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STUDENT REPORT

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Global Systems Design

3D Printed injection mould tools: Case study and experimentation.

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Abstract

3D Printing has long been used for prototyping, however, 3D printers always been tied to certain materials that fit each technology. In recent years, industrial 3D printer manufacturers have advertised that 3D printing can be used to produce injection moulding tools in order to produce injection moulded prototypes and small series production. The value of this method is that the prototypes are manufactured with the same materials and the same process as in the actual production. This means that the mechanical properties of the part and the production tool can be tested before ramping up production.

The project's objective was to test the 3D printer manufacturers' claims about concept's savings on both price and time, by examining the current industrial applications as well as performing a pilot study to test the implementation of the concept in a real industrial project.

Based on case studies, the concept's economic savings were evaluated. The savings turned out to be significant for all the studied moulds when used for prototype manufacturing. In the case of short series production, the economic viability, is highly dependent on the 3D printed forms durability, which can be difficult to determine.

The pilot study was conducted in collaboration with an experienced plastic manufacturing company. The implementation of the concept proved to be more challenging than expected. However, much was learned from the experiment, and further systematic experiments would certainly produce improved results with good repeatability.

There is no doubt that there are great savings to be done by 3D printing injection mould tools rather than milling the tools in aluminum, but it requires planning. The commissioning of 3D printed injection moulding tool is more difficult and time consuming than traditional metal tools. If additional tools must be printed due to unforeseen challenges during commissioning, both the cost and time-related saving decline.

Resumé

3D Print teknologi har længe været brugt til prototypefremstilling, dog har 3D printere altid været bundet til bestemte materialer der passer til den enkelte teknologi. De senere år har de industrielle 3D printer producenter reklameret med at 3D print kan bruges til at producere sprøjtestøbe forme med henblik på på at fremstille sprøjtestøbte prototyper og små serie produktioner. Værdien i denne metode er at prototyperne bliver fremstillet med de samme materialer, og den samme process som ved den reelle produktion. Dette betyder at emnets mekaniske egenskaber og at produktionsværktøjet kan testes.

Projektets målsætning var at teste 3D printer producenternes påstande, om at konceptet gav store besparelser på både prismæssigt og tidsmæssigt, ved at undersøge de aktuelle anvendelser i industrien samt at udføre et pilot forsøg for at afprøve implementeringen i et reelt industrielt projekt.

På baggrund af casestudier blev konceptet's økonomiske besparelser testet. Besparelsen viste sig at være betragtelig for alle de undersøgte emner, når det drejede sig om at fremstille prototyper. Ser man på små serieproduktioner, er den økonomiske levedygtighed dog meget afhængig af den 3D printet forms holdbarhed, som kan være svær at fastlægge.

Pilot forsøget blev udført i samarbejde med en erfaren plastfremstillings virksomhed. Implementeringen af konceptet viste sig at være mere udfordrende end forventet. Dog blev der lært meget af forsøget, og yderligere systematiske forsøg ville med sikkerhed kunne frembringe forbedret resultater med god gentagelighed.

Der er ingen tvivl om at der er store besparelser i at 3D printe sprøjtestøbeforme frem for at fræse formene i aluminium, men det kræver planlægning. Indkøringen af 3D printede sprøjtestøbeværktøj er mere vanskelig og tidskrævende end ved traditionelle metal værktøj, og skal der printes flere forme pga. uforudsete hændelser under indkøring, falder både de prismæssige og tidsmæssige besparelser.

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Preface

The seed of this project was planted during my internship at 3D Printhuset which lasted from September 2015 to December 2015. While studying various 3D printer manufacturers' brochures, i noticed they advertised some of their machines as being capable of printing injection moulding tools. Having some basic knowledge about injection moulding and the great forces that are applied to the tools, I was skeptical about it. This enticed me to do some preliminary research on the topic. By chance, I had the opportunity to attend the *Additive Manufacturing for the Plastic Industry* conference in November, where Lars Kannegaard from Grundfos held a talk describing Grundfos' experience with the concept. I was amazed by their results and was prompted to learn more about it and dig deeper. Seeing the potential of the concept, 3D Printhuset agreed to support the project by providing access to their 3D printers. 3D Printhouse also had a potential partner for the project, an injection moulding company in Jutland. Unfortunately, a few weeks into the project they pulled the plug. This was an unfortunate setback, as the project would have to be revised, but luckily I stumbled upon Henrik Larsen, the CEO of an injection moulding company called Metako. He was keen on testing the concept and willing to dedicate resources to the project.

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I would like to thank my supervisors Lazaros Nalpantidis (AAU) and Jakob Jørgensen (3D Printhuset), for their guidance and support throughout this project. I would also like to thank Lars Kannegaard, Birger Lind and Jan Schøn from Grundfos, and Klaus Mortensen and Jan Søgaard from Bang & Olufsen for for sharing their expertise with me. Thanks also go to Henrik Larsen and Michael Jensen from Metako, for their interest in the project and for the many hours spent guiding and helping me. Last but not least, thank you Line for taking such good care of our 10-month old daughter, Agnes, while I worked on the project, and thank you Agnes, for letting me sleep (occasionally).

Glossary

anisotropic Anisotropic materials are materials that exhibit varying physical properties depending on the direction.

Digital ABS Stratasys print material for the J750 and Connex3, compatible with injection moulding. http://www.stratasys.com/materials/polyjet/digital-abs.

pattern A pattern is a replica of an object to be cast or moulded. The pattern is used to create the cavity, or mould, which will be used in the casting or moulding process.

photopolymer A photopolymer is a photosensitive fluid polymer material. When exposed to ultra violet light, the material is cured and solidifies.

polymer Large molecules composed of many repeated subunits. Commonly, the term polymer refers to synthetic polymers, otherwise known as plastics.

quench Rapidly cooling an object by submerging it in a liquid.

Visijet S300 3D Systems' support material for the ProJet MJP 3500 and ProJet 3600 printers. http://www.3dsystems.com/materials/visijetr-s300.

Visijet M3-X 3D Systems' print material for the ProJet MJP 3500 and ProJet 3600 printers, compatible with injection moulding. http://www.3dsystems.com/materials/visijetr-m3-x.

Acronyms

ABS Acrylonitrile butadiene styrene.

CAD Computer Aided Design.

CNC Computerised Numerical Control.

DPI Dots Per Inch.

EDM Electrical Discharge Machine.

FDA Food and Drug Administration.

FDM Fused Deposition Modeling.

FFF Fused Filament Fabrication.

HDT heat deflection temperature.

PA Polyamide.

PC Polycarbonate.

PEEK Polyetheretherketone.

PET Polyethylene terephthalate.

PMMA Polymethyl methacrylate.

POM Polyoxymethylene.

PP Polypropylene.

PPE Polyphenylene Ether.

PPS Polyphenylene Sulfide.

PS Polystyrene.

PUR Polyurethane.

PVC Polyvinyl chloride.

RTV silicone Room temperature vulcanising silicone.

SLA Stereolithography.

SLS Selective Laser Sintering.

$\mathbf{T_g}$ Glass transition temperature.

Chapter 1

Introduction

Additive manufacturing has been known to cut cost and lead time in product development processes (Gibson, Rosen, & Stucker, 2015), and especially prototyping. Now that the technology has evolved even further, there is reason to believe that Additive manufacturing can also cut cost and lead time in the later phases of product development, and also production.

Since the 80's, when the first Additive manufacturing technology, Stereolithography, was developed, rapid prototyping has been used during the early phases of the product development process, where visual and even functional prototypes are required. However, rapid prototyping also serves a purpose in the later stages when testing and refining the product and when preparing for production ramp up. The performance can be tested and assembly processes can be refined. However, in many cases this requires parts in the end-use materials, preferably manufactured using the same processes as in the final production. Although it is possible to 3D print in materials matching production grade plastics (Acrylonitrile butadiene styrene (ABS) for example), the physical properties of the part will not match the properties of an injection moulded prototype. This is due to the fact that to this date, most 3D printing technologies rely on principles where the parts are printed layer by layer, resulting in parts that exhibit anisotropic[1] mechanical properties.

Injection moulding is by far the best and most used manufacturing method for mass production of plastic parts. Some of the many advantages of injection moulding are high tolerance precision, repeatability, large material selection, and high throughput with little to no supervision. Advances in 3D printing, specifically metal 3D printing, has allowed the production of highly optimised injection moulding tools with complex shapes and advanced cooling designs, which could not be produced with traditional methods. Both metal 3D printing and the traditional methods for developing and manufacturing injection moulding tools are expensive and time consuming. Fortunately, high investment cost is acceptable when dealing with mass production, where the goal is low unit cost and high

[1] Anisotropic materials are materials that exhibit varying physical properties depending on the direction

throughput.

In recent years, the largest industrial 3D printer manufacturers (3D Systems, Stratasys) have showcased the possibilities of 3D printing injection moulding tools with resin/plastic printers. With 3D printed injection moulding tools, it is possible to test the properties of the part (fit, flexibility, strength, function) in the end use material. The concept has shown to be beneficial for many, but at a price. The tools degrade rapidly compared to traditional tooling, and are not suited for all materials. Still, this concept might be well suited for small production series or for testing part designs before investing in traditional tooling in steel or aluminum.

The purpose of this project is to explore and highlight the potential and the limitations of 3D printing injection moulding tooling. Although the concept has been marketed by 3D printer manufacturers for some time, little to no scientific documentation has been published to this day. To the best of the author's knowledge, this is the first non-commercial, thus objective, review of the current state of the art. This is as well an attempt to highlight little discussed aspects of the concept and its shortcomings. Finally, the author hopes to contribute to the scientific community by shedding some light on this scientifically unexplored subject and inspire others to dig deeper by performing further systematic studies and experiments.

The project is done in collaboration with two companies: 3D Printhuset and Metako. Established in 2014, 3D Printhuset is a company that aims to spread the knowledge of 3D printing and 3D scanning, by providing hardware, courses and services. 3D Printhuset's incentive to participate in the project is that the concept, if viable, can be offered as a prototyping service. Metako is a tool making and plastic manufacturing company, based in Hillerød, Denmark. Metako's employees have lifelong experience with tool making and injection moulding. Their incentive is to master the concept and gain a competitive advantage in the industry.

Research question

It is hypothesised that 3D printing injection moulding tooling presents a great advantage over soft tooling (aluminium tooling) which is the traditional method for manufacturing injection moulded prototypes. According to industrial 3D printer manufacturers (3D Systems, Stratasys), using a 3D printer to manufacture injection moulding tooling reduces the tooling cost and lead time (3D Systems, 2015; Stratasys, 2014a).
This project aims to study the potential and limitations of the process by answering the following questions:

- What are the current applications of 3D printed injection moulding tools?

- Are 3D printed injection moulding tools financially viable for all types of parts?
- What are the challenges of implementing 3D printed injection moulding tools in an manufacturing company?

Scope

The project focuses on materials and technologies that have already been proven to work, and are available for testing. 3D Printhuset kindly provided access to their 3D Systems ProJet 3500 HDMax to print injection moulding tools in the Visijet M3-X[2] material. Metako has provided access to their injection moulding machines, Computerised Numerical Control (CNC) milling machines and personal assistance from their production manager and tool maker, Michael Jensen. In the pilot experiments, the mould to be tested was chosen in collaboration with Metako, and, given their experience, Metako also helped defining the test settings for the experiments.

[2]3D Systems' print material for the ProJet MJP 3500 and ProJet 3600 printers, compatible with injection moulding. http://www.3dsystems.com/materials/visijetr-m3-x

Chapter 2

Method

The overall method of this project is divided in two steps: Study and experimentation.

To gain familiarity with the concept and to acquire insight into the challenges of applying the concept, exploratory research was conducted. As scientific literature on the subject is scarce, given that the topic is very new, this part of the project relies heavily on the information collected from meetings with Grundfos and Bang & Olufsen.

Grundfos has successfully used 3D printed injection moulding tools to manufacture part prototypes, therefore they were an essential source of knowledge and experience. Fortunately they agreed to meet, discuss their findings and share photos and notes of their results. The involved Grundfos employees were:

- Lars Kannegaard - Senior Product Engineer, Rapid Prototyping specialist
- Birger Lind - Project Manager, Prototyping Assembly specialist
- Jan Schøn - Programmer, Rapid Prototyping technician

Bang & Olufsen had not used the concept, but it was known to them. They were chosen as a case study as they could provide further insight into the industry requirements and possible applications. The involved Bang & Olufsen employees were

- Klaus Mortensen - Technology Specialist
- Jan Søgaard - Prototype Engineer

The meetings with Grundfos and Bang & Olufsen helped shape the course of the project by providing real life cases, requirements and challenges in the industry.

Furthermore, during the course of this project, the author had the chance to attend the "3D Printing Live!"[1] conference where manufacturing companies having embraced 3D printing and 3D printing service providers were present. This was an opportunity to gather more information on the topic.

[1]http://www.3dprinting-live.com/

The 3D printer manufacturers, Stratasys and 3D Systems, were deliberately not contacted as they were considered to be biased towards making machine sales. Their different agenda might have jeopardised the project's integrity. Although a few manufacturer pamphlets and brochures have been used as sources for this report, the selling points and arguments they provide was treated as biased (material datasheets were not considered as biased). As Henri Pointcaré once pointed out in his book *Science and Hypothesis, 1902*:

> *"Experiment is the sole source of truth. It alone can teach us something new; it alone can give us certainty."*

The financial viability of the concept was based on a comparison to machined aluminum moulds (which are also used for prototypes and small series) and was evaluated based on the moulds Grundfos had successfully printed and used, as well as a sample keychain mould supplied by 3D Systems (all Computer Aided Design (CAD) files were made available for the project). These moulds were chosen for the study as the feasibility of using them for injection moulding had already been established by Grundfos and 3D Systems. All costs figure in Danish Kroner (DKK).

To compare the costs of 3D printed moulds and machined aluminum moulds, the following scenario was set: All equipment and processes are available in-house (injection moulding, 3D printing, and milling). Equipment investment cost and maintenance cost are not included. The labour salary is set to 200DKK per hour for the 3D printer operator and 250DKK for the injection moulding operator whom is responsible for mould assembly, machine setup and supervision. Salaries were estimated in collaboration with 3D Printhuset and Metako using the danish wage salary statistics website[2].
Print material and support material volumes are evaluated by the author using 3D Systems' software, material costs are calculated by using material retail prices. Printing time is evaluated by the software, post processing time is evaluated by the author[3].
The aluminum tooling costs are evaluated by Metako. The details of Metako's aluminum tooling cost calculations are not disclosed as they contain confidential information.
As the set scenario is that all the equipment and the processes are owned in house, profit margins are not added to the calculation, thus reflecting a company's internal calculations. For the transparency's sake, for all comparisons, it is prerequisite that the 3D printed mould and the aluminum moulds use the same master moulds.

A pilot experiment on Metako's machines was set up to evaluate some of the challenges and limitations of the concept using the available 3D printing material (Visijet M3-X). The goal of the pilot experiment was to pave the road for a full-blown experiment which unfortunately could not be carried out within the timeframe of this project. A pilot experiment should uncover minor errors and challenges, to improve the future design of a

[2]http://løn.info/

[3]The author has considerable experience printing and post processing prints with the used printer, experience which was gathered during his internship at 3D Printhuset.

full-blown experiment, before substantial resources are used on it. A mould design to be used with the experiments was chosen in cooperation with Metako. The mould insert was 3D printed, precision milled to fit the frame, and used for injection. Injections parameters were recorded for all injections, and all results were kept and catalogued.
3D file preparation, printer setup, and post processing was carried out by the author and according to 3D Systems instructions. All milling and injection moulding operations were carried out by Metako's personnel, in the presence of the author.

Report structure

The project's is structured in six chapters:

- The Introduction chapter introduced the reader to the topic and describes the purpose and hypothesis of the project.
- The Background chapter is intended for the reader to acquire basic knowledge about the concepts used and discussed in the project. Furthermore it describes the context of the subject and related work.
- The Case Studies chapter is a study of Bang & Olufsen's and Grundfos' experience with 3D printed Injection Moulding (IM) tools and provides an evaluation of the concept, versus aluminum tools, with regards to cost.
- The Pilot experiment chapter documents the field research done for the project. The results of the experimental tests made in collaboration with Metako are described and evaluated.
- The Discussion & Outlook chapter identifies the shortcomings of the experimental technique and suggests improvements. Future possibilities of the concept are also discussed in this chapter.
- The Conclusion provides a summary of the most important points made in the project and shows the overall significance of the project's findings.

Chapter 3

Background

Proofs of concept

The concept of 3D printing injection moulding tools has been integrated in several industries where it has shown to be beneficial. Companies have recently (2014-2015) reported using photopolymer 3D printing to produce injection moulding tools, reducing their development time and cost substantially.

Grundfos[1], a danish pump manufacturer, has produced several prototypes using 3D printed injection moulding tools. The Grundfos case is thoroughly described in section 4.2.

Diversified Plastics[2] made use of 3D printed injection moulding tools to rapidly manufacture prototypes for their long-time customer, Coloplast (Diversified Plastics, 2014). Coloplast, a global medical device company, needed prototype parts in the end use material, a rubber-like plastic material which could not be machined. According to Diversified Plastics, it was possible to reduce the tooling time from 5 weeks (aluminum or soft steel) to 1 week. The tooling cost was reduced from an estimated of 11.500 USD to 1.500 USD. Stratasys, the 3D printing technology provider, published a video documenting the case[3].

Bi-link[4] delivers injection moulded prototypes produced with 3D printed injection moulding tools for their customers (3D Systems, 2015), which are mainly electronics and medical manufacturing companies. Having incorporated a ProJet® 3500 HDMax into the workflow, they are able to deliver real-time production-grade test parts in a day's time. 3D Systems, the 3D printing technology provider, published a video documenting the case[5].

Whale pumps[6], a manufacturer of water and heating systems, has reduced their design and product launch process by 20%, their R&D processes by 35% and their tooling lead time by 97%, according to Stratasys (Stratasys, 2014b). They are now able to design

[1] www.grundfos.dk
[2] www.divplast.com
[3] www.youtube.com/watch?v=qoousDCGmM8
[4] www.bi-link.com
[5] www.youtube.com/watch?v=FWOQj00qC6o
[6] www.whalepumps.com

during day, print overnight, and test next morning with end-product materials. Stratasys published a video documenting the case[7]. Whale pumps also provides rapid prototyping services in end use materials to external customers in the automotive and aerospace industries.

Worrel, a design and product manufacturing company working on medical devices, are producing final material injection moulded prototypes in 95% less time and 70% less cost with 3D printed injection moulding tools (Stratasys, 2014c). Worell and Stratasys have attended international tradeshows together to promote the concept to the medical industry. According to Worrel, the concept also accelerates the FDA regulatory process as the first products can be manufactured quickly in the end-use materials which are Food and Drug Administration (FDA) approved.

Unilever uses 3D printed injection moulding tools to produce prototypes in their household care and laundry division. According to Unilever, they are able to produce their prototypes 40% faster than with conventional tooling (Unilever, 2015). Unilever also 3D prints thermoforming[8] moulds to test mould designs.

This shows that the technological feasibility and the commercial interest has been established a few years ago. However, the process and its limitation has not been thoroughly documented. There are several possible explanations to this:

- The constant advances in 3D printing, and more specifically the available print materials, would quickly render tests obsolete.
- All tests are carried out in companies wanting to have a competitive advantage, by not disclosing the process detail.

On a side note: Diversified Plastics, Bi-Link and Whale pumps, also offer 3D printing services to external customers. Although it might just be a sign of wanting to diversify, it could also be a sign of surplus capacity in their 3D printer, which in turn could mean that 3D printing injection moulding tools is not as big of a business for them as it seems. Furthermore, a majority of the aforementioned uses of the concept are from the United States of America. This could be interpreted as a sign that american companies are pioneering in 3D printing technology application, however, it is more likely due to the fact that Stratasys and 3D Systems, which both are american companies, have focused their marketing efforts on the home territory.

3.1 Additive Manufacturing

Additive manufacturing is older than the World Wide Web (WWW) (Berners-Lee, 1989; Hull, 1986), but it hasn't evolved and spread as quickly. Additive manufacturing is the

[7] www.youtube.com/watch?v=TOKj6CsZ92M

[8] Thermoforming is a process where a heated sheet of plastic is is forced against a mould with a desired shape. The plastic sheet takes the shape of the mould and solidifies when cooled. Thermoforming is mainly used in the packaging industry.

process of fabricating parts by adding material, in contrast to traditional manufacturing methods such as milling and turning where material is removed to fabricate the part. Traditional methods can often be described as subtractive manufacturing, although the term is rarely used. The term "3D printing" is often used as a synonym for additive manufacturing.

Today, it is possible to 3D print in a wide variety of materials such as plastics, plaster and metals. Metal printers are widely used for manufacturing production grade injection moulding tools, as they offer lead time and cost reduction and improved functionality to the moulds(Cotteleer, Neier, & Crane, 2014). However, metal printing is a technology reserved for companies with substantial capital and very specific needs, as the printers are extremely costly. To the author best knowledge, only five metal 3D printers are installed in Denmark, one at Lego, one at Grundfos, one at Novo Nordisk, and two in the Danish technological Institute (DTI). Plaster printers, such as the ProJet ColorJetPrinter 660 from 3D Systems, produce visual prototypes only. The material is simply not fit for functional prototypes, much less injection moulding. Although the quality of Fused Filament Fabrication (FFF) and Fused Deposition Modeling (FDM) printing has greatly improved recently, the surface quality of the produced parts is not smooth enough to be used for injection moulding. That being said, the technology is constantly evolving, and the potential of "hobbyist" printer should not be neglected.

The additive manufacturing technologies most relevant for this project are Stereolithography (SLA), Selective Laser Sintering (SLS) and jetting, all of which 3D print in various plastic materials.

SLA and SLS were for many years the only available 3D printing technologies. SLA is the oldest technology, developed by Charles Hull in 1986 (Hull, 1986). In SLA printers, a photosensitive polymer resin is stored in a tank where an ultraviolet laser traces a pattern on the surface of the resin, solidifying it. The first layer rests on top of a piston which is gradually lowered in the tank, when the second layer is cured, it fuses with the layer below.

