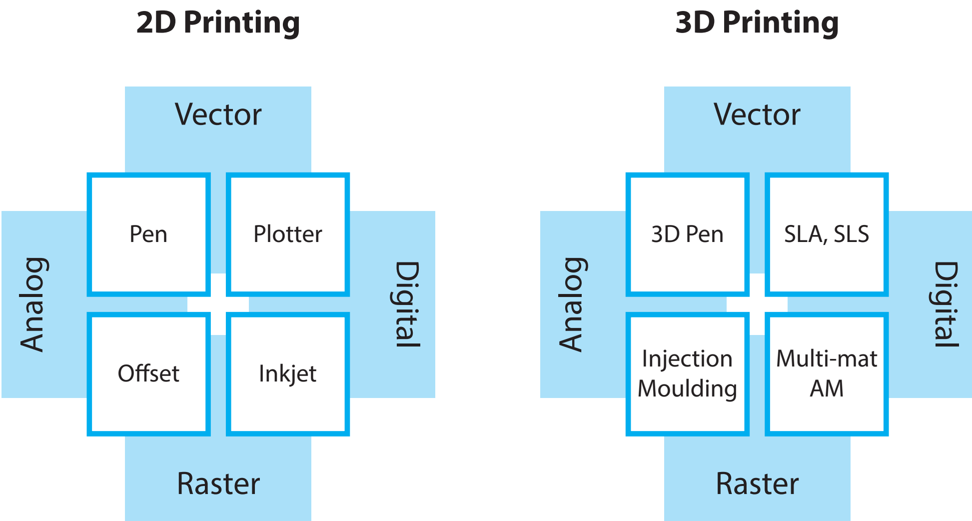


Figure 5 Vector versus Raster-based processes in 2D and 3D.

As discussed earlier, the availability of high-volume production, high quality, full color inkjet (2D) systems has mainly influenced the printing business as a result of the different economies of scale. On-demand books and small-batch jobs became a reality. Nonetheless, costs aside, most digital prints could also be produced using offset and are therefore not new in their appearance, at least not to the human eye.

However, the implications of a similar transition in 3D digital processes could be more far-reaching. Identical to 2D printing, the economies of scale are different compared to the traditional methods. Yet, the technology also allows the fabrication of objects that are impossible to create using traditional manufacturing tools. For example, the “Strandbeest” illustrated in

Figure 6 is an object that consists of many interlocking parts. It was 3D printed without the need for complex molding or assembly (Jansen, Doubrovski, & Verlinden, 2014). It would have been virtually impossible to produce it using traditional production methods such as injection molding.

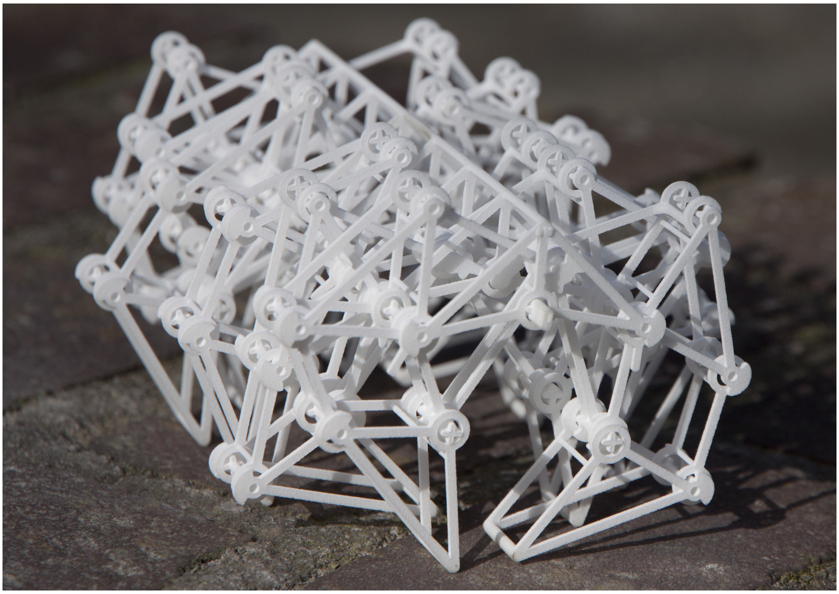


Figure 6 3D printed Strandbeest (Jansen et al., 2014).

Most currently available AM machines, including the one used for the Strandbeest, process one single material per batch. Although the process is fully digital, there is usually no possibility to locally vary, for example, the density or the composition of the material. In a sense, these 3D printers are the 3D equivalent of a 2D plotter, and were therefore placed in the *vector* domain.

Yet, a handful of AM technologies can locally vary the material composition on voxel (volumetric pixel) level, given a set of base materials. These multi-material machines are currently based on inkjet technology. The fact that separate drops of material are deposited in a raster-like manner, provides a potentially unprecedented level of control over the material composition. Similar to 2D inkjet, Multi-material AM was therefore positioned in the *raster* domain of the quadrant in the overview of Figure 5. While inkjet in 2D allowed producing images that appear similar to the ones produced using offset, inkjet in 3D can go beyond what was ever possible with injection molding, especially when combining different materials with different properties on voxel level. Work by Oxman (2011) illustrates such possibilities (Figure 7).

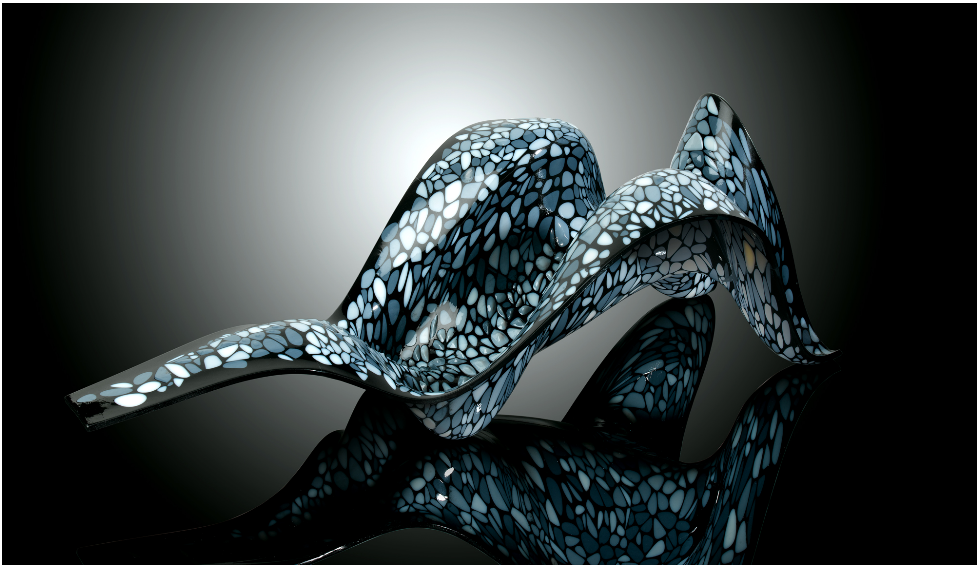


Figure 7 Example of multi-material 3D printing (Oxman, 2011).

1.4 Brief history of Additive Manufacturing

1.4.1 AM in the pre-digital era

The first principles for accurate and reproducible layer-wise manufacturing of 3-dimensional objects were presented as early as 1890 (Bourell, Beaman, Leu, & Rosen, 2009). These processes were analog, required significant manual labor, and therefore cannot be considered AM in its current definition. Some processes proposed in the 1950s, strongly resemble present-day AM technologies. As an example, Figure 8 shows an illustration from a 1956 patent of a so-called *photo glyph* process, which has many similarities with current Vat Photopolymerization processes. In the proposed process, a layer of photosensitive emulsion (containing silver halide) is developed and solidified by projecting an image from a cathode-ray tube screen onto the layer, resulting in a two dimensional image. After lowering the solidified layer, a new layer of emulsion is applied and the process is repeated. The end result is a transparent solid carrying a developed three-dimensional image inside (Munz, 1956).

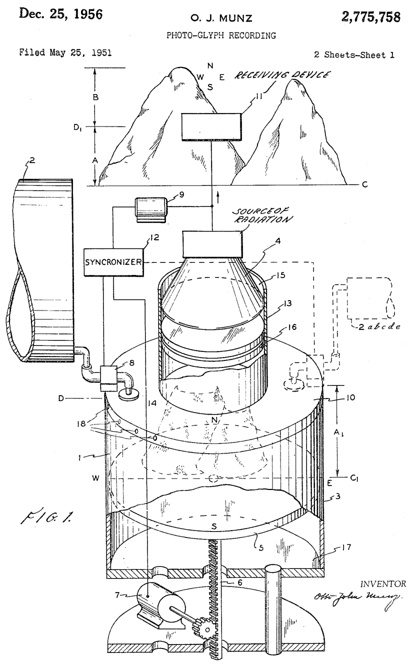


Figure 8 Image of early AM system from 1956 (Bourell et al., 2009).

1.4.2 AM in the digital era

Similar to the origins of many other inventions, individuals in different parts of the world have been working on comparable approaches in what seem to be independent initiatives. In the period after 1960 several papers and patents were published from USA, Japan, France, and Denmark. These concerned digital processes to fabricate objects using photo-curable resin, strongly resembling some of the AM technologies in use today. It is unclear who first developed a fully working system, but the first commercially available AM machines were sold by the 3D Systems company that Charles Hull founded in 1986. These machines, and the many machines that followed them, were marketed as Rapid Prototyping systems. A comprehensive overview of the early history of AM is provided by Bourell et al. (2009), by Gibson, Rosen, et al. (2010), and by Wohlers and Caffrey (2014)

1.5 Recent developments of AM in industry

Below, an overview is presented of the developments that were observed in this research by attending conferences, industry fairs, consulting industry reports, and following daily developments online using the Google Alerts service. While this section is focused on industry, the developments of AM in academic literature are discussed in Chapter 2.

1.5.1 Widening of applications of AM

AM has been used by industrial designers mainly as a tool for Rapid Prototyping for over two decades. However, the application of AM for final part production accounts for a steadily growing portion of the total revenue of the global AM market (Wohlers & Caffrey, 2014). While in 2003, end-production represented less than 4% of the total AM revenue, this portion has grown to more than one third within 10 years. This growth is illustrated in Figure 9.

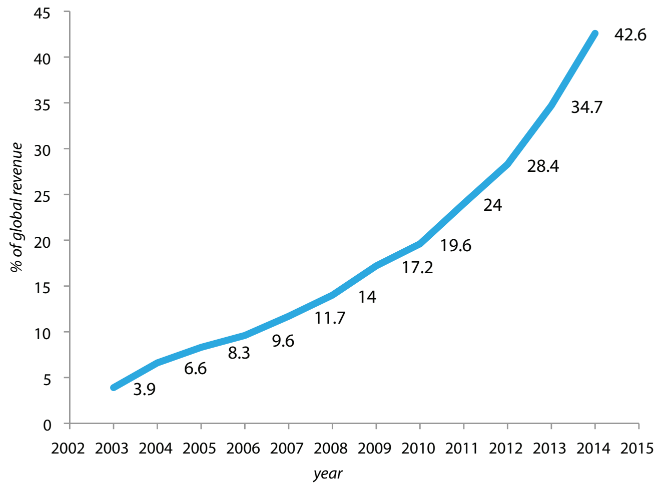


Figure 9 Percentage of global revenue of AM for final part production has been growing steadily (Wohlers & Caffrey, 2014).

Custom medical and healthcare products are among the categories of products that clearly benefit from AM. Metal joint implants and dental crowns are often manufactured in high volumes using AM (Wohlers & Caffrey, 2014). Likewise, most of the custom-fit hearing aids are also manufactured using AM. Hearing aids are often used as the example of an industry that made the transition from traditional manufacturing to AM. Other ubiquitous examples include jewelry, accessories, fashion objects, and home decoration like lampshades.

GE has started to use AM parts in jet engines for commercial aircraft, and the company has announced to be aiming to produce as many as 100 000 AM parts by 2020 ("The FAA Cleared the First 3D Printed Part to Fly in a Commercial Jet Engine from GE," 2015). Boeing has been using AM to manufacture parts for the Environmental Control Systems of some aircraft. The possible geometrical complexity of AM allowed Boeing to consolidate multiple components into one complex part, therefore requiring less assembly (Neil Hopkinson, Hague, & Dickens, 2006). Also, a growing number of companies that make large volumes of consumer products are publicly exploring how they can benefit from AM. These include New Balance and Nike ("New Balance Pushes The Limits Of Innovation With 3D Printing," n.d.; Nike, n.d.). A growing application of AM is the use of AM to support traditional manufacturing and assembly. AM is used to make components such as jigs, fixtures, and handheld assembly devices ("Materialise RapidFit," n.d., "Stratasys: Jigs and Fixtures," n.d.).

1.5.2 Developments among AM system manufacturers

Even though the first AM machines were sold more than 25 years ago, there are ample signs that advancements are still being made today. While an increasing number of AM machines are marketed as production machines instead of prototyping machines, major developments in the AM technology itself were also observed. Within the last two years alone, several novel AM technologies have been presented. Also, major improvements to existing systems have been demonstrated.

1.5.2.1 Changes in how AM systems are marketed

Since AM was initially used mainly for rapid prototyping, most AM system manufacturers marketed their machines as prototyping systems, including the high-end machines. However, a shift was observed in how some of the high-end machines are being marketed. Some system manufacturers now claim to have developed AM machines suitable for production. These companies include Arcam, who focus on AM for aerospace and medical implants ("Arcam AB - Additive Manufacturing for Implants and Aerospace, EBM," n.d.) and 3D Systems, who sell production machines based on both Vat Photopolymerization and Powder Bed Fusion ("3D Systems," n.d.). A new player in AM is DMG Mori, a company originally specialized in CNC lathing and milling stations. In 2014, DMG Mori released a machine that is a hybrid of an additive and subtractive (milling) process ("Lasertec 65 3D - DMG MORI," n.d.).

1.5.2.2 New multi-material AM technologies

In 2014, Stratasys released a new series of AM machines, "Objet Connex3". These are Material Jetting systems that build up objects by combining 3 different base materials of different colors and properties. Currently available base materials have different colors, transparencies, and stiffness ("Connex3 3D Production Systems," n.d.). Océ - a Canon company is currently developing a high-resolution multi-material printing technology, which can produce reproductions of fine art (Elkhuizen et al., 2014). In 2014, Hewlett-Packard (HP) also announced they were entering the professional 3D printing market with a newly developed technology, which can be considered a combination of the AM categories Binder Jetting and Powder Bed Fusion. The technology promises full-color capabilities and the possibility to locally vary material properties ("HP 3D Printers and Printing Solution," n.d.).

1.5.2.3 Role of 2D the printing companies in AM industry

Larger 2D printing manufacturers have entered the 3D printing market. As mentioned in the previous section, HP and Canon have developed novel multi-material AM systems. Ricoh has been supplying the inkjet heads for Stratasys' 3D printers. In addition, Ricoh has been the distributor of AM systems from various manufacturers. In 2015, Ricoh launched its own Powder Bed Fusion AM system ("Ricoh Launches 3D Printer RICOH AM S5500P," n.d.). Signs from other leading 2D printing companies entering the 3D printing market include new patents on 3D printing, such as a recent patent by Xerox (Patricia J. Donaldson & Folkins, 2015).

1.5.2.4 Developments in smaller AM companies and start-ups

The past 5 years has seen the arrival of numerous inexpensive (sub-€5000) AM machines. The trend appears to be that increasingly more advanced AM systems are becoming available to a larger audience. This is fuelled by an active ecosystem of start-up companies. Initially, the inexpensive machines solely used Material Extrusion technology and were based on the RepRap project (RepRap.org, n.d.). However, more recently, start-ups have also developed inexpensive AM systems based on a different technology, namely Vat Photopolymerization ("Formlabs: Desktop Stereolithography (SLA) 3D Printers," n.d.). Until now, technologies other than Material Extrusion and Vat Photopolymerization are mostly limited to prices higher than €20 000. The current exceptions to this are the young companies Blueprinter and Sinterit, Both have developed Powder Bed Fusion systems that are sold below the €20 000 euro mark ("Blueprinter," n.d., "Sinterit," n.d.). In the same year, the Dutch start-up LuxExcel has made their technology for 3D printing of optics available though and online printing service ("Luxexcel | 3D Printed Optics," n.d.). Originating from a research group at Harvard University, a start-up company named Voxel8 has announced the first commercial 3D printer that combines regular printing plastics with conductive inks in 2015 ("Voxel8," n.d.). Such developments pave the way towards printing fully functional electromechanical products.

Apart from start-ups that develop AM machines, there are numerous companies that are developing and selling new materials for 3D printers ("Functionalize," n.d., "Recreus FilaFlex," n.d.)

1.5.3 Changing focus of AM service bureaus

AM technology is becoming available to a larger audience through service bureaus that expand their focus towards consumers and AM for end production. In many cases, the user of the AM technology is the consumer of the manufactured product and not necessarily the designer. In the 25 years since its foundation, Materialise has grown into one of the largest AM service bureaus worldwide ("Materialise," n.d.). In line with the application of AM, Materialise focuses on providing a rapid prototyping service for the industry. It wasn't until 2009 that the company started an online service aimed at a larger audience ("Online 3D Printing Service | i.materialise," n.d.). The setup is similar to the service of Shapeways, where individuals can upload a design and order a 3D print, or sell 3D prints of their design through the service. Apart from the increasing focus of service providers on consumers and end production, a trend was identified of increasing number of AM technologies and materials becoming available on these services. Online platforms for collaborative consumption have also been introduced. An example is 3D Hubs, which connects nearly 25 000 3D printing service providers worldwide ("3D Hubs," n.d.). These include private individuals who own inexpensive 3D printers, but also larger companies that own industry-grade AM machines.

1.6 Challenges for the AM industry

Apart from the challenges for design that are discussed in the following chapters of this thesis, four major challenges regarding AM technology were identified.

1.6.1 Productivity

The speed of fabrication of most AM systems is relatively low. For example, producing an object the size of a mobile phone requires a printing time usually not less than one hour. Some systems, such as Powder Bed Fusion, require an additional warming up and cooling time of the build chamber of several hours. Building multiple objects in one batch can reduce the time per object, but the productivity is still not near to what is common in traditional manufacturing. Apart from the speed of the actual printing, a significant amount of time has to be spent on various pre- and post processes, such as removing the printed parts from the printing chamber and removing support material. Currently, these steps are not automated and require manual labor.

1.6.2 Material development

Most 3D printed parts still have poorer performance than traditionally processed materials in terms of properties like tensile strength and heat resistance (Wohlers & Caffrey, 2014). Also, compared to the selection of materials that can be injection molded, the choice of materials for

AM is limited. Some categories of AM technologies like Material Extrusion can process a significantly larger set of materials compared to, for example, Vat Photopolymerization.

1.6.3 Cost of ownership

AM machines that are marketed as production machines cost at least €20 000 (Wohlers & Caffrey, 2014). In addition, some 3D printers require the use of materials that are branded and sold by the machine manufacturers. Consequently, these materials are sold with a relatively high margin. In combination with maintenance and other consumables, such as print heads, this leads to a cost of ownership few organizations can afford.

1.6.4 Repeatability, reproducibility, and standardization

A single 3D model, printed on different AM systems, can have significantly varying dimensions, tolerances, and properties. Such variations can also occur between AM machines of the same brand and even between print jobs on one single machine. Therefore, ensuring 3d printed product performance remains challenging and even the biggest AM service providers are cautious with claiming that 3D printed products are completely reliable. Illustrating this are the terms and conditions of Shapeways (Inset 1). Shapeways categorizes its products into categories such as *toys*, *home lighting*, and *dining* and ample games, gadgets, fruit bowls, and light shades can be found. However, the company discourages the use of the products for anything but decorative purposes.

> “PLEASE NOTE THAT THE MATERIALS WE USE FOR MANUFACTURING THE MODELS MAKE THE MODELS SUITABLE ONLY FOR DECORATIVE PURPOSES AND THEY ARE NOT SUITED FOR ANY OTHER PURPOSE. THE MODELS ARE NOT SUITED TO BE USED AS TOYS, TO BE GIVEN TO CHILDREN. THE MODELS SHOULD NOT COME IN CONTACT WITH ELECTRICITY OR FOOD OR LIQUIDS AND SHOULD BE KEPT AWAY FROM HEAT.” (“Shapeways Terms and Conditions,” 2015)

Inset 1 Shapeways Terms and Conditions from 2015 (excerpt).

Major organizations for standardization have initiated the development of standards regarding Additive Manufacturing (“Standard Terminology for Additive Manufacturing Technologies,” 2012). A project funded by the European Commission presented a roadmap for standardization (Verquin et al., 2014). Even though AM standards are still under development, some companies have succeeded in obtaining certification for specific AM parts to be used in commercial airliners. (“GE Aviation’s First Additive Manufactured Part Takes Off on a GE90 Engine,” n.d., “Materialise Additive Manufactured Parts Ready to Fly Following Certification for Aeronautic and Aerospace Sector,” n.d.)

1.7 Hypothesis and research objective

This chapter discussed how AM significantly differs from traditional manufacturing methods because of three principles.

- *AM is a digital technology which makes the unit cost significantly less depending on batch size, allows small-series production and customization. Also, the lead-time of a manufactured part is significantly shorter than when traditional manufacturing is used.*
- *Manufacturing effort is considerably less depending on the complexity of geometry because of the layer-wise or voxel-wise manufacturing method*
- *Multi-material systems can locally vary material properties*

1.7.1 Hypothesis

As designers utilize methodologies that are tailored to the specifications of traditional manufacturing technologies, and AM has significantly novel aspects, there is a need to re-think the nature of these workflows. In this research project, the expectation was formulated that designers face limitations in terms of design tools, methods, and procedures when AM is used as the primary production method in manufacturing of consumer durables. In the context of this work, a design methodology that is tailored at manufacturing using AM is referred to as a Design for Additive Manufacturing (DfAM) methodology. Taking into account the unique aspects of AM and the observed developments in the AM industry, the expectation was expressed that AM could have profound implications on the products around us, including the product's life cycle and the discipline of design. The above-mentioned understandings led to the formulation of a hypothesis of this research project.

> *Hypothesis: Designers can utilize AM for consumer durables beyond its current use, given an adequate new Design for Additive Manufacturing methodology is provided.*

Although it was observed that AM is being increasingly used as a new manufacturing technology, AM could have an even larger impact on design than is now the case. Especially the ability to locally control material properties is one of the most essential, promising, and challenging aspects of AM for consumer durables in the long term.

1.7.2 Research objective

Based on the hypothesis, the objective of this work was to develop a DfAM methodology that supports designers in the identification and utilization of the game-changing affordances of AM to allow the application of AM beyond its current use. Therefore it is important to state that the aim went beyond supporting designers in developing better products, or supporting designers in developing products in a better way. As there is a wide range of types of products, within the scope of this research, the focus was set on consumer durables. The development of such a methodology requires an understanding of the current situation. Therefore, the following research questions were formulated, which also constitute the intended theoretical contribution of this work;

> *What are the game-changing characteristics (affordances) of AM when used as a manufacturing method for consumer durables?*

> *What are the limitations in the available design methodologies that designers who use AM currently face?*

1.7.3 Definition of AM affordances

In the context of this work, an AM affordance is defined as:

> *"The available and perceived aspect of an AM system that allows the designer to obtain a desired result in a part or product, which is impossible or significantly more difficult to achieve using traditional production methods."*

Therefore, this concerns *AM system-designer* affordances, which is analogous to the *artifact-user* affordances, as described by Maier and Fadel (2009). In this research, the AM system is analogous to the artifact and the designer who applies AM is analogous to the user. In other words, aspects of the AM machine (artifact) offers potential design possibilities to the designer (user). The terms in the original *designer-artifact-user system* of Maier and Fadel (2009) were therefore adapted, as illustrated in Figure 10. It has to be clarified that in this scope the *user* is the designer who uses an AM system and not the user of the product that is manufactured.

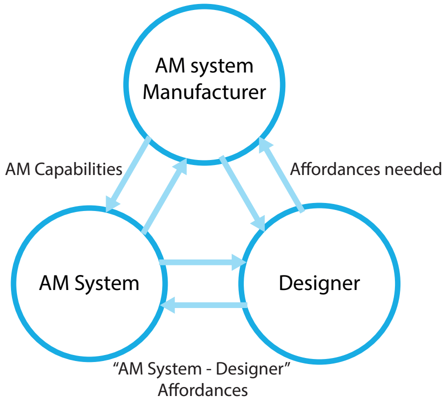


Figure 10 Adapted designer-artifact-user system, from (Maier & Fadel, 2009).

As discussed by Maier and Fadel (2007), "affordance" is a broad concept, and it is considered an "infinite search space". It is therefore impossible to create a complete overview of affordances of AM systems. However, it is still of importance to understand how designers can identify affordances and understand which affordances are of main interest given a design task. In turn, this understanding can inform AM system developers to develop AM systems that comply with the needs of designers.

An affordance can be intended or unintended, which means that it is possible to find affordances of an AM system that were not intended by the developers of the AM system.

1.8 Research approach

As well as obtaining an initial understanding regarding the novel aspects of AM, the aim of this chapter was to present the research approach. The research approach that was taken in this project comprised four Research Cycles and is discussed below. An overview of the Research Cycles and the corresponding chapters of the thesis in which they are discussed is illustrated in Figure 11.

Blessing and Chakrabarti (2009) have developed a design research approach, the Design Research Methodology (DRM). Similar to the intention of DRM, this research also aims to develop design support. In the DRM approach, *Success Criteria* are defined in the first phase of the research. These criteria are then used to evaluate the performance of the developed design support. However, in this project, the focus was not on improving an existing design process. Since AM systems are still maturing and designers are constantly adopting new workflows to work with AM, it was more important to gain a deeper understanding of the current situation and possible future opportunities. For this reason, setting up and measuring *Success Criteria* was not intended in this project. This is in line with Eckert, Clarkson, and Stacey (2004), who argue that using *Success Criteria* is not meaningful when one is interested in insight and not evaluation. Instead, the *Reference Model*, an instrument described in DRM, was used to map and describe the current situation of design for AM.

As the interest of this work was on how design can change as a result of the constantly developing capabilities of AM, considering only what exists today would have provided a limited scope of the situation. Therefore, several stages of design-inclusive research were incorporated, complementary to research in which the current situation and current practices were mapped.

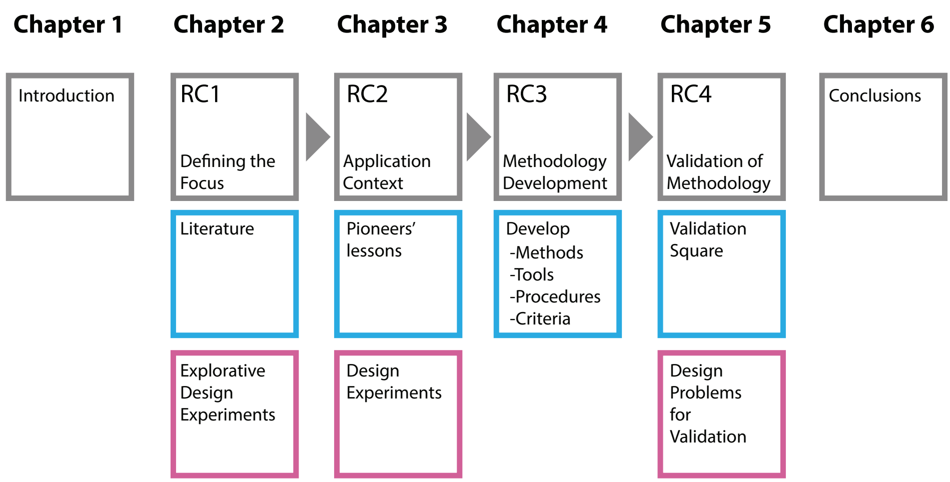


Figure 11 Overview of the Research Cycles and chapters of this thesis. Research approach is indicated in cyan, design stages are indicated in magenta.

1.8.1 Research Cycle 1: Defining the focus

The aim of the first Research Cycle was to define a focus for the DfAM methodology. This was approached through a literature study on the state of the art and developments of AM, and mapping proposed DfAM approaches. In addition, several explorative design experiments were performed to obtain first-hand experience on the affordances of AM and to understand what might be key limitations in current design and manufacturing when using AM.

In the Introduction, it was argued that the digital and additive nature of AM provides the ability to manufacture objects that are geometrically complex and that have locally varying material properties. In addition, the increased ability to make customizable products is an important affordance as well. DfAM approaches found in literature aim for each of these individual aspects. However, it was argued that it is by *combining* these affordances that many new opportunities for new products arise. No DfAM approaches that focus on this goal have been identified. Therefore, a knowledge gap for this research project was defined:

> *It is not known what design methodology can support designers to develop products for AM in which the customizable attributes are not just geometry but also physical properties and functionality. The variation of these is achieved by utilizing the possibility of AM to locally vary material properties.*

1.8.2 Research Cycle 2: Learning from the application context

Complementary to the analysis of the literature in Research Cycle 1, in the second Research Cycle, the analysis of the existing situation was extended beyond the literature into industry. The focus was on understanding what new types of products are being designed by the early adopters in industry and to learn what processes are currently applied when designing for AM.

AM pioneers at world-leading companies were interviewed and a series of design experiments were performed. An understanding was obtained on the affordances of AM identified and applied by the pioneers in the industry. In addition, the design experiments performed in the lab provided an opportunity to explore the possibilities of affordances that are not yet economically feasible. The experiences of the pioneers and the design experiments resulted in an understanding of the limitations of the currently available methods, instruments, and procedures.