SLS, which was developed a few years later by Carl Deckard (Deckard, 1989), uses a laser to sinter[9] small grains of plastic, ceramic and other materials. A thin layer of powder is spread on a platform, the cross section of the part is sintered, and the platform lowers, allowing a new layer of powder to be spread and sintered.

Jetting technologies are a more recent addition to the 3D printing technologies (Eshed, Kritchman, & Menchik, 2008). As with SLA, jetting technologies use photosensitive polymer resins. Instead of filling a tank with resin, the material is "jetted" in the form of microscopical droplets onto a platform, and subsequently cured with ultra violet light. 3D Systems and Stratasys both manufacture industrial 3D printers based on proprietary variants of the jetting technology. 3D Systems markets their technology as "MultiJet

[9] Fusing particles without melting them to the point of liquefaction

Printing"[10], while Stratasys markets their technology as "PolyJet 3D printing"[11].

3.2 Rapid Prototyping in Product Development

In product development, prototypes fall into several categories (Ulrich & Eppinger, 2012). Additive manufacturing allows to create physical prototypes, as opposed to analytical prototypes which represents a product in non-tangible ways, usually mathematically in the form of a simulation. For example, Injection moulding tools and the process itself can be simulated in software such as Moldex3D. Although simulations are often able to answer a lot of questions and help reduce iterations, they do not produce a model that looks and feels like the end product as physical prototypes do. Furthermore, the prototypes which are the subject of this study are comprehensive prototypes, in the sense that they implement all attributes of the product, in contrast to focused prototypes which implement a few attributes, or functions, such as a form, a mechanism or a material.

The product development process can be divided into six generic steps, as seen in figure 3.1 (Ulrich & Eppinger, 2012, p. 14). Traditionally rapid prototyping has been used during the early phases of the product development process, namely the concept development and the system-level design phases. In these phases, the feasibility of concepts and the industrial design are tested with experimental prototypes are tested. This phase often includes many iterations, hence there is a great incentive to use 3D printing to manufacture both visual and functional prototypes.

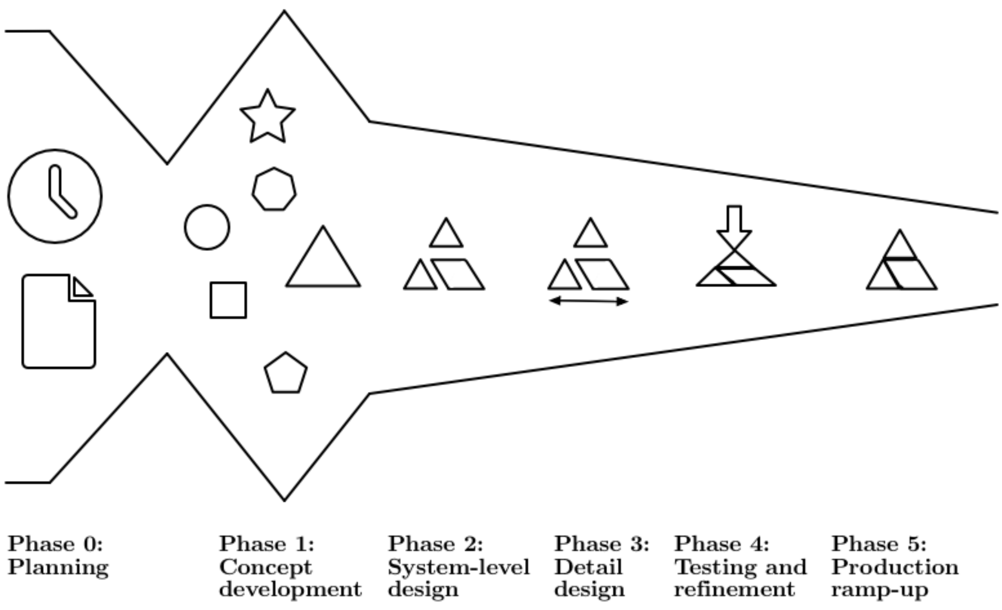


Figure 3.1: The generic product development process according to Ulrich & Eppinger, adapted from Ulrich and Eppinger, 2012, p. 14).

[10]http://www.3dsystems.com/media/3d-printing-process-mjp
[11]http://www.stratasys.com/3d-printers/technologies/polyjet-technology

In the later phases of product development, the product is tested and refined, then production is ramped up. These phases require tests of fabrication and assembly processes are tested for performance, reliability and durability. Furthermore, in industries such as medical product manufacturing, regulatory approvals must be obtained. These tests and approvals requires prototypes in the end-use materials, manufactured with the same processes that are used in later production. When developing a product which is to be mass produced, it is very likely that it will include parts that are injection moulded. As injection moulding tooling are costly and have a long lead time, "soft moulds" (aluminum) are manufactured first to test and refine the design and to prepare for the production ramp-up.

3.3 Rapid Tooling

Rapid tooling is a term which is typically used to describe the process where additive manufacturing is used to either quickly manufacture patterns to create moulds from, or to manufacture the moulds directly. The goal of rapid tooling is to lower tooling time and tooling cost. Unfortunately, the tradeoff is shorter tool life and wider tolerances, due to which, rapid tooling is mainly used for prototyping and lower production volumes.

In October 2000, the MoldMaking Technology magazine published an article containing an extensive list of then current rapid tooling technologies (Dickens, Hague, & Wohlers, 2000). In 2000, additive manufacturing was not an as essential part of rapid tooling as it is today. Of the 22 listed technologies a few are worth mentioning here as the put 3D printed tooling in perspective.

Room temperature vulcanising silicone (RTV silicone)[12] is used to easily produce moulds at room temperature: A master pattern[13] is created and suspended in a box, into which RTV silicone is poured, surrounding the pattern and forming the mould. After mould removal and separation, a two-part thermoset is moulded within the cavity. In this case the pattern can easily and precisely be produced with additive manufacturing.

Instead of using additive manufacturing to create the pattern, 3D Systems devised a process named Direct AIM, where AIM stands for ACES Injection moulding. Accurate Clear Epoxy Solid (ACES), is an early name of SLA printed materials. Direct AIM is in a sense the origin of 3D printed injection moulding tools, but the print materials used then are not nearly as durable as the ones used today, and the low tool strength resulted in a high risk of failure.

[12]Vulcanisation is a chemical process where natural rubber or related polymers are converted to more durable materials.

[13]A pattern is a replica of an object to be cast or moulded. The pattern is used to create the cavity, or mould, which will be used in the casting or moulding process

3.4 Injection Moulding

Injection moulding is a plastic manufacturing process. The industrial machines are fully automated and, due to the high investment costs and the high throughput, they are mostly used for mass production. Some of the smallest injection moulded parts are weighed in micrograms, e.g. parts for watches or hearing aids, and require injection moulding machines with clamping forces of less than 10 tons. Large parts such as car body parts, although not necessarily heavy, require clamping forces of more than 8000 tons. Small manual injection moulding machines are also available but are mostly used for prototyping and hobby projects, but not for manufacturing.

A simple, albeit complete, schematic of an injection moulding machine by Brendan Rockey[14], University of Alberta Industrial Design, is shown in figure 3.2. As the figure shows, the machine is divided in two parts: the injection part and the clamping part.

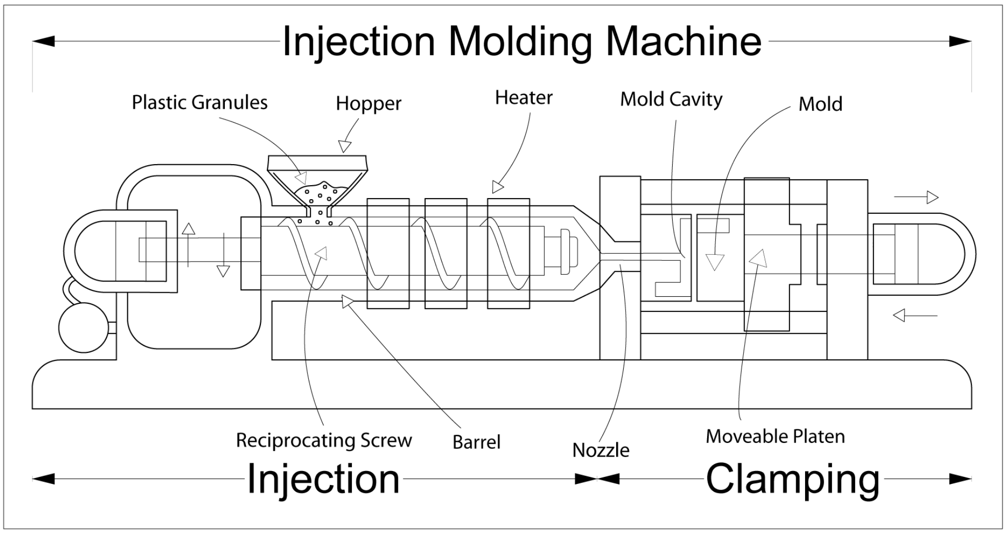


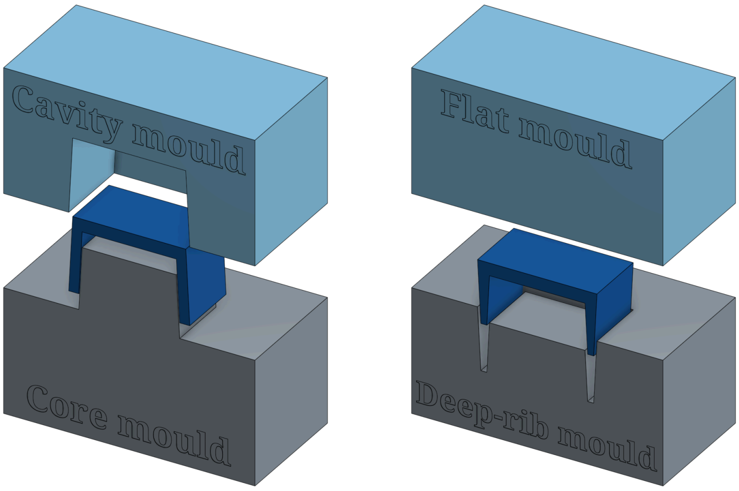
Figure 3.2: Schematic of an injection moulding machine, created by Brendan Rockey, University of Alberta Industrial Design, for Injection Molding Wikipedia article, 26 February 2009. Licensed under CC BY 3.0.

In the injection part, plastic granules are fed into a hopper which delivers the granules into the injection barrel. In the barrel, a screw rotates while reciprocating (moving forward and backwards), moving the granules forward in the system, whilst mixing them. The granules are gradually heated by several heating rings set to specific temperatures matching the material's requirements. While advancing in the barrel towards the nozzle, the granules soften into viscous plastic.

In the clamping part of the machine, two-part mould or tool (the two terms are used interchangeably) is mounted. There is often more than one method to mould a given part. For example, a "U" shaped part could be moulded using the core-cavity method or the deep-rib method (Figure 3.3). The core-cavity method (figure 3.3a) is often the most

[14]Source: https://commons.wikimedia.org/wiki/File:Injection_moulding.png
License: http://creativecommons.org/licenses/by-sa/3.0/

economic and easiest method: The mould part mounted on the fixed side (nozzle side), is called the cavity mould, whereas the mould part mounted on the moveable platform (or platen) is called the core mould. The alternative, the deep-rip method (figure 3.3b), may seem as a simpler approach as one of the mould parts is flat, however, the deep ribs are can be difficult and costly to machine and polish.



(a) Core cavity method (b) Deep-rib method

Figure 3.3: Two standard mould design principles.

The moulds are designed so that when the injected plastic cools down, it will (usually) clamp onto the core mould, due to shrinkage, when the mould opens. When the mould opens, it also draws the runner and the sprue out of the fixed mould.The sprue is the material that is left over in the injection nozzle, the runners are the channels in which the material flows to the parts, and the gates are the connection to the parts (figure 3.4). Ejector pins integrated into the core mould are pushed forward when the mould reaches the end position, thus ejecting the part. This process description is, to say the least, simplified.

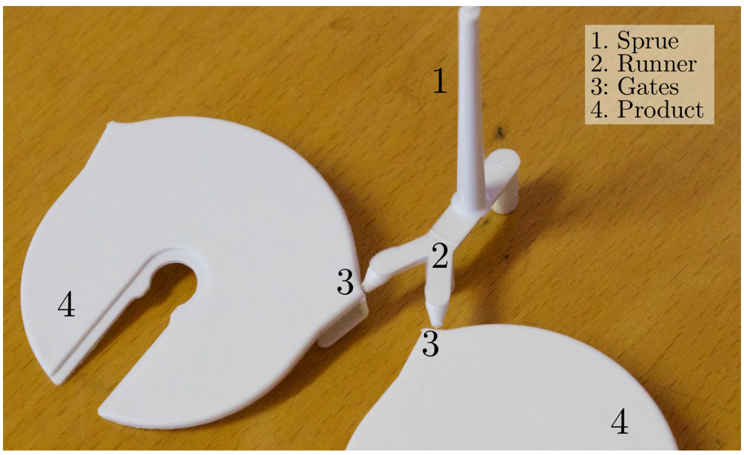


Figure 3.4: A sample injection moulded object

Although some parts in the moulds may be reused as we will see in the pilot experiment (Chapter 5), every produced part requires a dedicated tool, which is costly. Depending on how many parts are being produced, the tooling cost is often the main driver when calculating part cost.

The most common material for injection moulding tools is tool steel. Tool steel is a variety of carbon steel or alloy steel with distinctive hardness, and resistance to deformation and abrasion, which makes it suitable for tooling. Due to it's hardness, it is much more difficult to machine than aluminum for example. Mild steel and aluminums are also suited for tooling, and are commonly used to manufacture prototypes. These "soft tools" are easy to machine but are not as durable as tool steel, and will not withstand the wear and tear of mass production. Though aluminum tools have been reported to withstand more than 100.000 shots, when using modern hardened aluminum and surface coatings (Baranek, 2008).

The cost of producing injection moulding tool is very dependent of the size, the level of detail and the part features, as all those parameters greatly affect the machining time. A generic tooling workflow was created based on an analysis of several of Metako's recent orders, it is depicted in figure 3.5. According to Metako, although simulation software is used to optimise the tooling design, the tooling process can unfortunately be fairly iterative as there are so many parameters to consider.

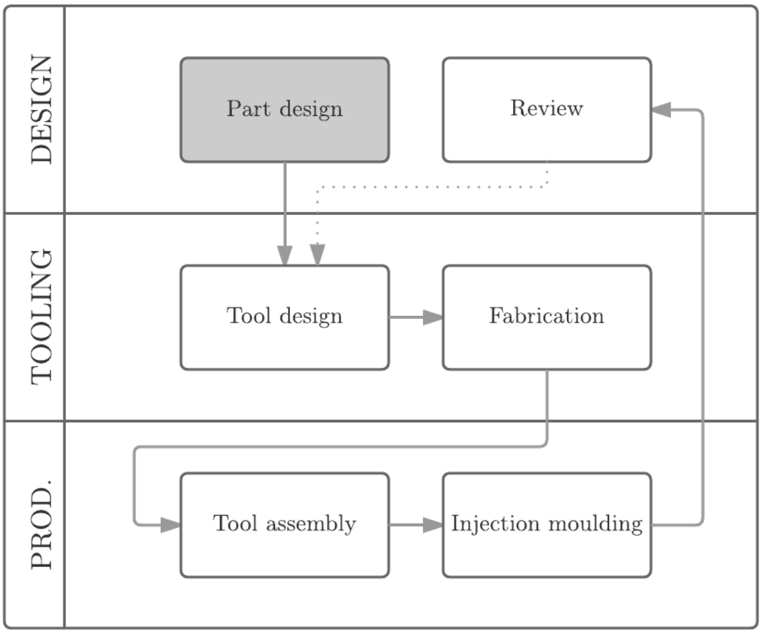


Figure 3.5: Generic tooling workflow

The generic tooling workflow depicted in figure 3.5 spans across the product design department and the tooling and production departments of a company. In the figure the workflow is linear, this reflects smaller manufacturing company, such as Metako. In Metako, the same employee will implement a design change into the tool design, fabricate the tool and injection mould the part(s). There are advantages to having employees with competencies across the whole workflow. For example, Design for Manufacturing, the process of maturing a design for production and optimising it for the production processes, is implemented at an early stage. In general, this will expedite the whole process. On the other hand, resources are tied up as it is not possible to take many projects in.

3.5 Plastic materials

Plastic materials are synthetic polymers[15] and are categorised as either thermoplastics, thermoplastic elastomers (elastic plastics) and thermosets (Jensen et al., 2005).
Thermoplastics are plastics that become viscous (they soften) when brought above a specific temperature and become pliable and mouldable, and solidifies upon cooling. Depending of their chemistry, thermoplastics can be rubber-like, as strong as aluminum or as brittle as glass. Thermoplastics are usually recyclable if the material has not degraded. Thermoplastics include both commodity plastics such as ABS (used for Lego™ bricks), Polyethylene terephthalate (PET) (used for plastic bottles), Polyvinyl chloride (PVC) (used for credit cards), as well as engineering plastics such as Polyphenylene Sulfide (PPS), Polycarbonate (PC), Polyetheretherketone (PEEK), Polyoxymethylene (POM) and Polyamide (PA) (nylon).
Thermoset plastics are thermosetting resins that undergoes a chemical transformation during processing. During processing the resins are "set" and become solid. The end product, a thermoset plastic is a highly cross-linked[16] polymer, which cannot be remoulded. Thermoset plastics are generally stronger than thermoplastics, and are more resistant to heat and solvents. As thermosets cannot be remoulded, they are rarely recyclable. Thermosets include silicone, Polyurethane (PUR), melamine (used in kitchenware), bakelite (used in old telephones and radios), and epoxies.
Both thermoplastics and thermosets can be processed by injection moulding, although the latter requires specialised machines.

[15] Large molecules composed of many repeated subunits. Commonly, the term polymer refers to synthetic polymers, otherwise known as plastics

[16] Three-dimensional network of molecular bonds.

Chapter 4

Case Studies

Stratasys and 3D Systems advertise the endless potential of 3D printed injection moulding tools and the ease of use and implementation. Rather than taking a salesman's words for granted, it is better to gather first-hand knowledge from experienced product engineers and prototyping engineers. Therefore the author visited Bang & Olufsen and Grundfos to better understand the industrial requirements of the concept and the challenges of implementing it.

4.1 Bang & Olufsen

Bang & Olufsen (B&O), based in Struer in Denmark, designs and manufactures high end televisions, music systems, loudspeakers, and multimedia products. In Denmark B&O uses CNC mills, lathes and a Ultimaker 2+ (A high end hobby FFF printer) for prototyping and in the Czech Republic, where most of the production takes place, a Stratasys FDM[1] printer is used tor prototyping. For SLS and SLA prints, external suppliers such as Davinci Development[2] and Materialize[3] are used. The prototyping technique is chosen based on the what needs to be verified, whether it's a design, a mechanism or an assembly.

Small series based on aluminum and steel moulds are manufactured by both local injection moulding manufacturers and manufacturers from Asia and Eastern europe.

The concept of 3D printing injection mould tools was not new to B&O. The concept had been considered for manufacturing prototype moulds, using an existing small injection moulding machine from Babyplast[4] currently used for prototyping. However, at that time the estimated gains were not significantly high compared to the prototype moulds currently available from their suppliers. A specific local supplier had devised a proprietary method for designing and manufacturing prototype aluminum moulds to a competitive price and a short lead time, supposedly using a modular system, although the details about it could

[1]FDM and FFF are virtually the same processes. FDM is trademarked by Stratasys, while the term FFF was coined by the opensource RepRap community.

[2]http://www.davinci.dk

[3]http://www.materialise.com

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

not be disclosed. Given the local and well proven solution, and given the high investment cost of industrial 3D printers, the concept was never pursued.

That being said, B&O were keen on discussing the subject and it's potential. Several key requirements were highlighted.

- Moulds must be produced in 1-2 days.
- Should not require jigs and steel parts to be produced for each mould.
- Commissioning must be fast (a few shots).
- Produced part must be identical to parts produced with steel tools.

To say the least, for B&O time and quality is of the essence. Regarding the time factor, the issue of process ownership was discussed. The concept relies on three key machines: The 3D printer, the CNC milling machine (for adjustments) and the injection moulding machine. If not all equipment is owned in-house, some of the processes must be outsourced, and outsourcing tend to prolong lead times. Thus the optimal scenario, meaning the scenario where a company stands to profit the most from the concept, is when the full process is done in-house.

4.2 Grundfos

With an annual production of more than 16 million pump units, Grundfos is one of the worlds largest and leading pump manufacturers. The company is based in Bjerringbro in Denmark and employs more than 18.000 employees globally (Grundfos, 2016).
Founded in 1945, Grundfos has extensive experience of producing parts with injection moulding. A large part of the manufacturing is done in Eastern Europe, still, 25 injection moulding machines are running in the manufacturing facilities in Bjerringbro and 25 machines are running in manufacturing facilities in France. For testing purposes, the Grundfos Technology Center in Bjerringbro uses seven injection moulding machines ranging from 80 tons to 350 tons pressure. For prototype manufacturing, a Stratasys[5] Objet Eden 500V resin printer, a Objet 500 Connex 3, and a Concept Laser[6] metal printer are used. Grundfos also uses external partners for rapid prototyping when it requires materials that cannot be produced in-house.

4.2.1 Project Origin

The idea of 3D printing injection moulding tools came to Lars Kannegaard and Birger Lind in 2010, where they saw a great potential for reducing prototyping lead time and cost for prototypes in end-use materials. Unfortunately, due to other commitments, the project laid dormant until 2013, when Stratasys demonstrated the feasibility of 3D printing injection moulding at the Euromold 2013 conference in Germany. This demonstration rebooted the project and enticed Lars and Birger to test the concept on their own.

The live demonstration made use of a Connex resin 3D printer, printing the moulds for a small toy car in the material Digital ABS[7], and a Babyplast injection moulding machine[8]. According to a video[9] of the demonstration the injection moulding process duration was approximately 2 minutes, unfortunately the injected material type is not disclosed.

4.2.2 Incentive

Grundfos' main incentive for testing the concept was that, if succesfull, they would be able to produce prototypes in the right end-use materials, in contrast to the current additive manufacturing technologies which are bound to a specific range of materials. Traditionally, when end-use materials prototypes were required, aluminum moulds were produced. They estimated they would be able to reduce the tooling lead time by 70% and the tooling cost by 50%. Besides having to outperform soft tooling with regards to lead time and cost, the main requirement was that the process had to work with technical plastics such as glass-reinforced PA, PPS and PC, which are the materials Grundfos mainly use in

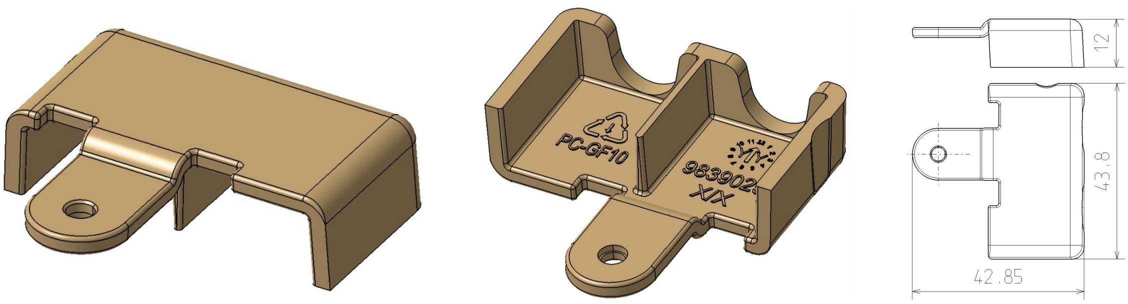
[5] www.stratasys.com
[6] www.concept-laser.de
[7] Stratasys print material for the J750 and Connex3, compatible with injection moulding. http://www.stratasys.com/materials/polyjet/digital-abs
[8] www.babyplast.com
[9] www.youtube.com/watch?v=EVdvuI8fp5s

their products. Grundfos has high requirements for the parts as they operate in high-temperature and often in contact with water and oil. These plastics are typically more difficult to injection mould compared to POM and ABS, which are commodity plastics. Finally, it was a requirement that the process did not require to redesign the part and mould, as it would prolong the lead time and render the concept useless.

4.2.3 Results

First mould

The experiment started with a simple part, as depicted in figure 4.1. The part is simple in the sense that it is relatively easy to injection mould as all vertical faces are drafted and there is no advanced feature such as threads or snapfits which require special mould designs to implement. The two-part standard mould design used for hard tools was used without alteration.



(a) Top view (b) Bottom view (c) Dimensions

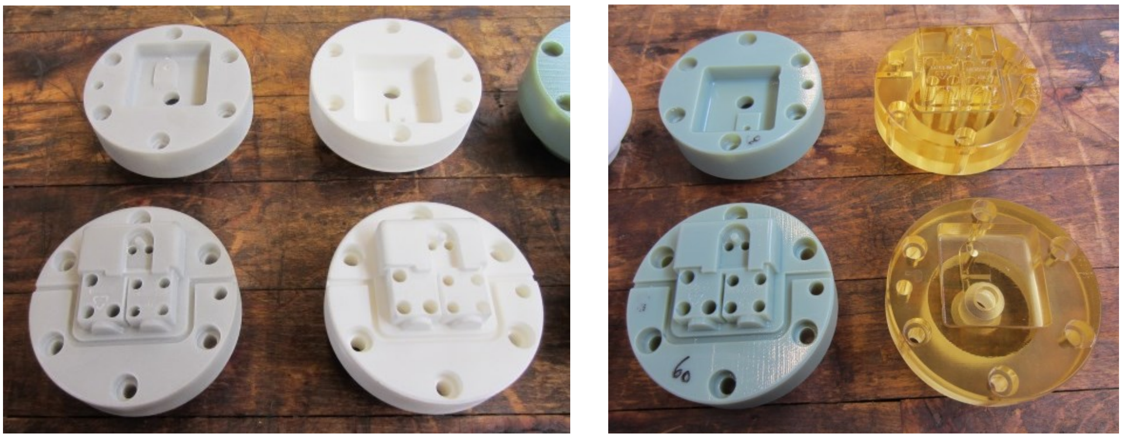
Figure 4.1: CAD representation of the first part to be moulded, courtesy of Grundfos (All rights reserved)

Grundfos tested various materials for the moulds: PA2200, PA3200GF, Fullcure 720 and Digital ABS. PA2200 and PA3200GF are both proprietary powder based polyamide[10] materials from EOS[11], where PA3200GF is glass-reinforced to increase part stiffness. Both materials are white. Parts are created using SLS technology. Fullcure 720 and Digital ABS are proprietary resin based photopolymer[12] materials from Stratasys. When cured, Fullcure 720 is a transparent material which according to Stratasys mimics the properties of Polymethyl methacrylate (PMMA)[13], and Digital ABS is light green and mimics the properties of ABS[14]. The moulds are depicted in figure 4.2 and the material specifications are described in table 4.1. The hole in the cavity moulds is intended for a metal sprue bushing, which is often used to prevent direct contact between the moulds and the nozzle.

[10] Commonly known as nylon.
[11] www.eos.de
[12] A photopolymer is a photosensitive fluid polymer material. When exposed to ultra violet light, the material is cured and solidifies
[13] Commonly known as acrylic glas or under its trade name "plexiglas".
[14] For reference, the standard Lego bricks are made in ABS

Specification	ASTM	DigitalABS	Fullcure720	PA2200	PA3200GF	Units
Tensile strength	D-638-03	55-60	60	48	51	MPa
Elongation at break	D-638-05	25-40	15-25	24	9	%
Modulus of elasticity	D-638-04	2600-3000	2870	1700	3200	MPa
Flexural Strength	D-790-03	65-75	76	58	72	MPa
Flexural Modulus	D-790-04	1700-2200	1718	1500	2900	MPa
Shore Hardness (D)	Scale D	85-87	n/a	75	80	-
HDT @ 0.45MPa	D-648-06	58-68	48	n/a	n/a	°C
HDT @ 1.82MPa	D-648-07	51-55	44	n/a	n/a	°C
T_g (Glass transition temperature)	DMA, E"	47-53	49	130	140	°C
T_m (Melting temperature)	ISO 11357-1	n/a	n/a	172-180	172-180	°C

Table 4.1: Material specifications of the 3D printed moulds. *Note:* Data from Stratasys and Eos brochures, May 2016.



(a) PA3200GF & PA2200 moulds (b) Digital ABS & Fullcure 720 moulds

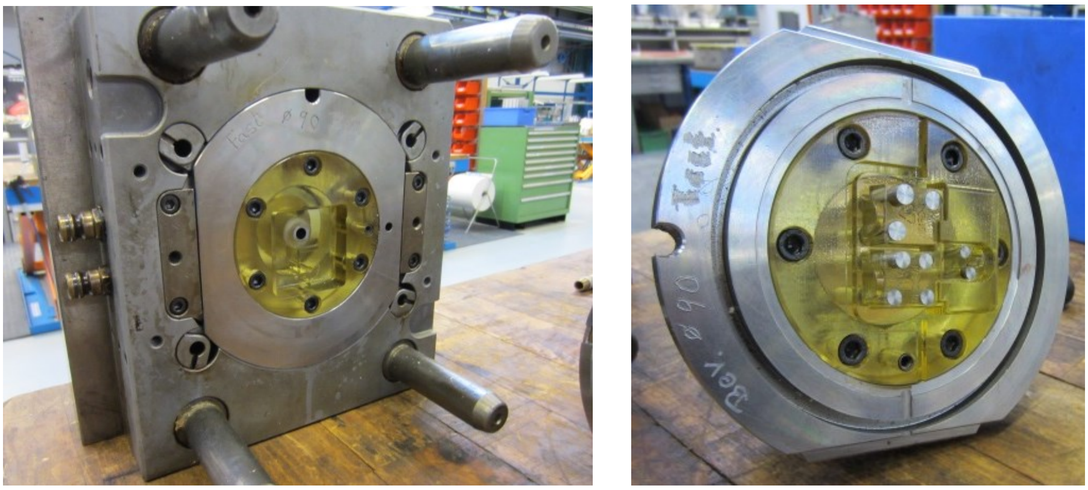
Figure 4.2: Pictures of the 3D printed moulds, courtesy of Grundfos (All rights reserved)

The moulds were mounted in the existing master moulds (figure 4.3), used for the original production. As the moulds design has not been altered, when mounted, it is flush with the master mould.

The PA2200 and PA3200GF moulds were tested with both PA66 30GF (30%glass-filled PA) and PPS 40GF (40% glass-filled PPS). Although it was expected the SLS-produced moulds would work well because of the high temperature resistance of the material, they failed with both materials. The parts failed to be be properly ejected, due to the surface roughness of the moulds, although the draft angle in the moulds was 3°(which should be more than enough for such a small part, according to Grundfoss).

Controversially, both PA66 30GF and PPS 40GF parts were successfully moulded in the Fullcure 720 and Digital ABS moulds. The Fullcure 720 mould also performed well with POM, PPE 20GF (20% glass-filled Polyphenylene Ether (PPE)) and PC 10GF (10% glass-filled PC).

At first, it seemed counterintuitive that the process would work properly with a material such as Digital ABS as its Glass transition temperature (T_g) and heat deflection



(a) Cavity mould (b) Core mould

Figure 4.3: Fullcure 720 moulds mounted in the master moulds, courtesy of Grundfos (All rights reserved)

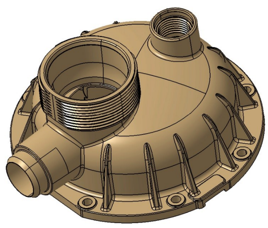
temperature (HDT) [15] (Refer to table 4.1) are well below the injection temperature of even low temperature materials such as ABS, which is in the range of 190°C to 250°C. The moulds were expected to degrade due to the high temperature. However, it seems as the low thermal conductivity of the moulds (compared to aluminum or steel moulds) renders the moulds less prone to thermal degradation as one would expect. This sets a certain minimum requirement for the cycle time as the mould surface has to cool down. Water cooling could be implemented into the mould, but would not be as effective as with hard tools because of the low thermal conductivity of the print materials. Due to the smooths surfaces of the prints, the parts were ejected without any problems. Twenty useable parts were produced.

It was not Grundfos' intention to test the limits of the printed moulds, hence the moulds were not tested extensively.

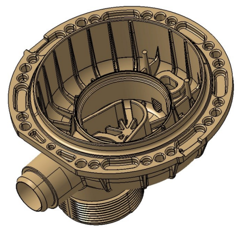
Second mould

Following the success with Fullcure 720 and Digital ABS, a more advanced part was tested. The pump housing in figure 4.4 was chosen due to its many challenging features. Firstly, the pump housing is much larger than the first part which was tested (approximately $300cm^3$ vs. $5cm^3$). Secondly it has features such as threads (internal and external) and undercuts which require advanced mould designs to be implemented for automating production.

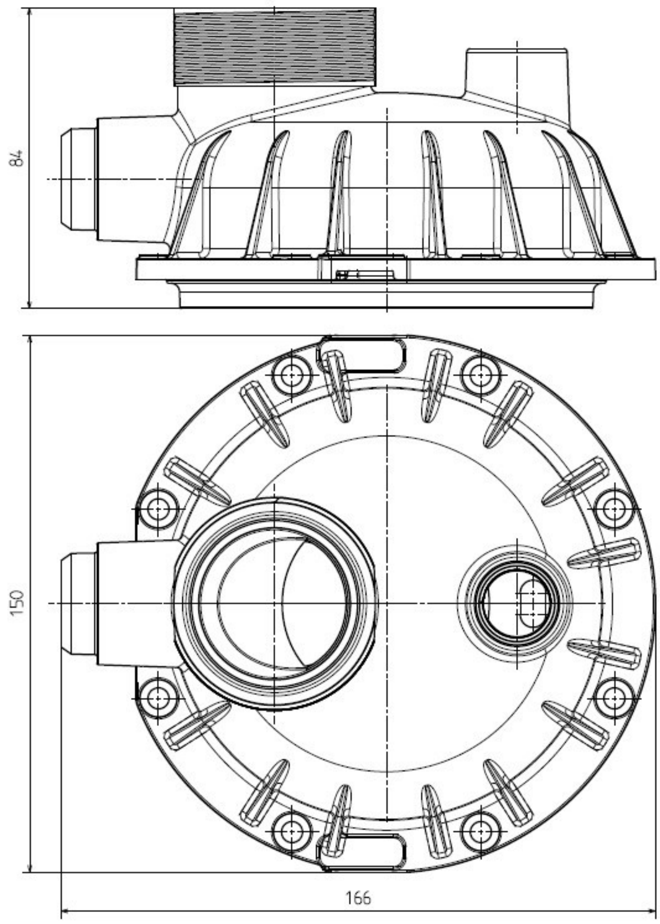
[15]The heat deflection temperature is the temperature at which a polymer sample deforms under a specified load. It is measured as described in ASTM D648.



(a) Top view



(b) Bottom view



(c) Dimensions

Figure 4.4: CAD representation of the second part to be moulded, courtesy of Grundfos

In mass production, threads and undercuts features can be integrated into the moulds by using automated sliding mechanisms and lifter systems. These automated integrations are far too costly to be designed into prototype moulds, hence these features are included by designing the mould in multiple parts, nine in total, to be assembled manually before each individual injection, as seen in figures 4.5 and 4.6.

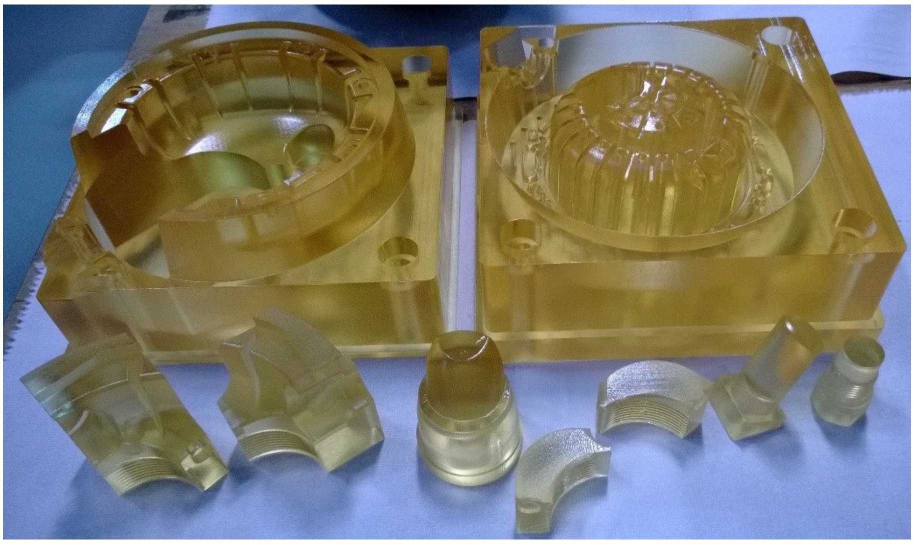
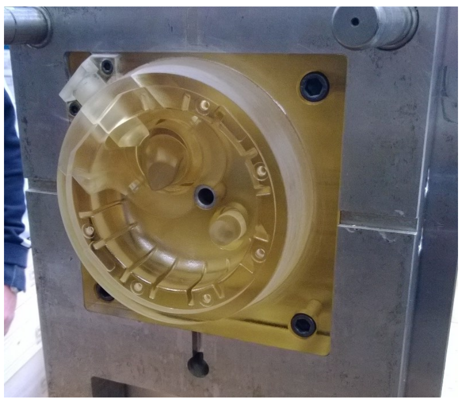


Figure 4.5: Picture of the moulds before assembly, courtesy of Grundfos (All rights reserved)

When assembled, the moulds showed to be off-tolerance. The expected print tolerance was ±0.2mm and the moulds had been printed exactly as the original CAD drawings, as excess material could easily be sanded off manually. However, the mould was 0.7mm too large on one side and 0.2mm too small on the other (wether it was X or Y print direction was unfortunately not noted). This required several adjustments.

(a) Core mould



(b) Cavity mould

Figure 4.6: Picture of the pump housing moulds assembled in the master moulds, courtesy of Grundfos (All rights reserved)

The end-use material for this part which is a 30% glass-reinforced blend of PPE and Polystyrene (PS) was used (PPE-PS-GF30, also sold as NORYL HFG300).

As in traditional tooling commissioning, the moulds were injected with minimum volume and pressure, and the settings were increased gradually. This is done to inspect the material flow to identify critical zones.

The processing parameters are shown in table 4.2. The clamp force keeps the mould closed when injecting, its value depends mostly of the injected material. Easy flowing which require low injection pressure, requires low clamping force compared to stiffer materials which require high injection pressure. The injection pressure is the primary pressure for injecting the material, followed by the holding pressure. Mould release agent was sprayed in the cavity mould.

Parameter	**Value**	**Unit**
Clamp force	500	KN
Injection Pressure limit	500	bar
Measured injection pressure at switch over	360	bar
Holding pressure	20	bar
Shot size	330	cm^3
Switch over point	51.1	cm^3
Temperature range	265-275	°C
Injection time	18,24	sec
Injection speed	8	mm/sec
Holding time	25	sec
Cooling time	110	sec

Table 4.2: Injection parameters for the second mould, courtesy of Grundfos

The Fullcure 720 moulds quickly showed signs of degradation as the injected material caused tears and cracks. After seven shots, the mould was discarded. The Digital ABS mould was then assembled and mounted. It showed to be more durable as there was no sign of deterioration. The sixth trial shot showed 100% filling (figures 4.7 and 4.8).

Figure 4.7: Trial shots of the pump housing, courtesy of Grundfos (All rights reserved)

As with the previous part, twenty parts were produced with satisfying results. According to Grundfos, the mould showed no sign of deterioration or degradation.

Figure 4.8: Picture of a successfully injection moulded part, courtesy of Grundfos (All rights reserved)

The whole process took less than 10 days. This includes printing, post-processing, mould assembly, commissioning and twenty successful injections. In comparison, Grundfos evaluated that it would have taken approximately 5 weeks to produce the prototype with aluminum moulds. All in all, the experiment was considered to be very successful, and the case was shared throughout the product development department.

4.3 Financial viability

To evaluate the financial viability of 3D printing injection moulding tools, three mould sets are compared: Grundfos' two moulds which were described in the case study and a sample keychain mould, provided by 3D Systems (figure 4.9).

As mentioned in chapter 2 (Method), the moulds were chosen as the feasibility of using them for injection moulding had been established by Grundfos and 3D Systems. Please refer to 2 (Method) for an overall description of the cost calculations and refer to appendix A for the detailed cost calculations. Refer to appendix D for screenshots of the 3D Systems print software, source of the print times and material usage. The mould durability is an estimation from the author and Metako, evaluated based on the mould design, the results from Grundfos and the experience that the author and Metako have gained from executing the pilot experiment (chapter 5). The author acknowledges that there is a certain level of uncertainty tied to the estimation, it is however the best possible estimate given the available information.

The total cost of production of parts, using the 3D printed moulds, is based on the quantity of produced parts ($P_{Qu.}$), the part unit cost (P_{Cost}), the mould change cost (M_{cost}) and the estimated the mould durability ($M_{dur.}$). The mould change cost includes both the mould cost and the labour of switching moulds. Although the durability would vary in reality, in the calculations it is considered to be fixed, thus the mould is changed whenever the fixed durability is reached. This is done in the calculations by rounding up the number of required moulds (equation 4.1).

$$Production_{Cost} = P_{Qu.} \times P_{Cost} + M_{cost} \times \lceil \frac{P_{Qu.}}{M_{dur.}} \rceil \tag{4.1}$$

The total cost of production of parts, using the milled moulds, is calculated in a similar manner, although the milled mould durability is not included, as it exceeds the plotted production volumes by far. Effectively, the milled mould cost is only included once.

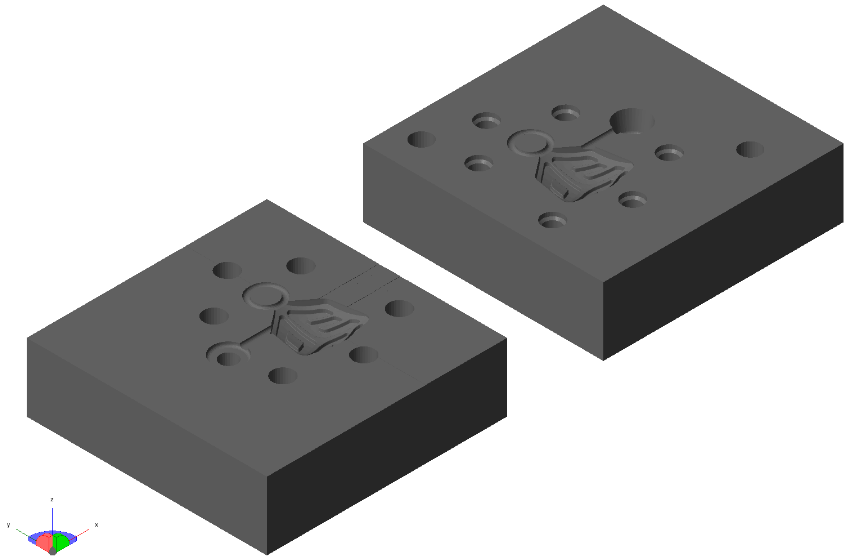


Figure 4.9: Isometric view of 3D Systems' keychain mould

4.3.1 Grundfos' 1st mould

The cost of manufacturing Grundfos' first mould, which is a relatively simple mould, is described in table 4.3. As the table shows, the 3D printed mould costs approximately a third to manufacture. Grundfos succeeded to produce twenty parts without seeing any degradation in the moulds nor on the parts. The mould durability has been estimated to 80 parts, mainly due to the simplicity of the mould, meaning that it is expected that the 3D printed mould must be changed after 80 parts are produced, due to wear and tear.