1.8.3 Research Cycle 3: Methodology development

In the third Research Cycle, the findings from Research Cycle 1 and Research Cycle 2 were combined to formulate a design methodology for AM that incorporates *procedures*, *methods*, *instruments*, and *criteria*. The methodology is focused on supporting designers to develop customizable products in which both the geometry and the local material property are customized to the user's needs. The methodology includes two circular design stages (loops). The first loop supports the designer in identifying usable affordances of AM, while the second loop supports the development of the customizable design, in which, apart from geometry and material, AM process-related parameters are included to achieve the desired final properties.

1.8.4 Research Cycle 4: Validation of methodology

In the last Research Cycle, the developed methodology was validated by applying the principle of the *Validation Square* (Seepersad, Pedersen, Emblemsvåg, Bailey, & Allen, 2006). In this procedure, the design methodology is validated on theoretical versus empirical aspects and structural versus performance aspects. Two design problems were used to discuss the validity of the methodology.

1.9 Thesis content

The research approach that is presented in this chapter (**Chapter 1**) consists of four Research Cycles. The identification of the knowledge gap and formulation of the research focus (Research Cycle 1) is presented in **Chapter 2,** which is followed by an exploration of the application context (Research Cycle 2) in **Chapter 3**. The formulation of the DfAM methodology (Research Cycle 3) is presented in **Chapter 4**. The validation of which (Research Cycle 4) is presented in **Chapter 5**. Finally, the thesis is concluded in **Chapter 6** with the discussion of the research questions, reflection, and future work.

Chapter 2

Research Cycle 1: Defining the focus

Related publications

Doubrovski, E. L., Verlinden, J. C., & Geraedts, J. M. P. (2011). Exploring the Links Between CAD Model and Build Strategy for Inexpensive FDM. In *NIP & Digital Fabrication Conference. Minneapolis: Society for Imaging Science and Technology*.

Doubrovski, E. L., Verlinden, J. C., & Geraedts, J. M. P. (2011). Optimal design for additive manufacturing: Opportunities and challenges. In *ASME 2011 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. Washington, DC, USA.

Geraedts, J. M. P., Doubrovski, E. L., Verlinden, J. C., & Stellingwerff, M. C. (2012). Three Views on Additive Manufacturing : Business , Research , and Education. In I. Horváth, A. Albers, M. Behrendt, & Z. Rusák (Eds.), *Proceedings of Tools and Methods for Concurrent Engineering*. Karlsruhe.

The previous chapter defined the general objective of this research. In this chapter, the first Research Cycle is discussed. The main goal of this Research Cycle was to define the focus of the research: what specifically should the Design for Additive Manufacturing (DfAM) methodology focus on? This was approached by combining a literature study with several design experiments. Literature was studied to understand how AM is developing and to map the current state of DfAM. In addition, four explorative design experiments were performed to understand what the possible bottlenecks are in the available design instruments and procedures when designing for AM.

2 Research Cycle 1: Defining the focus

2.1 Introduction

As discussed in the previous chapter, using Additive Manufacturing (AM) as a production method in the manufacturing of consumer durables appears to have unique aspects compared to conventional production methods, such as machining and injection molding. It was also argued that these new aspects make AM significantly different from established production methods. Therefore, the hypothesis was formulated that designers can utilize AM beyond its current use, when provided with an adequate new Design for Additive Manufacturing (DfAM) methodology.

The objective of the first Research Cycle, discussed in this chapter, was to define a focus for the DfAM methodology; what is the knowledge gap regarding DfAM for consumer durables? And, regarding the vision described in the previous chapter, for which DfAM approaches is there still a need? This Research Cycle was approached by an analysis of the relationship between the developments of AM technology and the developments of the available and proposed DfAM approaches.

To achieve this, first, an overview was made of the trends in research and development of AM technology. This provided an indication of future directions of development of AM systems and its emerging capabilities. It is not within the scope of this research to provide a complete overview of AM developments. Those interested in such an overview are referred to review articles published with regularity (Dimitrov, Schreve, & Beer, 2006; Gao et al., 2015; Levy, Schindel, & Kruth, 2003). Second, an overview was made of the research that aims to support designers in developing products for AM; the proposed DfAM approaches. Finally, in order to obtain first-hand experience of what might be key limitations in current design and manufacturing for AM, four explorative design experiments were performed.

2.2 Academic landscape of AM

2.2.1 Increasing focus of journals

In 1995, the Rapid Prototyping Journal (Emerald) was launched as the only major journal fully dedicated to AM technologies. Its title reflects the main application of AM in that period and the initial focus of the journal. More than 10 years after the launch of the Rapid Prototyping journal, a new academic journal with a focus on AM was released: “Virtual and physical prototyping” (Taylor

& Francis). During this period, many articles on AM research were published in various journals on advanced manufacturing, materials, and physics.

Over the last three years, the academic community has shown an increased focus on the topic of AM; a growing research community is working on AM materials, processes, and applications. The increased attention is also reflected in the arrival of new journals specifically focused on AM, shown in Table 1. Finally, educational books on manufacturing now also discuss AM alongside other (traditional) manufacturing methods (Tempelman et al., 2014).

Publisher	Journal Title	Year launched
Elsevier	Additive Manufacturing	2014
Mary Ann Liebert	3D Printing and Additive Manufacturing	2014
Springer	Progress in Additive Manufacturing	2015

Table 1 Recently launched academic journals on AM.

As AM is a manufacturing technology that is actively developing, research on AM is published in various domains. A search on Scopus ("Scopus," n.d.) using the terms "Additive Manufacturing" and "3D printing" showed that publications on AM mainly belong to the subject areas engineering, material science, physics, and computer science. Other, less frequently occurring subject areas include mathematics, chemical engineering, medicine and biochemistry, and business.

2.2.2 Observed trends in research on AM processes

It is not within the scope of this work to provide an extensive overview of all presented advancements on AM processes. The goal was to map the developments of AM that are taking place in order to understand how AM is evolving and to what future affordances this could lead. Developments regarding bio-printing and nano-scale printing were not investigated since these were considered currently less relevant in the scope of consumer durables.

2.2.2.1 Incremental improvements of AM systems

Many research efforts focus on better understanding and controlling AM processes to improve the capabilities of AM systems. These efforts include achieving higher build speeds, more predictable properties of printed parts, and a larger set of materials that can be processed. Since most of these aspects strongly depend on the process control of AM systems, optimizing process control has received considerable attention in academic research. Exemplifying these developments, a selection of related research is presented below.

Improving build rate

Recent developments of the oldest AM system, Vat Photopolymerization, have shown that the process can be increased in speed by orders of magnitude (Pan, Zhou, & Chen, 2012; Tumbleston et al., 2015). Also for other AM processes, developments to increase the build rate have been published. For example, for Powder Bed Fusion systems (Schleifenbaum, Diatlov, Hinke, Bultmann, & Voswinckel, 2011) and Material Extrusion (Igor Yakubov & Uzan, 2015).

Improving surface quality

Various efforts to improve the surface quality of 3D printed parts have been published. It has been demonstrated that often improvements can be obtained by adjusting the printing strategy without major modifications of the hardware itself. For example, a re-melting strategy can increase surface quality and material density for metal Powder Bed Fusion (Yasa, Deckers, & Kruth, 2011). For Material Extrusion, the influence of process parameters and chemical post-processing on surface quality were investigated (Galantucci, Lavecchia, & Percoco, 2009). Jariwala, Ding, Zhao, and Rosen (2007) presented a process planning method for micro-stereolithography, which allows a differentiation in layer thickness.

Improving mechanical properties

One approach to improve the strength of parts produced using Material Extrusion is to deposit the material in curved layers conforming to the designed geometry. Chakraborty, Shreddy, and Choudhury (2008) have presented an approach for curved tool path generation. A physical proof-of-concept of curved layers for Material Extrusion has been shown (Singamneni, Diegel, Huang, Gibson, & Choudhury, 2010). Other technologies, such as Powder Bed Fusion, are still physically bound to the planar layer wise build-up. For these technologies, solutions are sought in new scanning patterns of the energy beam (Yasa et al., 2011). New exposure processes have also shown to improve the geometrical accuracy as well as the structural properties of projection-based Vat Photopolymerization (Mitteramskogler et al., 2014).

Closed-loop control in AM processes

The currently poor reliability and repeatability of 3D printed parts is caused in part by the lack of monitoring and real-time process control within AM systems. Most AM systems currently operate with open loop-systems, meaning that parameters like deposition rate for Material Extrusion systems and laser power for Powder Bed Fusion systems are determined in the slicer and are not adjusted based on measurements during the AM process. Closed-loop control has been identified as a principle that can potentially increase quality and repeatability of parts produced by AM (Tapia & Elwany, 2014). For example, taking into account temperature distribution of the previous layer, Nassar, Keist, Reutzel, and Spurgeon (2015) proposed a method to plan the strategy for deposition of the next layer for Directed Energy Deposition systems. This results in a better control of the microstructure of the printed metal parts. An approach to capture plume geometry has been presented, which has shown to be related to the printed geometry for Directed Energy Deposition (Nassar, Starr, & Reutzel, 2015). Closed-loop control is also being developed to increase the accuracy of new Vat Photopolymerization systems (Zhao & Rosen, 2015). Efforts to enable in-situ measurement for Powder Bed Fusion systems include layer-wise optical monitoring of the entire printing area (Foster et al., 2015) and the melt pool (Farshidianfar, Khajepour, & Gerlich, 2016). A thorough overview of research efforts on process monitoring and simulation for metal AM has been published by Tapia and Elwany (2014).

When closed-loop control systems are used, AM machines could locally adapt the printing strategy in order to correctly manufacture the geometrical features of the designed geometry. Such developments can change the role of design rules, which generally inform the designers of design features given a static manufacturing system.

2.2.2.2 New generations of AM systems

The research on AM processes that was discussed in the previous section focused on incrementally improving AM systems. Complementary to these developments, some efforts are paving the way for AM technologies that are not just improved on specific aspects, but can be considered as new generations of AM systems.

Novel AM principles

While most of the AM processes that current research is focused on fit one of the seven categories of AM, a number of developments result in technologies that combine principles from several AM categories. For example, the High Speed Sintering process (N Hopkinson & Erasenthiran, 2004) and HP’s MultiJet Fusion (“HP 3D Printers and Printing Solution,” n.d.) combine principles of Material Jetting, Binder Jetting, and Powder Bed Fusion.

Metal AM processes generally rely on a metal powder as the base material, which is heated using an energy beam. Recent efforts by TNO (Kees Buijsrogge, n.d.) and Océ Technologies (“DEMCON integreert zijn mechatronica-expertise met inkjet,” n.d.) have demonstrated the ability to directly jet droplets of molten metal using principles similar to inkjet. Another approach ejects metal droplets by focusing a laser onto a thin metal film (Visser et al., 2015).

Expanding systems to multi-material

Over the past 20 years, efforts have been made to allow systems to manufacture parts that are composed of multiple materials. These include processes within all seven categories of AM. An elaborate overview of research on this has been provided by Vaezi, Chianrabutra, Mellor, and Yang (2013).

The fact that AM processes in the Material Jetting category generally use inkjet technology makes them suitable for making multi-material parts. A number of commercial AM system manufacturers offer 3D printers that can process multiple materials in a single build, while new developments in academia keep exploring new systems and possibilities (Sitthi-Amorn et al., 2015).

Also, technologies in AM categories that intrinsically would seem not suitable for multi-material have been demonstrated to be modifiable into multi-material systems, such as Powder Bed Fusion (Jepson, Beaman, Bourell, & Wood, 1997) and Vat Photopolymerization (Choi, Kim, & Wicker, 2011).

Even though multi-material systems in all AM categories have been demonstrated, there are currently few commercially available systems with multi-material capability. The publications mentioned above discuss issues that were encountered as a result of two or more materials being combined in one AM fabricated part. These issues include: cracking, material incompatibilities, and improper interfaces of the different materials in the built object. Many of these issues have not yet been addressed, which could explain the limited commercial availability of multi-material AM technologies. Also, while the capabilities of high-resolution multi-material systems are promising, there is still a lot to learn about the properties and behavior of multi-material prints, such as mechanical properties (Vu, Bass, Meisel, & Orler, 2015) and visual properties (Elkhuizen et al., 2014).

Component embedding

Various researchers have investigated the embedding of components into 3D printed parts. These efforts are essential steps in developing technologies that can manufacture fully functional consumer products. These include embedding components in Vat Photopolymerization (Lopes, MacDonald, & Wicker, 2012), ultrasonic consolidation (Siggarda, Madhusoodananb, Stuckera, & Eamesb, 2006), Material Jetting (Meisel, Elliott, & Williams, 2015), and Powder Bed Fusion (Hoerber et al., 2014).

Hybrid AM

A number of initiatives focus on combining Additive with Transformative, Joining, and Subtractive processes. Combining milling (subtractive manufacturing) with Additive Manufacturing is, for example, valuable when surface finish and accuracy are crucial. An extensive overview of hybrid manufacturing efforts is provided by Zhu, Dhokia, Nassehi, and Newman (2013). Such new hybrid processes require new process planning (Newman, Zhu, Dhokia, & Shokrani, 2015).

2.3 Proposed approaches Design for Additive Manufacturing

In the previous section, a brief overview was provided on research and development of AM systems. In this section, research on DfAM-related topics is discussed.

2.3.1 Identified need for DfAM in the literature

As the application of AM for the production of end products has grown, the need for design methodologies and design knowledge has been increasingly clear. These methodologies and knowledge are commonly referred to as Design for Additive Manufacturing (DfAM). However, it has to be noted that in literature DfAM is referred to highly inconsistently (Kumke, Watschke, & Vietor, 2016). Not all research that is said to contribute to DfAM comprises comparable approaches, nor is all work considered in this chapter referred to as DfAM.

More than two decades ago, envisioning that AM would increasingly be applicable as a manufacturing process, Campbell (1994) discussed the need of designers for a methodological approach. The profound impact that the use of AM can have on design has since also been recognized (Hague, Campbell, Dickens, & Reeves, 2001). Hague et al. (2001) identified the opportunities of AM as being the freedom in shape and the possibility to make one-off products, which allows for mass customization. In later work, the need for DfAM has been expressed as the need for designers to access comprehensive information about the mechanical properties of AM materials (Hague, Mansour, & Saleh, 2004). Yang and Zhao (2015) discussed evidence that conventional design theory is not adequate for AM.

Rosen (2007) defined DfAM as: "*Synthesis of shapes, sizes, geometric mesostructures, and material compositions and microstructures to best utilize manufacturing process capabilities to achieve desired performance and other life-cycle objectives*". Also, the objectives of DfAM have been expressed as to "*Maximize product performance through the synthesis of shapes, sizes, hierarchical structures, and material compositions, subject to the capabilities of AM technologies*" (Gibson, Rosen, et al., 2010). In addition to the possibilities of AM and the need for DfAM approaches, the limitations of existing

CAD packages have also been identified. CAD needs to be able to represent models with hundreds of thousand of features (Rosen, 2007). Another challenge for CAD is representations of material and property distributions (Gibson, Rosen, et al., 2010). In line with these challenges, Seepersad (2014) argues that advances in representing and optimizing intricate geometries are needed and has added that design knowledge regarding material properties and capabilities of AM machines need to be made accessible to designers.

2.3.2 DfAM approaches found in literature

A number of publications discuss research related to DfAM. These can represent research on methods, tools, and knowledge, and are intended to support different phases of the design process. In this project, the literature on DfAM was grouped using the following six categories:

1. *Identification and Utilization of AM Affordances*
2. *Structure Generation and Optimization*
3. *Methods for Heterogeneous Modeling*
4. *Methods for Customization*
5. *Design Rules for AM*
6. *Design Evaluation and AM Process Selection*

2.3.2.1 Identification and utilization of AM affordances

Even though the need for methods to support designers in identifying and utilizing the affordances of AM has been widely recognized, little research has been performed on this specific aspect of DfAM. In one of the most extensive efforts to address this, Maidin, Campbell, and Pei (2012) have developed a knowledge-based support tool for designers for the creation of products using AM. A repository is used that contains AM design features. In order to make this knowledge accessible to designers, these design features have been organized into a taxonomy. Four main reasons for using AM have been chosen as the four main taxons. Another approach to support designers in finding and applying unique aspects of AM includes the use of a wiki (Doubrovski, Verlinden, & Horvath, 2012). The European project "Support Action for Standardisation in Additive Manufacturing" described a "Design Standard" that includes the sub-process "Identification of general AM-potential" (Verquin et al., 2014).

2.3.2.2 Structure generation and optimization

The ability of AM to manufacture highly complex geometries has fuelled the development of tools and algorithms that support designers in generating structures that exhibit desired properties. This section provides an overview of such tools and algorithms. To discuss the proposed approaches, the three-link chain model (3LCM) is used. This model originated from the material science domain (Olson, 1997) and was introduced to the AM domain by Rosen (2007). The model, illustrated in Figure 12, considers the relationships between the performance, properties, structure, and process.

Originally, the 3LCM linked material science to material engineering. Analysis of materials follows the deductive path, by investigating the material's structure that follows from its processing and deducing the properties and eventually the performance by cause and effect logic. Complementary, material engineering follows an inductive path by determining the desired performance and properties, the material structures that comply with this performance and processes that result in the desired structures (Olson, 1997).

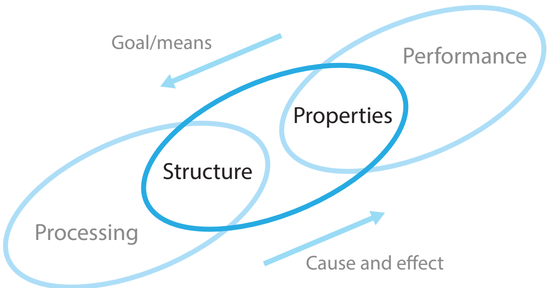


Figure 12 The thee-link chain model (Olson, 1997; Rosen, 2007).

As explained by Rosen (2007), traversing from performance to processing represents a design process, while traversing in the reverse direction represents simulation. Following the inductive (design) path, depending on the needed structure, a suitable AM process for manufacturing can be selected that can create the needed structure. In the deductive (simulation) path, starting with an AM technology, a designer can deduce what structures a specific AM process can manufacture. These structures influence the product's properties and thus it can be reasoned whether the performance of the product will be satisfying (Rosen, 2007).

In this chapter, the structure-properties link of the 3LCM was used to map the proposed approaches on the generation of structures and the properties that are aimed for. The structures that were found in literature were categorized into three scale ranges: micro, meso and macro. Structures with feature sizes between 0.1 and 10 mm are considered meso scale. All structures with smaller features are counted among the micro-scale and all larger-sized structures are considered macro scale.

In literature, various efforts were identified in which methods are proposed to generate specific structures to achieve specific properties. An overview of publications was created in which specific properties have been considered (Doubrovski, Verlinden, & Geraedts, 2011b). Figure 14 shows this overview in which the research efforts are categorized according to the type of properties that are aimed for and the scale of the structures that are generated using the proposed methods.

Below, a selection of research efforts that propose methods for structure generation is discussed. These illustrate the wide variety of properties that can be achieved using AM.

Stiffness and strength

Achieving the desired strength or stiffness while using a minimum amount of material is often one of the central objectives in engineering. Methods that support achieving this goal are broadly covered in literature. An approach to minimize the volume/stiffness or the volume/strength ratio is the use of topology optimization, which has been an established field of research even without applying AM to manufacture the resulting structures (van Dijk, Maute, Langelaar, & van Keulen, 2013). More recently, topology optimization algorithms tailored for AM have been developed (Brackett, Ashcroft, & Hague, 2011). Since topology optimization is generally computationally demanding, other approaches have been proposed to optimize strength and stiffness. For example, Graf, Chu, Engelbrecht, and Rosen (2009) presented a method that fills a volume with unit cells from a library guided by results of a Finite Element Analysis. Using the three-link chain model as a framework, Rosen (2007) developed a method that supports the design of lattice structures. H. Wang, Chen, and Rosen (2005) describe a modeling method for the generation of lattice structures that conform to a curved surface Figure 13.

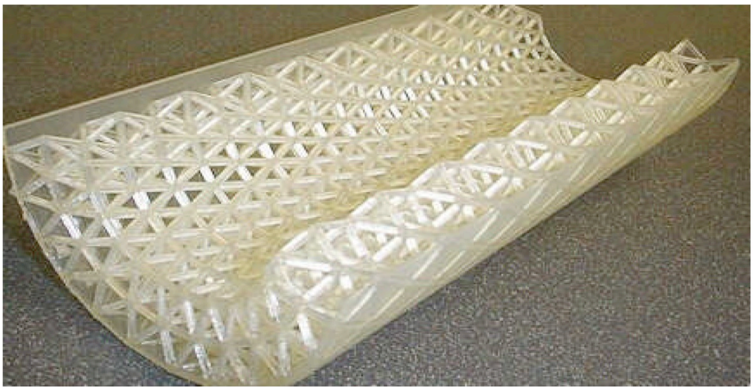


Figure 13 Conformal lattice structure (H. Wang et al., 2005).

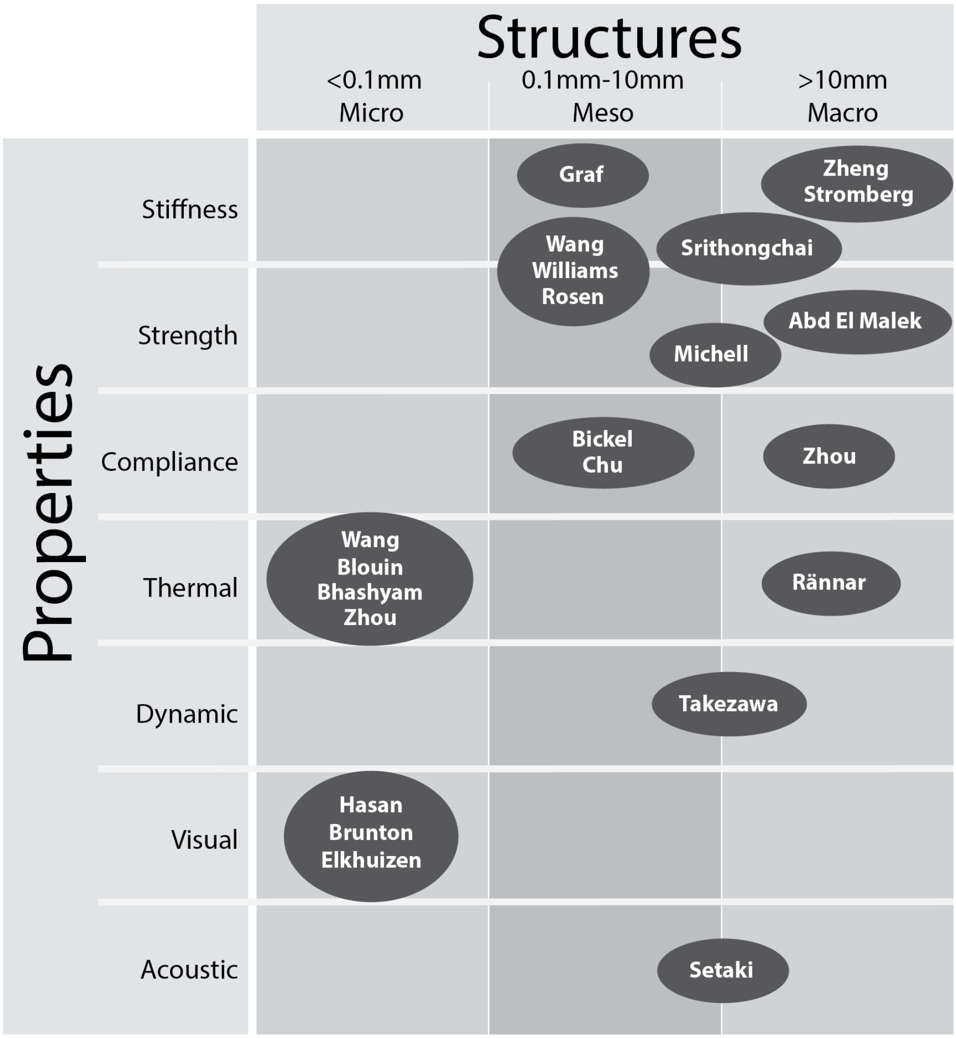


Figure 14 Overview of proposed methods for structures generation in the literature (Doubrovski et al., 2011b). The references mentioned in this figure are (Abd El Malek, Senousy, Hegazi, & Metwalli, 2005; Bhashyam, Shin, & Dutta, 2000; Bickel et al., 2010; Blouin, Oschwald, Hu, & Fadel, 2005; Brunton, Arikan, & Urban, 2015; Chu, Graf, & Rosen, 2008; Elkhuizen et al., 2014; Graf et al., 2009; Hašan, Fuchs, Matusik, Pfister, & Rusinkiewicz, 2010; Michell, 1904; Rännar, Glad, & Gustafson, 2007; Rosen, 2007; Setaki, Tenpierik, Turrin, & van Timmeren, 2014; Srithongchai, Demircubuk, & Dewhurst, 2003; Stromberg, 2010; Takezawa, Nishiwaki, Izui, & Yoshimura, 2005; H. Wang et al., 2005; J. Wang & Shaw, 2006; Williams, Mistree, & Rosen, 2005; Zheng & Gea, 2005; H. Zhou, 2010; M. Y. Zhou, Xi, & Yan, 2004).

Compliance

The ability to manufacture complex geometries and material distributions provides opportunities to make structures that exhibit a desired deformation behavior. For example, Bickel et al. (2010) presents an optimization process that generates multi-material compliant structures, which mimic the deformation properties of sample materials (Figure 15). Li, Chen, and Zhou (2009) have developed a computational framework for the design of mesostructures for target displacements. The authors also give an example of how their method is applied in the modeling of a morphing airfoil (Chu et al., 2008). Their process allows a cell structure to be optimized in order to morph into the desired shape given a certain load.

Figure 15 Sample and replicated object with similar deformation (Bickel et al., 2010).

Visual properties

While most approaches found in literature are intended to support designers in obtaining desired mechanical properties, other properties, such as tactile and visual also play an important role in the field of Industrial Design Engineering (Karana, Hekkert, & Kandachar, 2010). Among the few researchers working on visual properties of AM structures, Hašan et al. (2010) developed a process to model and fabricate translucent objects of which the subsurface scattering is controlled. High-resolution multi-material AM is also being used to replicate the color, texture, and gloss of fine art (Elkhuizen et al., 2014). Figure 16 illustrates details of a 3D printed reproduction of a painting. New 3D error diffusion algorithms have been developed for 3D printed translucent materials manufactured using Material Jetting (Brunton et al., 2015). Such developments pave the way for designers to manipulate the perceptual properties, and generate completely new material experiences.

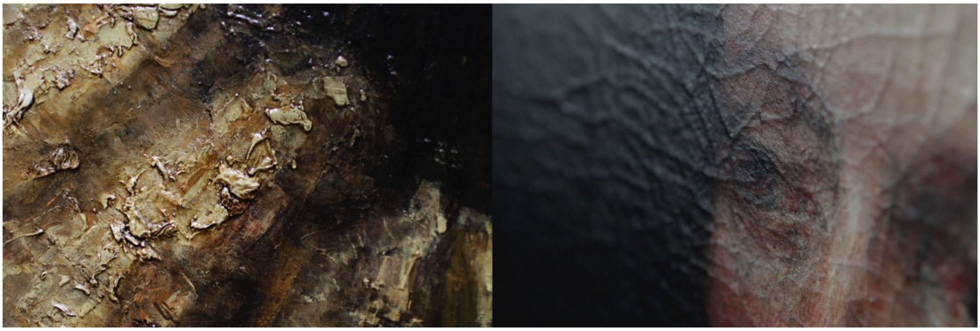


Figure 16 Details of a 3D printed reproduction of a painting, illustrating the color and texture (Elkhuizen et al., 2014).

Acoustic properties

Properties for acoustic absorption for applications in architecture have been explored by structures in the macro scale (Setaki et al., 2014). Research on the acoustic performance of saxophones is being performed by introducing new mesostructures in saxophone mouthpieces (Doubrovski, Verlinden, Geraedts, Horvath, & Konietschke, 2012). This research project will be discussed in more detail in Research Cycle 2.

Novel properties

More recently, new approaches have been presented that utilize AM's abilities to manufacture structures with completely novel properties. These include meta-materials (Garcia et al., 2012), active origami structures (Ge, Dunn, Qi, & Dunn, 2014; Kwok, Wang, Deng, Zhang, & Chen, 2015). The latter belong to a new category of structures that can change over time, commonly referred to as 4D printed structures (Tibbits, 2014).

2.3.2.3 Heterogeneous 3D modeling

Various efforts have been made to develop CAD tools that support the design of objects with local composition control (Chiu & Yu, 2008; Liu, Maekawa, Patriakalakis, Sachs, & Cho, 2003). Vidimce, Wang, Ragan-kelley, and Matusik (2013) present a programmable pipeline for the generation of heterogeneous objects. In this approach, the material definition is decoupled from the geometry, allowing designed material distributions to be applied to various 3D geometries.

However, these methods are aimed at assigning material distributions to an already existing geometry and do not support the design of the main geometry itself. Feature-based design could allow for concurrent design of geometry and material. Samanta and Koc (2008) present a feature-based material blending method that includes optimization steps, while the feature-based method developed by Qian and Dutta (2004) allows assigning materials based on desired graded mechanical properties.

Alongside the developments of the CAD tools, several initiatives exist to expand the 3D file formats allowing the representation of heterogeneous object. This is currently a major limitation in the widely used STL file format. Models for representation of heterogeneous objects based on ISO 10303 (STEP) have been proposed (Patil et al., 2000; M. Y. Zhou, 2006). A newly founded consortium consisting of major AM system manufacturers and CAD software developers is currently developing an AM file format that is intended to support the capabilities of AM, including heterogeneous objects ("3MF," n.d.).