Grundfos - Mould 1	Value	Unit	Data Source
Print data (printed in one batch)			
Visijet M3-X weight	464	g	3D Systems software
Visijet S300 weight	271	g	3D Systems software
UHD resolution Print time	22,7	hours	3D Systems software
XHD resolution Print time	40,3	hours	3D Systems software
Print setup and post processing	2,2	hours	Author
Total lead time (UHD, 29 micron)	24,9	hours	Calculated
Total lead time (XHD, 16 micron)	42,5	hours	Calculated
3D printed tools cost			
Visijet M3-X	998	Dkk	Calculated
Visijet S300 (support material)	339	Dkk	Calculated
Labour (setup & post process)	440	Dkk	Calculated
Total 3D printed tooling cost	1776	Dkk	Calculated
3D printed mould durability	80	parts	Metako/author
Milled aluminum tools cost			
Setup and machining time	16	hours	Metako
Total aluminum tooling cost	5853	Dkk	Metako/author
Injection moulding cost			
Total setup time	0,75	hours	Metako
Total setup cost	187,5	Dkk	Calculated
Part material cost (PPS 40GF)	0,25	Dkk	Calculated
Tool cost (fab. & setup)			
3D Printed mould	1964	Dkk	Calculated
Milled aluminum mould	6040	Dkk	Calculated
3D Printed mould relative cost	33%	Dkk	Calculated

Table 4.3: Moulds cost calculations for 1st Grundfos mould

Based on the estimated mould durability (80 parts), the part production cost is compared for the two moulds (figure 4.4). As the graph shows, the 3D printed mould is expected to be replaced after 80 parts are produced. In the figure, the cost of each mould change includes both the cost of printing a new mould and the setup cost, as the old mould must be disassembled and the new mould must be mounted in the injection moulding machine.

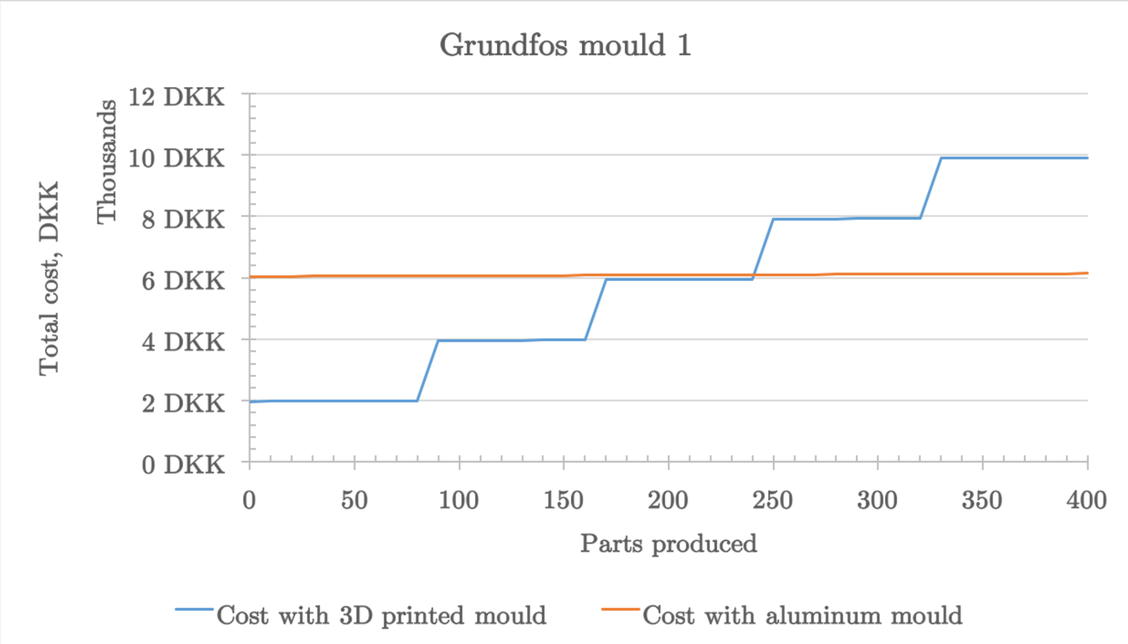


Table 4.4: Comparison of the total production cost with 3D printed moulds and milled aluminum moulds, based on the number of parts produced (Grundfos, mould 1).

The added cost of setting up a new mould is negligible compared to the cost of printing the mould. Hence, the break-even point is approximately three sets of 3D printed moulds, which corresponds to roughly 200 parts produced.

4.3.2 Grundfos' 2nd mould

As mentioned in the case study, Grundfos' second mould is very advanced as it integrates multiple complicated features which are costly to manufacture. This is reflected in the milling cost figuring in table 4.6, which is more than 30 thousands DKK. Comparatively, the 3D printed mould costs roughly 8 thousands DKK. Although Grundfos succeeded in producing twenty parts with no sign of degradation, due to the complexity of the mould and the fact that it had to be disassembled and reassembled for each cycle, the mould durability was evaluated to forty parts.

Grundfos - Mould 2	Value	Unit	Data Source
Print data (printed in two batches)			
Visijet M3-X weight	3084	g	3D Systems software
Visijet S300 weight	383	g	3D Systems software
UHD resolution Print time	64,3	hours	3D Systems software
XHD resolution Print time	113,8	hours	3D Systems software
Print setup and post processing	4,5	hours	Author
Total lead time (UHD, 29 micron)	68,8	hours	Calculated
Total lead time (XHD, 16 micron)	118,3	hours	Calculated
3D printed tools cost			
Visijet M3-X	6631	Dkk	Calculated
Visijet S300 (support material)	479	Dkk	Calculated
Labour (setup & post process)	900	Dkk	Calculated
Total 3D printed tooling cost	8009	Dkk	Calculated
3D printed mould durability	40	parts	Metako/author
Milled aluminum tools cost			
Setup and machining time	86	hours	Metako
Total aluminum tooling cost	31480	Dkk	Metako/author
Injection moulding cost			
Total setup time	1,5	hours	Metako
Total setup cost	375	Dkk	Calculated
Part material cost (PPS 40GF)	14,85	Dkk	Calculated
Tool cost (fab. & setup)			
3D Printed mould	8384	Dkk	Calculated
Milled aluminum mould	31855	Dkk	Calculated
3D Printed mould relative cost	26%	Dkk	Calculated

Table 4.5: Moulds cost calculations for 2nd Grundfos mould

The part production cost is compared in figure 4.6. Again, the break-even point (four 3D printed moulds) correlates with the relative manufacturing cost of the two moulds. The figure also shows that for both methods, the slope is steeper than the previous mould. The steep slope shows the high part cost, which is due to the manual disassembly and reassembly of the mould which is necessary for each cycle.

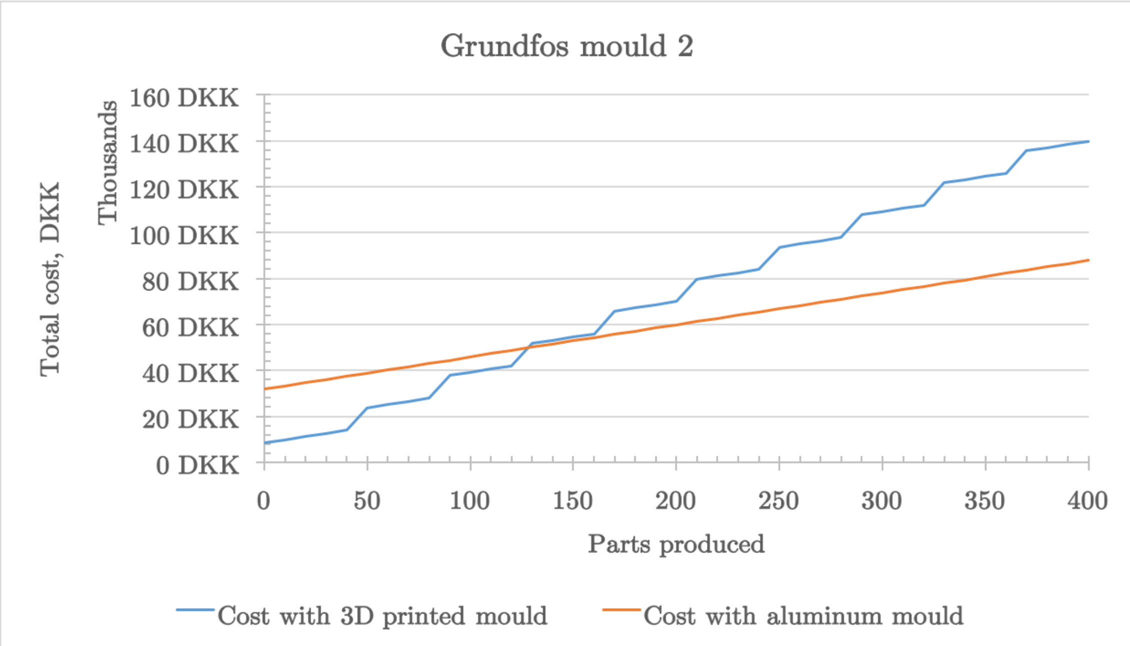


Table 4.6: Comparison of the total production cost with 3D printed moulds and milled aluminum moulds, based on the number of parts produced (Grundfos, mould 2).

4.3.3 3D Systems keychain mould

The keychain mould, is a sample mould that 3D Systems distribute to their resellers and potential customers, in order to test the concept. It is the simplest mould in the case study, which is reflected in the mould costs (table 4.7). The mould durability was evaluated to 100 parts.

3D Systems keychain mould	Value	Unit	Data Source
Print data (printed in one batch)			
Visijet M3-X weight	285	g	3D Systems software
Visijet S300 weight	56	g	3D Systems software
UHD resolution Print time	8,7	hours	3D Systems software
XHD resolution Print time	15,2	hours	3D Systems software
Print setup and post processing	1,2	hours	Author
Total lead time (UHD, 29 micron)	9,9	hours	Calculated
Total lead time (XHD, 16 micron)	16,4	hours	Calculated
3D printed tools cost			
Visijet M3-X	613	Dkk	Calculated
Visijet S300 (support material)	70	Dkk	Calculated
Labour (setup & post process)	240	Dkk	Calculated
Total 3D printed tooling cost	923	Dkk	Calculated
3D printed mould durability	100	parts	Metako/author
Milled aluminum tools cost			
Setup and machining time	11	hours	Metako
Total aluminum tooling cost	4065	Dkk	Metako/author
Injection moulding cost			
Total setup time	0,75	hours	Metako
Total setup cost	187,5	Dkk	Calculated
Part material cost (PPS 40GF)	0,06	Dkk	Calculated
Tool cost (fab. & setup)			
3D Printed mould	1110	Dkk	Calculated
Milled aluminum mould	4253	Dkk	Calculated
3D Printed mould relative cost	26%	Dkk	Calculated

Table 4.7: Moulds cost calculations for 3D Systems keychain moulds

As with the previous moulds, the break-even point (four moulds) correlates with the relative manufacturing cost of the two moulds (figure 4.8).

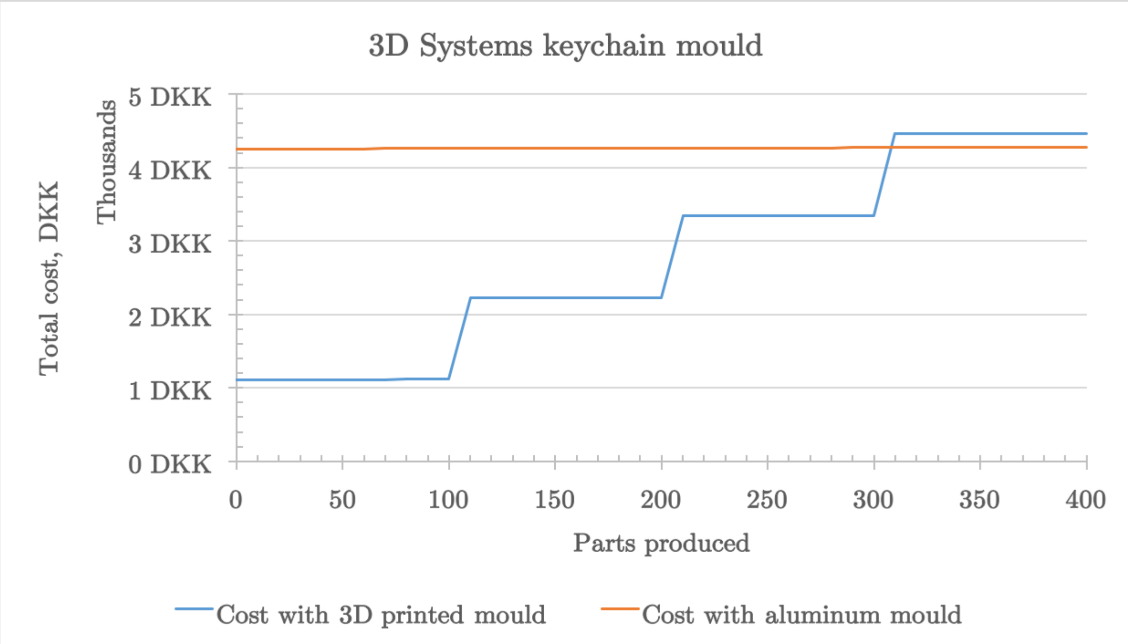


Table 4.8: Comparison of the total production cost with 3D printed moulds and milled aluminum moulds, based on the number of parts produced (3D System keychain mould).

Based on the three mould designs that have been analysed, the cost of 3D printing the moulds clearly lower than the cost of machining the moulds. The savings depends both on the complexity and size. For 3D printed moulds, the size is the main cost driver, while for the milled moulds, the complexity is the main cost driver.

The viability is of course very dependent of the quantity of parts that are required, and the durability of the 3D printed moulds. An evaluation of the mould costs calculations is done in chapter 6, section 6.1 (Financial viability evaluation).

Chapter 5

Pilot experiment

The pilot experiment brings to the test the information and considerations that was gathered through the literature review and case studies. This chapter brings the project results closer to reality, and showcases details of the process that have been omitted in the manufacturers pamphlets or might have been missed in the project's case studies.

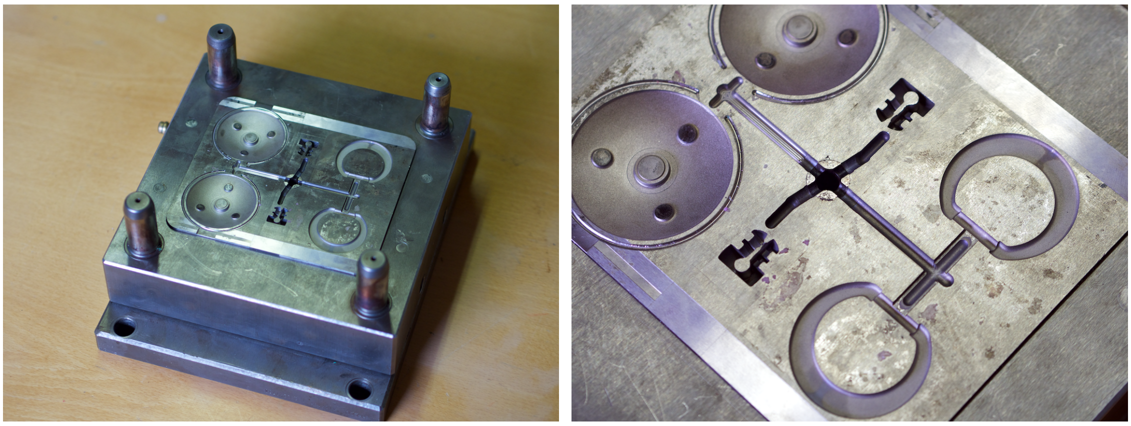
Metako[1] is a danish plastic manufacturing and tooling company with 20 years of experience with the processes. The company is located in Hillerød and has five injection moulding machines (40-100T), three CNC milling machines, and an Electrical Discharge Machine (EDM) at their disposal. Metako agreed to use an existing project for the pilot experiment.

5.1 The case

Metako is currently working on redesigning a part in a pacifier assembly being manufactured for a customer. The pacifier design proved to be faulty as the assembly could not withstand the required pull force without breaking (10kg as per european regulations). The moulds had already been manufactured (figure 5.1). Rather than spending weeks on mechanical design and simulations to correct the faulty design, Metako agreed to use this mould as a test case to quickly implement and test a correction, without spending time and money on aluminum tools.

As seen in figure 5.1, the mould is designed in several parts. The master mould works as a frame for the three inserts. The central insert is the one which needs to be redesigned.

[1] www.metako.dk



(a) The cavity mould (b) Central part which needed redesign

Figure 5.1: The original mould (cavity)

5.2 Equipment and materials

The 3D printer used for the pilot experiment is a 3D Systems Projet 3500 HDMax, which is installed in 3D Printhuset's production facilities in Copenhagen. The highest resolution of the printer is 750 x 750 x 1600 Dots Per Inch (DPI) (in xyz directions) with 16 micron layers. The DPI resolution says more about the level of detail than the actual accuracy which is 0.025mm to 0.05mm per 25.4mm of part dimension, or roughly 0.1% to 0.2% The accuracy is marketed as "typical" accuracy as it may vary depending of build parameters, geometry, size, orientation and post-processing.
Visijet M3-X was used as print material. The material is marketed as having the look and feel of injection moulded ABS, and being both tough and resistant to high temperatures. The Visijet M3-X specifications are described in table 5.1 together with Stratasys' Digital ABS for comparison. Visijet S300[2] was used as support material. Visijet S300 is a wax-like material with a low melting point (60°C), is removed after printing by heating up the parts in an oven. The oven used for the post processing is a 3D Systems InVision Finisher (formerly known as ProJet Finisher), which is a thermostat controlled oven with forced air circulation. As the mould contained small details and crevasses, a GeneralSonic GS4 ultrasonic cleaner was used to clean the moulds thoroughly.
To injection mould the parts a Battenfeld BA 400, a 40-ton injection moulding machine, was used.

The end use material for the part being Polypropylene (PP), that material was used in the experiment.

[2]3D Systems' support material for the ProJet MJP 3500 and ProJet 3600 printers. http://www.3dsystems.com/materials/visijetr-s300

Specification	ASTM	Digital ABS	Visijet M3X	Units
Tensile strength	D-638-03	55-60	49	MPa
Elongation at break	D-638-05	25-40	8,3	%
Modulus of elasticity	D-638-04	2600-3000	2168	MPa
Flexural Strength	D-790-03	65-75	65	MPa
Flexural Modulus	D-790-04	1700-2200	n/a	MPa
Shore Hardness (D)	Scale D	85-87	n/a	-
HDT @ 0.45MPa	D-648-06	58-68	88	°C
HDT @ 1.82MPa	D-648-07	51-55	n/a	°C
Glass transition temperature)	DMA, E"	47-53	n/a	°C
Melting temperature)	ISO 11357-1	n/a	n/a	°C

Table 5.1: Visijet M3X and Digital ABS specifications, *Note:* Data from 3D Systems and Stratasys brochures, May 2016.

5.3 The process

Mould design

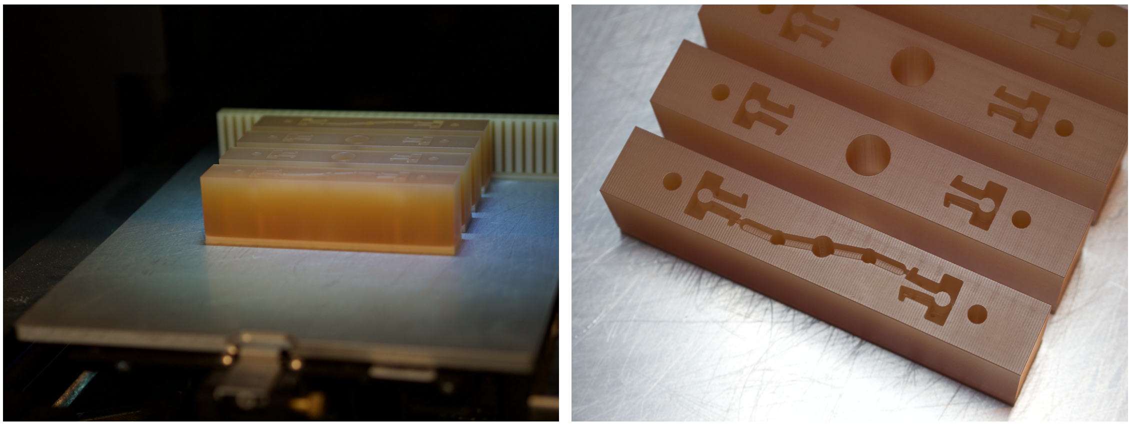
The threaded holes for fastening and the holes for the pin ejectors were part of the original mould design and were not changed. The guiding holes in the parts were redesigned to be slightly smaller as they would be milled to precision after printing. Furthermore, they were redesigned to go through the whole part, so the holes wouldn't require support material when printing. The fastening holes were designed as straight holes, which would have to be threaded after printing. The cavity mould and the core mould went through the same design changes with regards to guiding holes and fastening holes. Learning from Grundfos' experience, before printing the moulds, 0.5mm was added to all sides and to the bottom of the mould. This would provide enough extra material so the moulds could be milled to fit the master mould perfectly. The runner was originally designed into both sides of the mould, it was redesigned so that the full runner depth was located in the core mould, according to Metako, this would ensure that the whole part would stay in the core mould when opened.

1. Threaded holes for fastening
2. Holes for guiding pins
3: Holes for pin ejectors

Figure 5.2: Cross section of the core mould

3D printing the moulds

Two sets of moulds were printed flat on the print bed in the highest resolution available (750 x 750 x 1600 DPI 16μ layer), the total print time was approximately 26 hours (figure 5.3). The "wall" which is seen behind the moulds in figure 5.3a is automatically generated by the printer software. Its purpose is to clean the print heads at each layer. On the same figure, the bottom white layer which is visible is the support material (the print material is never deposited directly on the aluminum plate).

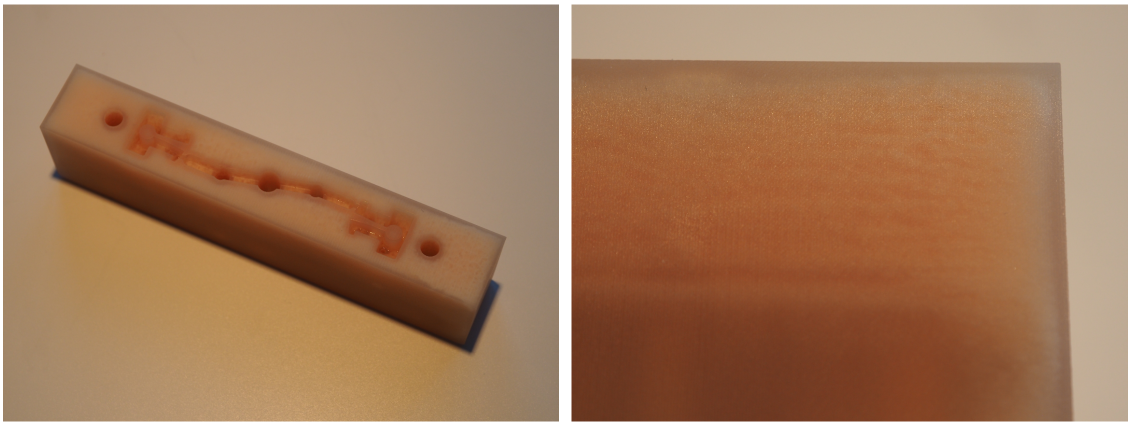


(a) Moulds in the printer (b) Close-up of the fresh moulds

Figure 5.3: The newly printed moulds

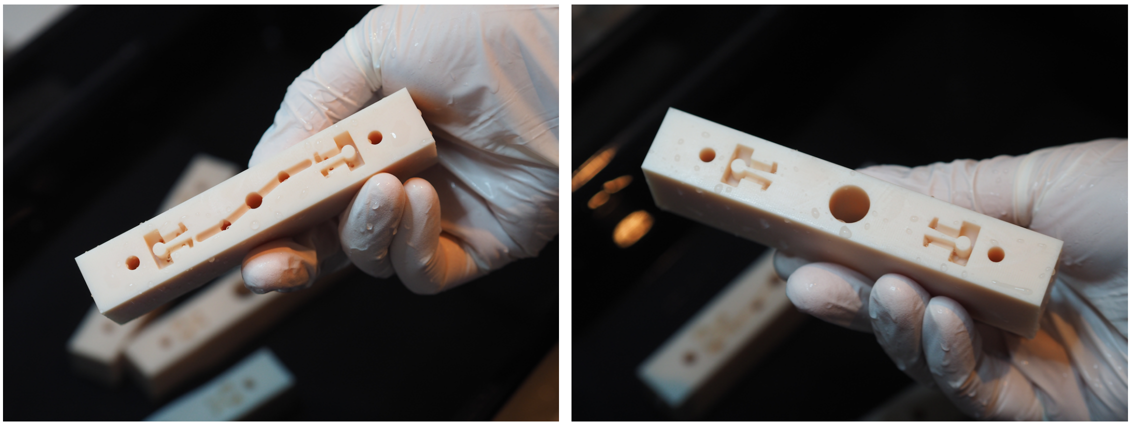
To remove the bulk wax, the moulds were placed in the ProJet Finisher oven at 65°C, as per recommendation of 3D Systems. The moulds were removed from the oven after approximately one hour and thirty minutes. Some support material still remained, nested in the pin ejector holes and the holes for fastening.

The mould's colour and opacity had changed (figure 5.4, this is normal according to 3D Systems. To obtain the expected uniform opaque white finish, prints must be quenched in water. Before quenching, the residual wax was removed in ultrasonic bath at 65°C, using 3D Systems' EZ Rinse cleaning solution. After 20 minutes in the ultrasonic bath, the moulds were quenched in room temperature tap water, resulting in opaque white parts (figure 5.10). It is unknown whether the material properties are altered by the quenching.



(a) Top view (b) Close-up of the surface

Figure 5.4: The moulds after bulk wax removal



(a) Core (b) Cavity

Figure 5.5: The quenched moulds

5.3.1 Mould inspection and adjustments

A visual inspection showed that the moulds were incredibly smooth and detailed. Besides from the obvious design changes, the moulds seemed identical (figure 5.6). Please refer to figures C.1a and C.1a in appendix C for close up photographies of the part patterns in the moulds.

The 3D printed moulds were measurements with an industry grade Mitutoyo digital caliper, with a resolution of 0.01mm. The measurements showed that the moulds had warped and were slightly curved along the long side (X axis in the printer). Unfortunately, as the moulds were not measured straight out of the printer, it is uncertain when this warping occurred. It is most probably due to heat of the cleaning process or the quenching. To measure the curvature, two sets of measures were taken:

- Laying on the side, the part height was measured in seven increments along the length.
- Laying upside down (part details facing down), the distance between the surface

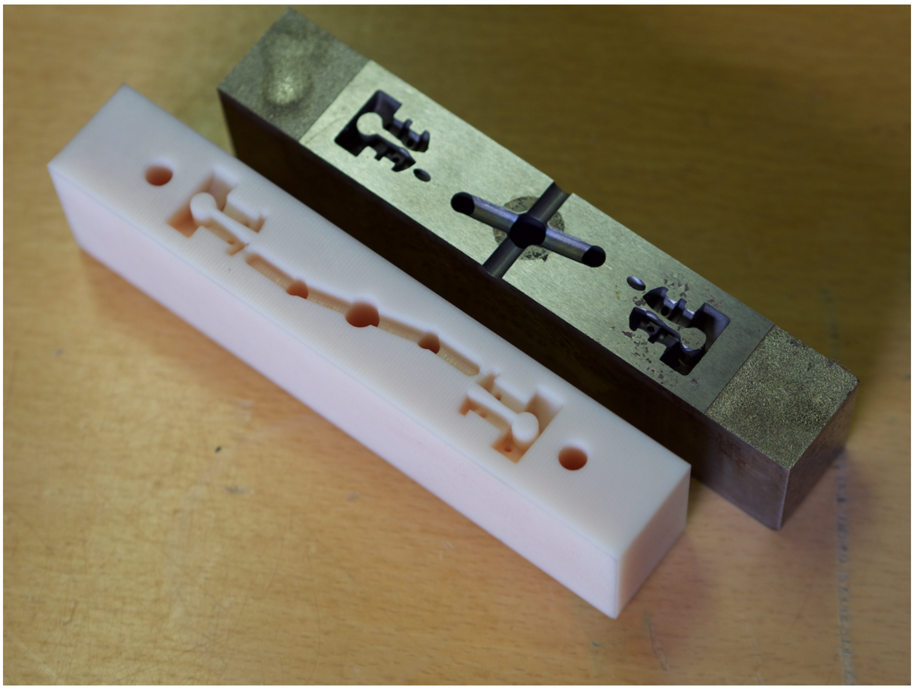


Figure 5.6: The 3D printed insert and the original insert, side by side.

facing up (bottom side of the mould) and the underlying surface was measured.

The curvature of the top side of the mould was deduced from the two measurements (please refer to B.1 in appendix B for the measurement data). The cavity mould measurements were plottet to visualise the curvature (figure 5.7).

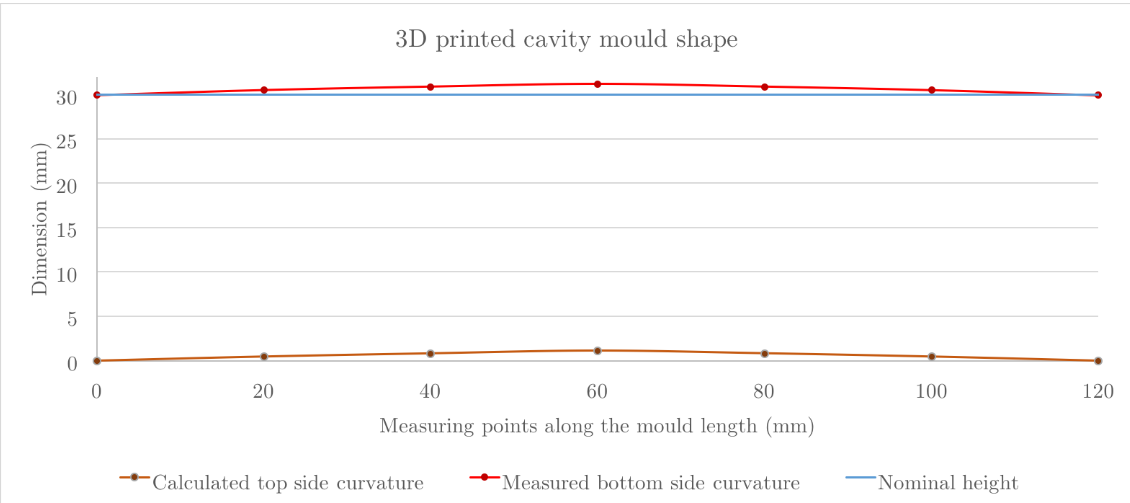
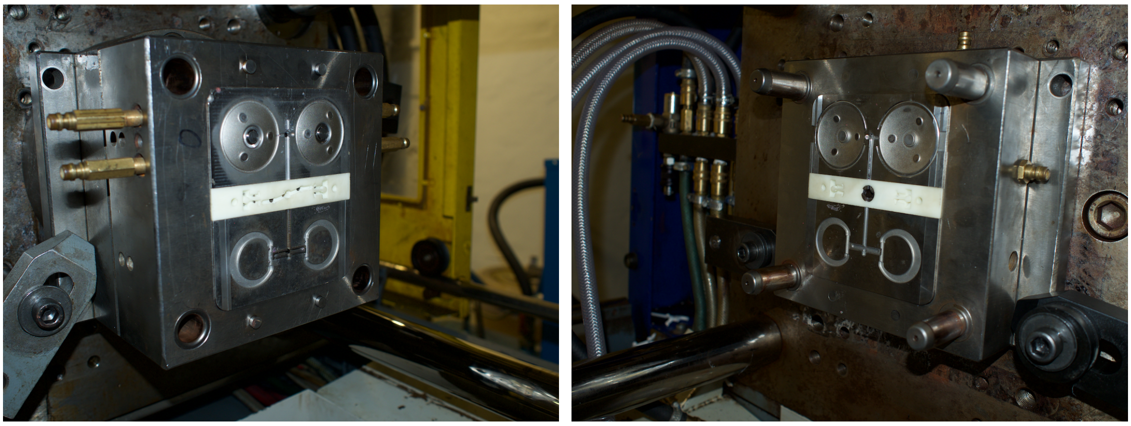


Figure 5.7: The measured cavity mould curvature.

This unfortunate curvature meant that the both moulds (the core side of the mould had warped into a similar shape) had to CNC milled flat, which would affect the final shape of the part. Approximately 0.45mm was removed from the side with the part features, thus the part would no longer be circular but oval.

Although the this meant that the produced parts would not match the original parts, thus that the quality of the parts could no longer be assessed quantitatively, it was decided that the experiment should continue. The produced part could still be assessed qualitatively.

The moulds were inserted into the master moulds and mounted onto the injection moulding machine (figure 5.8).



(a) Core (b) Cavity

Figure 5.8: Mounted moulds

5.3.2 Injection

All produced parts were catalogued separately and settings were recorded. Table 5.2 shows the injection parameters and an assessment of the parts. The cooling time between shots was kept at 15 seconds for the whole experiment and mould release agent was sprayed into both moulds roughly every five shots. Grundfos had recommended to start the injection moulding with low temperature, pressure and speed to avoid damaging the mould.

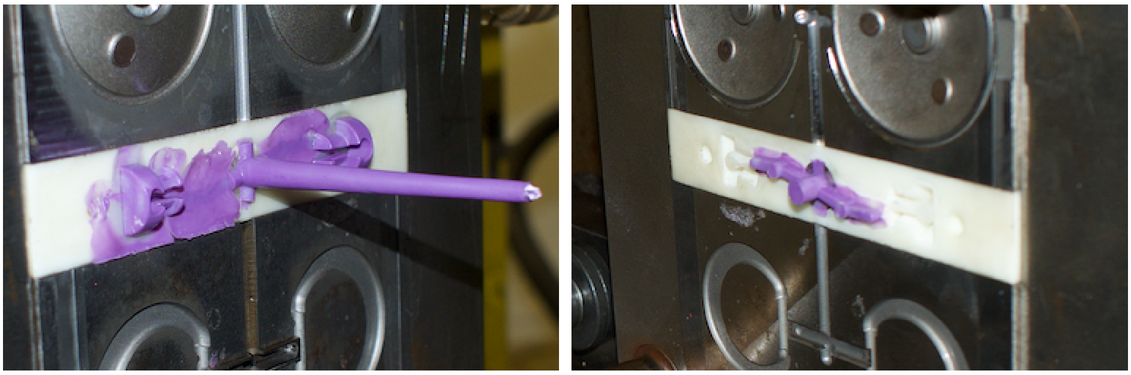
The first shots were effectuated at 160°C(nozzle temperature), 35 Bar holding pressure, an injection speed rate of 15 (unit-less machine setting) for 0.60 seconds. Seeing that the mould was not filled, the temperature was increased to 190°C. The jump from 160°Cto 180°C may seem steep, but the change is not instantaneous in the machine, thus the effect is gradual.

By the 7th shot, both parts were fully filled, but also excessive flash had been produced (5.9a). Flash is excess material caused by leakage between the two moulds. As the shots 8 to 10 were not consistent (the 10th shot was partly stuck in the inlet, figure 5.9b), the temperature was increased by 5°C. The Injection duration was also reduced by 20 seconds to reduce the flash quantity, unfortunately this affected the filling.

Shot #	Nozzle temp (°C)	Pressure (Bar)	Injection speed rate**	Injection duration (s)	Part A filled?***	Part B filled?***	Flash quantity (0-3)****
1	160	35	15	0,60	no	no	2
2	160	35	15	0,60	yes	no	1
3	160	35	15	0,60	no	no	3
4	180	30	15	0,60	no	no	3
5	180	33	15	0,60	no	no	3
6	180	33	15	0,60	no	no	3
7	180	40	15	0,60	yes	yes	3
8	180	35	15	0,70	yes	no	3
9	180	35	15	0,60	yes	no	3
10	180	40	15	0,30	yes	yes	3
11	185	40	15	0,20	yes	no	1
12	185	40	18	0,45	yes	yes	1
13	185	40	18	0,45	yes	yes	3
14	185	40	18	0,45	yes	yes	3
15	185	40	18	0,45	yes	yes	3
16	185	40	18	0,45	yes	yes	3
17	185	40	18	0,45	yes	yes	3
18	185	40	18	0,45	yes	yes	3
19	185	40	18	0,45	yes	yes	3
20	185	40	18	0,45	yes	yes	3
21	185	40	18	0,45	yes	yes	3
22	185	40	18	0,45	yes	yes	3
23	185	40	18	0,45	yes	yes	3
24	185	40	18	0,40	no	no	0
25	185	40	18	0,40	no	no	0
26	185	40	18	0,40	yes	yes	3
27	185	40	18	0,40	yes	yes	3
28	185	40	18	0,40	yes	no	0
29	185	40	18	0,40	yes	yes	2
30	185	40	18	0,40	no	no	0
31	185	40	18	0,40	no	no	0
32	185	40	18	0,40	no	no	0
33	185	40	18	0,30	yes	yes	3
34	185	40	18	0,30	no	no	1
35	185	40	18	0,30	no	no	1
36	185	40	18	0,30	no	no	1
37	185	40	18	0,30	no	no	1
38	185	40	18	0,30	no	no	1
39	185	40	18	0,30	no	no	1
40	185	40	18	0,30	no	no	1
41	185	40	18	0,30	yes	yes	1
42	185	40	18	0,30	no	no	1
43*	185	40	18	0,30	yes	yes	1
44	185	40	18	0,30	no	no	1
45	185	40	18	0,30	yes	no	0

* The mould broke
** Unit-less machine setting
*** It was not possible to differentiate left and right part after ejection
**** Qualitative assessment (0 = no flash, 3 = extensive flash)

Table 5.2: Injection settings

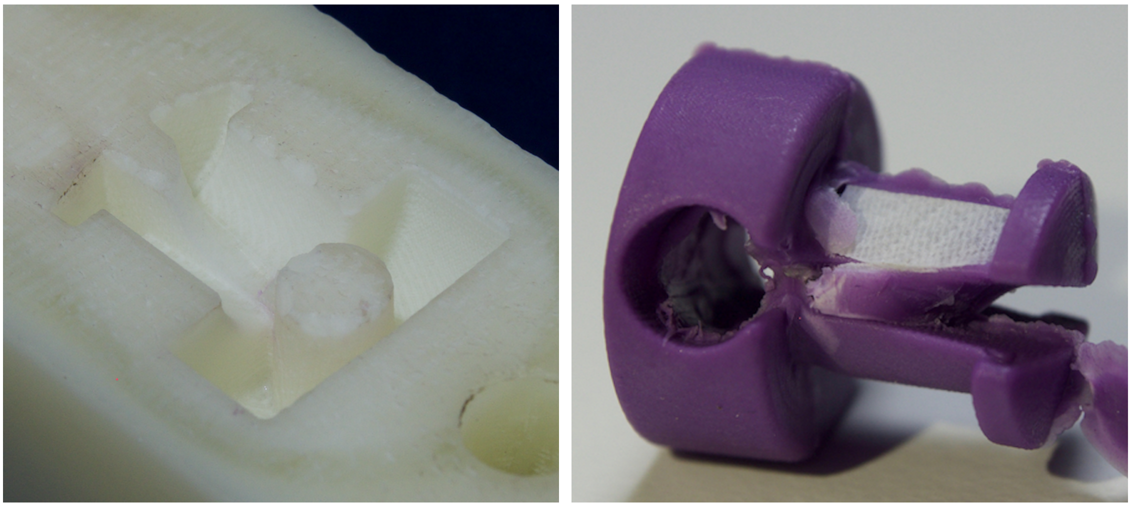


(a) 7th shot, showing excessive flash (b) 10th shot, runner is stuck in the inlet

Figure 5.9: Moulding challenges

The parameters were kept stable by the 13th shot to increase consistency. Shots 13 to 23 were consistent although they all exhibited flash around the runners and the parts. To reduce the flash the injection duration was gradually lowered. Unfortunately, this also affected the part filling.

The 43th shot was stuck in the cavity mould, and upon manual removal a part of the mould broke off (figures 5.10a and 5.10b).

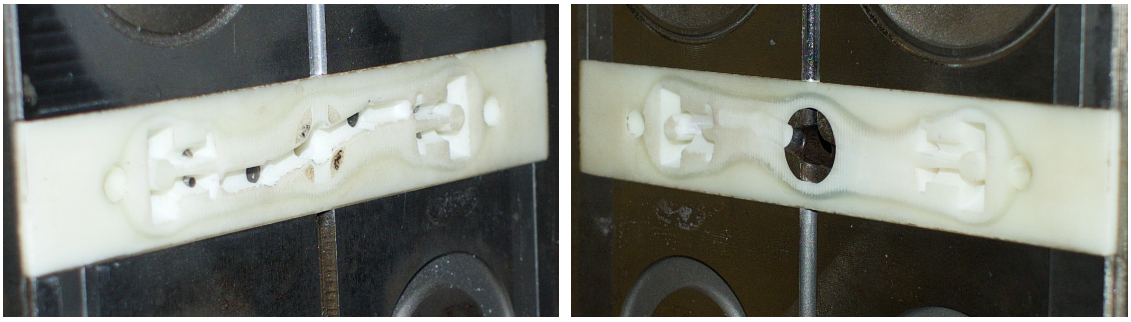


(a) Broken mould (b) Part with mould piece (43rd shot)

Figure 5.10: The broken mould

The experiment was stopped two shots after, resulting in 45 shots in total. A quick visual inspection of the moulds after the 45 shots, showed that the mould colour had changed (figures 5.11a and 5.11b). The discolouration had occurred due to the material temperature, and might have been avoided by increasing the cooling time.

As the 3D printed moulds could not produce the parts in time for Metako's project deadline. The experiments were put on hold to free the resources required to fulfil the order within the deadline. Unfortunately it was not possible, within the project's timeframe, to continue the experiments with the second set of moulds that had been printed.

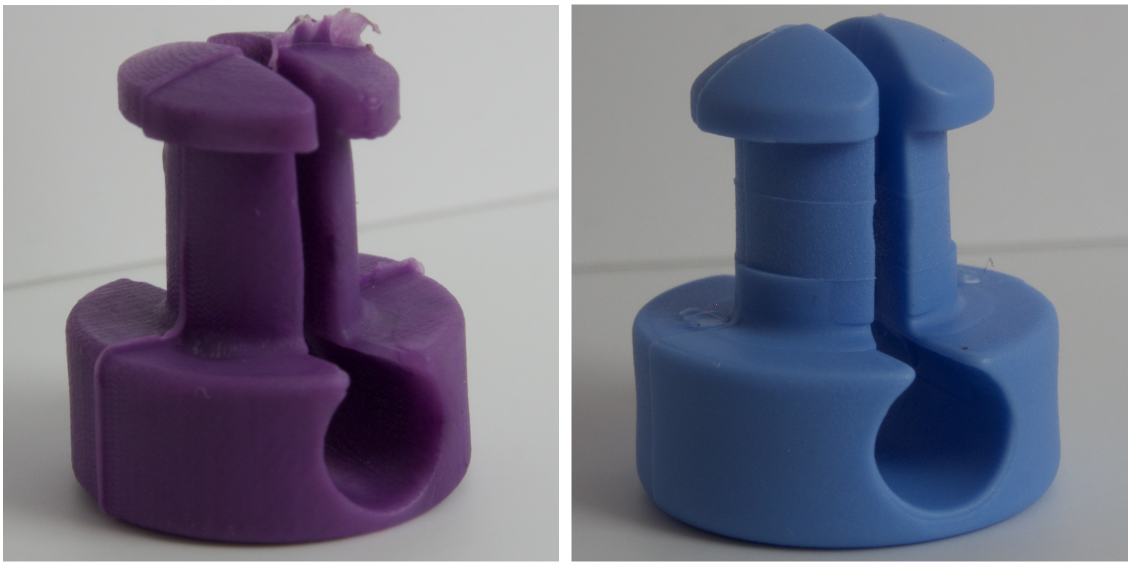


(a) Core (b) Cavity

Figure 5.11: The discoloured moulds after 45 shots.