2.3.2.4 Methods for customization in AM context

Hermans (2012) introduced a lay design model, providing a vocabulary for describing the types of toolkits that can be developed for lay designers. A toolkit is a collection of design tools aimed at the design of particular products (Hermans, 2012). Personalization has been explored by providing consumers with templates, which can be considered a customizable design (Campbell, Ariadi, & Evans, 2014). If consumers are allowed to modify a design, the validity and functionality of the end result needs to be guaranteed. Addressing this, Shugrina, Shamir, and Matusik (2015) have presented a method in which computationally intensive analysis of possible solutions of a parametric design is done offline. This supports the development of an intuitive interface for the user in which only valid designs are presented.

While these examples focus on mass customization by lay designers, products can be customized without the consumer playing an active role in the design process, for example, when scan data of the human body is used to define dimensions of a product.

2.3.2.5 Design rules for AM

Design rules are intended to support the design and dimensioning of features that can be acceptably manufactured. These guidelines can focus on different aspects of a design, such as surface quality, accuracy, stiffness, tolerances, but also aspects of the process such as build time and costs. One of the current challenges is the lack of empirical data regarding these aspects. Several authors are working to collect such data in order to formulate design guidelines. Zimmer and Adam (2011) have defined "Standard Elements", elements that are often found in designs. Based on these elements, specimens have been produced on different AM machines. Examination of these specimens allowed the researchers to define design guidelines. A similar approach has been taken by Thomas (2009) for the development of design rules for Selective

Laser Melting, a Powder Bed Fusion technology. Gibson, Goenka, Narasimhan, and Bhat (2010) have investigated elastomeric properties of AM materials, aimed at the production of living hinges. More recent efforts include the work of Seepersad, Govett, Kim, Lundin, and Pinero (2012) who are empirically examining the limits for several design features produced by Selective Laser Sintering, a Powder Bed Fusion technology. These include wall sizes, hole diameters, embossed typography and gears. In a similar approach applied to PolyJet (Material Jetting), the key parameters have been identified that influence manufacturing constraints such as "feature size", "support material removal", and "self-supporting angles" (Meisel & Williams, 2015). In addition to the discussed academic work, commercial 3D printing services, such as Shapeways ("Shapeways," n.d.), provide online guidelines for the different AM technologies while the user communities of the service providers share an ever growing amount of knowledge on online forums.

All of the above efforts to develop design rules prove to be very time consuming while the results are process specific. Therefore, considering the number of AM processes and process variables, it is clear that developing a complete set of guidelines that cover all the available AM processes requires a major effort. Another challenge for developing AM design rules is the rapid development of the AM technologies, which poses a risk for the knowledge to become obsolete or incorrect within a short period of time.

2.3.2.6 Design evaluation and process selection

Complementary to design guidelines which support the design process, analytical tools are being developed that support the evaluation of an already made design, or support the choice of an AM process for this design. One approach is the development of an online service (Willit3dprint.com, n.d.). Based on an AM process, chosen by the user, the service analyzes a 3D design for manufacturability, surface roughness, use of support, built time, and cost. Following the outcome of the analysis, the user can choose to change the design, the material, build parameters, or produce the part on a different AM system. The digital nature of AM potentially allows more insight in the exact energy use and costs of the manufactured parts. Baumers et al. (2012) have presented an implementation for estimation of energy flows and cost for a metal Powder Bed Fusion system.

Various knowledge-based AM process selection and planning tools for AM are being developed (Munguia, Bernard, & Erdal, 2011; Singh & Sewell, 2011). By providing a technology and processing materials guide, the approach aims to enable AM users to assess the capabilities of AM technologies, materials and build scenarios given a finalized 3D design. Munguía, Lloveras Llorens, and Laoui (2010) provide an overview of AM selection methods. A review of the different process planning tasks in AM is provided by Kulkarni, Marsan, and Dutta (2000). The authors divide the process planning into two domains: the model domain and the layer domain. Part orientation and support structure generation are within the model domain, while path planning is within the layer domain.

When developing customizable products, design evaluation and process planning can become challenging, as the final features of each customized product are not known beforehand. A selection method of an AM technology under the geometric uncertainty inherent to mass customization is presented by Wilson and Rosen (2005).

2.3.3 Scope of DfAM approaches in the design phases

The different research efforts on DfAM discussed in this chapter each focus on specific phases of the design process, ranging from conceptual design to detail design. Therefore, the design process in its totality is not covered by any of the proposed DfAM approaches. The limited scope of currently proposed DfAM approaches was also pointed out by Laverne, Segonds, Anwer, and Le Coq (2014) and Kumke et al. (2016), who placed the found approaches in the four design phases of Pahl and Beitz and VDI-2221 respectively. The design methodologies of Pahl and Beitz (2013) and VDI-2221 (1993) are widely accepted in design practice and divide the design process into 4 main phases (Roozenburg & Eekels, 1995):

1. *Planning and clarifying*
2. *Conceptual Design*
3. *Embodiment design*
4. *Detail design*

The European project "Support Action for Standardisation in Additive Manufacturing" presented a design strategy in which the sequence of decisions and design steps is suggested Verquin et al. (2014). The strategy partially covers elements from all of the four design phases described above. Ponche, Hascoet, Kerbrat, and Mognol (2012) presented a global design approach where during the design of the geometry the design requirements and constraints of the AM process are considered. The focus of the proposed methodology is on engineering tasks. The early design phases are not included, since the methodology assumes that the functional specifications of the design are defined beforehand.

The methodological framework for DfAM developed by Kumke et al. (2016) covers all phases of the design process. While it is intended to support designers in finding design solutions that utilize AM potentials, the development of customizable products is not systematically supported.

The manufacturing steps such as orienting and slicing are considered to be outside of the scope of DfAM (Kumke et al., 2016). This thesis argues that these, and other process-related parameters, should be included in DfAM as to their position in the design process, which is discussed in the next section.

2.4 Learning the limitations: Explorative experiments

In addition to the overview of recent developments of the AM technology and DfAM approaches in literature, four explorative experiments were performed. Performing these experiments provided an opportunity to understand the current possibilities and limitations of available design instruments and workflows.

2.4.1 Method

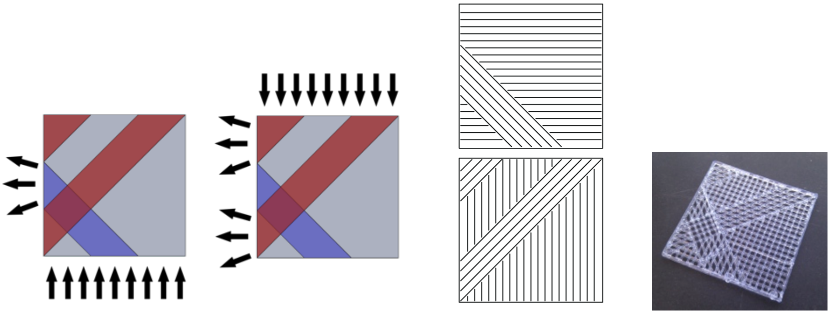
In these explorative design experiments, the focus was on the design and fabrication of objects with specific visual and mechanical properties. A full elaboration of these design experiments can be found in (Doubrovski, Verlinden, & Geraedts, 2011a). The parts were built on an inexpensive Material Extrusion AM system, the RepRap Mendel (RepRap.org, n.d.). While inexpensive (sub €5000) Material Extrusion 3D printers could be considered low-tech compared to their more expensive counterparts, their increasing popularity and use make it an important category in the AM market. Also, the growing user communities like 3D Hubs ("3D Hubs," n.d.) increase the application of these printers as a means of production.

In a standard workflow for Material Extrusion, 3D geometry, designed using 3D CAD software, is imported into a printer-specific program, commonly known as a slicer. In this step, settings such as layer thickness, print speed, and temperature are set. The slicer outputs a g-code file, which holds printer-specific tool paths and contains exact information about the movement of the axes and material extrusion and other values such as extrusion temperature and cooling rates.

In the discussed experiments, the aim was to achieve specific properties, which were not possible to achieve using the standard workflow described above. For example, the settings of the standard slicer did not provide sufficient possibilities to build the needed structures. Below, the four experiments, and the design and manufacturing workflow that was devised in order to achieve the target properties are described.

2.4.2 Light guides

Light guides (or optical fibers) are used for light transport, typically for display purposed or communication. A light guide is composed of a transparent core and cladding. Light is transported through the core from one end to the other since the lower index of refraction of the cladding causes total internal reflection. This experiment explored the possibility of printing material patterns that conduct light through a volume. Possible applications of such structures are integrated optical communication between components within a product and illumination of buttons and displays.



a b c

Figure 17 a) Intended working principle b) designed tool paths c) fabricated sample.

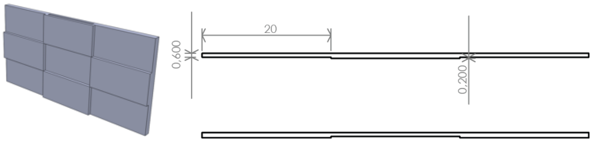
To conduct light though a desired path, it was necessary to define the exact tool paths of the 3D printer. This was achieved by drawing the desired paths for each layer in vector graphics software (Illustrator) and converting the drawings into tool paths using CAM software. The intended working principle, tool paths, and printed result are illustrated in Figure 17. Apart from the paths of the light guides, the geometry of the guides themselves is also important for their light-conducting properties. In order to obtain the correct cylindrical geometry of the light guides, the extrusion rate and travel speed needed to be precisely controlled.

This exploration showed that is it feasible to implement light guides in a volume built by Material Extrusion, if the designer is able to directly draw tool paths within the object volume.

When these experiments were performed in 2011, the fabrication of light guides using AM was not broadly covered in literature and light guides processed using a Material Extrusion system had not yet been described. Y. Chen, Zhou, and Lao (2011) describe a process similar to Stereolithography that allows the creation of directed light guides. Willis, Brockmeyer, Hudson and Poupyrev (2012) have demonstrated the fabrication of light guides using Material Jetting.

2.4.3 Reflection and refraction

Structures built using Material Extrusion with transparent materials can display distinctive reflective and refractive properties. For example, the reflectivity of the 3D printed surface was found to vary distinctively. This explorative experiment aimed to control this phenomenon.



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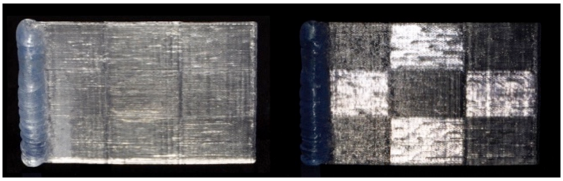

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Figure 18 a) Test piece with alternating thickness b) section view of layers c) fabricated part with varying reflectance patterns.

A test piece was designed that consists of a checkered pattern of thicker and thinner areas, illustrated in Figure 18a. On the thinner areas, the extruded beads of the front and the rear were intended to fuse, while the thicker areas allowed the front and the rear to be deposited without fusing. Before the tool paths were made, the needed distance of the paths required for full fusion versus non-fusion were empirically determined. The coordinates for the tool paths were edited directly using spreadsheet software. The resulting layout of tool paths is illustrated in Figure 18b. The fabricated part Figure 18c exhibited the desired reflective properties. As can be seen, under some lighting angles, the single-path areas is significantly more reflective than the areas where two paths are fused.

The experiment showed that with Material Extrusion is it possible to build structures that have varying reflective properties while using only one material. To obtain this, it is imperative to have precise control over the fusion of paths within a layer. In this example, the build parameters layer thickness and material deposition speed determined the degree of reflectance.

2.4.4 Compliant structures

In this experiment, an internal structure that results in a flexible (compliant) object was explored. A truss was designed consisting of parallel and perpendicular elements, similar to the common geometry that is used as internal infill on inexpensive Material Extrusion printers. A simplified model of this structure is shown in Figure 19. The goal was to fabricate a structure that deforms symmetrically when compressed.

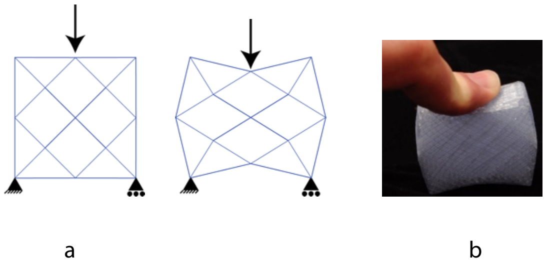

Figure 19 a) Model of flexible internal structure b) fabricated test piece under deformation.

A solid block was modeled and sliced using standard settings of the RepRap slicing software. In order to make the piece flexible, the bonding between the printed layers was inhibited by extruding the infill structure at a lower temperature. This was achieved by manually editing the extrusion temperature in the g-code file. A fabricated test piece under deformation is shown in Figure 19b.

This experiment brought to light that it is possible to create flexible, compliant objects with designed deformation by locally controlling the extrusion temperature. The overall geometry and the deposited structure were not altered.

2.4.5 Clicking button

In this design experiment, the goal was to fabricate a clicking button using a Material Extrusion system. Figure 20a illustrates a section view of the intended deformation behavior. The footprint of the entire structure is 18mm by 18mm. The challenge was to control the structure of the flexible elements and therefore the deformation properties on a small scale.

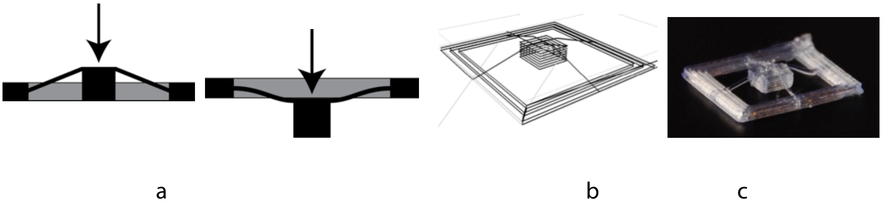

Figure 20 a) Section view of clicking behavior b) Visualization of tool paths c) Fabricated button.

If the standard slicing software had been used, the final build-up of the connecting structures would have been unpredictable. In order to directly influence the fabricated structures, the tool paths were generated by manually editing the coordinates using spreadsheet software. The challenges were finding the correct printing speed and cooling rate at which the flexible elements would be extruded without collapsing.

This exploration showed that flexible structures can be fabricated on a small scale if the exact material extrusion patterns can be controlled.

2.4.6 Discussion on explorative experiments

The main awareness that was gained from these explorative design experiments is the importance of process-related parameters during the design process. Process-related parameters can generally be set in both the slicer as well as the printer's controller software. They include tool path settings, temperature settings, cooling rates, and build orientation. In a regular AM design and manufacturing workflow, influencing these parameters is not included in the design process, but is done once the design is finalized. Figure 21 illustrates the analogy of process-related parameters for 2D printing and 3D printing.

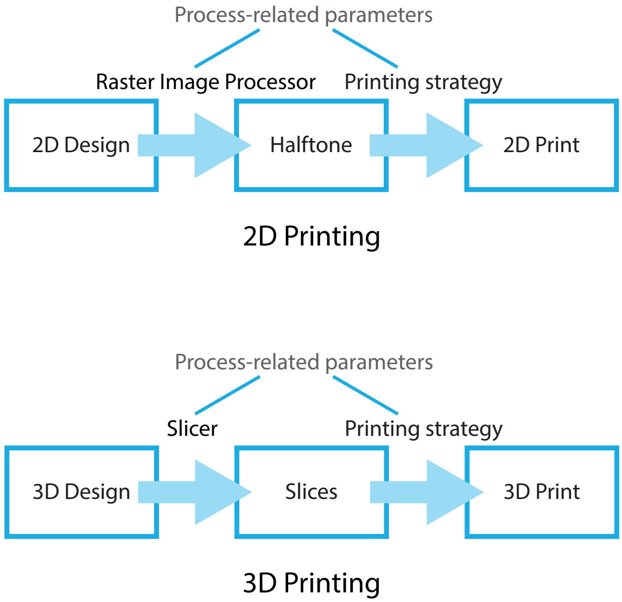

Figure 21 Process-related parameters in 2D and 3D printing.

From the experiments it was understood that being able to influence these parameters during the design stage, provides new opportunities for designers to obtain desired properties of the printed result. It became possible to locally control a surprising variety of properties while only using one build material. However, cumbersome workflows needed to be devised during the explorative design experiments indicating the lack of adequate design tools.

It has been widely understood that process-parameters influence the final properties of printed parts. For example, the influence of tool paths on properties of parts produced by functionally graded Directed Energy Deposition (Muller, Hascoet, & Mognol, 2014) and Material Extrusion (Ahn, Montero, Odell, Roundy, & Wright, 2002). The influence of such parameters has also been discussed in section 2.2.2.1. However, in proposed DfAM approaches, it is not typical to include any aspects of process-related parameters in the design process. Rosen (2007) presented the concept of Manufacturable Elements, which are intended to ensure AM process planning specifically for the designed geometry. In the presented approach, a method is suggested to find the process parameters that will result in a part that meets the design requirements. In more recent work, Rosen (2014) mentions a scenario in which design problems are formulated considering simultaneously part design, material design and manufacturing design. The performed experiments provided first-hand understanding of how such design problems can be formulated. It also illustrated how the inclusion of process-related parameters provides opportunities for the designer to achieve properties that were not possible to define in existing CAD tools. While the experiments were performed using Material Extrusion, a similar principle can also be applied to other AM technologies. For example, in Powder Bed Fusion and Vat Photopolymerization processes these would include layer thickness, laser intensity, laser scanning speed, and scanning patterns.

2.5 Conclusions

2.5.1 Academic landscape

This first Research Cycle focused on academic literature on AM processes and DfAM approaches. In addition, in order to obtain first-hand experience on what might be key limitations in current design and AM production, several explorative design experiments were performed.

Over the last years, academia has seen an increase in research activity on AM. This illustrates that, even though numerous AM systems have been in use for several years, much has to be learned about the exact factors and processes that make up the AM systems. This indicates that AM is still a maturing technology and that many elements can be improved. Research and development on AM processes of the past two decennia can be grouped into two rough categories.

Category 1: Research and development that aims to incrementally improve AM systems. This includes research to improve productivity, material properties, and surface quality of 3D printed parts. Among these is the development of closed-loop control in AM systems, which provides opportunities to further increase reliability and quality of AM.

Category 2: Research and development on new AM processes that can be considered a new generation of AM systems. These include processes that allow the fabrication of structures that have significantly new behavior such as AM processes that can produce parts with locally varying material properties. These also include systems that can embed components such as electronics, which provides opportunities for developing completely new product properties. Even though such developments are promising, commercially available systems that have these capabilities are currently severely limited.

2.5.2 DfAM approaches

The need for DfAM was expressed in academic literature over a decade ago. Currently, DfAM is an ambiguously used term and work that presented as DfAM targets a large variety of topics and different phases of the design process. These proposed DfAM approaches have been grouped into six categories:

1. *Identification and Utilization of AM Affordances*
2. *Structure Generation and Optimization*
3. *Methods for Heterogeneous Modeling*
4. *Methods for Customization in AM context*
5. *Design Rules for AM*
6. *Design Evaluation and AM Process Selection*

There is limited understanding of how these different approaches can be connected into a complete design process that supports the design of customizable products.

The explorative experiments exemplified the importance of including process-related parameters (which are components of the manufacturing process) in the design process. It has been demonstrated that, if process-related parameters are considered during the design process, the designer obtains new possibilities in defining and manufacturing part properties. The considered process-related parameters included extrusion temperature, nozzle speed, and printing patterns. A surprising variety of properties of the printed parts became achievable by defining not what (geometry and material) but how (process-related parameters) the AM machine builds up the object. Using only one base material, parts with varying mechanical and visual properties were printed. Similar principles could also be applied to other AM technologies.

2.5.3 Identifying the research focus and knowledge gap

The previous chapter argued that the digital and additive nature of AM potentially provides the ability to manufacture objects that are geometrically complex and that have locally varying material properties. The explorative experiments provided a first-hand understanding that the inclusion of process-related parameters in the design process gives the designer unprecedented opportunities in varying material properties. Current methods, instruments, and procedures are inadequate for this, raising the question what methods, instruments, and procedures need to be developed.

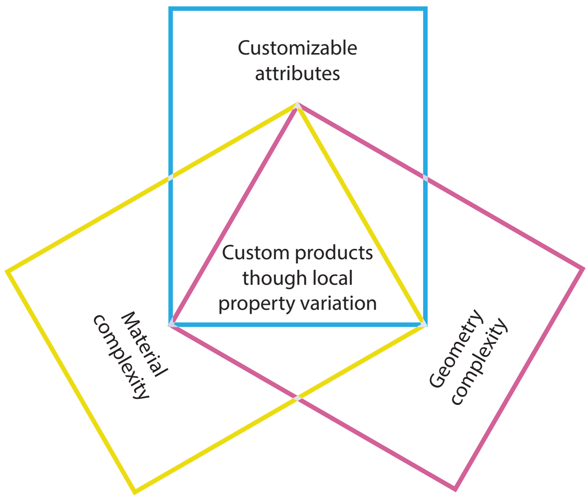

Figure 22 AM Affordance Triad.

The ability to make products with customizable attributes is an important affordance of AM in the scope of consumer durables. DfAM approaches found in literature usually target each of these individual aspects. However, combining these affordances gives rise to many new opportunities for new products. This combination of affordances is illustrated in Figure 22 and is referred to in this work as the Affordance Triad. While various approaches that can be considered DfAM were mapped, no approaches that focus on this combination were identified.

Therefore, the knowledge gap for this research project was defined as:

> *It is not known what design methodology can support designers in developing products for AM in which the customizable attributes are not just geometry but also physical properties and functionality. The variation of these is achieved by utilizing the possibility of AM to locally vary material properties.*

Chapter 3

Research Cycle 2: Learning from the application context

Related publications

Doubrovski, E. L., Cencen, A., Bennekom, S. M. van, Verlinden, J. C., & Geraedts, J. M. P. (2014). Challenges in Design and Digital Fabrication of Embeddable Electronics and Freeform Surface Interfaces. In *Proceedings of ISCIE/ASME 2014 International Symposium on Flexible Automation*. Awaji, Japan.

Doubrovski, E. L., Verlinden, J. C., Geraedts, J. M. P., Horvath, I., & Konietschke, V. L. M. (2012). Acoustic Investigation of Novel Saxophone Mouthpiece Designs Produced by Additive Manufacturing. In I. Horváth, A. Albers, M. Behrendt, & Z. Rusák (Eds.), *Proceedings of Tools and Methods for Concurrent Engineering*. Karlsruhe, Germany.

Jansen, B., Doubrovski, E. L., & Verlinden, J. C. (2014). Animaris Geneticus Parvus: Design of a complex multi-body walking mechanism. *Rapid Prototyping Journal, 20*(4), 311–319. http://doi.org/10.1108/RPJ-10-2012-0087

Lorenzoni, V., Doubrovski, E. L., & Verlinden, J. C. (2013). Embracing the Digital in Instrument Making: Towards a Musician-tailored Mouthpiece by 3D Printing. In *Proceedings of the Stockholm Music Acoustics Conference 2013* (pp. 419–424). Stockholm, Sweden.

Lussenburg, K., van der Velden, N. M., Doubrovski, E. L., Geraedts, J. M. P., & Karana, E. (2014). Designing with 3D Printed Textiles: A case study of Material Driven Design. In *Proceedings of the 5th International Conference on Additive Technologies* (pp. 74–81). Vienna, Austria.

In the previous Research Cycle, the research questions were approached from the perspective of academic literature. This sparked my curiosity to learn from the current state in industry and design practice. The aim of the second Research Cycle was to complement the understanding of the existing situation beyond the state of the art in academic literature. Therefore, interviews were held with employees of world-leading companies who are applying AM as a production method.

In addition, being a designer, I had the ambition to explore the possibilities and limitations of AM. This Research Cycle was an opportunity to perform and coach a series of design acts. In turn, the analysis of the design process of the design acts allowed learning about the limitations of the currently available methods, instruments, and procedures.

3 Research Cycle 2: Learning from the AM application context

3.1 Introduction

The previous chapter discussed the proposed DfAM approaches. However, it was still unknown how design projects for AM are approached in industry. Therefore, complementary to the analysis of the literature in Research Cycle 1, in the Research Cycle 2, the analysis of the existing situation was extended beyond the academic literature. The focus was on understanding what new types of products are being designed by pioneers in industry and to learn what workflows are currently applied when designing for AM. Also, it was still unknown how affordances of AM are perceived, how they are utilized in practice, and to what new types of products AM can lead.

Interviews were held with employees in four pioneering companies that are active in the field of AM. Pioneering companies are considered those companies who are among the first to experiment with new techniques of using AM for the manufacturing of consumer durables. Pioneering companies are also referred to as *pioneers* in this work.

Also, four design experiments were undertaken, which were intended to yield first-hand understanding of the shortcomings of the available design instruments, methods, and procedures when designing for AM.

Reflecting the twofold approach of this Research Cycle, this chapter is likewise composed of two parts; the first section discusses the interviews with employees at the pioneering companies while the second part presents the analysis of the four engineering studies that were performed.

3.2 Pioneers' lessons

3.2.1 Outline

The goal of the pioneers' lessons was to learn what methods, procedures, and instruments are used in industry and what limitations in the available methodologies can be identified. Also, to better understand the possible game-changing characteristics of AM, it was intended to learn what affordances of AM are considered important by pioneers and how these affordances are applied in products. Therefore, a differentiation was made between AM affordances that were only mentioned by pioneers and affordances that were actually applied in the designs of new products.

3.2.2 Method

Employees of companies who are among the first to investigate using AM for the manufacturing of consumer durables were contacted to participate in a series of interviews. The companies and the participants themselves were met at various AM-related events, such as trade fairs and conferences. Therefore, this method of sampling can be regarded as convenience sampling. A total of 10 employees were interviewed individually, and each session took approximately 45 minutes. The participants were mainly industrial designers, however, a material engineer, production manager, engineering manager, and managing director were also among the interviewees. The interviews were held in meeting rooms at the companies' buildings. An audio recording of all interviews was made. An interview guide (Appendix A) document was used to make sure that all intended topics were discussed. An overview of the companies is provided in Table 2.

3.2.2.1 Protocol

Before each interview, the participants received a one-page document, which described the background of the research and listed the topics that were to be discussed during the interview. The interview itself started with a description of the aims of the research. The remainder of each session was conducted as a semi-structured interview while making sure the topics mentioned in the interview guide were discussed. After the interviews, the AM facilities of each company were visited in a brief tour.

3.2.2.2 Analysis

The audio recordings of the interviews were transcribed and coded using the Atlas.ti software package. The analysis comprised iterative steps of analyzing the interviews. Initially, the interviews were coded, generating a variety of themes. In later iterations, common themes were identified and grouped.

	Employees	**Founded**	**Years working with AM**	**Participants**
Company 1	800-1000	1990	24	4
Company 2	4000	1906	12	4
Company 3	50-100	2007	7	1
Company 4	20	1996	2	1

Table 2 Overview of companies that participated in the interviews.

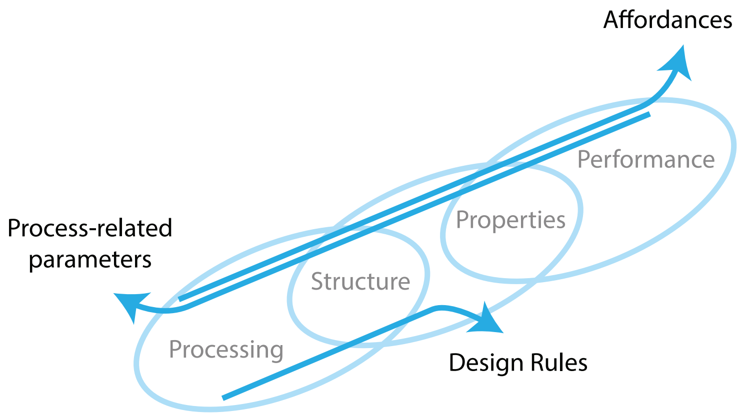

Figure 23 Relationship of the themes discussed in the interviews.

3.2.3 Results

The topics regarding Design for Additive Manufacturing that were discussed with the pioneers were grouped into four main themes. These themes are; *Affordances*, *Design Rules*, *AM Process Related Parameters*, and *Issues*. Apart from the theme *Issues*, the themes can be explained as paths through the Three-Link Chain Model, which also illustrates their relationship. The visual representation of the themes as paths within the 3LCM is illustrated in Figure 23.

Affordances, defined in Chapter 1, can be considered within the scope of the 3LCM. An *affordance* allows a designer to achieve a desired result, or *performance* in a product. As visualized in the 3LCM, the *performance* of a part is determined by its *properties,* which are the result of its *structure* (geometry and material composition), which in turn is the result of the characteristics of the *AM process*. However, not all affordances can be expressed within the 3LCM. For example, the ability to economically manufacture customized products cannot be described within the scope of the 3LCM.

The theme *Process-related parameters* concerns settings and print parameters in the AM machine and machine-specific software. As found in the previous Research Cycle, apart from the designed geometry and the specified material, process-related parameters determine, to a large extent, the final properties of a manufactured part. These parameters influence how the printer builds up an object (printing *processing*) and therefore has direct consequences for the built *structure*. In return, the *structure* influences the *properties* and the final *performance* of the part.

Design rules, or design guidelines, are a set of rules that support the designer in designing and dimensioning features for a given manufacturing process. For traditional manufacturing such as injection molding, these rules include draft angles, wall thicknesses and radii. In the scope of the 3LCM, Design rules, or engineering guidelines, are criteria for *structures*, which are dictated by the possibilities and limitations of the (manufacturing) *process*.

3.2.3.1 Discussed theme: Affordances

During the interviews, the participants mentioned numerous affordances of AM. After several iterations of grouping, 15 distinct affordances of AM were identified. However, not all of these mentioned affordances have actually been utilized by the participants in the discussed projects. By visualizing how often affordances were mentioned and how often these affordances were actually utilized by the participants (Figure 24), four affordances clearly stand out. The most frequently mentioned design possibilities that AM affords are:

- *Manufacturing of **geometrically complex** parts*
- *Develop parts and products with **customizable** attributes*
- ***Integration of functions** into parts*
- *Developing parts with **short lead-time***

As discussed in Chapter 1, the two main unique characteristics of AM are the digital aspect and the layer/voxel-wise manufacturing process. The affordances that have been brought up by the participants during the interviews were categorized into a hierarchical overview based on this division. The result is an affordance structure of the affordances mentioned by the pioneers and is presented in Figure 25.

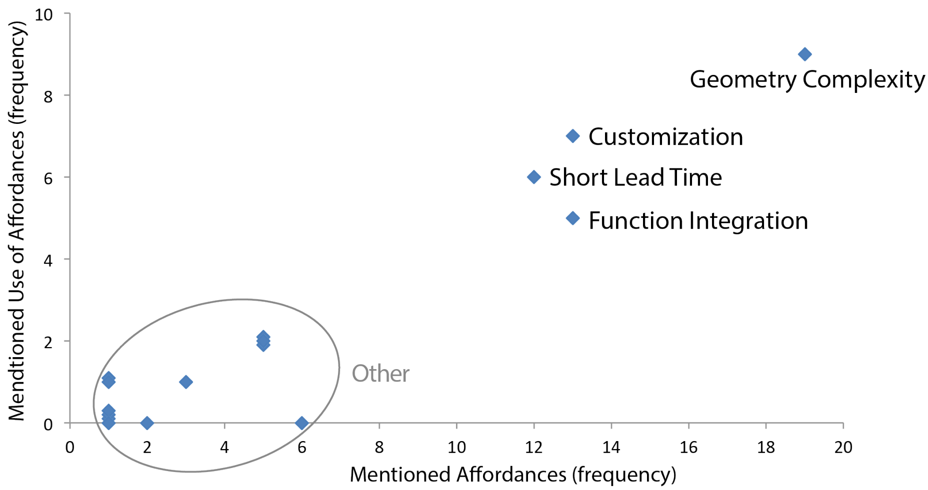

Figure 24 Mentioned and used affordances by the pioneers.

In affordance-based design, as discussed by Maier and Fadel (2007), an affordance structure is developed for the product that is being designed. The affordance structure is used during the design process to evaluate, for example, how developed concepts satisfy the intended affordances.

The affordance structure presented in this work could have a different role than in affordance-based design. It could be a growing overview of affordances of AM that support companies in the decision making on whether AM should be used in manufacturing. Also, it could support designers in deciding what affordances of AM could be meaningful to apply during the design of a product, comparable to the design feature database as proposed by (Maidin et al., 2012).

Participants expressed their view that designers are often unaware of the possibilities of AM. Within the companies, no systematic approaches were observed that aim to explore, document, and share AM affordances among designers. Alternatively, participants mentioned that ambitious design projects are often initiated to explore and understand the affordances of AM.

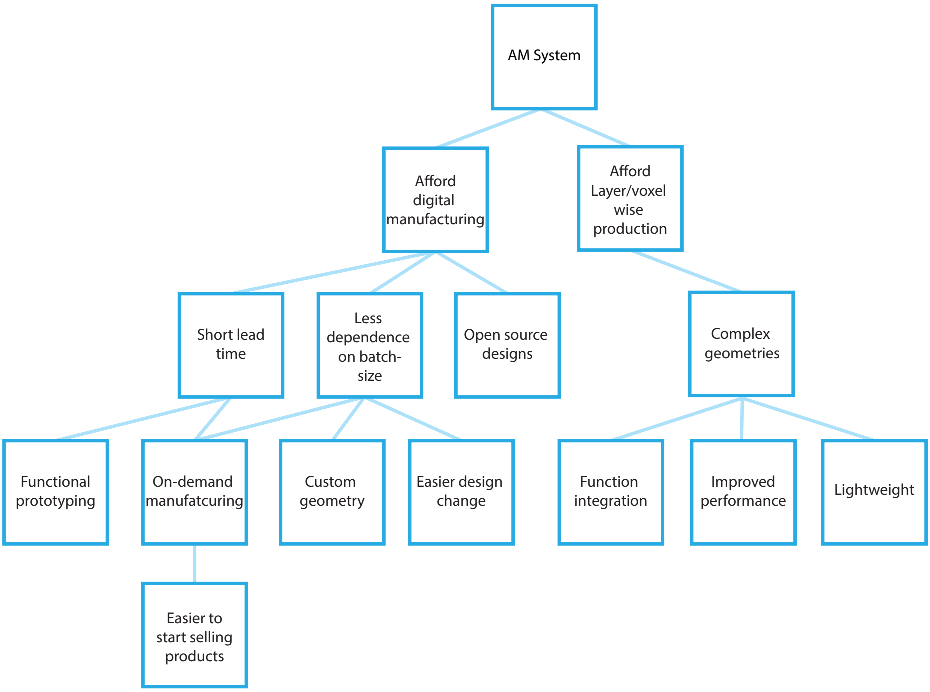

Figure 25 Pioneers' AM affordance structure.

3.2.3.2 Discussed theme: Design rules

During the interviews, most of the participants indicated that there is a lack of formal design rules for AM, and that many design rules for AM are still unknown. As a result, most designers at the pioneering companies make intuitive choices when designing a product or part. Design rules are occasionally documented based on experience. Therefore, most of the design for AM knowledge and expertise within the companies is available only within the minds of the designers. The usage of design rules that have been published in literature, as discussed in Research Cycle 1, was not observed. A pattern that became noticeable at all companies is that the designers usually chose an AM technology at the beginning of the design process, and tailored their design towards it. This choice of AM technology is usually intuitive.

Two of the visited companies are working on a systematic development of design rules in-house. However, because AM processes differ significantly in manufacturing principle, their design rules are also different. This makes the development of a complete set of design rules for all AM technologies a challenging task.

The theme *Design Rules* is strongly related to the theme *Issues*. For example, a print can fail when some walls of the design were modeled too thin. This can be either regarded as a sign that a design rule was not respected, or as a sign that the AM process is still immature and unable to manufacture such geometry. With the continuously developing AM technologies, the question remains what issues will be solved, and which aspects will remain as design rules. It is however clear that design rules are constantly evolving.

3.2.3.3 Discussed theme: Process-related parameters

Participants indicated that within the companies it is well understood that (apart from the designed geometry, chosen AM system, and specified material) the AM process-related parameters influence the final properties of the part. However, how these parameters influence the result is still not completely understood. In just one of the four companies (Company 2), designers are actively involved in setting the process-related parameters, such as slicer settings. This is not the case in other companies, where the designers are only involved in designing the geometry, choosing the AM system, and assigning the material. In these companies, only the technicians who operate the AM machines are involved in setting the process-related parameters, which is usually an iterative procedure. A sketched scenario from one of the visited companies provides an illustrative example:

> *"If a design comes out of the AM machine not as intended, or even failed, the design either goes back to the designers for adjustments, or the technician attempts to manufacture the part again with adjusted settings. For Powder Bed Fusion systems, laser power and speed are occasionally adjusted. Part orientation is an obvious parameter and often specifically chosen by the technician based on the design."*

3.2.3.4 Discussed theme: Issues

During the coding of the interviews, many topics that were mentioned by the participants were characterized as problems, or issues. The issues expressed by participants were categorized into issues regarding the design tools, AM systems, the final (printed) results, and materials for AM. The many issues that were discussed indicate that AM technologies are still immature and provide signs of required developments.

Issues related to design tools

Although the AM systems used are able to produce complex geometries, several participants indicated that many limitations arise when modeling and representing complex geometries in CAD software. Issues include very large file sizes and computer crashes as a result of this. Only in Company 1, participants indicated that AM-specific software is used. Other companies use regular, commercially available CAD packages, which, according to the participants, lack specific AM support.

Some of the issues are related to the currently used file format, the STL file format. Most participants expressed that they experience regular issues with this file format. A common problem is the occurrence of faulty meshes and extremely large file size when complex geometries are represented.

Related to the topic of *design rules*, participants indicated that it is currently difficult to imagine what the properties of the AM part will be while making a 3D CAD model.

Issues related to AM systems

Participants expressed that they experience issues with the currently available AM machines. It was mentioned that current AM machines have not been designed as production machines, and therefore cause various issues when these are used for production. Mentioned issues include bad print-process control and the requirement of significant manual labor. For example, removing manufactured parts from the build tray and removing support material are very labor-intensive processes.

Also, the accuracy and reliability of the AM machines were mentioned as aspects that require improvements. Inconsistencies of manufactured parts were often mentioned. For example, the location of a part in the build tray of a Powder Bed Fusion system has a significant influence on the dimensional accuracy of that part. Advanced users in Company 1 are aware of this and compensate for such deviations in the CAD file by altering the designed geometry. The opinion was expressed that the development of the AM machines is slower than expected and, as stated by one participant "ownership of an AM machine requires tender love and care in order to obtain good results."

Participants also experience issues related to the processing of the 3D files. These problems occur because of the limitations of the file format (STL) used but also because of the way the printer-specific software handles the files. For example, very complex geometries lead to slicing errors.

According to participants from Company 1, the material costs for AM are too high. The build quality and durability were expressed as relatively low. Other mentioned problems regarding the printed results are anisotropy, warping, and overall low accuracy. As stated by one participant "objects that are on the edge of what is possible do not always succeed".

Issues related to material palette for AM

Participants expressed the desire to use a larger set of materials than is currently available. The limited palette of materials was mentioned as a limiting factor of what the companies can achieve. It was also identified as a factor that is slowing down overall developments in AM applications. The overall range of material suppliers available for AM, as well as the material selection for each individual AM system was mentioned as a problem.

Furthermore, some AM systems are designed to process only the materials supplied from the vendor, limiting the palette even further. The current material costs are considered very high compared to material costs in traditional manufacturing.

Issues related to material properties for AM

Apart from the palette of materials for AM, the properties of the available materials are considered a major problem. Participants mentioned that many materials are not suitable for manufacturing because the mechanical properties are inferior to the properties of materials that are common in traditional manufacturing. While the properties of AM materials are sufficient for many prototyping applications, this is not the case for manufacturing end products. Also, problems with the materials during the AM process were mentioned. For example, some materials shrink during the AM process, which can lead to distorted printed parts.

Only materials for Selective Laser Sintering (Powder Bed Fusion) and Fused Deposition Modeling (Material Extrusion) were identified as coming close to the materials that are used in traditional manufacturing. Other technologies use materials that simulate properties of engineering materials.

Participants from Company 1 and Company 2 observed a shift in how materials are developed and distributed. An increasing number of AM material manufacturers offer their materials directly to the owners of the AM systems. This is expected to drive down the cost and accelerate the development of materials with improved properties. The companies visited also experiment with their own materials in existing AM systems. Since little is known about the behavior of these non-standard materials, Company 2 has set up a material-testing lab.

3.2.3.5 Role of ambitious design projects

Among the pioneering companies visited, a pattern was observed that ambitious design projects are systematically initiated. These projects appear to be key instruments to explore the affordances of AM, find limitations, and understand the design rules. In such projects, a company sets ambitious goals for a product to be manufactured using AM and assigns an active group of designers and engineers to the project. For example, one company hired external designers with very little experience in AM to come up with novel designs that were difficult to produce using traditional production methods. Engineers with experience on AM were then assigned to collaborate with the designers in order to find the boundaries of what is possible to produce.

It was observed that affordances, issues, and design rules are mainly explored as a result of these design projects and not through systematic testing, such as the efforts discussed in the previous chapter. Ownership of an AM system appears essential for such projects.

3.2.4 Looking ahead

The previous Research Cycle discussed that developments of AM systems that allow local variation of material properties are considered to be among the AM developments that could be most disruptive for industrial design. However, the most often mentioned AM affordances by the participants were related to customization and the possibility to manufacture geometrically complex parts. The utilization of multi-material functionalities was not mentioned as an important topic that the pioneering companies are currently working on. This could be explained by the still immature nature of commercially available multi-material AM systems and the context of the visited companies. Even though the companies are interested in the long-term developments and impact of AM, the participants are dealing with the current hands-on issues, giving less thought to applications that cannot be capitalized on the short term. When asked about multi-material printing, two participants indicated that, for now, the materials of multi-material printers are not durable enough to make final products.

3.3 Design experiments

3.3.1 Motivation

Because of the current limitations of AM, such as high material cost, productivity and durability, not all AM affordances are yet feasible in a commercial setting. For example, while it was discussed as an essential development in Research Cycle 1, it was found from the pioneers' lessons that AM systems which have the ability to locally vary material properties are not applied in industry. Therefore, from the pioneers' lessons, little could be understood regarding the future possibilities and limitations of designing for such systems.

A series of design experiments were organized to explore the utilization of AM affordances, which were not yet commercially feasible. In these design experiments, challenging design briefs were formulated that focused on customizable products and, where possible, included local variation in material properties. Also, effort was made to allow the designers performing the design experiments to integrate the control of process-related parameters into the design process.

Considering the on-going developments in AM processes and materials, as discussed in the Introduction and Research Cycle 1, issues with durability and material costs are assumed to be significantly reduced in the coming years. Contrary to an industrial setting, as is the case with the pioneering companies, these assumptions allowed the design of envisioned product concepts that utilize immature AM principles.

3.3.2 Method

Four design experiments were performed, of which three were performed as the thesis assignment by MSc students of the Faculty of Industrial Design Engineering of the Delft University of Technology under supervision of the author of this thesis. After completion of the design experiments, the design process was analyzed. In the analysis, the focus was on understanding the design methods, procedures, and instruments that were used by the designers. In this chapter, each design experiment is discussed, including the initial design brief, what the resulting product encompasses, and what procedures and instruments were used to achieve the result. The projects had different contexts and targets, but all explored customizable products produced using AM.

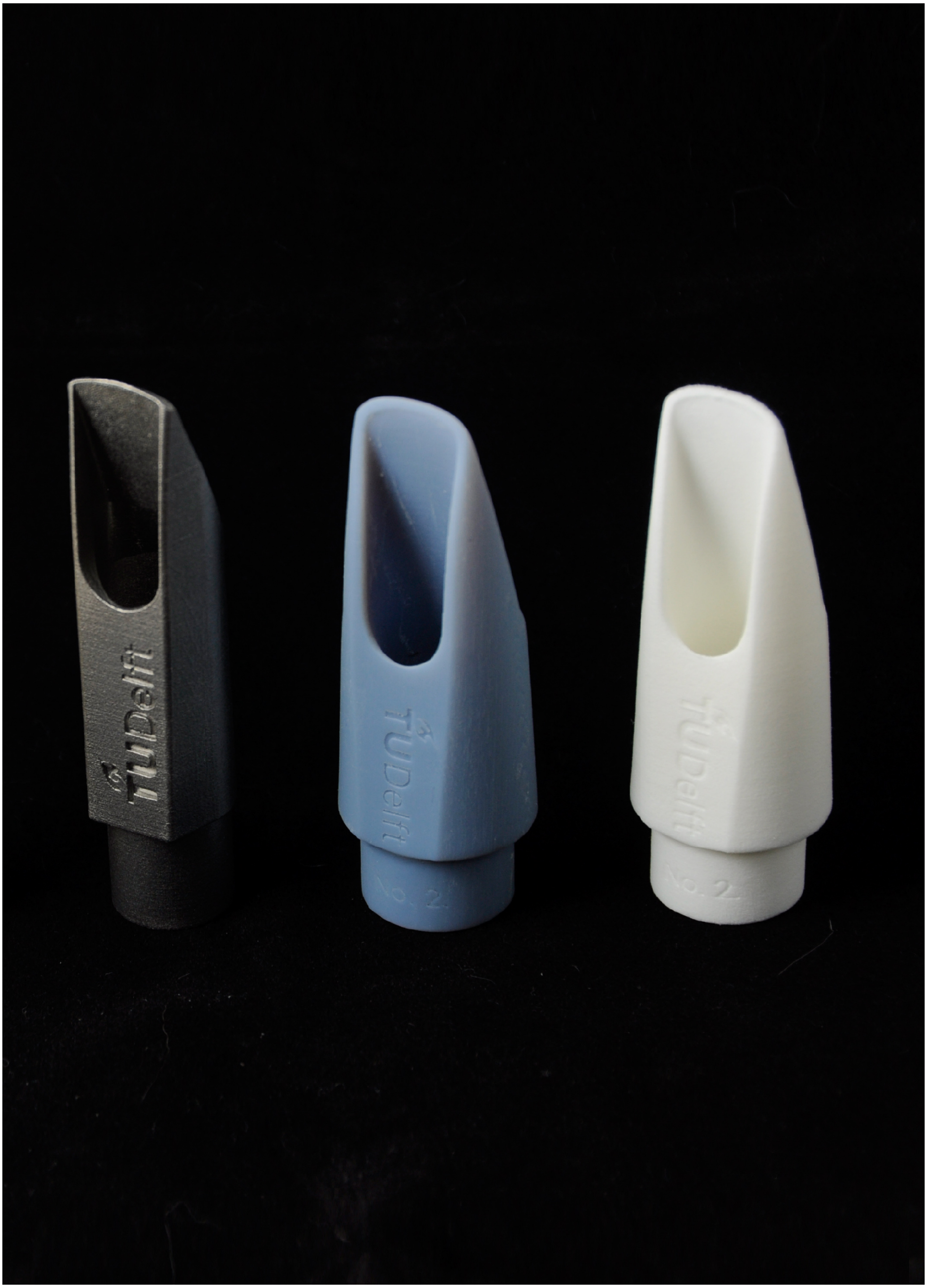

Figure 26 Various saxophone mouthpiece designs made on different AM systems (Doubrovski, Verlinden, Geraedts, et al., 2012).

3.3.3 Design Experiment 1: Saxophone mouthpieces

3.3.3.1 Brief description

The inner geometry of a saxophone's mouthpiece has a strong influence on the response, timbre, and intonation of the musical instrument. AM offers advantages in terms of reducing production costs for customized mouthpieces and allowing the construction of inner geometries that are difficult or impossible to manufacture by traditional machining. The goal was to develop a mouthpiece that can be customized given the user's preference on sound and playability.

The assumptions regarding the future developments of AM technology that were made for this design experiments are that the following will be available in the near future:

- *Materials that are safe for long-term contact with the human body*
- *Materials that are sufficiently durable for prolonged use as a saxophone mouthpiece*

Experiments were performed to understand the benefits and limitations of different AM technologies for this application. Also, different AM systems, materials, printer settings, and build orientations were tested. Figure 26 illustrates a collection of mouthpiece geometries fabricated on different AM systems.

3.3.3.2 Conceptualized result

The conceptualized result is a parameterized model of a saxophone mouthpiece, the geometry of which is adapted given a user's preference for sound and playability (Figure 27). This was elaborated for a number of acoustic properties and geometries. To fully develop the concept, more knowledge is needed on how the inner geometry influences the sound and playability of the instrument. Also, a better understanding is required on how musicians express their preference. As a prototype, a parametric 3D model was developed in which the tip opening of the mouthpiece (an important variable influencing the playability) can be adjusted.

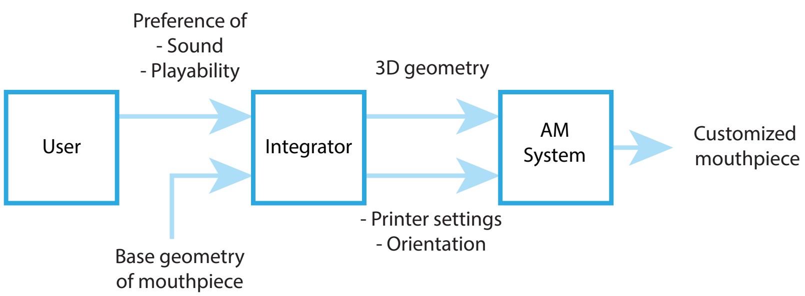

Figure 27 Conceptualized workflow with integrator for custom saxophone mouthpieces.

Figure 28 Prototype illustrating use of Freeform Surface Interfaces. Designed by Steve van Bennekom (Doubrovski, Cencen, Bennekom, Verlinden, & Geraedts, 2014).

3.3.4 Design Experiment 2: Freeform surface interfaces

3.3.4.1 Brief description

At present, constituents of product interfaces are separate parts, such as buttons, scroll wheels, indicator lights and flat-panel displays embedded in a housing. As shown by Willis et al. (2012), Material Jetting AM processes offer a possibility of manufacturing double curved displays by printing optical light guides in complex subsurface geometries. This design experiment sought to explore the implication of printable Freeform Surface Interfaces (FFSI) in the design of interactive products.

The assumption regarding the future developments of AM technology that was made for this design experiments is:

– *The resolution and material properties of multi-material AM will improve to allow manufacturing light guides that have significantly less signal loss.*

During the design process, the possibilities of manufacturing structures that influence the optical properties of the material were explored using various AM systems. Based on experiments and literature, the principle of light guides for freeform surface interfaces was used.

3.3.4.2 Conceptualized result

A steering wheel with a freeform surface interface was designed and manufactured (Figure 28). The steering wheel was a demonstrator of a conceptualized workflow that generates the 3D geometry for freeform surface interfaces given the input of 1) a base geometry, 2) target surface for the interface and 3) location of light source (Figure 29). The automated generation of the light-guide geometry still remained a challenge and needs further development.

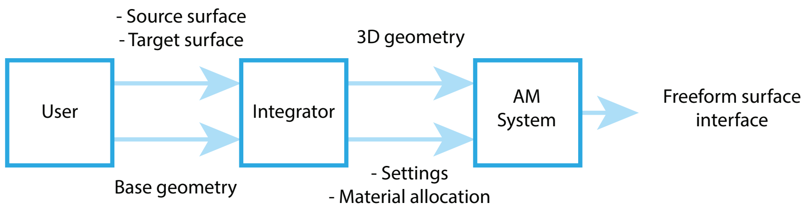

Figure 29 Conceptualized workflow with integrator for freeform surface interfaces.

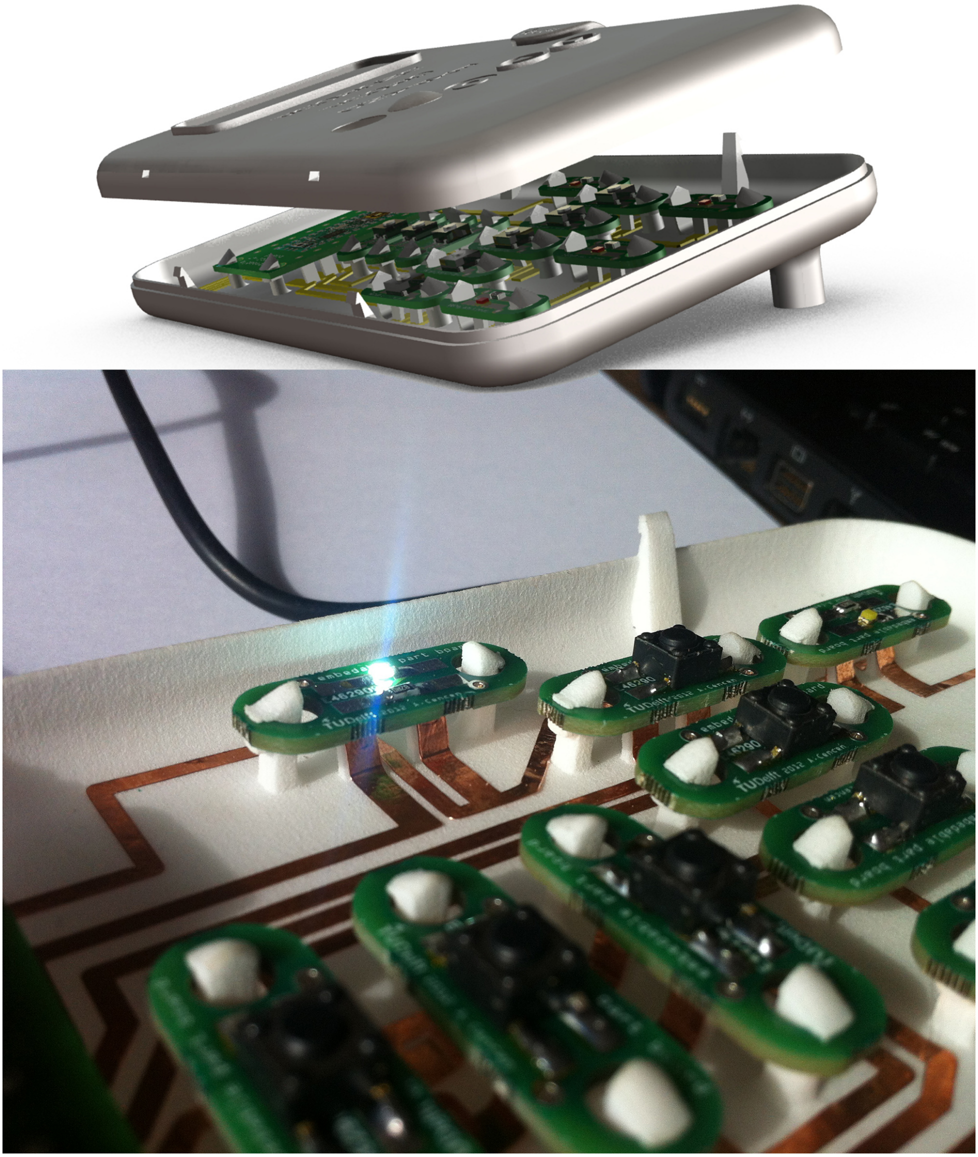

Figure 30 Prototype illustrating use of embedded electronics. Designed by Argun Cencen (Doubrovski et al., 2014).

3.3.5 Design Experiment 3: Embedded electronics

3.3.5.1 Brief description

At present, products that include electronic parts typically contain printed circuit boards (PCBs). These PCBs are usually flat and therefore impose a shape on the product itself. AM systems that can combine conductive materials with plastics potentially can eliminate PCBs as discrete components. Instead, elements of the product itself could be used to house the needed components, as demonstrated by Lopes et al. (2012).

The assumption regarding the future developments of AM technology that was made for this design experiments is:

- *The possibility to manufacture plastic parts with conductive traces will become commercially available in the near future. (Three years after completion of this project, Voxel8 ("Voxel8," n.d.) printer was announced)*

During the design process, various principles were explored to combine the housing of a product with electrically conductive material.

3.3.5.2 Conceptualized result

The conceptualized result included the materialization of a product consisting of two 3D Printed shells, a conductive layer, and various embeddable components (Figure 30). A setup was made consisting of a combination of different software packages, and allowed a customizable design to be made in which the user indicates the type and location of buttons and other components. The devised workflow (Figure 31) then generates the required geometry for the electronic components and circuit layout. As a proof of concept and demonstrator of the principle, a customizable computer controller was designed and manufactured. The conductive traces were digitally manufactured using a vinyl cutter, but still required manual assembly.

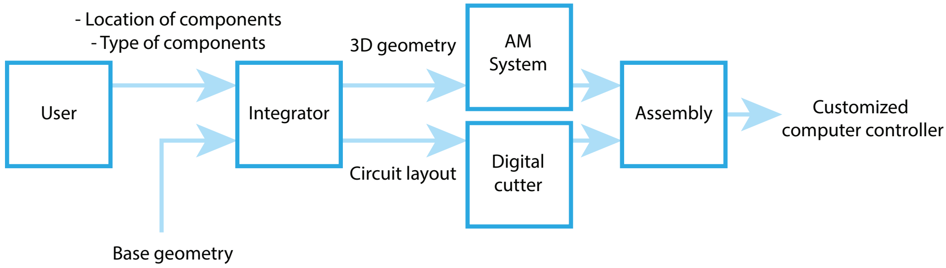

Figure 31 Conceptualized workflow with integrator for freeform surface interfaces

Figure 32 Developed prototype illustrating use of 3D printed textiles. Designed by Kirsten Lussenburg (Lussenburg et al., 2014).

3.3.6 Design Experiment 4: 3D printed garments

3.3.6.1 Brief description

Garments belong to a product category in which both the functional and experiential aspects are crucial. This project had the ambition to target both of these aspects in a customizable, digitally fabricated garment (Lussenburg, van der Velden, Doubrovski, Geraedts, & Karana, 2014). The Material-Driven Design approach (Karana, Barati, Rognoli, & Zeeuw van der Laan, 2015) was adopted for this project.

The assumption regarding the future developments of AM technology that was made for this design experiments is:

- *Materials that are suitable for everyday use as clothing will be developed*

During the early phases of the design process, various tests were made, testing different AM systems, materials, structures and machine settings. Several possible designs were created and their feasibility as a 3D Printed textile was evaluated.

3.3.6.2 Conceptualized result

A concept was developed by adapting a pattern that resembles lace. The structure was manufactured using Material Extrusion. The pattern has a distinctive visual appearance and can be locally adapted by varying the size and thickness of the structure. As a demonstrator of this principle, a corselet was designed and manufactured (Figure 32). The envisioned integrator applies the base pattern onto a 3D scanned geometry of the body. The output of the integrator is a custom geometry of the corselet combined with locally varying structure (Figure 33). Locally changing the parameters of the structure allowed varying the mechanical properties. In some areas a stretchable structure is required, while in other areas more support is needed which was achieved by locally varying the stiffness of the structure.

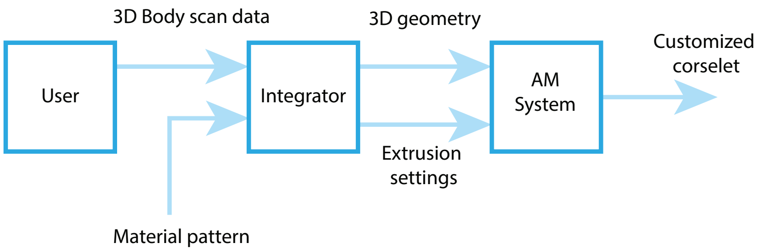

Figure 33 Conceptualized workflow with integrator for 3D printed garments.