5.4 Part quality

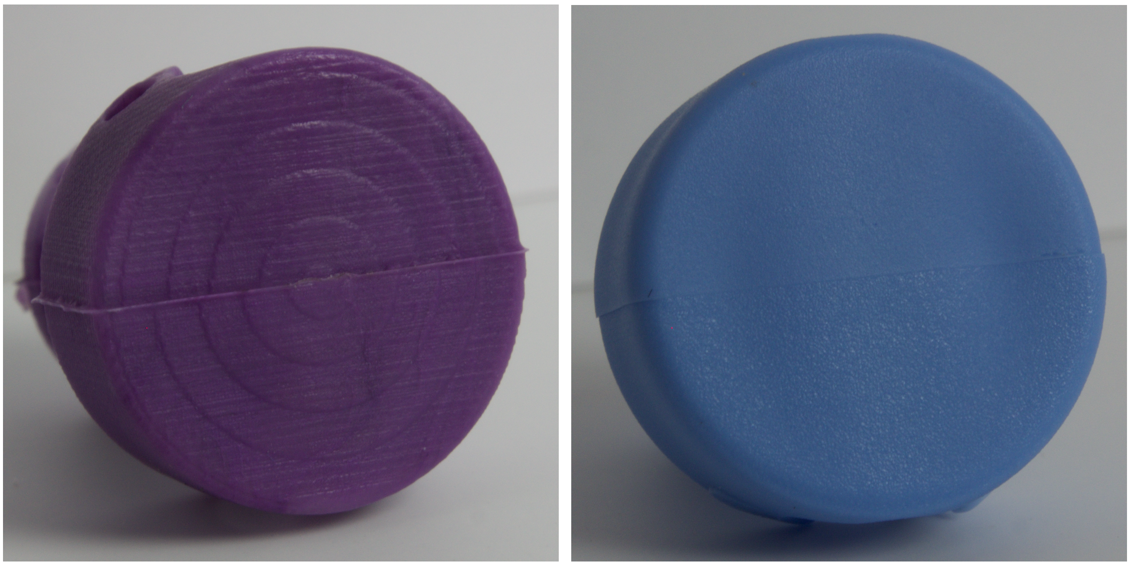
Metako manufactured steel moulds in order to produce the part for their customer. The newly produced part were used as a baseline for a qualitative assessment the parts produced in the experiment. Aside from the obvious differences due to the flash and the redesign, the quality of the parts produced with 3D printed tools is better than Metako expected (figures 5.12a and 5.12b). The corners are sharp, and the curved surfaces are smooth. The major difference is the part's bottom surface (figures 5.13a and 5.13b), where the 3D printed mould has left both layer markings and rings. The layer markings can be attributed to the print direction as the markings orientation corresponds with the print direction, although they were not expected to be visible as the printer's vertical resolution is 16μ (0.016mm).



(a) Produced with 3D printed mould (b) Produced with steel mould

Figure 5.12: Side view of parts

The ring markings are difficult to explain, as the corresponding mould face was completely flat in the CAD file which was sent to the printer software. Such patterns can also appears on vertical surfaces when printing with FFF printers, where the defect is attributed to high printing speeds and vibrations. Whether the phenomenon is related, is difficult to say.



(a) Produced with 3D printed mould (b) Produced with steel mould

Figure 5.13: Bottom view of parts

Please refer to figures C.2 and C.3 in appendix C for detailed high resolution close-ups.

An evaluation of the experiment results is done in chapter 6, section 6.2 (Pilot experiment evaluation).

5.5 Cost comparison

As in the case studies, a cost comparison was made on the two mould fabrication methods. The mould durability was evaluated to 60 parts. In the experiment, the mould broke after only 43 shots were effectuated, this is however due to human error (forceful removal of the part from the mould). Apart from the discolouration, the mould did not seem degraded.

The cost of 3D printing the moulds is approximately 14% of the cost of manufacturing the moulds in aluminum (table 5.3). This is due to the fact that, while the 3D printer is unaffected by the level of detail of a part and small features, the milling operations are strongly affected. Small details often require slow milling from various angles and several tool changes.

Metako mould	Value	Unit	Data Source
Print data (printed in one batch)			
Visijet M3-X weight	177	g	3D Systems software
Visijet S300 weight	47	g	3D Systems software
UHD resolution Print time	12,6	hours	3D Systems software
XHD resolution Print time	22,4	hours	3D Systems software
Print setup and post processing	1,2	hours	Author
Total lead time (UHD, 29 micron)	13,8	hours	Calculated
Total lead time (XHD, 16 micron)	23,6	hours	Calculated
3D printed tools cost			
Visijet M3-X	381	Dkk	Calculated
Visijet S300 (support material)	59	Dkk	Calculated
Labour (setup & post process)	240	Dkk	Calculated
Total 3D printed tooling cost	679	Dkk	Calculated
3D printed mould durability	60	parts	Metako/author
Milled aluminum tools cost			
Setup and machining time	16	hours	Metako
Total aluminum tooling cost	5815	Dkk	Metako/author
Injection moulding cost			
Total setup time	0,75	hours	Metako
Total setup cost	187,5	Dkk	Calculated
Part material cost (PPS 40GF)	0,43	Dkk	Calculated
Tool cost (fab. & setup)			
3D Printed mould	867	Dkk	Calculated
Milled aluminum mould	6003	Dkk	Calculated
3D Printed mould relative cost	14%	Dkk	Calculated

Table 5.3: Moulds cost calculations for Metako moulds

Given the substantial difference in cost of fabrication, the break-even occurs after seven mould changes, or roughly 400 parts produced (figure 5.4).

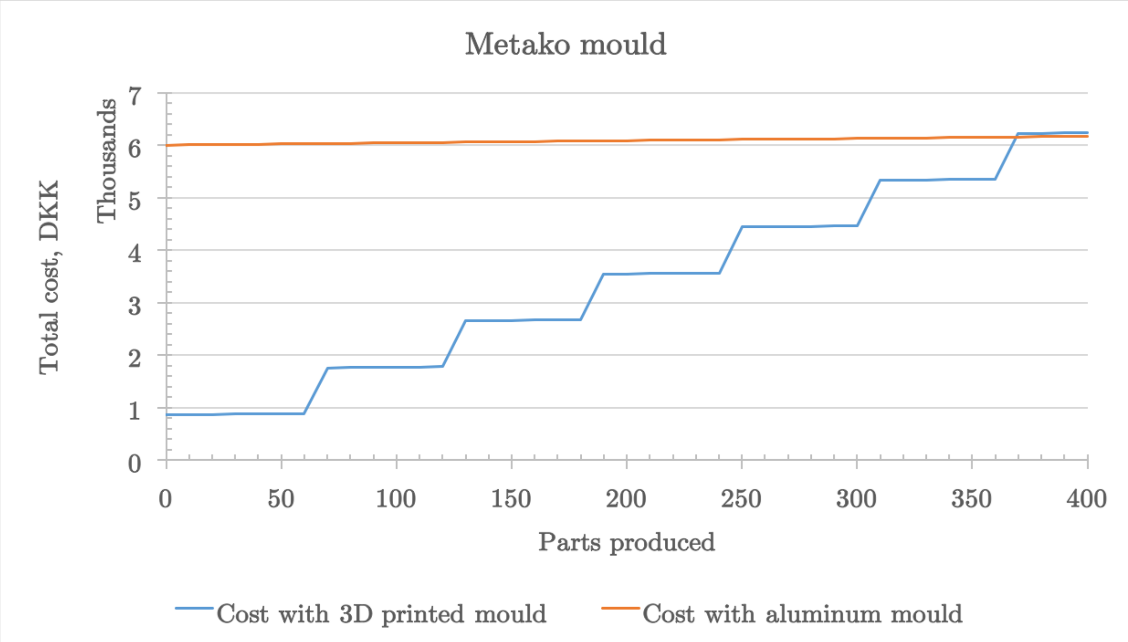


Table 5.4: A comparison of the total production cost with 3D printed moulds and milled aluminum moulds, based on the number of parts produced (Metako mould).

Chapter 6

Discussion & Outlook

6.1 Financial viability evaluation

The cost comparison of manufacturing moulds by 3D printing and by CNC milling in aluminum has been done for four moulds. The four moulds each exhibit specific characteristics that affect both the cost of printing and the cost of milling in different ways.

The cost of 3D printing is driven by the volume and quantity of parts to be printed. The volume of the parts affects the material costs, and the quantity of parts affect the post processing time as each part must be cleaned. Multiple parts can be inserted in an oven for cleaning, but detailed parts will often need to be thoroughly cleaned manually.

Within the size range of parts that can be 3D printed, the cost of CNC milling is driven by part complexity. The cost of raw aluminum is almost negligible, although there are often additional handling costs involved in raw material procurement.

Based on the experience gathered while calculating the costs, the effect of a mould's characteristics on the cost of manufacturing was evaluated (table 6.1). The effect of the various characteristics not weighed, but from table 6.1 it can be deduced that the financial advantage of 3D printing injection moulding tools is greater when dealing with small complex moulds, when simply comparing the mould manufacturing cost.

	3D printing	**CNC milling**
High part quantity	negative	negative
High complexity	neutral	negative
High volume	negative	neutral*

*Within the size range of parts that can be 3D printed

Table 6.1: Cost effect of generic mould characteristics

The four mould designs analysed in the project are assessed in table 6.2, using the same characteristics of table 6.1. The greatest relative cost savings (86%) are seen on the mould from Metako. This correlates with table 6.1, as Metako's mould is both complex and small. The smallest relative cost saving (67%) is seen on the first Grundfos mould. Again, this correlates with the previous table, as the mould is fairly large and has low complexity. The two remaining moulds show the same cost saving (74%), although being very different. Where the second grundfos mould is large, complex and made of multiple parts, the keychain mould is small and simple. This might be due to the effects negating each other.

	3D printed mould cost*	**Part quantity**	**Part complexity**	**Part volume**
Grundfos mould 1	33%	low	low	medium
Grundfos mould 2	26%	high	high	high
3D Systems keychain mould	26%	low	low	low
Metako mould	14%	low	high	low

*Compared to the cost of CNC milling an aluminum mould

Table 6.2: Calculated relative cost of printing the moulds and mould characteristics

Based on the four mould designs that have been analysed in the project, it seems as there are tremendous cost savings to be made by 3D printing the moulds rather than machining the moulds, even though the savings may depend on the mould design.

While the direct cost savings on the moulds may be high, one must look at the bigger picture. Figures 4.4, 4.6, 4.8 and 5.4, showed the total cost of production taking into account the mould durability. These figures clearly showed that the concept was, at best, financially viable for smaller series production.

In this project the financial viability was solely evaluated based on the direct costs of manufacturing. While this is sufficient when considering whether to injection mould prototypes with 3D printed tools or CNC milled tools, when considering small series production, the production time should also be evaluated.

Although moulds can be printed much faster than they can be milled, with regards to production speed they present several disadvantages.

Firstly, as the moulds are more "delicate" than metal moulds, the injection moulding setup process (mould assembly and trial shots) is longer, as it takes time to adjust the settings necessary to produce quality parts. Though standard procedures could be developed to minimise the time needed.

Secondly, the cycle time is considerably longer with 3D printed injection moulding tools. To minimise the mould degradation, the mould must be allowed to cool between the shots. The cooling time for Grundfos' second mould was 110 seconds. Metal moulds are often water cooled, allowing very short cycle times. Due to the low thermal conductivity of the 3D printed material, water cooling the moulds is very ineffective.

Thirdly, the 3D printed moulds have limited durability compared to metal moulds. Thus they must be changed before the quality of the produced parts is affected.

Consequently, before using 3D printed moulds for small series production, a thorough financial viability evaluation must be done.

Furthermore, in this project, the cost comparisons were based on a scenario where all equipment and processes are owned in-house. This scenario is ideal, financially, in the sense that there are no margins added to the manufacturing costs. Furthermore in a scenario where the processes are outsourced, longer lead times are to be expected.

6.2 Pilot experiment evaluation

The goal of the pilot experiment was to uncover and evaluate the challenges of using 3D printed injection moulding tools. During the pilot experiment challenges were met, to say the least. While some of the challenges could not have been foreseen, others could have been avoided with a more systematic approach.

The 3D printed moulds warped while going through the cleaning process. The warping is most probably due to internal stress in the material which is released when it is heated. The uniformity of the warping indicates that the internal stresses were horizontal, coinciding with layer orientation of the print process. This might have been avoidable by printing the moulds at a slight angle. Alternatively, the moulds should have been placed in a vice when hot, before quenching.

Given the deformity of the moulds, adjustments were necessary. However, the height difference between the 3D printed inserts and the master moulds was not checked after assembly. The excessive flash observed while injection moulding was most probably due to the moulds not being properly closed. This could have been remedied by inserting thin sheets of metal behind the insert.

During the first experiment, shots 13 to 23 produced consistently good parts, but with excessive flash. A second experiment was planned with the second set of moulds that were 3D printed. Unfortunately, it could not be realised within the project's timeframe. Had there been time, the plan was to adjust the moulds (the second set had also warped), insert sheets of metal to ensure full closure of the moulds, and continue to injection mould, using the same parameters as for shots 13 to 23.

A second experiment would, hopefully, have produced enough parts and data for a more thorough analysis of the durability of the mould. It would have been possible to measure the parts and plot the dimensions in order to see analysis the uniformity of the parts. If the mould was degrading, it would also have been possible to see it on the part dimensions.

In retrospect, the concept should have been tested with a simpler mould design and with a more systematic approach. Although this would not have presented a direct advantage for Metako, the academic value could have been much higher.

The standard dumbbell-shaped test specimens described in the Standard test method for tensile properties of plastics (ASTM-D638, ASTM International, 2003) are simple to injection mould and simple to measure. Furthermore if moulded successfully, the samples can be used to test the material properties.

The traditional method of setting up an injection moulding process is to iteratively test settings based on material property values and experience. This method is not scientific as it is mostly based on the knowledge and experience of the operator. By using the systematic method of Design Of Experiments (DOE), the process could have been set up systematically, furthermore the results and data would have had great academic value, and it would have increased the reproducibility of the experiment. In the article "An application of design of experiments for optimization of plastic injection molding processes", Dowlatshahi describes how DOE can be used to identify the causes of defects in the early phases of injection moulding processes (Dowlatshahi, 2004). According to Dowlatshahi the productivity was increased while maintaining high quality standards. With a scientific DOE approach, the process would have been optimised systematically, and the mould durability could have been thoroughly tested.

Had it been possible, the moulds should have been tested with various materials to better evaluate a moulds durability paired with a specific material. Specifically, the moulds could be tested with glass filled PPS as it is a very harsh material to inject due to the abrasiveness of the glass fibres.

6.3 Application possibilities

The use of 3D printed injection moulding tools for prototyping and low volume production has been thoroughly described in the case studies and in the pilot experiment. Those are the obvious applications for the concept and also the selling points of the 3D printer manufacturers.

During the course of the project, less obvious application possibilities emerged from brainstorming and from interesting discussions with the project supervisor, the people involved in the project and friends.

6.3.1 Injection moulding on demand

The great advantage of 3D printing, is that the tools can be printed on demand, based on a CAD file. At Bang & Olufsen, spare parts availability is guaranteed up to 10 years after the last production run. This means that for the injection moulded parts, the moulds are stored in 10 years. Storing moulds is costly as the moulds must be regularly maintained. The most common damage during storage is rust, and the maintenance of moulds averages 5% of the initial manufacturing cost, per year (Bryce, 1999).

By resorting to 3D printed moulds for spare parts, no physical inventory is required as the low cost moulds may be printed on demand.

6.3.2 Hybrid moulds for mass customisation

In the pilot experiment, the 3D printed mould is inserted in a master mould. In large scale production, exchangeable date and symbol inserts are used to annotate moulded parts. When switching material, the mandatory recycling symbol can be easily changed to match the new material.

In the same way, production grade moulds could be designed to accept 3D printed mould inserts with the purpose of mass customisation. Thus a logo or a name could be integrated into the mould design at a low cost.

6.3.3 The low cost IM alternative

There is a low cost manual alternative for injection moulding: Bench-top injection moulders. Coloplast currently uses one for prototyping (figure 6.1). The moulds are printed in Visijet M3-X on a 3D Systems 3500 HDMax, just as in the pilot experiment. According to Lars Olaf Schertiger[1], Senior R&D Specialist at Coloplast, this simple setup is perfect for their need, which is rapid prototypes in end use material within a day's time.

The setup is of course only suitable for small parts, and very small series as it manual. However, if the goal is to print just a few prototypes, the setup might just outperform an industrial injection moulding machine as an industrial setup is more time consuming and requires a skilled operator.

[1]The author and Lars Olaf Schertiger met at the "3D Printing live!" conference, May 19th in Copenhagen.

(a) The setup (b) Model

Figure 6.1: Picture of the injection moulding prototyping setup at Coloplast, courtesy of Coloplast (All rights reserved)

6.4 Outlook

The 3D printing technologies are constantly evolving and advancing. During the course of this project, three technological breakthroughs, which could affect the potential of this project's concept, were announced.

In April, Carbon 3D unveiled the M1 printer, which is the first commercial CLIP-based[2] additive manufacturing technology[3]. Although it is difficult to tell whether the available resins can be used to manufacture moulds, the CLIP technology produces isotropic parts. This means that the printed parts could mimic the material properties of injection moulded parts.

In May, Sculpteo, an international 3D print service provider, unveiled their patent pending process to smooth laser sintered plastics (parts produced with SLS technology), the "Smoothing Beautifier"[4]. According to Sculpteo the process creates smooth surfaces that resembles injection moulded parts. Grundfos had high expectations to the SLS printed moulds, but the granular matte surface of the SLS moulds prevented the parts to be ejected properly. Using the "Smoothing Beautifier" it might be possible to produce moulds that

[2]Continuous Liquid Interface Production
[3]http://carbon3d.com/news/carbon-unveils-the-m1-first-commercial-clip-based-additive-manufacturing-machine
[4]http://www.sculpteo.com/blog/2016/05/17/introducing-the-smoothing-beautifier-a-new-standard-for-high-quality-3d-pri

are more durable than both the Digital ABS and the Visijet M3-X moulds.

In May, HP printer unveiled their The HP Jet Fusion 3D 3200 Printer[5]. If the printer lives up to HP's promises, there is no doubt that their printer will be able to print durable moulds.

[5]http://www8.hp.com/us/en/hp-news/press-release.html?id=2243327

Chapter 7

Conclusion

The goal of the project was to investigate whether 3D printed injection moulding tools was truly as cost effective and easy to implement as the industrial 3D print manufacturers advertise.

The current requirements and applications of the concept were analysed directly in the industry, by performing the case studies of Grundfos and Bang & Olufsen. The information gathered from the companies was used as basis for an evaluation of the financial viability of the concept.

To test the implementation, the concept was applied in an industry project in collaboration with an experienced plastic manufacturing company. Although substantial information about the implementation had been gathered from Grundfos, many challenges were met. Unfortunately, the pilot experiment did not fully succeed in producing the required parts, but the experimentation process gave valuable insight into the challenges of implementing the concept.

The concept proved to be financially viable in the specific scenario of a company which owns both a suitable industrial 3D printer, CNC milling equipment and injection moulding machines. Furthermore the pilot experiment uncovered many challenges related to both the printing process and the injection moulding process.

The concept is without doubt financially viable when used for prototyping, and specifically for small complex parts. However, if used for small series production, the financial viability is highly dependent of the 3D print material's durability when used as a mould. Furthermore, unless the implementation approach is streamlined and ameliorated, the time and cost savings may significantly drop due to necessary process iterations.

Using the experience gathered in this project, the next step is a systematic experiment, based on the Design of Experiments methodology, with the end goal of producing a scientific application guide.

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Appendix A

Cost calculations

Unit data and costs used in calculations	Value	Unit	Data source
Materials costs			
Visijet M3-X print material	2150	Dkk/kg	3D Printhuset
Visijet S300 support material	1250	Dkk/kg	3D Printhuset
6061 Aluminum	20	Dkk/kg	Metako
PPS 40GF	30	Dkk/kg	Metako
PP	12	Dkk/kg	Metako
Material densities			
6061 Aluminum	2,70	g/cm3	Datasheets
PP	0,95	g/cm3	Datasheets
PPS 40GF	1,65	g/cm3	Datasheets
Salaries			
3D Print technician	200	Dkk/h	3D Printhuset and official statistics
Injection moulding operator	250	Dkk/h	Metako and official statistics

Figure A.1: Unit data and costs used in calculations

GRUNDFOS - MOULD 1			
MOULD DETAILS	**All parts**	**Unit**	**Data Source**
Width (X)		mm	CAD
Length (Y)		mm	CAD
Height (Z)		mm	CAD
Bounding box volume		cm3	CAD
Mould part volume		cm3	CAD
Total volume	**368**	cm3	CAD
PRINTING (one batch print)	**All parts**	**Unit**	**Data Source**
Visijet M3-X weight	464	g	3D Systems software
Visijet S300 weight	271	g	3D Systems software
UHD resolution Print time	22,65	hours	3D Systems software
XHD resolution Print time	40,28	hours	3D Systems software
Print setup	0,20	hours	Authors estimate
Post process	2,00	hours	Authors estimate
Total work time	2,2	hours	Calculated
Total lead time (UHD, 29 micron)	24,9	hours	Calculated
Total lead time (XHD, 16 micron)	**42,5**	**hours**	Calculated
3D PRINTED TOOLING	**All parts**		
Visijet M3-X	998	Dkk	Calculated
Visijet S300	339	Dkk	Calculated
Labour (setup & post process)	440	Dkk	Calculated
Total	**1776**	**Dkk**	Calculated
ALUMINUM TOOLING	**All parts**		
Raw material volume (+10% waste)	980	cm3	CAD
Raw material weight	2646	g	CAD
Setup and machining time	16	hours	Estimated by Metako
Raw material cost	53	Dkk	Calculated
Raw material cutout	200	Dkk	Estimated by Metako
Milling cost	5600	Dkk	Estimated by Metako
Total tooling cost	**5853**	**Dkk**	Calculated
INJECTION MOULDING			
Mould assembly	0,25	hours	Estimated by Metako
Machine setup	0,50	hours	Estimated by Metako
Total setup time	0,75	hours	Calculated
Total setup cost	**187,5**	**Dkk**	Calculated
Produced part size	5	cm3	CAD
Produced part weight	8,25	g	Calculated
Part material cost (PPS 40GF)	**0,25**	**Dkk**	Calculated

Table A.1: Moulds cost calculations for 1st Grundfos mould

Est. 3D printed mould durability (parts prod.)		80
	3D Printed mould	Milled aluminum mould
Tool change cost	1.964 DKK	6.040 DKK
Part cost	0,25 DKK	0,25 DKK

Produced parts	Cost with 3D printed mould	Cost with aluminum mould
0	1.964 DKK	6.040 DKK
10	1.966 DKK	6.043 DKK
20	1.969 DKK	6.045 DKK
30	1.971 DKK	6.048 DKK
40	1.974 DKK	6.050 DKK
50	1.976 DKK	6.053 DKK
60	1.979 DKK	6.055 DKK
70	1.981 DKK	6.058 DKK
80	1.984 DKK	6.060 DKK
90	3.950 DKK	6.063 DKK
100	3.952 DKK	6.065 DKK
110	3.955 DKK	6.068 DKK
120	3.957 DKK	6.070 DKK
130	3.960 DKK	6.073 DKK
140	3.962 DKK	6.075 DKK
150	3.965 DKK	6.078 DKK
160	3.967 DKK	6.080 DKK
170	5.934 DKK	6.082 DKK
180	5.936 DKK	6.085 DKK
190	5.939 DKK	6.087 DKK
200	5.941 DKK	6.090 DKK
210	5.944 DKK	6.092 DKK
220	5.946 DKK	6.095 DKK
230	5.948 DKK	6.097 DKK
240	5.951 DKK	6.100 DKK
250	7.917 DKK	6.102 DKK
260	7.920 DKK	6.105 DKK
270	7.922 DKK	6.107 DKK
280	7.925 DKK	6.110 DKK
290	7.927 DKK	6.112 DKK
300	7.930 DKK	6.115 DKK
310	7.932 DKK	6.117 DKK
320	7.935 DKK	6.120 DKK
330	9.901 DKK	6.122 DKK
340	9.903 DKK	6.125 DKK
350	9.906 DKK	6.127 DKK
360	9.908 DKK	6.130 DKK
370	9.911 DKK	6.132 DKK
380	9.913 DKK	6.134 DKK
390	9.916 DKK	6.137 DKK
400	9.918 DKK	6.139 DKK

Table A.2: Part production cost for 1st Grundfos mould

GRUNDFOS - MOULD 2

MOULD DETAILS	All parts	Unit	Data Source
Width (X)		mm	CAD
Length (Y)		mm	CAD
Height (Z)		mm	CAD
Bounding box volume		cm3	CAD
Mould part volume		cm3	CAD
Total volume	**4251**	cm3	CAD

PRINTING(two batch print)	All parts	Unit	Data Source
Visijet M3-X weight	3084,0	g	3D Systems software
Visijet S300 weight	383,0	g	3D Systems software
UHD resolution Print time	64,3	hours	3D Systems software
XHD resolution Print time	113,8	hours	3D Systems software
Print setup	0,4	hours	Authors estimate
Post process	4,1	hours	Authors estimate
Total work time	**4,5**	**hours**	**Calculated**
Total lead time (UHD, 29 micron)	68,8	hours	Calculated
Total lead time (XHD, 16 micron)	**118,3**	**hours**	Calculated

3D PRINTED TOOLING	All parts		
Visijet M3-X	6631	Dkk	Calculated
Visijet S300	479	Dkk	Calculated
Labour (setup & post process)	900	Dkk	Calculated
Total	**8009**	**Dkk**	Calculated

ALUMINUM TOOLING	All parts		
Raw material volume (+10% waste)	8890	cm3	CAD
Raw material weight	24003	g	CAD
Setup and machining time	86	hours	Estimated by Metako
Raw material cost	480	Dkk	Calculated
Raw material cutout	900	Dkk	Estimated by Metako
Milling cost	30100	Dkk	Estimated by Metako
Total tooling cost	**31480**	**Dkk**	Calculated

INJECTION MOULDING			
Mould assembly	0,50	hours	Estimated by Metako
Machine setup	1,00	hours	Estimated by Metako
Total setup time	1,50	hours	Calculated
Total setup cost	**375**	**Dkk**	Calculated
Produced part size	300	cm3	CAD
Produced part weight	495	g	Calculated
Part material cost (PPS 40GF)	**14,9**	**Dkk**	Calculated

Table A.3: Moulds cost calculations for 2$^{\text{nd}}$ Grundfos mould

Est. 3D printed mould durability (parts prod.)		40
	3D Printed mould	Milled aluminum mould
Tool change cost	8.384 DKK	31.855 DKK
Part cost (incl. mould assembly)	140 DKK	140 DKK
Produced parts	Cost with 3D printed mould	Cost with aluminum mould
0	8.384 DKK	31.855 DKK
10	9.783 DKK	33.254 DKK
20	11.181 DKK	34.652 DKK
30	12.580 DKK	36.051 DKK
40	13.978 DKK	37.449 DKK
50	23.761 DKK	38.848 DKK
60	25.160 DKK	40.246 DKK
70	26.558 DKK	41.645 DKK
80	27.957 DKK	43.043 DKK
90	37.740 DKK	44.442 DKK
100	39.138 DKK	45.840 DKK
110	40.537 DKK	47.239 DKK
120	41.935 DKK	48.637 DKK
130	51.718 DKK	50.036 DKK
140	53.116 DKK	51.434 DKK
150	54.515 DKK	52.833 DKK
160	55.913 DKK	54.231 DKK
170	65.696 DKK	55.630 DKK
180	67.095 DKK	57.028 DKK
190	68.493 DKK	58.427 DKK
200	69.892 DKK	59.825 DKK
210	79.675 DKK	61.224 DKK
220	81.073 DKK	62.622 DKK
230	82.472 DKK	64.021 DKK
240	83.870 DKK	65.419 DKK
250	93.653 DKK	66.818 DKK
260	95.051 DKK	68.216 DKK
270	96.450 DKK	69.615 DKK
280	97.848 DKK	71.013 DKK
290	107.631 DKK	72.412 DKK
300	109.030 DKK	73.810 DKK
310	110.428 DKK	75.209 DKK
320	111.827 DKK	76.607 DKK
330	121.610 DKK	78.006 DKK
340	123.008 DKK	79.404 DKK
350	124.407 DKK	80.803 DKK
360	125.805 DKK	82.201 DKK
370	135.588 DKK	83.600 DKK
380	136.987 DKK	84.998 DKK
390	138.385 DKK	86.397 DKK
400	139.784 DKK	87.795 DKK

Table A.4: Part production cost for 2nd Grundfos mould

3D SYSTEMS KEYCHAIN MOULD

MOULD DETAILS	All parts	Unit	Data Source
Width (X)		mm	CAD
Length (Y)		mm	CAD
Height (Z)		mm	CAD
Bounding box volume		cm3	CAD
Mould part volume		cm3	CAD
Total volume	**237**	cm3	CAD

PRINTING (one batch print)	All parts	Unit	Data Source
Visijet M3-X weight	285,0	g	3D Systems software
Visijet S300 weight	56,0	g	3D Systems software
UHD resolution Print time	8,7	hours	3D Systems software
XHD resolution Print time	15,2	hours	3D Systems software
Print setup	0,2	hours	Authors estimate
Post process	1,0	hours	Authors estimate
Total work time	**1,2**	**hours**	**Calculated**
Total lead time (UHD, 29 micron)	9,9	hours	Calculated
Total lead time (XHD, 16 micron)	**16,4**	**hours**	Calculated

3D PRINTED TOOLING	All parts		
Visijet M3-X	613	Dkk	Calculated
Visijet S300	70	Dkk	Calculated
Labour (setup & post process)	240	Dkk	Calculated
Total	**923**	**Dkk**	Calculated

ALUMINUM TOOLING	All parts		
Raw material volume (+10% waste)	280	cm3	CAD
Raw material weight	756	g	CAD
Setup and machining time	11	hours	Estimated by Metako
Raw material cost	15	Dkk	Calculated
Raw material cutout	200	Dkk	Estimated by Metako
Milling cost	3850	Dkk	Estimated by Metako
Total tooling cost	**4065**	**Dkk**	Calculated

INJECTION MOULDING			
Mould assembly	0,25	hours	Estimated by Metako
Machine setup	0,50	hours	Estimated by Metako
Total setup time	0,75	hours	Calculated
Total setup cost	**187,5**	**Dkk**	Calculated
Produced part size	5	cm3	CAD
Produced part weight	4,73	g	Calculated
Part material cost (PPS 40GF)	**0,06**	**Dkk**	Calculated

Table A.5: Moulds cost calculations for 3D Systems keychain moulds

Est. 3D printed mould durability (parts prod.)		100
	3D Printed mould	Milled aluminum mould
Tool change cost	1.110 DKK	4.253 DKK
Part cost	0 DKK	0 DKK

Produced parts	Cost with 3D printed mould	Cost with aluminum mould
0	1.110 DKK	4.253 DKK
10	1.111 DKK	4.253 DKK
20	1.111 DKK	4.254 DKK
30	1.112 DKK	4.254 DKK
40	1.113 DKK	4.255 DKK
50	1.113 DKK	4.255 DKK
60	1.114 DKK	4.256 DKK
70	1.114 DKK	4.257 DKK
80	1.115 DKK	4.257 DKK
90	1.115 DKK	4.258 DKK
100	1.116 DKK	4.258 DKK
110	2.227 DKK	4.259 DKK
120	2.227 DKK	4.259 DKK
130	2.228 DKK	4.260 DKK
140	2.228 DKK	4.261 DKK
150	2.229 DKK	4.261 DKK
160	2.230 DKK	4.262 DKK
170	2.230 DKK	4.262 DKK
180	2.231 DKK	4.263 DKK
190	2.231 DKK	4.263 DKK
200	2.232 DKK	4.264 DKK
210	3.343 DKK	4.265 DKK
220	3.343 DKK	4.265 DKK
230	3.344 DKK	4.266 DKK
240	3.344 DKK	4.266 DKK
250	3.345 DKK	4.267 DKK
260	3.346 DKK	4.267 DKK
270	3.346 DKK	4.268 DKK
280	3.347 DKK	4.269 DKK
290	3.347 DKK	4.269 DKK
300	3.348 DKK	4.270 DKK
310	4.459 DKK	4.270 DKK
320	4.459 DKK	4.271 DKK
330	4.460 DKK	4.271 DKK
340	4.460 DKK	4.272 DKK
350	4.461 DKK	4.272 DKK
360	4.461 DKK	4.273 DKK
370	4.462 DKK	4.274 DKK
380	4.463 DKK	4.274 DKK
390	4.463 DKK	4.275 DKK
400	4.464 DKK	4.275 DKK

Table A.6: Part production cost for 3D Systems keychain moulds

METAKO MOULD

MOULD DETAILS	All parts	Unit	Data Source
Width (X)		mm	CAD
Length (Y)		mm	CAD
Height (Z)		mm	CAD
Bounding box volume		cm3	CAD
Mould part volume		cm3	CAD
Total volume	**237**	cm3	CAD

PRINTING (one batch print)	All parts	Unit	Data Source
Visijet M3-X weight	177,0	g	3D Systems software
Visijet S300 weight	47,0	g	3D Systems software
UHD resolution Print time	12,6	hours	3D Systems software
XHD resolution Print time	22,4	hours	3D Systems software
Print setup	0,2	hours	Authors estimate
Post process	1,0	hours	Authors estimate
Total work time	**1,2**	**hours**	**Calculated**
Total lead time (UHD, 29 micron)	13,8	hours	Calculated
Total lead time (XHD, 16 micron)	**23,6**	**hours**	Calculated

3D PRINTED TOOLING	All parts		
Visijet M3-X	381	Dkk	Calculated
Visijet S300	59	Dkk	Calculated
Labour (setup & post process)	240	Dkk	Calculated
Total	**679**	**Dkk**	Calculated

ALUMINUM TOOLING	All parts		
Raw material volume (+10% waste)	280	cm3	CAD
Raw material weight	756	g	CAD
Setup and machining time	16	hours	Estimated by Metako
Raw material cost	15	Dkk	Calculated
Raw material cutout	200	Dkk	Estimated by Metako
Milling cost	5600	Dkk	Estimated by Metako
Total tooling cost	**5815**	**Dkk**	Calculated

INJECTION MOULDING			
Mould assembly	0,25	hours	Estimated by Metako
Machine setup	0,50	hours	Estimated by Metako
Total setup time	0,75	hours	Calculated
Total setup cost	**187,5**	**Dkk**	Calculated
Produced part size	3	cm3	CAD
Produced part weight	36	g	Calculated
Part material cost (PP)	**0,43**	**Dkk**	Calculated

Table A.7: Moulds cost calculations for Metako moulds

Est. 3D printed mould durability (parts prod.)		60
	3D Printed mould	Milled aluminum mould
Tool change cost	867 DKK	6.003 DKK
Part cost	0 DKK	0 DKK

Produced parts	Cost with 3D printed mould	Cost with aluminum mould
0	867 DKK	6.003 DKK
10	871 DKK	6.007 DKK
20	875 DKK	6.011 DKK
30	880 DKK	6.016 DKK
40	884 DKK	6.020 DKK
50	888 DKK	6.024 DKK
60	893 DKK	6.029 DKK
70	1.764 DKK	6.033 DKK
80	1.768 DKK	6.037 DKK
90	1.772 DKK	6.042 DKK
100	1.777 DKK	6.046 DKK
110	1.781 DKK	6.050 DKK
120	1.785 DKK	6.054 DKK
130	2.657 DKK	6.059 DKK
140	2.661 DKK	6.063 DKK
150	2.665 DKK	6.067 DKK
160	2.670 DKK	6.072 DKK
170	2.674 DKK	6.076 DKK
180	2.678 DKK	6.080 DKK
190	3.549 DKK	6.085 DKK
200	3.554 DKK	6.089 DKK
210	3.558 DKK	6.093 DKK
220	3.562 DKK	6.098 DKK
230	3.567 DKK	6.102 DKK
240	3.571 DKK	6.106 DKK
250	4.442 DKK	6.111 DKK
260	4.446 DKK	6.115 DKK
270	4.451 DKK	6.119 DKK
280	4.455 DKK	6.124 DKK
290	4.459 DKK	6.128 DKK
300	4.464 DKK	6.132 DKK
310	5.335 DKK	6.137 DKK
320	5.339 DKK	6.141 DKK
330	5.343 DKK	6.145 DKK
340	5.348 DKK	6.150 DKK
350	5.352 DKK	6.154 DKK
360	5.356 DKK	6.158 DKK
370	6.227 DKK	6.162 DKK
380	6.232 DKK	6.167 DKK
390	6.236 DKK	6.171 DKK
400	6.240 DKK	6.175 DKK

Table A.8: Part production cost for Metako moulds

Appendix B

Measurements

3D Printed cavity mould measurements (mm)

Measuring point (X axis)	Nominal height	Measured height	Measured bottom side curvature	Calculated top side curvature
0	30	29,93	29,93	0,00
20	30	30,04	30,49	0,45
40	30	30,07	30,87	0,80
60	30	30,07	31,17	1,10
80	30	30,06	30,87	0,81
100	30	30,03	30,48	0,45
120	30	29,91	29,91	0,00

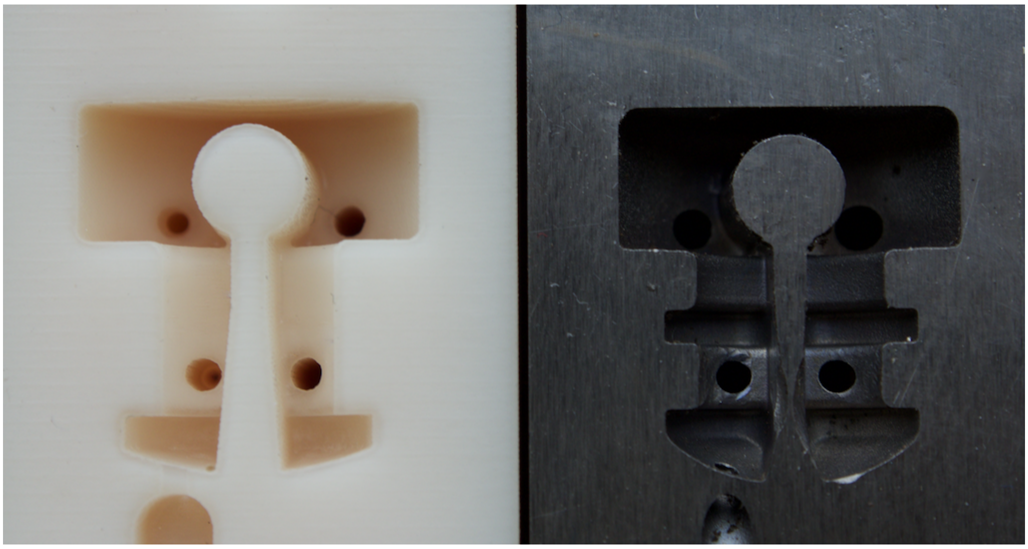
Measuring point (X axis)	Nominal width	Measured width
0	20,4	20,30
20	20,4	20,30
40	20,4	20,30
60	20,4	20,30
80	20,4	20,30
100	20,4	20,30
120	20,4	20,30

Measuring point (Z axis)	Nominal height	Measured height
0	120,4	119,90
30	120,4	119,90

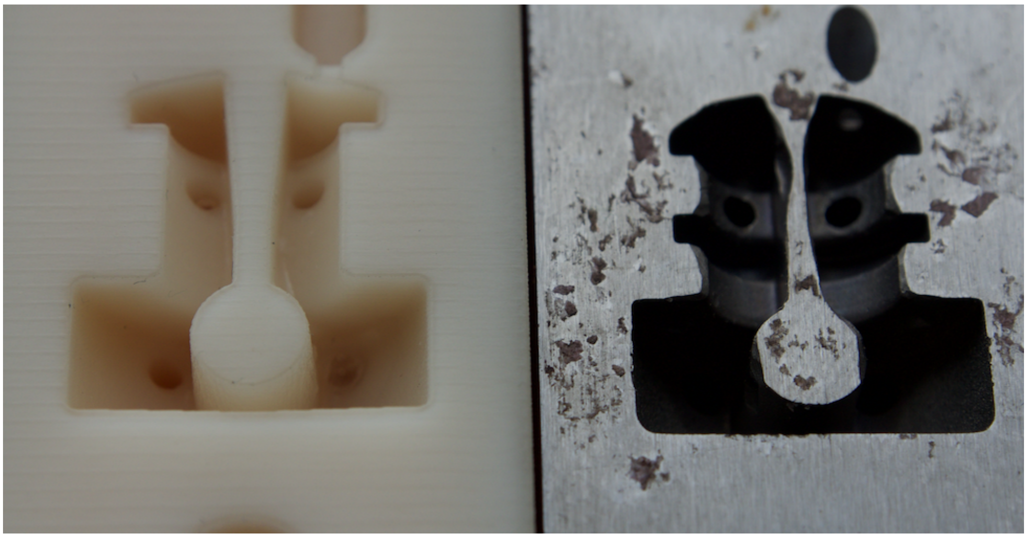
Table B.1: 3D Printed cavity mould measurements

Appendix C

Photographs



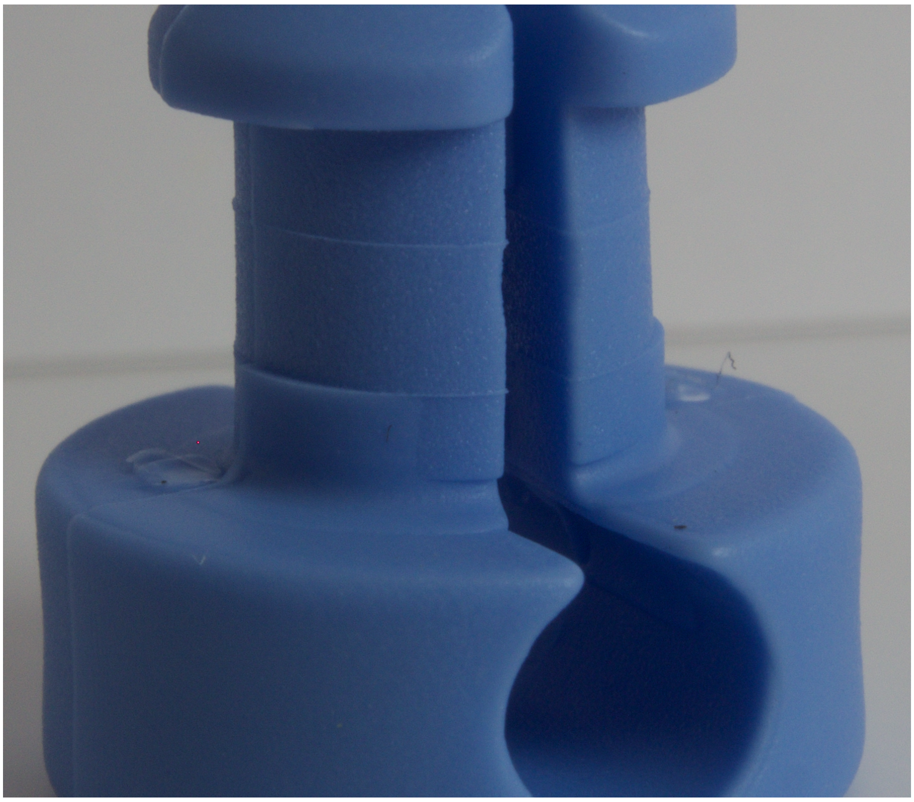
(a)