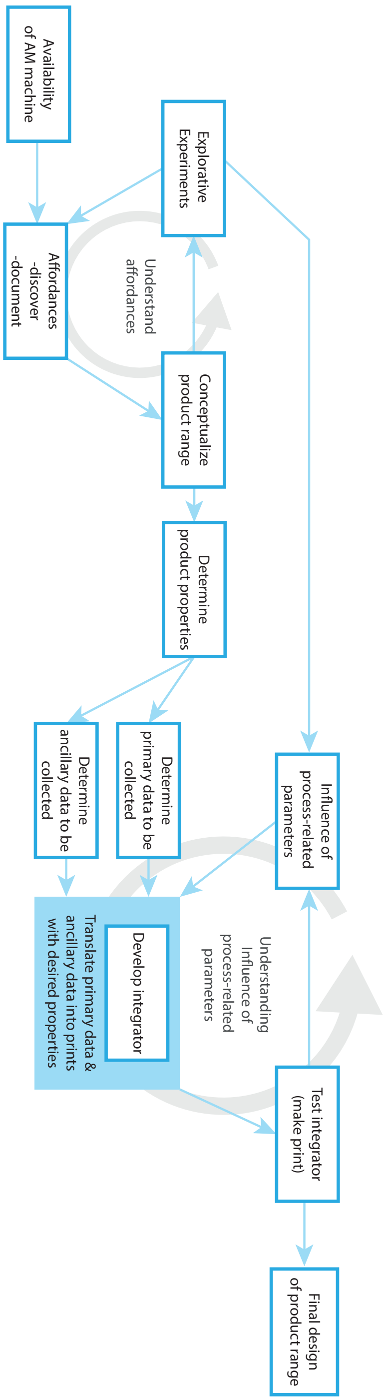

Figure 34 Procedure derived from design experiments.

3.4 Observations from design experiments

3.4.1.1 Customizable design represented as integrator

As the developed concepts contain design elements that are customizable, the workflow contains the process of integrating the basis of the design (primary data) with variable data (ancillary data), usually originating from user input. This *integrator* is a critical element in all design experiments, and the instrument for this integration has been -to some extent- developed for each design experiment. The ancillary data can encompass a wide range of data types, leading to different kinds and levels of customization. For example, the ancillary data for the 3D printed textiles is anthropometrical data from a 3D body scan, while in the case of the saxophone mouthpieces, the ancillary data is an expression of desired sound quality. Yet another type of ancillary data is used in the case of the computer controller with embedded electronics, where the user can indicate the location and type of buttons. The different types of ancillary data lead to different needs for how this data is processed in the integrator. The output of the developed integrators was observed to encompass a combination of the geometry, material composition and elements of the AM process-related parameters. An overview of the affordances utilized in the design experiments is provided in Table 3.

Design experiment	**Custom Geometry**	**Complex Geometry**	**Local property variation**
Saxophone mouthpieces	X	X	
Freeform Surface Interfaces	X	X	X
Embedded Electronics	X		X
3D Printed Textiles	X	X	X

Table 3 Use of affordances in design experiments.

The design experiments were result driven; for each experiment, a target was formulated containing both product requirements and the AM affordances intended to be exploited. The workflow for each project was developed specifically for each experiment to achieve the specific targets. The analysis of these developed workflows formed the basis for the reference model, which is a formulation of the existing situation, as described in the Design Research Methodology (Blessing & Chakrabarti, 2009).

By analyzing the design processes of the design experiments, a schematic overview of the steps taken during the design experiments was formalized, presented in Figure 34. Two circular sub-processes, or *loops* can be identified; the initial loop is related to *what* is being designed and fabricated, while the second loop is related to *how* the customizable design is realized and manufactured.

3.4.1.2 Loop 1: Understanding affordances

During the conceptualization phase of the design experiments, a cycle of "understanding affordances" was identified. In this loop, the designers sought to match the possibilities of the AM machine with the design brief.

3.4.1.3 Loop 2: Understanding influence of process-related parameters

The second loop that was identified is the cycle of "understanding the influence of the process-related parameters". The development of the integrator took place in this loop. During this loop, one or more prototypes were made. These prototypes served to evaluate 1) the base-design (the primary data), 2) how the design can be customized (what ancillary data should be collected), 3) how the data is integrated to form the customized products, and 4) how –apart from the geometry and material– the process-related parameters can be manipulated to obtain the desired properties.

3.5 Conclusions

In this Research Cycle, a series of interviews was conducted with employees who work at pioneering companies. Also, four design experiments were performed, intended to yield first-hand understanding of the adequacy of the available design instruments, methods, and procedures. In addition, the prototypes fabricated during the design experiments proved to be valuable technology demonstrators. These demonstrators supported the communication of this research beyond the academic landscape to an audience of tens of thousands through online platforms, design exhibitions, and other public events.

Below, the conclusions of this Research Cycle are discussed. In the next Research Cycle, the findings were further analyzed to formulate a proposed DfAM methodology.

3.5.1 AM Affordances in industry

The affordances of AM that participants mentioned most often during the interviews are related to geometrical complexity, function integration, customization, and short lead-time. These are also the affordances that were most often mentioned as having been applied in projects performed by the pioneers. These and other mentioned affordances are interrelated and were categorized into a hierarchal structure, which is illustrated in Figure 25.

Based on the findings in Research Cycle 1, AM systems that have the ability to locally vary material properties were considered as an important development. Various novel applications were found in literature. However, the AM affordance of local property variation was not found to be applied by the participants in industry. The current quality and durability of AM systems with multi-material capabilities appear to be the reasons why the pioneers do not yet utilize this.

3.5.2 Understanding current design processes for AM

It was understood from the participants' remarks that within their companies knowledge on design rules for AM is seldom systematically explored and formally documented. Instead, designers accumulate knowledge on design rules through experience and rely on intuitive choices. Ambitious design projects are often initiated within the companies to gain such knowledge and experience.

The importance of process-related parameters was also recognized by participants. Participants expressed that designers and engineers are aware that process-related parameters strongly influence the final properties of the manufactured parts. However, designers are usually not involved in the steps in which process-related parameters are considered. In one of the four companies, where small teams work on projects, designers work closely with machine operators to fine-tune both the design and process-related parameters to obtain the desired result of the manufactured product.

In the design experiments performed, several process-related parameters were incorporated in the design process. The features and properties that were achieved though the definition of process-related parameters were also among the elements that were customizable. This underlines the importance of process-related parameters in the realm of customizable products. During the design experiments, it was necessary to employ and devise cumbersome procedures in order to include process-related parameters in the designs. This was considered one of the indicators of the need for new design tools for AM.

In the design process of the design experiments, two circular processes were identified. In the first cycle, the affordances of the AM system were explored in relationship to the design brief. In the second cycle, the integrator was developed, considering what user data should be collected and how it should be processed to output the customized design. This cycle also sought to investigate how the desired properties can be achieved, by manipulating the design, material, or process-related parameters.

3.6 Discussion

The companies visited represent a variety of markets, and include the largest players in AM industry. However, the scope of this research allowed only a limited number of participating companies to be visited and a limited number of participants to be interviewed. Therefore, caution is required in drawing conclusions and generalizing the results from the interviews. Also, the topics that were discussed during the interviews were analyzed based on occurrence, while the context in which these topics were mentioned is also of importance.

It also has to be noted that the design experiments were performed either under supervision of the author or performed by the author himself. While this posed a risk of subjectivity, it also provided an opportunity to get first-hand understanding of the possibilities and limitations of the workflows with a focus on topics that were found to be important in previous chapters.

Chapter 4

Research Cycle 3: Design methodology development

The previous two Research Cycles focused on understanding and describing the current situation. A vision was formulated on what were found to be the most promising aspects of AM. Also, the industry's views on this were explored. Furthermore, an understanding of the currently available and used design methods, procedures, and instruments was obtained from a combination of a literature study, interviews with pioneers, and by performing design experiments. As the next step, my motivation was to learn from these findings and propose a design methodology that allows designers to utilize AM technology on a new level.

4 Research Cycle 3: Design methodology development

4.1 Objective

In the previous Research Cycle, the AM application context was explored in a two-fold approach; interviews with pioneers in the AM industry and design experiments provided new insights in the current possibilities (what can be designed and manufactured), as well as limitations of AM and the inadequacy of currently available design tools, methods, procedures (how it can be designed and manufactured). By analyzing the design experiments and the findings from the pioneers' lessons, the aim of this Research Cycle was to derive a design methodology for AM.

4.2 Approach

To create a framework for the methodology, an underpinning theory was formulated. As part of this theory, a Reference Model was developed, corresponding to the Design Research Methodology approach described by Blessing and Chakrabarti (2009). The reference model was used as a means of describing the current situation. The reference model was derived from the findings of the design experiments and insights from the pioneers' lessons. The underpinning theory, including the reference model, guided the development of the methodology

When deriving a methodology from current practices, it is important to consider the limitations of the currently available instruments. It was found in Research Cycle 2 that many elements in design and fabrication for AM are still in their infancy. This is the case for available materials for AM, AM systems, CAD software, and file formats. Considering the developments discussed in Chapter 2, a methodology covering the currently available instruments has the risk of becoming obsolete within a short period. While it was not within the scope of this research to develop a complete set of instruments, the methodology still needs to remain relevant even after major elements of AM have matured. Therefore, the aim was to derive a framing methodology whereby the instruments can be further developed while the overall strategy remains the same. A framing methodology is defined as "… a construct that defines the way of reasoning, the methodological approach, and the process flow …" (Horvath, 2008). It does not prescribe the exact methods and procedures; it introduces a strategy of reasoning.

4.3 Underpinning theory

The development of a design methodology requires an underpinning theory. This theory is discussed from both the product perspective and the designer perspective.

4.3.1 Product perspective (what things are designed & printed)

The topics discussed during the interviews with pioneers from the AM industry were divided into 4 main themes. The theme *affordances*, which is defined in Chapter 1 concerns unique aspects of AM that allow designers to obtain unique results in a manufactured part or product. The affordances that were identified were categorized into a hierarchical overview and divided into two categories; 1) affordances related to the digital nature of AM, 2) affordances related to the layer/voxel-wise build-up of objects. The digital nature of AM affords a significantly more economic manufacturing of small series and one-off products, giving the promise of large-scale on-demand and customized fabrication. The layer/voxel-wise build-up principle of AM affords the manufacturing of highly complex geometries and local variation of (material) properties without significantly increasing production costs.

From the interviews with the pioneering companies it was found that results afforded by the digital nature of AM and the voxel/layer wise build-up included custom products and function integration through complex geometries. Local variation of (material) properties was not found to be an affordance that currently plays an important role at the visited companies. However, three of the four design experiments conducted in Research Cycle 2 illustrated the value of combining both local variation of properties and custom geometry. Also, as found in Chapter 1, an increasing number of commercial AM systems that allow local property variation are becoming available. In the context of this research, it was stated that the challenge of developing a comprehensive DfAM methodology for consumer durables lies in successfully integrating the digital and voxel/layer wise aspects. This means that the methodology should support designers to utilize affordances that are the result of both of these aspects, including combinations of these, which is illustrated in the "affordance triad" in Figure 22.

4.3.2 Designers perspective (how things are designed & manufactured)

4.3.2.1 Reference model: graphical representation of the current situation

As a means of describing the findings of the current practices of DfAM, a graphical representation was used. The principles of the representation were based on the "Reference Model" as proposed by Blessing and Chakrabarti (2009). The reference model is composed of influencing factors, which include attributes and their relationships. An influencing factor is an aspect of the existing situation that influences other factors (Blessing & Chakrabarti, 2009). In this work, the relationships between the factors are illustrated using arrows. The signs at the ends of the arrows describe how values of attributes influence the linked factors. The factors and their relationships were formulated based on the findings from previous chapters. Prior to deriving the complete reference model, partial reference models were formulated, which are discussed below.

4.3.2.2 Understanding affordances

When the design experiments were conducted, there was no commercially available instrument that provided documented and accessible information on affordances of AM systems. The lack of an overview of the affordances of AM was also mentioned by the participants of the interviews, as discussed in the previous Research Cycle. The prototyping that was performed in the early phases of the design experiments was partially necessary due to this limited overview and accessibility of AM affordances. These experiments can provide the designer with a better understanding of the possible design features. In turn, a higher level of understanding of AM affordances can lead to a higher level of utilization of these affordances. These relationships were described using a partial reference model on factors related to affordances and is illustrated in Figure 35. Maidin et al. (2012) have shown that providing an instrument that communicates design features afforded by AM can support designers to incorporate such new features into their designs.

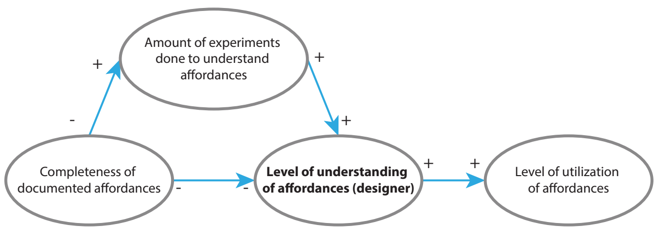

Figure 35 Partial reference model regarding AM affordances.

4.3.2.3 Adequate control over part properties

Process-related parameters, which were introduced in Research Cycle 1, include parameters such as printer settings, slicer settings, tool-path settings, and printing strategy. As discussed earlier, process-related parameters strongly influence the final properties of a manufactured part. This is in line with the process-structure-property relationship, as discussed by Rosen (2007). It was understood from literature and the design experiments that a higher level of control over the process-related parameters in the design process can result in more control over the (miso-meso-macro) structure of the manufactured part. In turn, this can provide an unprecedented control of the final properties. The partial reference model in Figure 36 illustrates the observed influencing factors for this. The level of control over part properties is also influenced by the currently available CAD tools and 3D file formats. For example, common CAD software packages generally allow geometry to be defined as a boundary representation. Volume-based definition of variations in properties are not possible. Commonly used 3D file formats for AM also have this limitation.

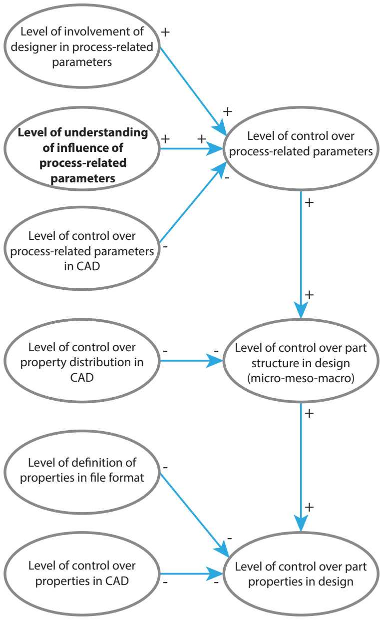

Figure 36 Partial reference model, control over part properties.

4.3.2.4 Understanding influence of process-related parameters

Even though it was understood that process-related parameters influence the properties of a manufactured part, how these principles could be used during the creative phases of the design process was not yet understood. Also, the explorative experiments in Research Cycle 1 and design experiments in Research Cycle 2 showed that there is insufficient information on the influence of process-related parameters on the physical properties of the part. To better understand this influence, numerous prototypes were made in the early stages of the design experiments. The expected relationship of influencing factors is illustrated in Figure 37. This partial reference model illustrates that the designers' level of control over the process-related parameters is influenced by their understanding of the influence of the process-related parameters and the level of involvement in the process-related parameters that they have in the context of their design task.

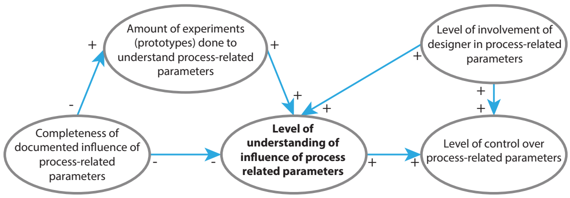

Figure 37 Partial reference model, understanding process-related parameters.

4.3.2.5 Completing the reference model

By combining the partial reference models discussed above, a complete reference model was created. This reference model is presented in Figure 38.

This model visualizes how the factors discussed influence the main factors *Level of customization* and *Usage of (other) AM affordances*. Together, these factors were thought to influence the quality and novelty of the designed and manufactured product. Obviously, many external factors can be envisioned that contribute to the novelty and quality of the product. However, these are not considered within the scope of this model.

In the design experiments, prototypes in the early phases of design projects were found to be instrumental in understanding the affordances of AM and for the designer to explore how specific process-related parameters can be used to obtain desired properties.

The importance of understanding affordances was discussed in the previous chapter. Apart from understanding AM affordances, the process of documenting, and communicating affordances were also shown to be essential elements during design for AM (Doubrovski, Verlinden, & Horvath, 2012).

Available CAD tools are severely limited in their ability to support definitions of properties, structures, or process-related parameters. In other words, designers currently work in an environment in which the AM systems they use have more capabilities to manufacture structures than can be defined in current CAD tools.

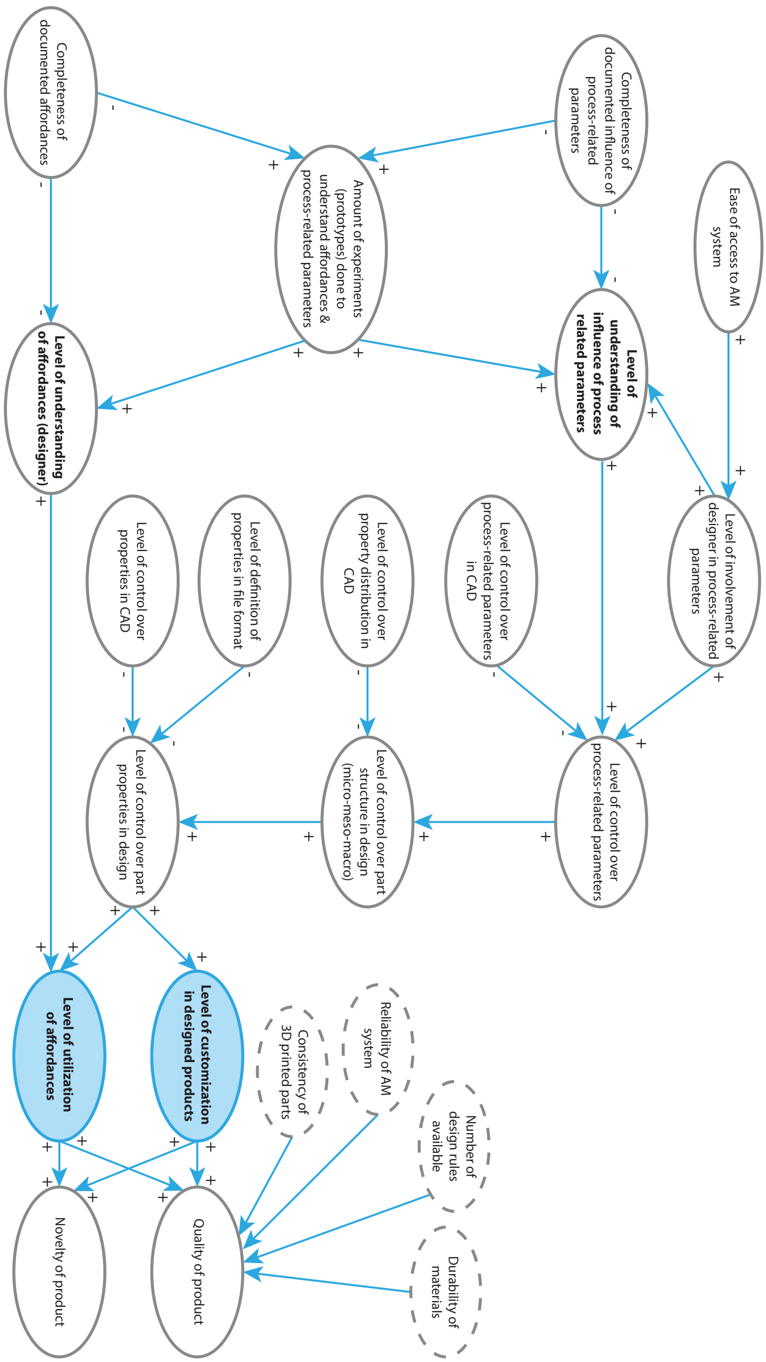

Figure 38 Reference model.

Although the theme *design rules for AM* was identified as an important topic for DfAM, the development of a complete set of design rules was not within the scope of this research and this methodology development.

From the overview of influencing factors described above, it was expected that a successful DfAM methodology should comply with the following requirements;

- *The methodology should facilitate systematic matching of AM affordances to design problems*
- *The methodology should facilitate the design and fabrication of products with customizable attributes (both custom geometry & custom properties)*
- *The methodology should facilitate design & fabrication of objects with locally adaptable intended properties*

4.4 Formulating the DfAM framing methodology

4.4.1 Impact model: desired situation

In the previous section, the reference model was used to describe the current situation. To describe the desired situation, an impact model was defined. The impact model formed the basis for the development of the methodology and was defined based on the reference model, as proposed by Blessing and Chakrabarti (2009).

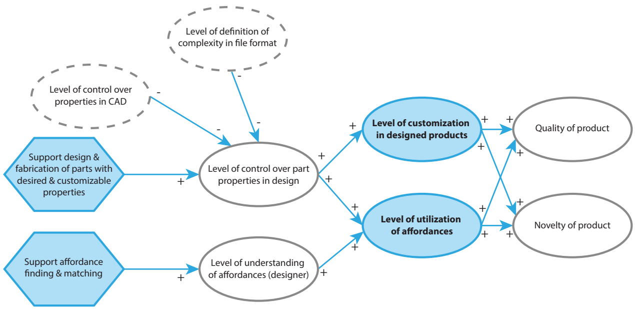

Figure 39 Impact model with design support (desired situation).

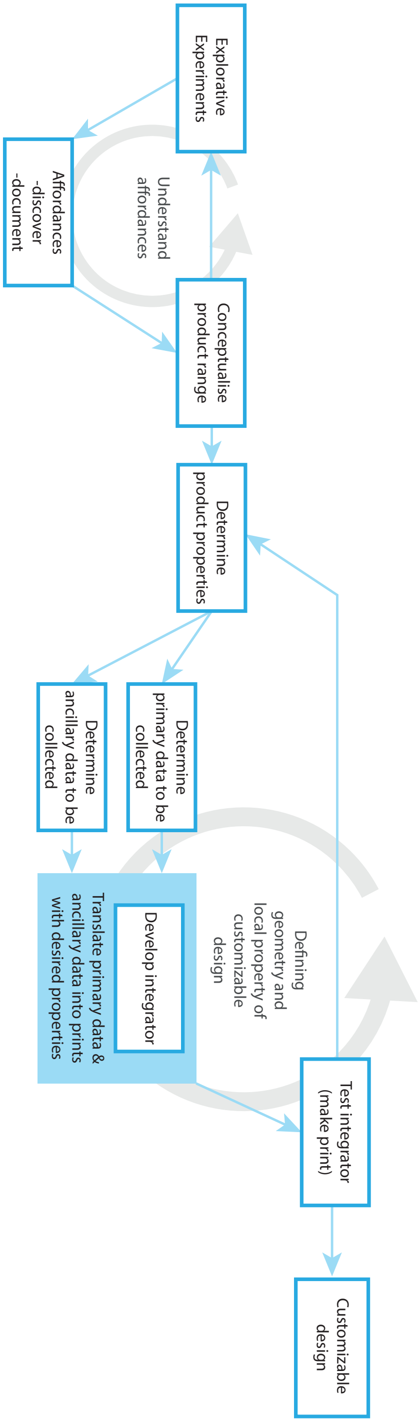

Figure 40 Proposed methodology for DfAM.

The factors described in the previous section mainly affect the *Level of customization* and *Usage of (other) AM affordances*. The two factors that influence this are the *level of control over the part properties* and the *level of understanding of affordances*. The aim of the methodology was to support designers in obtaining a better control over the final properties and in their level of understanding of the affordances. This intended design support is visualized as hexagons in the reference model in Figure 39. Other (external) factors, such as reliability of AM machines and quality of materials were left outside the scope of this research.

4.4.2 Proposed methodology

The proposed methodology is comparable to the double loop approach that was derived from the engineering studies of Research Cycle 2 and therefore also comprises two loops. The overall approach is visualized in Figure 40.

4.4.2.1 Loop 1: Understand affordances of AM

Finding and understanding AM affordances during the design experiments in Research Cycle 2, was mainly done by developing a series of explorative prototypes in loop 1. Even though the use of prototyping is likely to remain important in early phases of design, designers can be supported in understanding how AM can be used for the relevant design problem using newly developed instruments complementary to prototypes or experiments.

One possible instrument that can be used in the first loop was recently developed by (Maidin et al. (2012). This concerns a design feature database, supporting designers to utilize design features that are unique to AM. To structure the database, a taxonomy was introduced in which the top-level taxons were the general reasons for using AM technology. Another approach to document and communicate AM affordances to designers is through the use of a collaboratively edited content, as discussed by Doubrovski, Verlinden, and Horvath (2012). Since each AM system has its unique affordances and limitations, the instruments for AM affordance finding should make these differences insightful to the designers. In addition to the proposed AM selection procedures discussed in literature (Section 2.3.2.6), affordance overviews can assist designers in the selection of an AM system, in case this is not provided by the context of the design brief.

4.4.2.2 Loop 2: Define geometry and local properties of customizable design

Similar to the second loop that was identified in the analysis of the design experiments, the second loop in the proposed methodology focuses on developing the customizable design (or integrator). A future methodology was envisioned in which the designer is no longer involved in working on the level of the process-related parameters but instead develops an integrator in which primary and ancillary data is processed into products with desired customized properties. However, in the short term, the inclusion of process-related parameters in the design process is expected to remain essential, as explained below.

It has been discussed in other work that process-related parameters play an important role in defining the properties of a printed part (Rosen, 2007). This work showed that by including process-related parameters in the design process, a designer can obtain a larger set of final properties than would be available if he would only be able to design a geometry, choose an AM system, and pick the material to be used. In addition, in this research it is argued that process-related parameters are crucial elements for customization and obtaining the desired final properties of a part. However, examples showed that to achieve this level of control, cumbersome workarounds needed to be devised. This illustrates that new procedures and instruments need to be developed. To understand how these procedures and instruments could be conceptualized in a future methodology, a parallel was drawn with the workflow in a similar, yet more mature industry: 2D printing. The parallels between 2D printing and 3D printing are discussed in Inset 2.

As discussed in Inset 2, in 2D printing, the visual properties that were intended by the designer of the artwork can be produced, without the designer being involved in process-related parameters. Essential elements in the workflow that make this possible are the design software, page description language, and the raster image processor. The design software outputs a document, a printer-independent page description, which is interpreted by the printer-specific image processor. Each image processor translates the page description into printer-specific commands that ensure that each element of the page comes out visually as was intended in the design software.

In a similar manner, it is envisioned that in the near future the designer will be involved in making designs in which the geometry and local physical properties are customizable, without the need to be involved in the process-related parameters. The geometry and properties (which are 3D printer independent) are then to be interpreted by the software of the 3D printer. In this step, the printer-specific software processes the geometry and properties and determines the combination of base materials and the printing strategy that is necessary in order to obtain the required properties. Such instruments should allow the achievement of a variety of properties in the manufactured object (similar to how one 2D printer can produce millions of colors) and be independent from the manufacturing hardware (similar to how a page description file is printed visually identical on different 2D printers). Even though the workflows of 2D and 3D printing were presented as analogous, 3D printing faces a significant number of challenges to make this possible. The variety of properties that designers are used to working with and that can be achieved using AM is significantly greater than just color variation. Possible property variation includes, for example, gloss, stiffness, electric conductivity.

Academia is currently developing instruments that allow designers to specify final properties and software to process these definitions into AM manufactured objects, with promising results (D. Chen, Levin, Didyk, Sitthi-Amorn, & Matusik, 2013). Also, recent developments indicate that the industry is taking steps towards a more mature workflow. This includes Autodesk's 3D printing platform ("Spark - an open platform for connecting the 3D Printing ecosystem," n.d.) and developments in standardization of file formats ("3MF," n.d.). Even though the first instruments that allow designers to define desired properties have been demonstrated, these are not yet able to deal with customization. This means that that they do not allow designers to develop customizable designs -or integrators- in which the properties that are defined are the features that differ per user.

If the parallels between 3D and 2D printing are considered, the function of the 3D slicer has a strong resemblance to the 2D printing Raster Image Processor (RIP). One of the main functions of the RIP is to process the input, which describes how a page looks (usually in the form of a page description language like a PDF file) and output data that describes where and how the printer has to deposit ink or toner on a medium. The digital input file, which is defined by the artwork's designer, can contain vector graphics, such as text, or raster graphics such as photos and gradients, which can consist of millions of colors. Contrary to this high number of colors, inkjet color printers usually work with 4 or 6 colors of ink, while black-and-white printers have only a single ink color. To print a wider range of colors and produce gradients that appear continuous while still using a limited set of colors, the RIP applies Halftoning techniques. In a Halftone image, printed dots are varied either in size or spacing and thereby produce the illusion of a smooth gradient. Because physical machines are always prone to minor inaccuracies, this can result in small variations in ink droplet size, speed, and direction, or defect nozzles. Such inaccuracies create visual artifacts, such as color shifting. To overcome these problems, specific printing strategies are applied that eliminate visible imperfections. As the digital 2D printing industry has grown into a mature process over the past decades, this process has been optimized. The designer of the 2D artwork is not involved in setting the printing parameters or controlling the printing process on the level of printing strategy. Instead, a standardized system of color profiles, Halftoning, and optimized printing strategies ensure that text, vector images, and bitmap images are printed on paper with visual properties that match the intended properties of the designer as closely as possible. After decades of development, the digital process is able to compete with analog offset printing in terms of productivity, costs, and quality, even for larger production volumes.

Inset 2 Lessons from the 2D printing workflow.