(b)

Figure C.1: Close up of the cleaned moulds

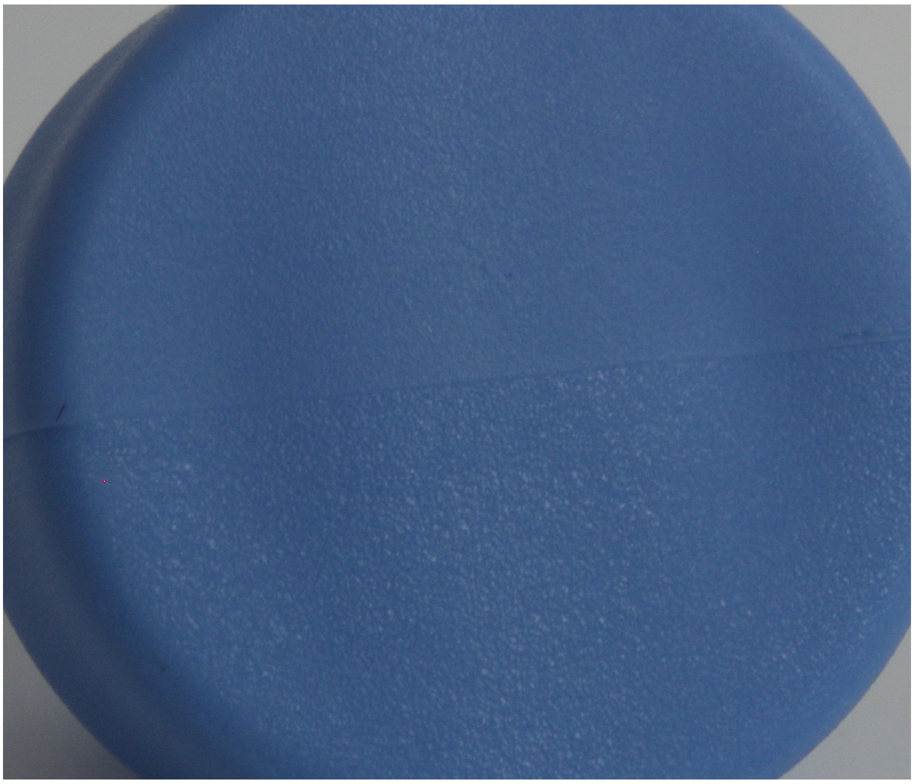
(a) Produced with 3D printed mould



(b) Produced with steel mould

Figure C.2: Side view of the produced parts (high resolution close ups)

(a) Produced with 3D printed mould



(b) Produced with steel mould

Figure C.3: Bottom view of the produced parts (high resolution close ups)

Appendix D

Software screenshots

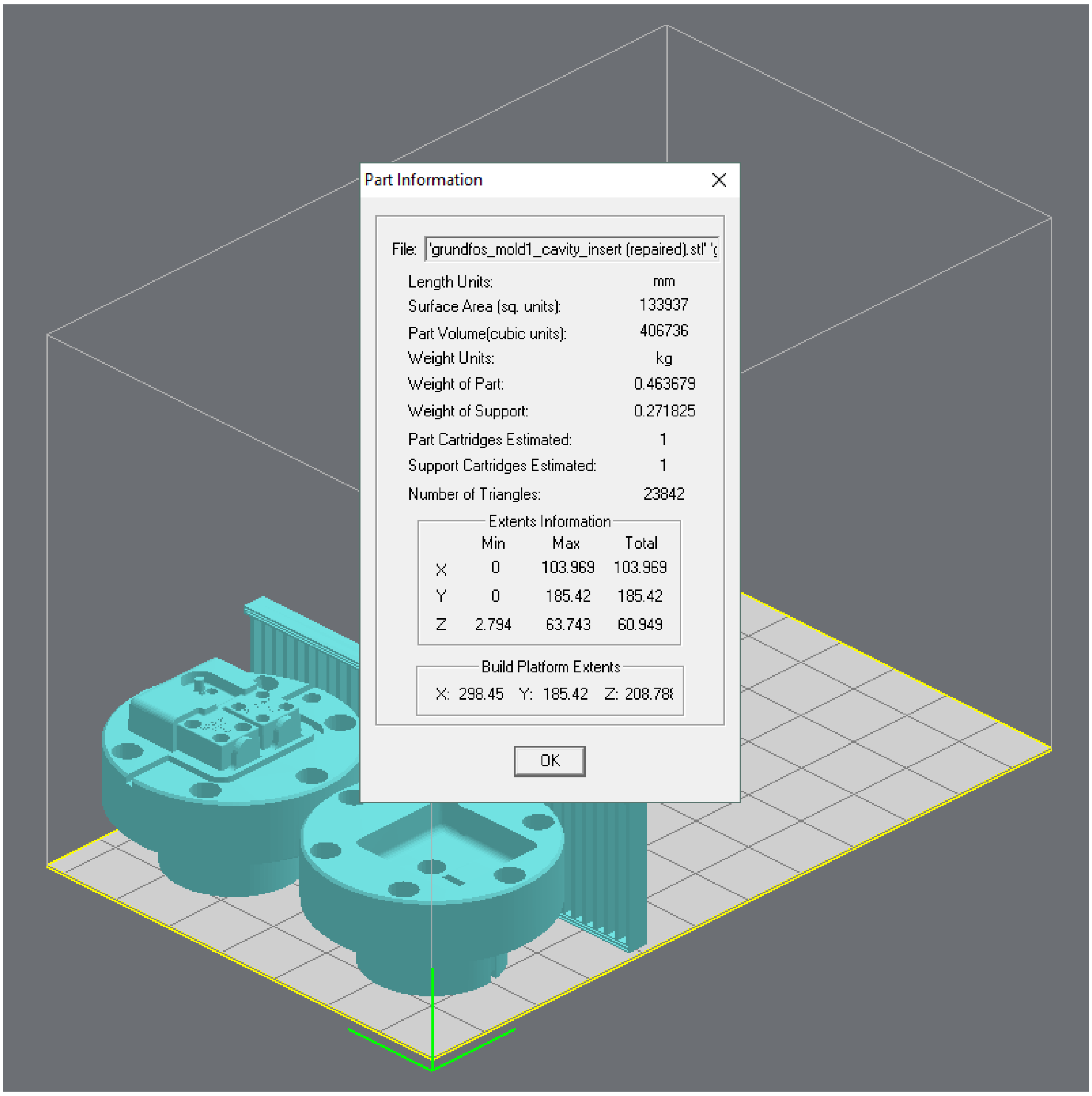


Figure D.1: Screenshot of 3D Systems Software, Grundfos mould 1 part info

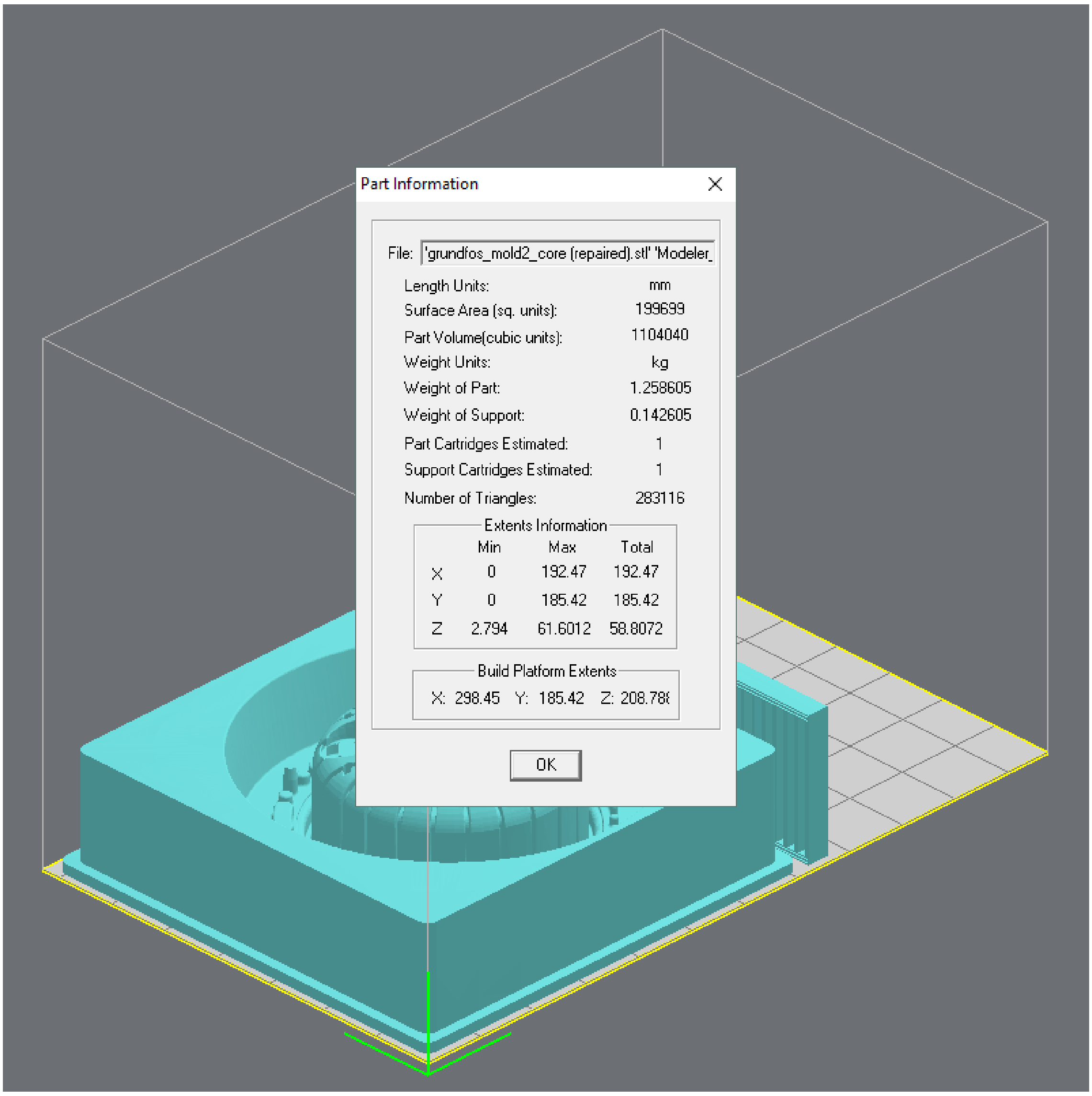


Figure D.2: Screenshot of 3D Systems Software, Grundfos mould 2, batch 1 part info

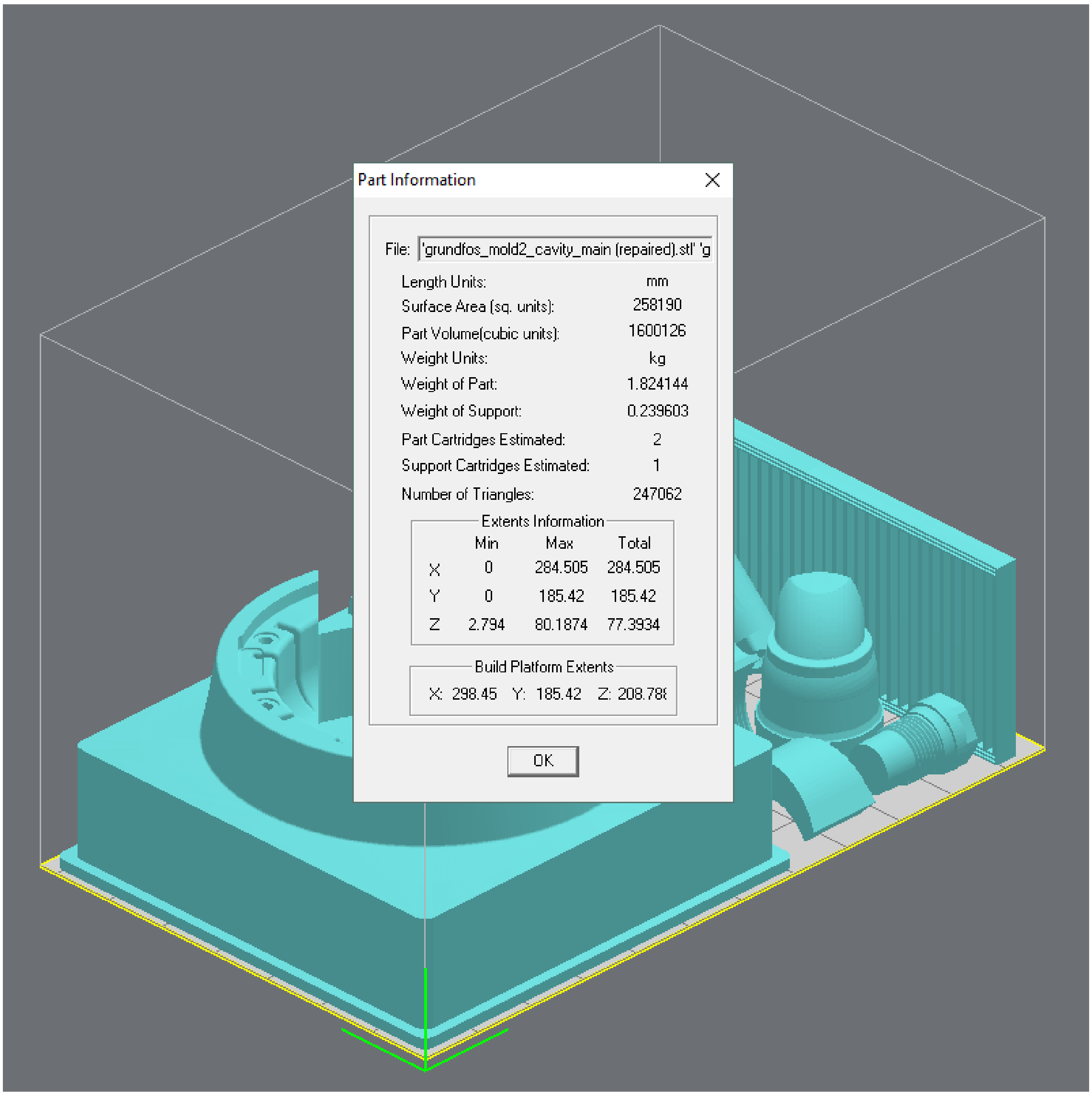


Figure D.3: Screenshot of 3D Systems Software, Grundfos mould 2, batch 2 part info

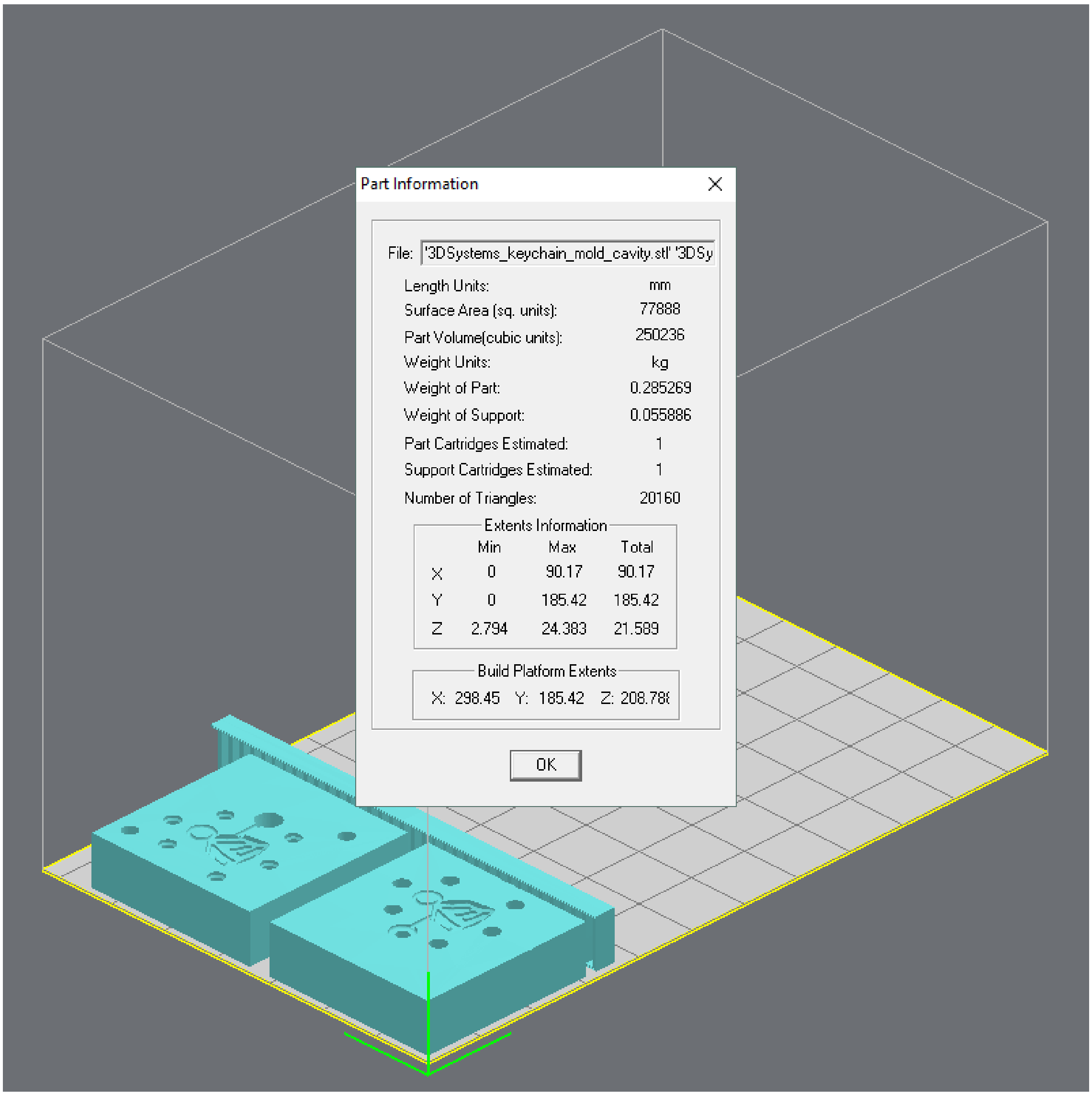


Figure D.4: Screenshot of 3D Systems Software, 3D Systems keychain mould part info

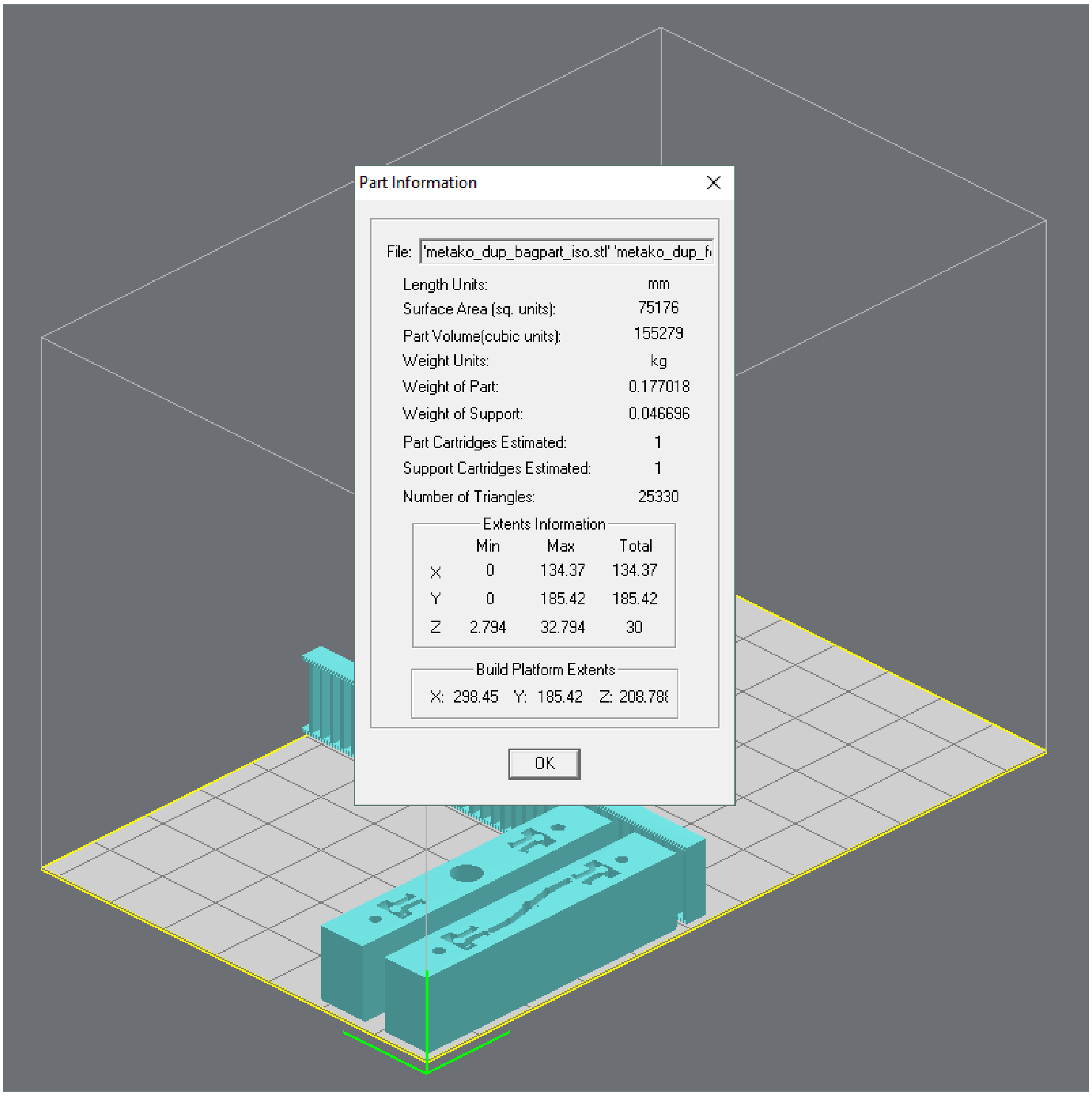


Figure D.5: Screenshot of 3D Systems Software, Metako mould part info