4.5 Concluding remarks on methodology development

The aim of this Research Cycle was to derive a framing methodology for DfAM from an understanding of the current situation. This was formulated as the question:

– *What are the limitations in the available design methodologies that designers who use AM currently face?*

Based on the analysis of the design experiments and pioneer's lessons from Research Cycle 2, a reference model was developed that describes the current situation of designers who use AM as a means of manufacturing. The major factors that were identified to be the current bottlenecks are the designer's *level of control over the part properties* and the *level of understanding of affordances*. Based on this reference model, an impact model was developed, that led to the formulation of a new methodology.

The methodology contains a proposed design process, which includes elements that are derived from the existing 2D printing workflow. Given the relationship between (AM) process, structure, and properties, the aim was to give the designer more control over the properties of the manufactured products.

At the heart of the proposed methodology is a double-loop approach. The first loop concerns a procedure for affordance finding, helping the designer understand what unique design features are afforded by a chosen AM system, while in the second loop the designer is guided to develop a customizable design, or an *integrator*. This integrator combines primary data (usually 3D geometry) with ancillary data (usually some form of user data). The primary data is mainly static - identical for all users - and includes the basic features of a design, while ancillary data is dynamic and can hold user data to make a customized design. For the development of this integrator, the designer is guided by a step-wise framing of the design as an operations overview. Since the inclusion of process-related parameters in the design process proved to be instrumental in defining properties, process-related parameters are included in the integrator. This is intended to support designers to make products in which the local properties can be customized.

Chapter 5

Research Cycle 4: Validation of DfAM methodology

Related publication

Doubrovski, E. L., Tsai, E. Y., Dikovsky, D., Geraedts, J. M. P., Herr, H., & Oxman, N. (2015). Voxel-based fabrication through material property mapping: A design method for bitmap printing. *Computer-Aided Design*, *60*, 3–13. http://doi.org/10.1016/j.cad.2014.05.010

The methodology that was derived in the previous Research Cycle required a validation by applying it to design cases. However, in the scope of this research, only a limited number of design cases could be preformed, which led to the question: "How can a design methodology be validated in the scope of a PhD project?"

During the course of this project, I got the opportunity to do research at the Mediated Matter group of the MIT Media Lab. The work performed there was part of a larger on-going project of the Mediated Matter group and Biomechatronics group of the MIT Media Lab. Two results from this project are discussed as example cases in the validation of the methodology.

5 Research Cycle 4: Validation of DfAM methodology

5.1 Introduction

In the previous chapter (Research Cycle 3), a Design for Additive Manufacturing methodology was developed based on the analysis and findings of four design experiments and interviews with employees from four companies active in the AM industry. In this chapter (Research Cycle 4), the aim was to validate the developed methodology.

The section below discusses the selection of the applied validation method, adapted to fit the scope of this research. Next, the implementation of the validation is presented, which includes the discussion of the two example design cases that were used to validate the principles of the methodology.

5.2 Validation method

5.2.1 Scope of the validation

As discussed in Chapter 4, the Design Research Methodology (DRM) framework of Blessing and Chakrabarti (2009) provided an appropriate framework to map the existing situation and desired situation. Following the DRM approach, measurable success criteria need to be formulated in order to evaluate a developed design methodology. However, the goal of this work was not to incrementally improve the current situation, but to formulate a vision on how products and the discipline of design can change when AM is used as a production method. This vision was accompanied with a set of requirements for the framing methodology that was developed. For this reason, measurable success criteria were not formulated in the reference model. The introduction of a significantly novel production technology such as AM, accompanied with a new design methodology can affect many aspects. Therefore, these changes could reach beyond the scope of pre-determined measurable success criteria, as described by Eckert et al. (2004).

In general, it is practically impossible to validate a design methodology by applying it to all possible scenarios. Also, the scope of this PhD research project allowed only a limited number of example cases to be discussed. This required a validation procedure tailored to validating design methods that, while using a limited number of example cases, provides sufficient evidence to generalize the findings. The Validation Square, which was proposed by Seepersad et al. (2006), provides a framework that guides the collection and formulation of such evidence to facilitate the generalization of the usefulness of the tested methodology, which is termed as a “leap of faith”.

5.2.2 Introducing the Validation Square

The process prescribed by the Validation Square (Seepersad et al., 2006) is divided into four quadrants, as illustrated in Figure 41. The first quadrant concerns evaluating the *Theoretical Structural Validity* of the methodology. This means that the logical consistency of the methodology itself is evaluated, disregarding the example cases that are used to test the methodology. In the second quadrant, the *Empirical Structural Validity*, the appropriateness of the example cases is assessed. In the third quadrant, the *Empirical Performance Validity* is evaluated by testing the performance of the methodology by applying it to a number of example design problems (example cases). Finally, given the results from quadrants 1, 2, and 3, the goal of the fourth quadrant is to collect sufficient evidence to accept the performance of the methodology beyond the example cases.

5.2.3 Adapting and Implementing the Validation Square

The procedure of the Validation Square needed to be adapted to a procedure for the developed Design for Additive Manufacturing methodology. This section discusses how the Validation Square was tailored to this purpose, taking into account the following considerations:

- *The nature of design problems for which the DfAM methodology was developed is different from the type of problems that are discussed in the Validation Square framework. While the framework is intended for validating design methods that are targeted at concrete design problems, such as creating a lightweight part, the DfAM methodology discussed in this thesis was aimed at facilitating a broad range of design problems and creative exploration within the envisioned scope of AM.*
- *In the Validation Square framework, it is advised to apply the developed design methods to several example design problems. Within the scope of this project, there was the opportunity to discuss two example cases. The example cases were performed prior to the complete articulation of the methodology. However, the main principles of the methodology were applied in the example cases.*

Below, the approach for the procedure of each quadrant in the Validation Square is discussed. An overview of the procedure that was applied for the validation is illustrated in Figure 42.

5.2.3.1 Re-formulation of requirements

Before completing the validation using the Validation Square, it was important to re-formulate the requirements that were defined for the developed DfAM methodology. According to Seepersad et al. (2006), the requirements should be expressed in two categories; 1) requirements for the outcomes of the methodology and 2) requirements for the procedures suggested by the methodology that led to the outcomes. These requirements support the evaluation of the DfAM methodology.

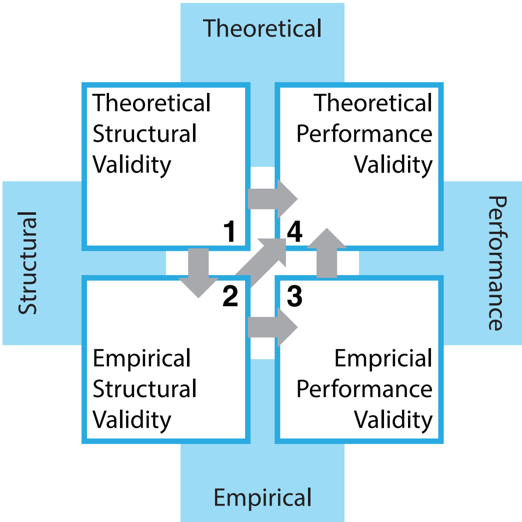

Figure 41 The validation square, adapted from (Seepersad et al., 2006).

5.2.3.2 Quadrant 1: Correctness of DfAM methodology & constructs

As described by Seepersad et al. (2006), in the first quadrant the *Theoretical Structural Validation* of the methodology is assessed. The focus of this quadrant is on the logical consistency of the DfAM methodology itself, and is therefore independent of the domain of the design problems in the example cases. The consistency was tested in a twofold approach. First, the constructs of the DfAM methodology were evaluated separately. Literature was the main source for the evaluation of the separate constructs. However, the evaluation also included references to the (partial) methods from design experiments that were discussed in Research Cycle 2 (Chapter 3). Next, the internal consistency of the entire DfAM methodology needed to be addressed. Logical arguments were used and, again, the design experiments from Research Cycle 2 were analyzed.

5.2.3.3 Quadrant 2: Appropriateness of domain and design problems in example cases

In the second quadrant, the *Empirical Structural Validation*, the appropriateness of the design problems in the example cases is assessed. In the case of this research, the design problem consisted of one domain (prosthetic sockets), which was represented by two design cases.

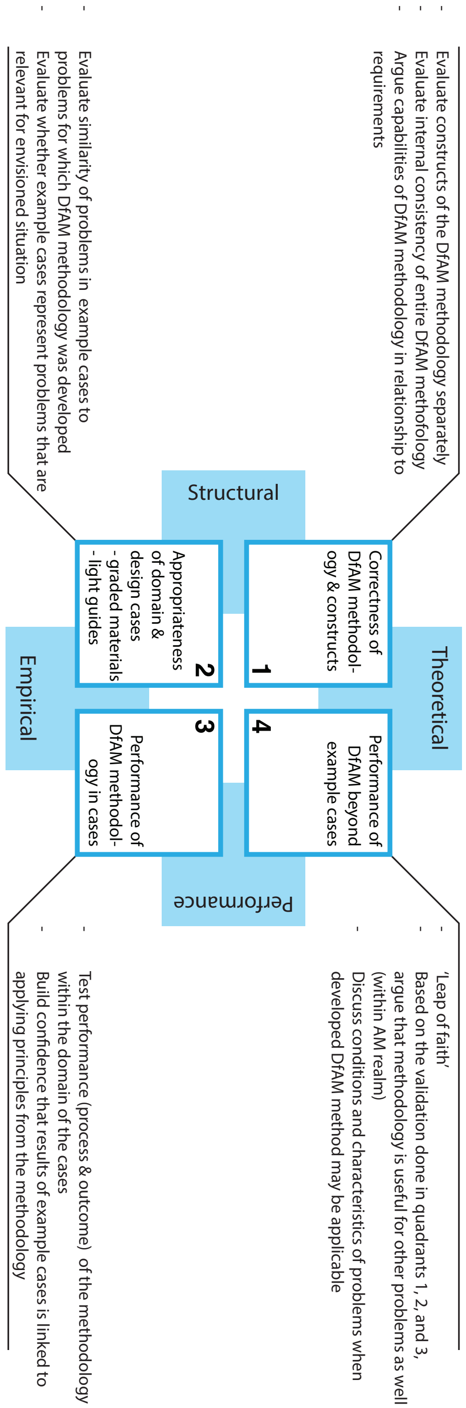

Figure 42 Overview of Adapted Validation Process Using the Validation Square.

The appropriateness of the domain and example cases needed to be assessed in two stages. First it was evaluated whether the example cases feature problems that are similar to the problems for which the DfAM methodology was intended. Next, it was evaluated whether the example cases represent problems that are relevant for the envisioned situation.

5.2.3.4 Quadrant 3: Performance of principles of the methodology in example cases

In the third quadrant, the *Empirical Performance Validation*, it was assessed how the methodology's principles performed in the two example cases. The challenge in this process was to build confidence that the results of the example cases were linked to the application of principles from the methodology. This was assessed by comparing the results of the example cases with results from a similar design problem in which the main principles of the methodology were not applied.

5.2.3.5 Quadrant 4: Performance of DfAM beyond example cases

The last quadrant in the validation process, the *Theoretical Performance Validation*, concerns accepting the performance of the DfAM methodology beyond the context of prosthetics. Based on the validation done in quadrants 1, 2, and 3, it is argued that the DfAM methodology is meaningful for other design problems as well, where AM is used to manufacture products with customizable properties. The acceptance of the general performance of the developed methodology can be considered a "leap of faith" which is facilitated by the evidence discussed in quadrants 1, 2, and 3 (Seepersad et al., 2006).

5.2.4 Prostheses as validation context and example cases

Essential in the procedure of the Validation Square is the application of the methodology on example problems *for Empirical Performance Validity* (3rd quadrant). This is done to evaluate the results of applying the method in terms of the requirements of the methodology (Seepersad et al., 2006). It was therefore important that the chosen problems were representative examples of problems for which the methodology was developed. In this work, not the entire methodology, but the main principles from the methodology were applied in the example cases.

In RC3, three affordances of AM were discussed that were considered essential in this work. These were represented using the 3D Printing Affordance Triad (Figure 22). The methodology developed in RC3 was aimed at supporting designers in developing products that utilize the combination of these three main affordances.

Numerous products can be imagined in which not just customized geometry but customization on the level of local properties is applied, including custom helmets, shoes, hearing aids, and (parts of) musical instruments. For a significant set of such products, customization is essential for their proper functioning and not just to match the user's preference.

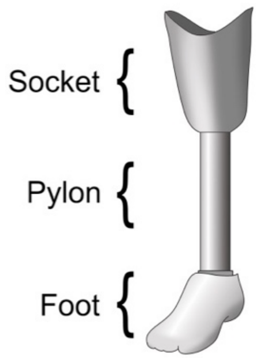

Figure 43 Overview of a lower-limb prosthesis (Doubrovski et al., 2015).

Prostheses, more specifically, lower-limb prosthetic sockets, are representative for this category, since they require a perfect custom fit in order to accommodate the user's comfort and health. Figure 43 illustrates the main component of a lower-limb prosthesis. The design cases discussed in the validation comprised the development of 3D printed prosthetic sockets. A more detailed description of issues of lower-limb prostheses addressed in the example cases can be found in (Doubrovski et al., 2015). The example cases were performed in the context of a larger project at the Mediated Matter group in collaboration with the Biomechatronics group of the MIT Media Lab. The Biomechatronics research group has a long history in research on prosthetic, orthotic, and exoskeletal design, and other topics aimed at human rehabilitation and augmentation.

Two design problems were addressed as the example cases for the validation:

- *Design problem 1: Develop a customizable lower limb socket that has a superior fit compared to traditional lower limb sockets (master thesis project by Elizabeth Tsai)*
- *Design problem 2: Develop a customizable lower limb socket with embedded pressure sensing functionality, which is incorporated into the 3D printed material (design performed by the author of this thesis).*

5.3 Execution of validation by using the Validation Square

After discussing how the Validation Square procedure has been adapted for this research, in this section the validation procedure itself is discussed for each of the four quadrants.

5.3.1 Formulating requirements

Prior to deriving the methodology in Research Cycle 3, several requirements for the methodology were formulated.

- *The methodology should facilitate systematic matching of AM affordances to design problems*
- *The methodology should facilitate the design and fabrication of products with customizable attributes (both custom geometry & custom properties)*
- *The methodology should facilitate design & fabrication of objects with locally adaptable intended properties*

The requirements were broken down into more specific requirements for both the outcome and the procedure of the methodology to support the quadrant-based validation process.

Requirements for the outcome of the methodology:

- *The utilization of a combination of AM affordances mentioned in the AM Affordance triad should be supported:*
    - *It should support the development of designs with customizable attributes*
    - *It should be possible to include local variation in material properties (material complexity) in the customizable attributes*

Requirements for the process of the methodology:

- *The designer should be supported in a systematic process to find, discover & document affordances of AM.*
- *The designer should be able to define intended local properties of products*
- *The designer should be supported in developing products with customizable attributes*

5.3.2 Quadrant 1: Correctness of DfAM methodology & constructs

In the first quadrant, the logical consistency of the DfAM methodology itself was evaluated, which is independent from the domain of the example problems.

5.3.2.1 Evaluation of individual constructs of DfAM methodology

The methodology was derived from the analysis of interviews with pioneers and of four design experiments from Research Cycle 2. These experiments provided the initial suggestion that the capabilities of these constructs are adequate. Below, the separate constructs of the methodology are discussed.

The process of finding and matching affordances of AM to design problems was performed in the design experiments through prototypes / explorative experiments on the available AM system. These explorative experiments were performed during the early stages of design and provided the designer with insights of the possibilities of the specific AM system. A study on affordance finding through explorative experiments and documenting using a wiki environment has been presented in the scope of this research (Doubrovski, Verlinden, & Horvath, 2012). A different approach, based on a database of AM design features, was presented to be helpful and inspirational during the conceptual phases of a design process (Maidin et al., 2012).

In the second loop of the DfAM methodology, the geometry and the properties of the product are defined. While it is still necessary for the designer to have a good understanding of how the process-related parameters contribute to achieving the desired properties, a definition of the goal properties is essential. Explorative experiments in Research Cycle 1 and the design experiments Research Cycle 2 showed how including process-related parameters in the design process allowed the designer to obtain the desired final properties. Novel approaches, such as the goal-based modeling approach (D. Chen et al., 2013), allow the designer to focus on the desired geometry and properties of the end result. The tool outputs geometry and material assignments. In the future, if such tools would also generate process-related parameters, designers will need to worry less about process-related parameters, and to instead focus on the desired geometry and properties of the end result.

5.3.3 Quadrant 2: Appropriateness of domain and design problems in example cases

The second quadrant addressed the appropriateness of the two example cases that were discussed for the validation.

5.3.3.1 Relevance of example cases for DfAM methodology

The first step was establishing whether the design problems of the example cases encompass similar issues as the issues for which the DfAM methodology was developed. As described in 0, the chosen example cases concerned the development of custom lower-limb prostheses. A more detailed introduction to the issues of lower-limb prosthetic sockets addressed in the example cases is discussed in (Doubrovski et al., 2015). The relevance of the chosen cases was assessed based on the requirements of the methodology.

The methodology should facilitate systematic matching of AM affordances to design problems

> The two design problems of the example cases contained several challenges that were difficult or not economically feasible to achieve using traditional (not AM) manufacturing methods. These challenges included embedding pressure sensing elements and applying a locally varying material stiffness and needed to be matched to the possibilities of the chosen AM system.

The methodology should facilitate the design and fabrication of products with customizable attributes (both custom geometry & custom properties)

> The implementation of customizable attributes was well represented in the design problems of the prosthetic socket. Custom fit is essential for the functioning of a prosthetic socket and the user's comfort and health. The design problem 1 included the development of a customizable socket where both geometry and material properties needed to be developed according to the user's anthropometrical measurements. Design problem 2 involved the development of different customizable attributes. The pressure sensing elements needed to be distributed along the surface of the custom socket given a density, which was either defined by an expert or informed by the user's tissue distribution.

The methodology should facilitate design & fabrication of objects with locally adaptable intended properties

> Both design problems required the design and definition of locally varying properties of the prosthetic socket. In design problem 1, this concerned locally varying material stiffness, while in design problem 2 transparency and index of refraction needed to be varied in order to incorporate pressure sensing elements.

5.3.3.2 Relevance of example cases in the envisioned future

As a second step in this quadrant, it was evaluated whether the example cases are relevant for the envisioned future situation; do these examples represent actual problems?

Relevance of addressed issues in the envisioned future

In Chapter 2, the expectation was expressed that important contributions of AM in the near future can come from applying AM for the production of consumer durables that require a combination of the three main affordances presented in the 3D Printing Affordance Triad (Figure 22). Many design problems that involve the development of custom-fitting products need to utilize a combination of the Triad's affordances. This is especially the case for products where not just the geometry needs to be customized, but also the properties or functionality. The domain of prosthetic sockets represents this category of products.

Relevance of addressed issues within the field of prosthetics

As the component that interfaces between the residual limb and the prosthesis, a properly fitting socket is essential for patient mobility, comfort, and health.

Conventional prosthetic sockets are fabricated today using a long, iterative, and labor-intensive artisanal process that does not utilize recent material advances and scientific instrumentation. As a result, current sockets often do not fit properly, leading to discomfort, pain, and occasionally skin breakdown in the residual limb (Johannesson, 2004).

The development of digitally fabricated sockets with geometry and material properties that are informed by digital measurements of the residual limb has been shown to provide the opportunity to improve the quality and availability of prosthetics (Sengeh & Herr, 2013). Similar improvements can be made to a wide range of products that need customization for better performance.

5.3.4 Quadrant 3: Performance of principles of the methodology in example cases

In this quadrant, the *Empirical Performance Validation*, it was assessed how the methodology's principles performed in the two example cases. Both the outcome and the process of the example cases were evaluated according to the requirements, which were defined in section 5.3.1.

5.3.4.1 Example case 1: Custom geometry and material

The utilization of one or a combination of AM affordance mentioned in the AM Affordance Triad should be supported

Aiming at reducing pressure points on the residual limb, a local variation of material stiffness was applied to the socket. The result of Example problem 1 was a process of limb tissue analysis combined with a voxel-based geometry and material generation that is derived from the limb tissue data. Two of the three AM affordances are represented in the final result: the devised workflow is an integrator, which processes user data, and outputs customized designs that utilize material complexity.

The designer should be supported in a systematic process to find, discover, and document affordances of AM technology

Documentation provided by the AM system manufacturer covered details of which and how different materials can be combined on the voxel level. The specific possibilities of the AM machine were instrumental in the development of the concept and integrator both in the first and second loop of the DfAM approach.

The designer should be able to define local intended properties of products

In the example case, the local stiffness of the socket was defined based on the data obtained by the local tissue measurements of the residual limb.

The designer should be supported in developing products with customizable attributes

The designer developed an integrator, which is built up as a procedural schematic of operations.

5.3.4.2 Example case 2: Integrating pressure sensing

The utilization of one or a combination of AM affordance mentioned in the AM Affordance triad should be supported

The final result of the design problem utilizes local variation in transparency and index of refraction to incorporate pressure-sensing elements, which are fabricated simultaneously with the prosthetic socket. This solution utilizes both the affordance of *customizable attributes* and *material complexity*.

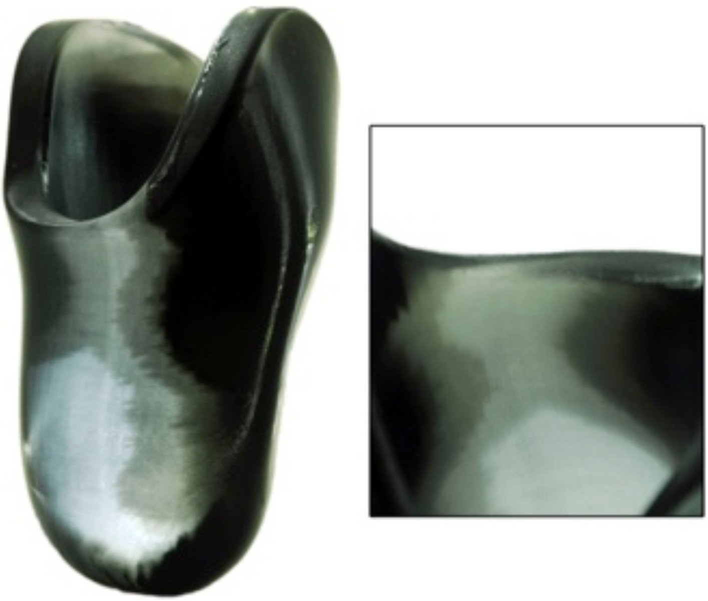

Figure 44 Result of Example Problem 1: Fabricated socket and detail view illustrating the achieved material transition. Designed by Elizabeth Tsai. Adapted from (Doubrovski et al., 2015).

The designer should be supported in a systematic process to find, discover, and document affordances of AM

In this example case, explorative experiments were performed to find solutions for using AM fabricated light guides to sense deformation within a flexible material. The systematic loop of explorative experiments and documentation eventually led to a design for the pressure sensing element, which was then incorporated into the integrator in the second loop of the DfAM approach. As an application of the AM affordances of geometry complexity, material complexity, and custom geometry, pressure-sensing elements based on the principle of light guides were conceptualized.

The designer should be able to define local intended properties of products

For the light guides pressure sensors, it was necessary to define the local variation in transparency and index of refraction of the material.

The designer should be supported in developing products with customizable attributes

Similar to the approach in example problem 1, the designer developed an integrator. This resulted in an automated process that generates structures for the pressure sensing elements given desired (custom) sensor density distribution.

5.3.4.3 Linking the results to the principles of the methodology

In the previous section, the evaluation of both the outcome and the process of the two example cases were discussed. However, it was also necessary to understand whether these results were actually linked to applying principles from the DfAM methodology. To evaluate this, the results of the example problems were compared to a similar case in which a custom prosthetic socket was designed and fabricated on the same multi-material AM system. In this case, performed by the author of this work, the principles from the methodology that were not applied were: inclusion of process-related parameters of the AM system in the design process, and the development of an integrator. Voxel-based control is considered to be an inclusion of process-related parameters in the design process. Traditionally, the voxels are generated in the slicer software, outside the designer's control.

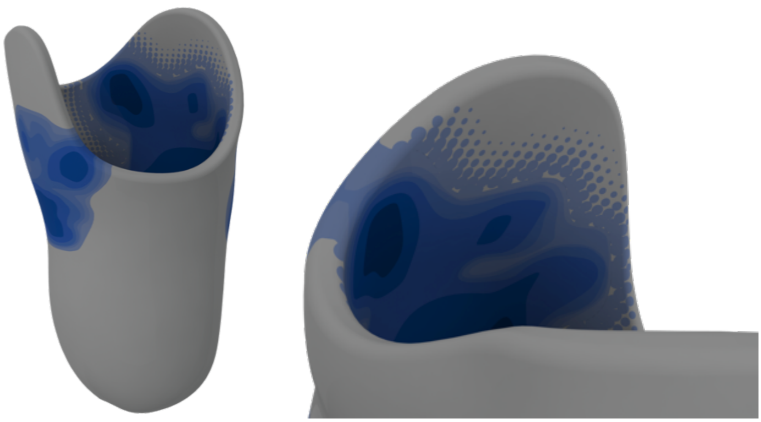

Figure 45 Attempted graded material distribution without application of main principles from methodology.

In the approach of this example case, a traditional design and AM workflow was applied. Therefore, the common STL file format needed to be used and, contrary to example problem 1, voxel-based control of the AM system was not available. This resulted in less control over material property variation during the design process. While using the STL file format, it was attempted to approximate smooth transitions between rigid and flexible materials. This was done by segmenting the 3D model into discrete volumes, corresponding to the available material combinations of the AM system. This segmentation can be seen in Figure 45. In addition to this segmentation, in an attempt to further smoothen the transition between the available materials, a pattern of solid spheres was generated, similar to a halftoning pattern. Compared to the outcome of design problem 1, in this example case, the designer had less control over transitions in material properties, while it was necessary to work on the memory limits of current computer systems.

Also, the segmentation and generation of 3D geometry was done manually; no integrator was developed to do this automatically. This means that for a given new set of data (residual limb geometry and tissue distribution), the same amount of manual effort would be needed. In contrast, the developed integrators in the two example cases allowed a more automated procedure to generate the printable files.

The comparison of the results of this case to the two example cases suggests that the results of the example cases are linked to the application of the principles from the methodology.

5.4 Conclusions

5.4.1 Quadrant 4: Performance of DfAM beyond example cases

In this last quadrant, the intention was to argue whether the developed DfAM methodology is useful for other problems, beyond the example cases discussed in the validation. The acceptance of the general performance of the developed methodology can be considered a "leap of faith" which was facilitated by the evidence discussed in quadrants 1, 2, and 3, as described by Seepersad et al (2006).

In the **first** quadrant, the logical consistency of the methodology itself and the constructs were discussed. One of the challenges was that within the scope of the project only two example problems were used for the validation. However, the validation procedure of the validation square takes this limitation into account. The **second** quadrant is instrumental for this. In this quadrant, it was argued that the example problems that were used in the validation are representative of the design problems for which the methodology was developed, accepting the appropriateness of the example design problems. A limitation of the scope of the design cases is the fact that only one AM technology (Material Jetting) was used. This was a deliberate choice; since, at the time of the validation, Material Jetting was the only available AM technology capable of combining materials with different properties on a voxel level. In the **third** quadrant, the methodology's performance regarding the requirements was evaluated. It was discussed that applying the main principles of the methodology led to the results of the example cases. It was argued that the requirements of the methodology were met; the developed prosthetic sockets are products with a custom local variation of material property and functionality. The performance of the results of the example cases -the printed prosthetic sockets- have not been user tested and therefore have not been validated in their performance as a product. In the **fourth** quadrant, considering the results from the first three quadrants, the performance of the DfAM methodology has been accepted beyond the context of prosthetics, to other design problems for consumer durables where AM is used as the primary manufacturing method.

Chapter 6

Conclusions

This chapter discusses the contribution of the thesis, reflects on the process of the conducted research project, and provides recommendations for future research.

6 Conclusions

As a designer who has been affiliated with digital tools, I started this research project driven by a personal interest: how can 3D Printing change the discipline of design and the products around us? The Delft University of Technology showed interest in this topic by initiating this research project and funding the first year. Océ Technologies, a Canon company, funded the remaining three years of the project. For me, this was an indication that the topic of my research was considered important by both academia and industry.

When this research project was initiated, there were signs that AM was increasingly being used as a production method. Over the years, the advancing AM technology has become available to a growing portion of the population. Parallel to this, a significant increase in the research in AM was observed at academic research institutes. Also, the AM industry has matured considerably. These developments are discussed in Chapter 1 and Chapter 2.

While AM had become more widespread as a production method in manufacturing, it was still unknown how this technology could influence the discipline of design, when AM is used as the primary production method in manufacturing of consumer durables. What are the unique capabilities of AM and how should designers work to benefit from these capabilities?

6.1 Contributions

The research approach consisted of four research cycles: (1) defining the focus of this research by identifying the knowledge gap, (2) conducting interviews with employees from pioneering companies and doing design experiments, which (3) provided insights for the methodology development, and (4) the validation of the methodology using the Validation Square as a framework.

The contributions of this thesis are two-fold. (1) a Design for Additive Manufacturing (DfAM) methodology was proposed, which intends to overcome the current bottlenecks in the design process and supports the utilization of the identified affordances of AM in the context of consumer durables, and (2) four demonstrators were developed, which materialize the developed vision of using AM in the context of consumer durables.

Parts of the knowledge presented in this thesis were published in two journal articles and 8 peer-reviewed conference papers. Also, one patent was filed. Some of the knowledge was incorporated in one book chapter on AM technologies. In addition, the author received the prize for *best young presenter* at the eCAADe conference, for presenting a paper on behalf of the Mediated Matter group of the MIT Media Lab, where a part of the research was performed.

6.1.1 Answers to research questions

What are the game-changing affordances of AM when used as a manufacturing method for consumer durables?

The literature presents overviews of the affordances of AM technologies. This thesis proposed a hierarchical structure of the major affordances based on the identified fundamental characteristics of AM: (i) the digital nature of the AM process and its control and (ii) the layer/voxel-wise manufacturing process.

The affordances of AM that were envisioned to be most important in the context of consumer durables were: the possibility to (1) manufacture products with customizable attributes, (2) manufacture parts with complex geometry, and (3) manufacture parts with locally adaptable material properties.

In correspondence with the expected main affordances of AM, it was found that the ability to manufacture customized products and to manufacture complex geometries were main reasons for industry to use AM as a means of production. However, it was observed that the ability to locally vary material properties by using multi-material AM was not applied in the visited companies. The reasons of not utilizing the ability of locally varying the material properties were identified to be mainly the inferior material properties of the parts made by currently commercially available multi-material systems.

In this project, a vision was formulated that the combination of the three main affordances provides new opportunities for products. Customizable attributes of products are typically obtained through customizing the geometry. For example, the geometry of a customized hearing aid is fitted to the inner shape of the customer's ear. However, it was recognized that new opportunities arise if local variation of the physical properties were also taken into consideration as customizable attributes of a product. The variation of these attributes can be achieved by utilizing the capability of AM to manufacture parts with locally varying material properties. Some new opportunities were explored in the conducted design experiments, which were discussed in Research Cycle 2. The prototypes developed in these design experiments demonstrated possible products with customizable properties.

What limitations of the available design methodologies do designers using AM currently face?

Various approaches that can be categorized as DfAM have been presented in the literature, targeting different stages of the design process. Active fields of research and development include structure optimization and generation, and the development of design rules for AM. However, DfAM approaches that support designers in developing products for AM in which the customizable attributes are both geometry and locally varying physical properties were not found. To develop such products, a designer needs to have adequate control over the properties of the printed part. It has been described in the literature that physical properties of printed parts are determined not only by the geometry and the material distribution, but also by the AM process-related parameters, such as rate of (local) deposition, temperature, and tool paths. However, process-related parameters are typically not considered during the design process. Based on the explorative design experiments conducted in Research Cycle 1, it was understood that new opportunities can arise for the designers to locally manipulate a printed part's physical properties and behavior when process-related parameters are considered in the design process. The control over properties that is obtained in this manner is not possible in a conventional design workflow for AM. It was found that industrial designers recognized that it is essential to deal with process-related parameters when defining properties of printed parts. However, it was found that procedures by which process-related parameters could be defined and manipulated were typically not included in the design process.

6.1.2 Proposed DfAM methodology

This thesis presents a design methodology aimed at addressing the identified limitations and providing support for designers to design and fabricate products that utilize the affordances discussed above. The design methodology consists of two interrelated design cycles and supports the development of consumer durables manufactured with AM (as the primary production method). The methodology is presented in Chapter 4 while the validation of the methodology is discussed in Chapter 5.

The proposed methodology includes procedures that iteratively combine elements of design methodologies with manufacturing methodologies, which had not yet been described in the context of customizable products. In this new methodology, the role of the designer is different than in the case of traditional manufacturing. Instead of developing one product suited to a large audience, a customizable design is developed. Among the customizable attributes is local material property. The methodology supports the definition of designs with customizable attributes by combining geometry and material assignment and considering AM process-related parameters, such as printing patterns, speed, and temperature. The principles of the methodology support designers in developing products that utilize new opportunities for product appearance and behavior.

6.2 Proposal for further research

Based on the outcomes and conduct of research performed in this project, some directions for further research are suggested. These are, on the one hand, intended to address the shortcomings of the completed research, and, on the other hand to approach new questions that emerged during the project. Also, insights from this research allowed the discussion of technological developments that were believed to be needed to support a widespread application of the developed methodology. The proposals for further research can be stated in these three categories;

7. *Immediate (follow-up) research activities to address the open issues*
8. *Research activities that require more resources than available in this project*
9. *New research activities in emerging fields that were identified during this research*

The future research opportunities can be seen from two different perspectives: (i) research that is needed to expand the technological know-how mainly in the industry, and (ii) research that is needed to expand scientific knowledge.

6.2.1 Immediate follow-up research

As immediate further research it is suggested to develop and validate the instruments of the proposed methodology. This includes development of CAD tools and adaptive 3D file processors that can support local property variation and customization of designs. It is also important to validate the methodology with AM processes other than Material Jetting, as well as to apply it to more design problems. The current challenge is the limited availability of AM systems that allow voxel-wise control over material properties on a high resolution. However, this has recently started to change (“HP 3D Printers and Printing Solution,” n.d.).

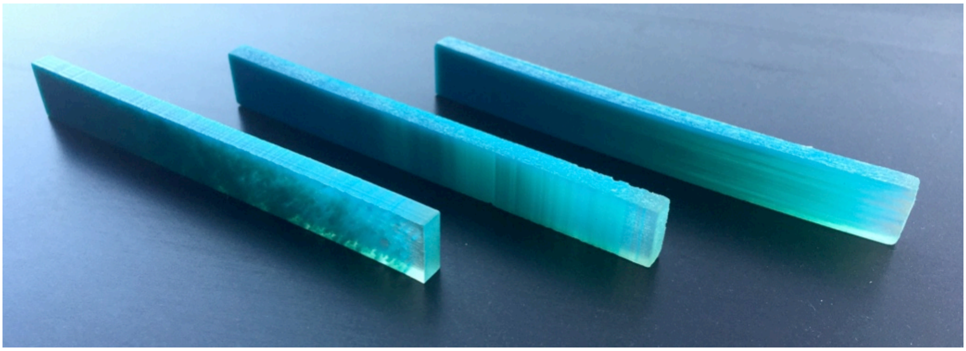

Figure 46 Three 3D prints of functionally graded test bars. By varying deposition patterns, different anisotropic physical properties were achieved. The volume-distribution from rigid to flexible is equal for all three bars.

Only a select number of properties were investigated in the presented research. There is still no exhaustive overview of how and which process-related parameters influence the printed part's properties. As a result, designers and 3D printer operators generally do not have sufficient information available to set the printer parameters to obtain precisely the final properties as intended in the design.

Also, a broader understanding is needed concerning how designers can utilize these new properties in new products. Therefore, it is planned to further investigate how new properties can be achieved and applied. Related on-going projects include:

- *Investigating the influence of process-related parameters of Selective Laser Melting on the aesthetic manifestation of 3D printed surfaces.*
- *Using designed material anisotropy (as illustrated in Figure 46) for 3D printed soft robotic grippers*
- *Development of 3D printed meta-materials to be applied in customized products. An example research project is a volume-adaptive prosthetic socket (Figure 47). This is a recent MSc project by Misja van Sitteren, who was supervised by the author of this thesis.*

Figure 47 Volume adaptive prosthetic socket. Designed by Misja van Sitteren.

6.2.2 Research and development requiring extended resources

6.2.2.1 Developing design rules for AM

Developing an extensive set of design rules lay beyond the scope of this work. On the other hand, many design rules can be conceived and utilized in designing various consumer durables. This raises the need for further research. As discussed in Chapter 2, there are several ongoing efforts to develop design rules for AM. Since these rules are specific for each AM system, the development of a complete set of design rules is laborious. With the nearly infinite number of design features and a constantly growing number of AM systems, a possible approach would be to partially crowd-source parts of the development of design rules.

6.2.2.2 Completing overview of AM affordances

The categorization of the AM affordances, as presented in Chapter 3, was based on the affordances mentioned by the participants of the interviews. Therefore, it is not complete and should be further expanded with affordances that might be identified in the future or were not discussed in this research.

It is essential that product designers are familiar with the possibilities of AM in general, as well as with the unique capabilities of specific AM systems. Currently, there is no available instrument that provides a complete overview of these affordances. A promising approach is the AM feature database presented by Maidin et al. (2012). This tool can inform the designer about the unique features of specific AM technologies during the early phases of the design process. Since each current and future AM system has its own unique affordances, such a database will remain a work in progress. Nevertheless, it can support the designer with the choice of an AM system given the required features of desired result.

6.2.2.3 New generation of CAD

From the design experiments, as well as the interviews with pioneers, scenarios were observed where the 3D printed result was limited by the capabilities of the commercially available CAD software and not the AM system itself. For example, while most 3D printers have little problems with fabricating complex shapes, and some 3D printers can combine different materials on voxel level, the common CAD packages have great difficulties working with such models. These limitations are in line with the challenges of CAD described in the literature (Chapter 2). The number of publications on methods for structure generation in CAD indicate that this field is actively being developed.

However, commercial workflows in which a designer can design geometries and define material property distribution of 3D printed parts are not yet available. Property-based modeling and manufacturing also requires the development of new file formats, and AM systems that take into consideration the desired properties during the printing process. Eventually, such developments could pave the way towards AM device-independency, making it possible to obtain consistent properties of a 3D print while using different AM systems.

To create customizable designs, the development of makeshift procedures and scripts was necessary in this research. To my knowledge, commercially available CAD packages do not support designers in the generation of designs that can be customized. For example, if a designer develops a design that needs to be adjusted given each user's unique scanned geometry, specific software needs to be written. It is therefore suggested that CAD software needs to be developed that supports the generation of customizable designs. Demonstrators developed in this research illustrated that for consumer durables it is valuable if the customizable attributes are both the geometry and local material properties.

6.2.3 Emerging fields for new research

6.2.3.1 Towards the use of fewer base materials

Materials that are used in traditional manufacturing processes, such as injection molding, come in a wide range of properties. This is reflected by the wide range of plastics that designers and engineers can choose from. This wide range of materials is necessary in order to obtain products with a wide range of desired properties. In other words, when a designer needs specific part or material properties, he needs to choose the best fitting material from the available set of materials.

In this research, it was shown that, if the designer is provided with adequate tools, procedures, and methods, he can be actively involved in adapting the properties of 3D printed objects. Varying the properties of 3D prints can be achieved through varying compositions of materials as well as by adapting AM process-related parameters. Also, structures can be manufactured that have completely new properties, such as materials with designed anisotropy and meta-materials.

Analogously to inkjet printing on paper, where most of the visible spectrum can be created by halftoning a set of 4 base colors, AM has the potential to achieve a wide range of material properties by combining a limited set of base materials.

Towards this end, a set of compatible base materials that are suitable for 3D printing needs to be developed. I believe more study is needed on how to combine these materials during 3D printing to achieve the wide range of properties that can be found today in the traditional manufacturing domain.

6.2.3.2 Towards device independence

Since different AM systems vary in terms of the applied physical principles, each AM system outputs a part with different physical properties, while printing from the same 3D geometry file. Also, one design can be produced on the same machine using different build orientations and printing settings. This can also strongly influence the final properties.

To overcome these issues, the development of a new design-description language is suggested. In this language, a designer should be able to define both the geometry and desired local properties. These desired properties would need to be interpreted and translated by the AM system into the printing strategy. This is in line with the recent developments of the 3D printing file formats AMF and 3MF.

The author envisions a scenario that is comparable to the workflows in the 2D printing industry. In 2D, device independency has been crucial for a widespread success of digital printing technology. The development of a new language (PostScript and PDF) and tools like color profiles are nowadays instrumental. This streamlined workflow has allowed an increasing number of users to design artwork and produce it using digital printing. However, these tools are used differently between professionals and hobbyists. While inexperienced users can design and print artwork, professional use still requires a good understanding of the workflow including color profiles, gamut etc. A similar scenario can be envisioned for the 3D printing industry. A new shape- and property description language could allow a large group of users to design and print parts, while advanced designers could utilize more advanced tools to ensure a desired result.

6.3 Dissemination of the results of the conducted research through demonstrators

In the second Research Cycle, four design experiments were performed. Three of these were performed as the graduation project of MSc students. The design experiments were intended to provide new insights about the bottlenecks of the currently available design processes. In addition, the fabricated prototypes in these design experiments proved to be valuable technology demonstrators. They supported the communication of this research beyond the academic landscape to an audience of tens of thousands though online platforms, design exhibitions, radio and television programs, and other public events.

The prototypes of the 3D printed textiles (Lussenburg et al., 2014) and 3D printed Freeform Surface Interfaces (Doubrovski et al., 2014) were exhibited during the Dutch Design Week in Eindhoven (2012 and 2014, approx. 70,000 visitors). The prototype of the Freeform Surface Interfaces was featured on Dutch national television in a show on technology. The project regarding customized saxophone mouthpieces was exhibited during the Dutch Design Week in Eindhoven (2012) and was featured during North Sea Jazz festival in Rotterdam (2012). Several of the saxophonists who perform daily on these 3D printed mouthpieces are among the top nationwide and worldwide.

Over the course of the research, two minor applied design experiments were performed. The aim was to obtain a first-hand understanding on how low-cost printers can be used to fabricate objects that are useful for a large audience. Two accessories for two popular electronic appliances were designed and distributed through two online open-source communities, Thingiverse ("Thingiverse - Digital Designs for Physical Objects," n.d.) and Instructables ("Instructables," n.d.). As of November 2016, the two designs have over 45 000 views. These design experiments are discussed in more detail in Inset 3.

6.3.1 The role of education in DfAM

Over the course of this research project, I have been involved in various demonstrations and AM workshops for the public. I have also participated in educational programs ranging from primary to academic education levels. These experiences helped shape a view on the role of education in an environment where digital manufacturing is ubiquitous.

In other fields that have made transition from analog to digital, new product ideas and developments have come from individuals who would otherwise not have had the opportunity to make and distribute their product. Examples include digitally distributed music and books. However, I believe a distinction should be made between literacy and skill. Literacy has become essential in our society. While the majority of the western population is literate, only a small portion has the skill and talent to write poems, novels, etc.

The distinction between literacy and skill can also be found in the digital domain. The availability of personal computers, and introduction of software packages like word processors created the need for skilled users. Initially, being able to utilize such programs was considered a specific skill, nowadays it is considered a proficiency, comparable to the status of literacy.

Applied design experiment 1:
Apple TV mount

A mounting bracket was designed that allows the Apple TV media player to be mounted on a wall. The design has been uploaded to the open source digital design sharing community Thingiverse. It was designed with the specifications of most inexpensive Material Extrusion 3D printers in mind. For example, the product can be printed without the need for support material and all features are well within the limits of what these inexpensive printers can fabricate.

(Feb 13, 2012-Nov 6, 2016)
12903 Views
2720 downloads
http://www.thingiverse.com/thing:295226

Applied design experiment 2:
Pebble Smart Watch Charger

The Pebble smartwatch requires a proprietary USB cable with a magnetic connection for charging. A new charger that can be 3D printed was designed specifically designed for inexpensive Material Extrusion 3D printers. The design was shared on the online community Thingiverse and Instructables. It can be printed within 20 minutes without the need for support material. After printing two short metal wires need to be inserted as leads. The design was featured on the homepage of Instructables two times and has been shared on numerous blogs worldwide.

(Apr 10, 2014-Nov 6, 2016)
Views: 16825 (Thingiverse), 19747 (Instructables)
2125 downloads (Thingiverse)

http://www.instructables.com/id/Pebble-Charger/
http://www.thingiverse.com/thing:295226

Discussion applied design experiments
These examples demonstrated the possibility to launch a product within a short period of time, with little investment while still being able to reach a significant number of customers. Traditional manufacturing would not have been economical for this type of product. The availability of 3D printing, in combination with an online platform for sharing design provides new opportunities for product development and distribution.

Inset 3 Applied Design Experiments.

Similarly, I believe it is important to differentiate literacy and skill in 3D modeling and 3D printing. Educational programs can be found worldwide where 3D printing is introduced in primary education. With literacy in 3D modeling and printing, the technology can be applied for personal use and as an instrument in various disciplines (same as writing is used for personal use and communication). In addition, widespread literacy can provide an important baseline for talent to apply this technology in completely new ways. However, it still remains a question on which aspects of the new technology the education should focus. For example, with the introduction of the PC, many schools initially taught students to work with DOS, which became obsolete when operating systems utilizing the desktop metaphor became widespread. I expect that many skills that are required to make a successful 3D print today, will likewise become obsolete. Therefore, in addition to understanding and being able to work with the currently available AM systems, I find it essential for students to understand how AM is evolving. This could be achieved by teaching not only what AM is today, but also the trends in research and development of AM and related topics, such as 3D scanning and 3D modeling. Additionally, by doing research projects in a lab environment in which students are exposed to and work on novel AM systems, students can understand how designers can play an active role in the development of AM. During the research project presented in this thesis, these principles were applied with the intention to provide a foundation for students to acquire their own vision on how AM can and should evolve, and what the future role of designers is, if AM is used as the primary means of production.

6.4 Reflection on the process

The research objectives were approached by a project consisting of four research cycles. Even though the cycles are presented and discussed in a sequential manner, the research was iterative. For example, during the design experiments, new themes for the literature study and expert interviews were formulated. Also, findings from the literature fueled themes to be explored in the design experiments.

In this research, the direct availability of AM systems was found to be essential. The hands-on experience that was obtained from the explorative design experiments in Research Cycle 1 was instrumental for identifying the current limitations of available workflows. The understanding of these limitations formed the basis for the developed DfAM methodology.

6.5 Implications of this research

The design projects in this research exemplified that the affordances of AM allow the creation of products in which the local variation of material properties is among the customizable attributes. This can inspire both industrial designers and AM system manufacturers on how AM technology can be meaningfully applied as a manufacturing method for consumer durables.

It was shown that the inclusion of AM process-related parameters in the design process provides unique opportunities to vary the printed part's properties. Currently, there is no comprehensive understanding for each AM system how process-related parameters exactly influence the part's properties. Therefore, for each AM system and for each property, it was needed to perform a series of experiments. The consideration of AM process-related parameters in the design process is not common practice. The double loop approach provides a framework for this. However, in the coming years, designers will need to be creative and devise workarounds in the design and manufacturing workflow in order to achieve results that go beyond what is possible using commercial workflows.

On the long term, promising material property variations that are explored using such workarounds can inform CAD software developers and AM system manufacturers on which features to include. A number of commercial initiatives give an indication that the industry is advancing in this regard. These include the partnership between Stratasys and Adobe ("Stratasys Partners with Adobe," n.d.), Autodesk's Spark platform ("Spark - an open platform for connecting the 3D Printing ecosystem," n.d.), Cuttlefish by Fraunhofer ("Cuttlefish.de," n.d.), and Monolith, which was recently acquired by Autodesk ("Monolith," n.d.). None of these products existed when this research project was initiated.

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Summary

Samenvatting

Summary

Introduction

A collection of new manufacturing technologies is coming of age. They are collectively called Additive Manufacturing (AM), or 3D printing. AM represents digital processes in which material is added (usually layer upon layer) to form an object. Although there are various reasons why using AM as a means of manufacturing could be beneficial, recent developments in productivity, cost, and quality have caused AM increasingly to be considered for manufacturing. It is expected that AM will have an increasing impact on the products that are being made, its designers, and its users. The combination of the digital and additive nature of the AM processes make them significantly different from traditional manufacturing processes such as (CNC) machining and injection molding on several aspects:

- *Unit cost depends significantly less on batch size, allowing small series production and customization*
- *Manufacturing effort depends considerably less on the complexity of geometry because of the layer-wise or voxel-wise manufacturing method*
- *Multi-material systems have the possibility to locally vary material properties*

Design methodologies are generally tailored towards traditional manufacturing processes. Considering the identified differences of AM compared to traditional manufacturing, it was hypothesized that (1) traditional design methodologies are not adequate when designing products for AM and (2) that given adequate design methodologies designers will be able to utilize the unique affordances of AM beyond its current use.

While there is an extensive effort in the academic community on AM processes, research on Design for Additive Manufacturing (DfAM) has been addressed less frequently. This triggered the question: what are the limitations of conventional design approaches and proposed DfAM approaches? In order to test the hypotheses, the objective of this research was

> *to develop a DfAM methodology that supports designers in the identification and utilization of the game-changing affordances of AM to allow the application of AM beyond its current use.*

AM has a wide range of possible applications; in this research, the focus was set on consumer durables. This is a close fit to both the Faculty of Industrial Design Engineering at which this research was conducted, as well as my own design background.

Project highlights

- *A design methodology was derived from an analysis of the currently available design and AM manufacturing processes through:*
    - *A series of interviews with AM pioneers from the industry*
    - *Design experiments that were performed in academic setting*
- *The outcomes of the design experiments served as technology demonstrators illustrating future applications of AM (displayed at various national exhibitions)*

Research design

The research approach that was taken in this research project comprised four Research Cycles. An overview of the Research Cycles is illustrated in Figure 1. In the first Research Cycle, the focus of the project was defined. The second Research Cycle mapped how designers currently work when applying AM. Based on the analysis of the current situation, a design methodology was proposed in the third Research Cycle. Finally, the developed methodology was validated in the last Research Cycle.

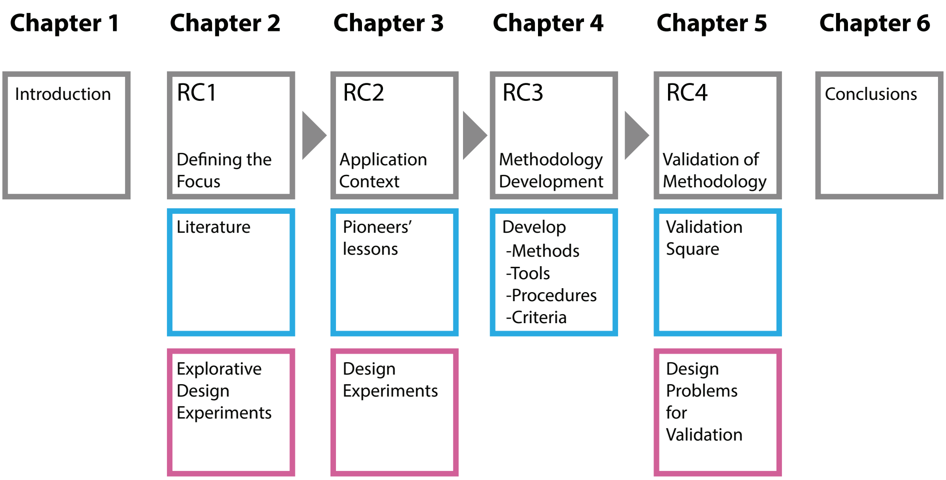


Figure 1 Overview of the Research Cycles and chapters of this thesis. Research approach is indicated in cyan, design stages are indicated in magenta.

Central to the approach are three stages of design, illustrated in magenta in Figure 1. These were conducted with the aim to provide opportunities to understand the available design tools and methods when designing for AM. Also, they provided new insights into how the unique aspects of AM can manifest themselves in new products. Finally, in the last Research Cycle, design acts were discussed as example cases to validate the proposed DfAM methodology.

Research Cycle 1: Defining the focus

The initial research objective described in the introduction was relatively broad. Therefore, the first Research Cycle was set up to define a focus for the DfAM methodology. Since several DfAM approaches have been proposed in literature, it was important to understand what can be considered the shortcomings of the proposed DfAM approaches in light of the developments of the AM technology. Therefore, academic literature on both the AM processes and DfAM approaches was studied. In addition, to obtain first-hand experience on what might be key limitations in current design and manufacturing of AM, several explorative design experiments were performed.

The final properties of printed parts are determined not just by the geometry and choice of materials, but also by the AM process-related parameters such as (local) deposition speed, temperature, printing patterns, and tool paths. However, process-related parameters are typically not considered during the design process. The explorative design experiments led to the following understanding: when process-related parameters are included in the design process, new opportunities arise for designers to locally tune a 3D printed part’s physical properties. The ability to control properties that is obtained in this manner is beyond what is possible in a regular design workflow in which geometry and material are defined. It was necessary to devise makeshift CAD tools to utilize these opportunities.

Various approaches that can be categorized as DfAM have been discussed in literature, targeting different stages of the design process. Active fields include structure optimization and generation, and design rules for AM. While most proposed DfAM approaches are focused on the capabilities of AM systems that can process one material per part, an increasing number of AM systems is being developed that can locally vary material properties. More recently, design tools have also been proposed to support this capability.

In the introduction, it was argued that the digital and additive nature of AM allows for the manufacture of objects that are geometrically complex and with locally varying material properties. However, the increased ability to make customizable products is an important affordance as well. DfAM approaches found in literature aim for each of these individual aspects. However, it was believed that it is by *combining* these affordances that many new opportunities for new products arise. Therefore, the knowledge gap for this research project was defined:

> *It is not known what design methodology can support designers to develop products for AM in which the customizable attributes are not just geometry but also physical properties and functionality. The variation of these is achieved by utilizing the possibility of AM to locally vary material properties.*

Experiments have indicated that AM process-related parameters play an important role during the design process by providing the designer with new opportunities to locally vary material properties. This raised the question of how to include the control of these parameters in a design methodology for customized products.

Research Cycle 2: Learning from the AM application context

In the previous Research Cycle, it was formulated that it was unknown which design methodology can support designers to develop products for AM in which the customizable attributes are both geometry and physical properties. With the objective to develop and validate a methodology that supports this, it was necessary to understand how AM is currently used in industry and to learn from the process of designing customized products. Academia and industry were considered complementary and equally important. Consequently, this Research Cycle consisted of a two-fold approach: (1) interviews with AM pioneers at world-leading companies were held and (2) a series of design experiments were performed in the academic setting. The prototypes resulting from the design experiments proved to be suitable demonstrators, showcasing envisioned future capabilities and applications of AM to designers.

The interviews with the pioneers provided opportunities to learn which affordances of AM are currently considered important in the industry. Also, the intention was to learn what design processes are implemented. Regarding the design process, the pioneers recognised that process-related parameters are essential in defining the properties of printed parts. However, the interviewed designers were not involved in the steps in which process-related parameters are defined.

It was observed that the ability to customize products and the ability to manufacture complex geometries are among the main reasons in industry to use AM. However, while in the first Research Cycle the ability to locally vary material properties using multi-material AM was identified as an important affordance, this is not yet applied in the industry. The mentioned reason for this was the inferior material property of the prints made by commercial multi-material systems.

Considering the developments of AM discussed in Research Cycle 1, it was expected that material issues of multi-material AM are not fundamental or permanent. Assuming that these issues will be solved though continuous developments of AM processes and materials, the design experiments were intended to explore the utilization of AM affordances that are not yet feasible in a commercial setting. In four design experiments the opportunities of customized products were explored and demonstrated. The designed products ranged from customizable saxophone mouthpieces to products with embedded electronics. In the analysis of the design process applied in the design experiments, two circular processes (loops) were identified. In the first loop the affordances of the AM system were explored in relationship to the design brief. In the second loop, a customizable design was developed. Also, in this loop it was investigated how the desired properties can be achieved by manipulating the geometry, material, and process-related parameters.

Research Cycle 3: Design methodology development

In this Research Cycle, a DfAM methodology was formulated based on interviews with pioneers and the design process of the design experiments from the previous Research Cycle.

The rapid development of AM posed a risk of the methodology becoming obsolete within a short period. Therefore, the aim was to formulate a framing methodology whereby the instruments can be further developed while the overall strategy remains the same. The methodology is focused on supporting designers to develop customizable products in which both the geometry and the local material property can be customized.

A reference model was developed by analyzing the data from the interviews with pioneers and the design experiments from the previous Research Cycle. The reference model is a graphical representation of the current situation. This model illustrated the main factors influencing the designer's *level of control over the part properties* and the *level of understanding of affordances*. For example, while some AM systems can manufacture parts with locally varying physical properties, CAD tools that allow designers to define such properties are lacking.

A set of requirements for the DfAM methodology was formulated from the overview of influencing factors in the reference model. These concern affordance finding, design of customizable products, and ability to define locally varying properties. At the heart of the proposed methodology is a double-loop approach, illustrated in Figure 2. The first loop supports the designer in identifying usable affordances of AM in the context of the design brief. In the second loop, the designer is guided in developing a customizable design, or *integrator*. The integrator includes geometry, material, and process-related parameters to achieve the desired final result. Principles to define and manufacture desired material properties are comparable to processes in the 2D printing workflow. The integrator combines primary data (the basis of the design) with ancillary data (some form of user data). The primary data is identical for all users and includes the basis of a design, while ancillary data is dynamic and can vary in order to make a customized design.

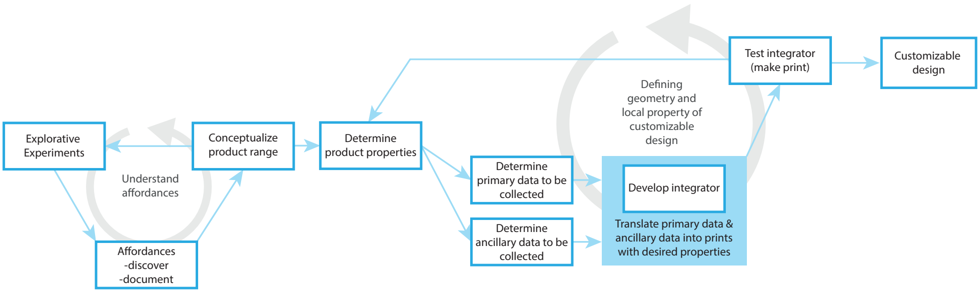


Figure 2 Double loop framing methodology for DfAM.

Research Cycle 4: Validation of DfAM methodology

The DfAM methodology that was developed in the previous Research Cycle needed to be validated. One of the challenges was that within the scope of the project only two example problems were used for the validation. These example design problems comprised the development of novel prosthetic sockets. The limited number of available cases required a validation method that takes this limitation into account. The method of the *Validation Square* provides a framework for this. In this procedure, a design methodology is validated using four quadrants. The quadrants divide theoretical versus empirical aspects and structural versus performance aspects. This framework was applied for the validation of the DfAM methodology.

In the first quadrant, the logical consistency of the methodology itself and the constructs were discussed. In the second quadrant, it was argued that the example problems that were used in the validation are representative of the design problems for which the methodology was developed. A limitation of the scope of the design cases is that only one AM technology (Material Jetting) was used. This was a deliberate choice; at the time the sockets were designed, Material Jetting was the only available AM technology capable of combining materials with different properties on a voxel level. In the third quadrant, the methodology's appropriateness was evaluated through a demonstrative validation. While the methodology was not yet completely articulated when the example design problems were performed, it was argued that the main principles of the methodology were applied.

During the development of the customizable socket, process-related parameters of the Material Jetting system were considered. These included the exact voxel patterns for a rigid and flexible material. In the developed integrator, these patterns, together with the socket geometry, were generated based on the desired shape and material distribution of the socket. The developed prosthetic sockets are customizable products with customized geometry, local variation of material property, and functionality. In the fourth quadrant, considering the results from the first three quadrants, the performance of the DfAM methodology has been argued beyond context of prosthetics to other design problems where AM is used as the primary manufacturing method.

Conclusions

The contributions of this thesis are two-fold and comprise 1) demonstrators that manifest the developed vision of AM in the context of consumer durables and 2) a proposed Design for Additive Manufacturing Methodology.

Essential for the DfAM methodology is the notion of affordances of AM in the context of consumer durables. Whereas AM affordances have been discussed in earlier work, this research presents a new framework to categorize affordances. The results of this research demonstrate that it is the combination of AM's ability to make customized products, complex geometry, and to locally vary material properties that *combined* provide opportunities to design completely new products, as illustrated in Figure 3.

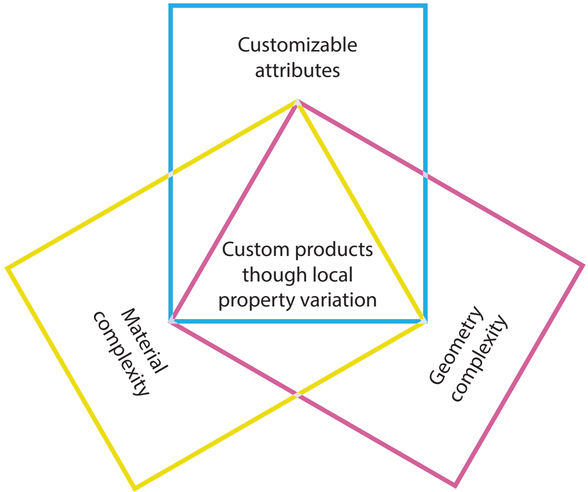


Figure 3 AM affordance triad.

However, it was found that utilizing these affordances requires a new DfAM methodology. In this new methodology the role of the designer is different than in traditional manufacturing. Instead of developing one product that fits a large audience, a customizable design is developed. Essential in this design not just the geometry but local material property is among the customizable attributes. The control over local property variation provides designers with new opportunities for product perception, behavior, and functionality and blurs the boundaries between material science and design.

The methodological contribution of this research is a framing methodology for DfAM that supports designers to develop products in this new field. The methodology includes procedures that iteratively combine elements from design methodologies with manufacturing methodologies, which have not previously been described in the context of customizable products. The methodology supports the development of customizable designs that are defined by a combination of its geometry and material assignment and by process-related parameters, such as printing patterns, speed, and temperature.

Design experiments showed to be indispensable to learn about the current design processes and in validating the proposed methodology. In addition, the fabricated prototypes in these design experiments proved to be valuable technology demonstrators. These supported the communication of this research beyond the academic landscape to an audience of tens of thousands through online platforms, design exhibitions, and other public events.

As immediate further research, it was suggested to develop and evaluate the instruments of the proposed methodology. This includes the development of CAD tools and adaptive 3D file processors that support local property variation and customizable designs. Also, the methodology needs to be evaluated with AM processes other than material jetting.

Many improvements on the side of AM systems are still needed, however these are only advantageous if designers are able to utilize the new possibilities. Therefore, further understanding is needed on how designers can use the freedom in geometry and material that recently started to go beyond the third dimension.

Samenvatting

Introductie

Driedimensionaal (3D) printen, of Additive Manufacturing (AM), is een verzameling nieuwe fabricagetechnieken die momenteel een snelle ontwikkeling doormaken. Deze technieken zijn gebaseerd op een digitaal aangestuurd proces, waarin laag voor laag materiaal wordt toegevoegd. Recente ontwikkelingen als verbeteringen in productiviteit, kosten en kwaliteit leiden ertoe dat AM steeds vaker wordt overwogen als productietechniek. Men verwacht daarom dat AM een toenemende invloed zal hebben op de ontwerpers, de producten die worden gemaakt en de gebruikers. Het feit dat AM een digitaal proces is, en het principe van laagsgewijs toevoegen van materiaal, maakt AM anders dan traditionele productietechnieken zoals spuitgieten of frezen op de volgende punten:

- *De kosten per geproduceerd product worden minder beïnvloed door de seriegrootte. Hierdoor word het mogelijk om zeer kleine series en op maat gemaakte producten te fabriceren.*
- *Vanwege de laagsgewijze opbouw, heeft de complexiteit van de vorm beduidend minder invloed op de productiekosten.*
- *3D printers die meerdere materialen kunnen verwerken, geven de mogelijkheid om lokaal de materiaaleigenschappen te variëren.*

Huidige ontwerpmethodieken zijn voornamelijk ingericht op traditionele productieprocessen. Gezien de genoemde verschillen tussen AM en traditionele productietechnieken, werd verondersteld dat (1) huidige ontwerpmethodes niet toereikend zijn om producten te ontwerpen die gefabriceerd worden met AM, en (2) dat ontwerpers in staat zijn om de mogelijkheden AM beter te benutten met een gespecialiseerde ontwerpmethodiek.

Hoewel in de academische wereld veel aandacht wordt besteed aan het verbeteren van de AM processen, heeft het onderwerp “ontwerpen voor AM”, of “Design for Additive Manufacturing” (DfAM) minder aandacht gekregen. Dit leidde tot de vraag: wat zijn de beperkingen van conventionele ontwerpmethodieken en voorgestelde DfAM methodieken? De doelstelling van dit project was:

> *Het ontwikkelen van een ontwerpmethodiek voor AM die ontwerpers ondersteunt in het identificeren en toepassen van de unieke mogelijkheden van deze fabricagetechniek beter te kunnen benutten dan nu mogelijk is.*

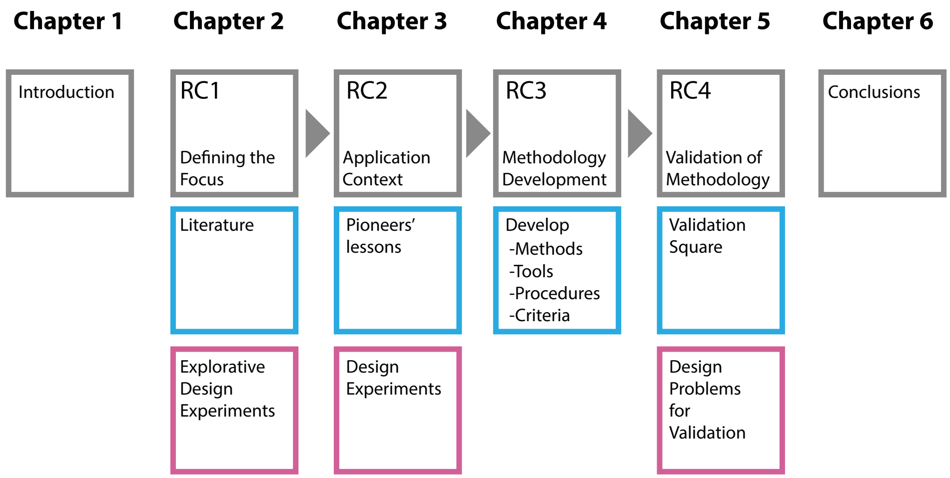
AM heeft een breed veld van mogelijke toepassingen. Om de toepassingen af te kaderen, richtte dit onderzoek zich op consumentenproducten. Dit zorgde voor een goede aansluiting op de faculteit Industrieel Ontwerpen waar dit onderzoek is uitgevoerd, alsook op mijn eigen ontwerpachtergrond.

Dit project in hoofdlijnen:

- *Een ontwerpmethodiek werd geconstrueerd uit een analyse van huidige ontwerpprocessen door:*
    - *een reeks interviews met pioniers in de AM industrie;*
    - *ontwerpexperimenten die uitgevoerd waren in een academische omgeving.*
- *De resultaten van desbetreffende ontwerpexperimenten dienden als demonstratie van de toekomstige mogelijke toepassingen van AM en zijn tentoongesteld op nationale exposities.*

Onderzoeksopzet

Het onderzoeksproject werd opgedeeld in 4 onderzoekscycli, of “Research Cycles” (RC). Afbeelding 1 geeft een grafische weergave hiervan. De focus van het project werd gedefinieerd in RC1. In RC2 is in kaart gebracht hoe momenteel wordt ontworpen wanneer AM wordt toegepast. Op basis van een analyse van deze huidige situatie, werd een ontwerpmethodiek voorgesteld in RC3. Ten slotte werd in RC4 de methodiek gevalideerd.



Afbeelding 1: Overzicht van de onderzoek cycli en de bijbehorende hoofdstukken in het proefschrift.

In de onderzoeksopzet stonden drie fases centraal waarin ontwerpprojecten werden uitgevoerd, zoals afgebeeld in roze op afbeelding 1; deze ontwerpprojecten waren bedoeld om te ervaren en toetsen welke ontwerpmiddelen beschikbaar waren wanneer voor AM ontworpen word. Voorts boden ze inzicht in hoe de unieke aspecten van AM zich kunnen manifesteren in nieuwe producten. Ten slotte zijn in de laatste RC twee ontwerpprojecten besproken als voorbeeldcasussen ter validatie van de DfAM methodiek .

RC1: Bepalen van de focus

De eerste onderzoekscyclus was opgezet om een richting te bepalen voor de DfAM methodiek binnen het initiële onderzoeksdoel. Het was belangrijk om te begrijpen wat de tekortkomingen waren van de DfAM methodieken, vooral in het kader van de continu toenemende mogelijkheden van AM. Hiervoor zijn de bestaande DfAM methodieken uit de literatuur in kaart gebracht. Daarnaast zijn vier verkennende ontwerp experimenten uitgevoerd.

De literatuur toont aan dat de uiteindelijke eigenschappen van een 3D geprint onderdeel niet alleen worden bepaald door de ontworpen geometrie en het gekozen materiaal, maar ook door de parameters van het 3D print proces, zoals printsnelheid, print temperatuur en printpatronen. Desondanks worden zulke printparameters doorgaans niet overwogen tijdens het ontwerpen. Uit de verkennende ontwerpexperimenten kwam het inzicht dat wanneer printparameters wel worden meegenomen in het ontwerpproces, er nieuwe kansen ontstaan voor ontwerpers om de eigenschappen van geprinte onderdelen lokaal te beïnvloeden. Deze mogelijkheid om eigenschappen te beïnvloeden gaat verder dan wat mogelijk is in een gebruikelijke aanpak, waarin alleen geometrie en materiaal worden beschreven. Omdat de huidige computer-aided design programma's (CAD) geen ondersteuning bieden voor zulke beïnvloeding van procesparameters, zijn voor elk van de verkennende ontwerpexperimenten eigen software oplossingen gemaakt.

Zoals genoemd in de introductie biedt de digitale aard van AM, gecombineerd met het additieve maakproces, mogelijkheden om complexe geometrieën en producten met lokaal variërende eigenschappen te maken. Daarnaast biedt AM de mogelijkheid om aanpasbare (op maat gemaakte) producten te produceren. De DfAM methodieken uit de literatuur richten zich meestal op één van deze drie unieke aspecten. In dit project werd echter aangenomen dat nieuwe productmogelijkheden ontstaan door juist deze mogelijkheden te combineren. Daarom werd de volgende hypothese geformuleerd.

> *Het is niet bekend welke ontwerpmethodiek ontwerpers kan ondersteunen in het ontwikkelen van producten die met AM geproduceerd worden, waarin zowel de geometrie als de lokale eigenschappen op maat gemaakt zijn.*

Experimenten in deze onderzoekscyclus toonden aan dat 3D print procesparameters een belangrijke rol spelen tijdens het ontwerpproces doordat ze nieuwe mogelijkheden bieden in het lokaal variëren van materiaaleigenschappen. Hierdoor ontstond de vraag hoe de controle over deze 3D print procesparameters kan worden gevat in een ontwerpmethodiek voor op maat gemaakte producten.

RC2: Lessen uit huidige toepassingen van AM

Met het doel om een ontwerpmethodiek voor bovenstaande AM producten te ontwikkelen, was het nodig om te analyseren hoe de huidige industrie gebruik maakt van AM en welke ontwerpprocessen dan gebruikt worden. Hiervoor was de aanpak tweeledig: (1) een reeks interviews bij wereldwijd toonaangevende bedrijven op het gebied van AM (pioniers) en (2) een reeks ontwerpexperimenten. De prototypes die resulteerden uit deze experimenten bleken tevens een middel om de beoogde mogelijkheden van AM te communiceren.

Uit de interviews bleek dat de pioniers bevestigden dat 3D print procesparameters een cruciale rol spelen in het bepalen van de eigenschappen van de geprinte onderdelen. In de huidige AM processen worden de geïnterviewde ontwerpers echter niet betrokken in de stappen waarin deze procesparameters worden bepaald.

Voorts bleek uit de interviews met de pioniers dat de voornaamste redenen om AM te gebruiken zijn: (1) de mogelijkheid van AM om producten op maat te maken en (2) om complexe vormen te produceren. In RC1 werd verondersteld dat de mogelijkheid om materiaaleigenschappen lokaal te variëren een belangrijke meerwaarde van AM is. Hoewel sommige geïnterviewde ontwerpers aangaven te verwachten dat dit op lange termijn belangrijk wordt, kwam uit de interviews naar voren dat dit momenteel niet werd toegepast. Als reden hiervoor werd genoemd dat de materiaaleigenschappen van huidige AM systemen, die meerdere materialen kunnen verwerken, op dit moment nog niet toereikend zijn voor gebruik in producten.

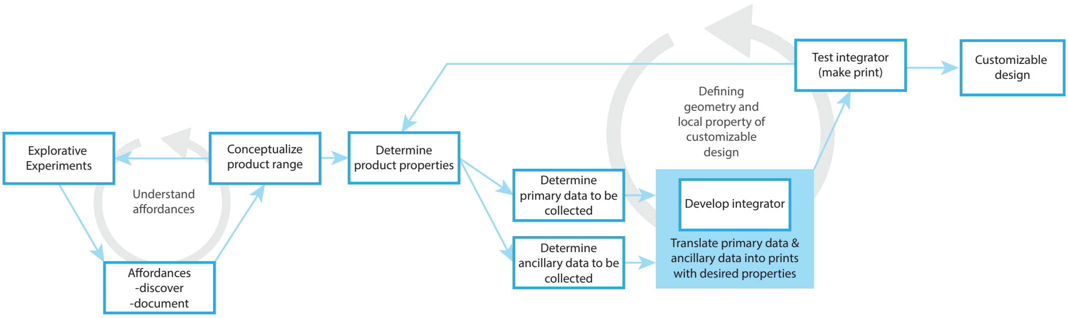
Gezien de ontwikkelingen van AM die besproken zijn in RC1, werd verwacht dat zulke beperkingen niet van blijvende aard zijn. Gezien de aanname dat ontwikkelingen in AM processen en materialen de beperkingen van materiaaleigenschappen kunnen oplossen, werden de ontwerpexperimenten opgezet om de mogelijkheden van AM te verkennen die (nog) niet uitvoerbaar zijn in een commerciële omgeving. In de vier ontwerpprojecten werden de mogelijkheden van aanpasbare producten verkend en gedemonstreerd. De ontworpen producten varieerden van saxofoonmondstukken tot producten met ingebedde elektronica. In de ontwerpaanpak van deze ontwerpexperimenten werden twee cyclische (iteratieve) processen waargenomen. In het eerste cyclische proces werden de mogelijkheden van AM verkend in relatie tot de ontwerpopdracht. In het tweede cyclische proces werd onderzocht hoe de gewenste eigenschappen kunnen worden bereikt door het beïnvloeden van de geometrie, materiaal en procesparameters. Deze kennis werd vervolgens gebruikt om een aanpasbaar product te ontwikkelen.

RC3: Ontwikkeling van de ontwerpmethodiek

In RC3 werd een DfAM methodiek geformuleerd op basis van de bevindingen uit de interviews en de ontwerpprojecten van RC2. De methodiek is gericht op het ondersteunen van ontwerpers in het ontwikkelen van producten, waarin zowel de geometrie als lokale materiaaleigenschappen aanpasbaar zijn voor de gebruiker.

Om de inzichten van de interviews en ontwerpexperimenten in kaart te brengen, werd een referentiemodel gemaakt. Een referentiemodel is een logische weergave van de aangetroffen factoren die van invloed zijn op het ontwerpproces. Dit model benoemde de belangrijkste factoren die van invloed zijn op de controle die ontwerpers hebben over de eigenschappen van de gemaakte onderdelen en het begrip van de mogelijkheden van AM. Ter illustratie: terwijl sommige AM systemen in principe objecten kunnen maken met lokaal variërende materialen en eigenschappen, ondersteunen de beschikbare CAD programma's zulke principes niet.

De aanpak van de voorgestelde DfAM methodiek bestaat uit twee ontwerpcycli (afbeelding 2). De eerste cyclus ondersteunt de ontwerper in het identificeren van unieke AM oplossingen voor de context van de ontwerpopdracht. In de tweede cyclus wordt de ontwerper begeleid in het ontwikkelen van een aanpasbaar product, of *integrator*. De integrator verwerkt primaire data (het basisontwerp) met aanvullende data (unieke informatie van individuele gebruikers). De primaire data zijn gelijk voor iedere gebruiker en beschrijven de basis van het ontwerp. De aanvullende data variëren per gebruiker. In de integrator worden geometrie, materiaal, en procesparameters gebruikt om de gewenste eigenschappen van het product te behalen.



Afbeelding 2: De voorgestelde DfAM ontwerpmethodiek.

RC4: Validatie van de DfAM methodiek

Het doel van dit hoofdstuk was het valideren van de beschreven DfAM methodiek. Een uitdaging hierin was dat in het kader van dit onderzoek slechts twee ontwerpcasussen als voorbeeld gebruikt werden. De kwadrant-gebaseerde validatiemethode die de "validation square" omvat, biedt een raamwerk voor deze beperking. De kwadranten van deze validatiemethode delen de validatie van de ontwerpmethodiek op in theoretische versus empirische aspecten, en structurele versus resultaatgerichte aspecten. Dit raamwerk werd gebruikt voor de validatie van de ontwerpmethodiek - de ontwerpcasussen hadden betrekking tot de ontwikkeling van aanpasbare prothesekokers.

In het eerste kwadrant werd de validiteit van de theoretische opzet getoetst. In het tweede kwadrant werd beargumenteerd dat de voorbeeld ontwerpcasussen representatief waren voor ontwerpproblemen waarvoor de methodiek bedoeld is. Een beperking van de gebruikte ontwerpcasussen is dat slechts één AM technologie (Material Jetting) was gebuikt. Dit was echter een bewuste keuze, aangezien deze technologie op dat moment de enige beschikbare was om objecten te produceren waarin verschillende materialen op micro-niveau gecombineerd werden. In het derde kwadrant werd de geschiktheid van de methodiek geëvalueerd middels een demonstratieve validatie. Hoewel op het moment van uitvoeren van de ontwerpcasussen de methodiek nog niet was geformuleerd, is betoogd dat de hoofdprincipes van de methodiek zijn toegepast. Tijdens het ontwikkelen van de aanpasbare prothesekokers, werden de 3D print procesparameters van de gebruikte printer in acht genomen. Deze parameters omvatten de precieze patronen waarmee druppels van elastische en harde materialen werden neergelegd door het AM systeem. Dit betekent dat de ontwerper in staat is om niet alleen te bepalen *wat* de 3D printer produceert, maar ook *hoe* dit wordt gedaan, hetgeen niet mogelijk is in de gebruikelijke workflow voor AM. In de ontwikkelde integrator, worden deze patronen, samen met de geometrie van de koker, gegenereerd op basis van gebruikersdata (meetgegevens). De ontwikkelde prothesekokers waren aanpasbare producten waarin de geometrie, lokale variatie van materiaalstijfheid, en functionaliteit op maat gegenereerd wordt op basis van gebruikersgegevens. Op basis van de validatie in de eerste drie kwadranten, werd in het vierde kwadrant beredeneerd dat de DfAM methodiek ook toepasbaar is voor andere ontwerpproblemen waar AM gebruikt wordt als de primaire productietechniek om op maat gemaakte producten te maken.

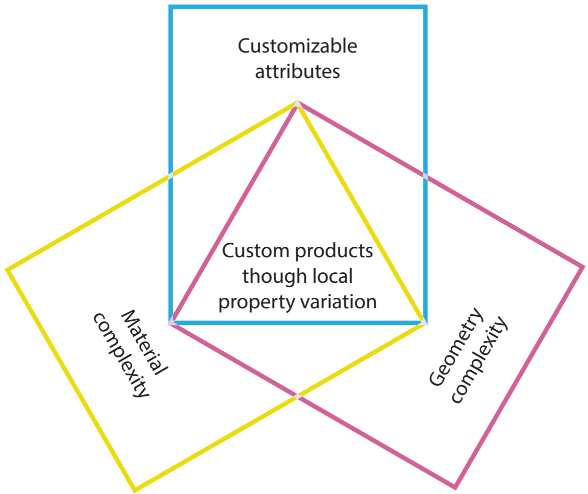
Conclusies

De bijdrage van dit proefschrift is tweeledig.

- *Een collectie prototypes die de ontwikkelde visie van AM in de context van consumentenproducten demonstreren.*
- *Een voorgestelde Design for Additive Manufacturing methodiek.*

De resultaten van dit onderzoek laten zien dat de *combinatie* van de volgende mogelijkheden nieuwe kansen biedt om vernieuwende producten met AM te ontwikkelen (Afbeelding 3).

- *De mogelijkheid om producten met aanpasbare attributen te produceren.*
- *De mogelijkheid om complexe vormen te produceren.*
- *De mogelijkheid om lokale materiaaleigenschappen te variëren.*



Afbeelding 3: Mogelijkheden die AM verschaft voor consumentenproducten.

Om deze mogelijkheden te benutten was een nieuwe DfAM methodiek nodig. In deze methodiek is de rol van de ontwerper anders dan in traditionele productieprocessen. In plaats van het ontwikkelen van één product dat gebruikt wordt door een grote groep gebruikers, wordt een aanpasbaar product ontwikkeld. Essentieel in dit aanpasbare product is dat niet alleen de geometrie, maar ook de lokale variatie in materiaaleigenschappen tot de aanpasbare attributen behoren. De controle te hebben over lokale materiaaleigenschappen biedt de ontwerper nieuwe kansen voor perceptie, gedrag, en functionaliteit van producten. De bijdrage van dit onderzoek is een DfAM methodiek die ontwerpers ondersteunt in het ontwikkelen van producten in dit nieuwe domein. De methodiek bestaat uit procedures die iteratief elementen uit ontwerpmethodes en productiemethodes combineert, iets wat nog niet is beschreven binnen de ontwerpwetenschappen.

Het uitvoeren van ontwerpprojecten was onmisbaar om te leren over de huidige ontwerpprocessen en voor het valideren van de methodiek. Bovendien waren de resulterende prototypes waardevolle demonstrators van AM technologie. Deze ondersteunden de communicatie van dit onderzoek buiten de academische wereld, aan een publiek van tientallen duizenden mensen middels online platformen, nationale exposities, (technologie) festivals en andere openbare evenementen.

Als vervolgwerkzaamheden werd de ontwikkeling voorgesteld van nieuwe CAD programma's en adaptieve bestandsprocessen die lokale variatie van eigenschappen en aanpasbare producten ondersteunen. Ook is het nodig de methodiek te valideren met overige AM processen. Om AM verder toe te passen als een productieproces, zijn nog veel verbeteringen van de AM systemen nodig. Deze zijn echter alleen zinvol als ontwerpers in staat worden gesteld om de mogelijkheden toe te passen. Daarom is meer begrip nodig over hoe ontwerpers de toenemende vrijheid in vorm en materiaal kunnen benutten die niet op lijken te houden bij de derde dimensie.

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About the author

Zjenja Doubrovski was born 15th of June 1983 in Moscow, USSR. He studied Integrated Product Design at the Delft University of Technology (TU Delft) and graduated (cum laude) in 2010. After his graduation, while working as a designer, he developed an interest in the application of Additive Manufacturing (AM) (or 3D printing) as a production method.

During his PhD project, funded by the TU Delft and Océ – A Canon Company, he worked on investigating new opportunities of AM and developing new design methods for AM. He embedded his research in education through lectures and workshops, and supervision of MSc students. The outcome of his own design projects and students' projects were displayed at various exhibitions. He was also actively involved in creating and expanding facilities for digital manufacturing that support research, education, and advanced model making at the faculty of Industrial Design Engineering.

After his PhD, he will continue working at the department Design Engineering of TU Delft, developing and applying new mechatronic principles that can be enabled by Additive Manufacturing. Ongoing and future projects include: new applications and design tools for both high-end and low-cost multi-material AM systems, developing and applying new 3D printed material behavior. Besides research, he is involved in education by teaching design students to apply traditional AM systems, and to take an active role in the development of new AM principles.

Appendix

Appendix A

Background Document Interviews with AM Experts/Designers
Principal researcher: Zjenja Doubrovski, M.Sc

Introduction
Thank you for your time and willingness to participate in this interview!

Additive Manufacturing (AM) has been used by industrial designers for the creation of prototypes for over a decade. Current developments in this technology are resulting in an increasing application of AM for end-production, making it important to consider how industrial designers should deal with the new possibilities and limitations of this new production method. The lack of design methodologies and design knowledge for AM has been increasingly identified. These methodologies and knowledge is commonly referred to as Design for Additive Manufacturing (DfAM).

As a part of ongoing PhD research at the Delft University of Technology, faculty of Industrial Design Engineering, a series of semi-structured interviews with AM experts and designers from the industry is conducted. The aim of the research is to investigate how Additive Manufacturing is changing the work of the Designer, the Products that are designed, and the impact on the User of the products. This document provides some background information on the research topic, the content, and procedure of the interview.

Following the principles of design inclusive research, we have modeled and built structures and objects that hold unique compliant, visual, and acoustic properties. With these design experiments we have, on one hand explored new possibilities of AM while also identifying the lack of design knowledge, tools and methods.

Purpose of the Interviews
Through these interviews with AM experts and designers, we aim to supplement our understanding of DfAM, best practices, and the current limitations in design knowledge. Therefore we are interested in your experience in designing and manufacturing new products for AM. Some questions to consider in advance:

- Which problems occur during the design and manufacturing of AM products?
- How do you deal with these problems?
- (Physical) examples are welcome!

Topic Map (topics that will be discussed)
- Current & future possibilities of AM technology
- Successful implementations/solutions
- The kind of products
- Current problems
- Tasks of the designer
- Limitations in knowledge (of the designer)
- Limitations in design tools
- Use of CAD software during design process
- Involvement of the end-user
- Customization

Procedure and Data
The interview session will last for approximately one hour and will be taken by PhD candidate Zjenja Doubrovski. You are one of circa 10 persons who are interviewed. The audio of the interview will be recorded, the data collected from these interviews will be used for research purposes and may be published in scientific publications. The data will be saved and processed anonymously. You can contact Zjenja Doubrovski (details above) if you wish to receive news regarding the publication of the results.

Interview Guide

- Introduction
- Describe process: semi-structured interview
    - Introduction and terminology
    - In depth: Design and AM
    - Open discussion: Future scenarios
- Hand over the background document and allow interviewee to ask additional questions

Part 1: Introduction

Respondent

- Background?
    - Study
    - Work
- How long have you been involved in product development?
- How long have you been working with AM?
- How would describe your tasks at [company]?
- Could you give an estimate on how many AM products you have been actively involved in designing (at [company])?

Additive Manufacturing

- What are for you the essential differences from traditional manufacturing
- Which AM technologies have you actively worked with?
- In-house or service providers?
- How much experience do you have with traditional design/manufacturing?
- Are you familiar with the term Design for Additive Manufacturing?

Part 2: Design and AM

- Could you discuss the process of a recent project you were involved in?
    - Product
    - Size and composition of the team
    - etc
- Could you discuss (more) example products where AM provides improvement (for example in terms of functionality)
- In your opinion, what were the main reasons to use AM?
- Which other unique features of AM have been applied in products?
- Which problems occur during the design and manufacturing of AM products?
- How do you deal with these problems?
- How do you think these problems should be dealt with?

Design Tools

- What CAD software do you use at [company]?
    - How is this software tailored for AM?
    - What other software do you use during design and manufacturing?
        - In which stages of the design process?

DfAM

- How is design for 3D printing supported at [company]?
    - Design guidelines? Used in which phase of the design process?
    - AM process support
        - Choose AM process
        - Build orientation etc
    - Software, for example structure generation (such as topology optimization)?
- How is new design knowledge documented and shared (within [company])
- How would you describe the problems that occur during the design and manufacturing of AM products?

AM process and design

- How do you use in the designs
    - Material variation
    - Multi-material
    - Anisotropy
    - Other effects inherent to AM such as stair-stepping
- How much are you, as a designer, involved in the AM production (which technology to use, which setting, build orientation etc.)?

- Are there examples where specific properties are achieved not by 3D geometry but by AM build process?
- Properties such as compliance, strength, visual appearance

Part 3: Discussion and Future

- What is your vision for 3D printing within [company]?
- What will that mean for the product development?
- What will that mean for the designer?
    - How do you foresee the work of designers?
        - Which tools will they need?
        - What knowledge will they need?
- What do you currently see as the main bottlenecks for implementing 3D printing?