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Fast and iterative prototyping for injection molding – a case study of rapidly prototyping

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Abstract

Injection molding is essential for mass manufacturing plastic parts in all sizes and shapes. However, predicting the quality of a mold is tricky, and while computer simulations are highly advanced, they rely on conservative models, leading to over-dimensioned parts. Furthermore, it becomes practically impossible to prototype a part with the real materials, since a simple mold drives costs and remodeling thereof is time consuming, if not impossible. By building our own desktop sized injection molding machine, we were able to explore the possibilities of prototyping injection molded parts and test a variety of mold materials in order to quantify the outcomes in a three-point bending test. Subsequently, the learnings were applied to a full-scale model, which was tested in an industrial setting. The outcome shows that one can apply rapid prototyping, and subsequent test-build-iteration circles to mass-manufactured parts, allowing for rapidly optimizing material usage, and user interactions.

Keywords: Prototyping; Wayfaring; Product Design; Additive Manufacturing; Injection Molding;

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1. Introduction

In a globalized furniture market, it is important to keep up with current trends in order to stay ahead of competitors. Furthermore, better and cheaper solutions are high in demand, which means that production is either based on cheap manual labor, or fully automated factories. One company that successfully manages to operate out of the high-priced country of Norway is Scandinavian Business Seating (SBS). They manufacture and sell 244’000 chairs worldwide from their production facilities in Røros, Norway. Obviously, such large production numbers require mass-manufacturing methods, such as injection molding. While this is an established means of mass-

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producing plastic parts, consuming about 32wt% of all plastics [1], it also poses several challenges and risks in respect to rapid prototyping and the vision of switching to recycled plastics.

Our work is focused on the fuzzy front end of product development. During this phase, there is a sheer infinite solution space that needs to be explored in order to find the best solution. By iteratively using prototypes to learn [2] and uncover unknown unknowns [3], this process is guided by dynamically emerging requirements. In this article, we argue for rapidly prototyping injection molded plastic components. To support these claims, the test results from a premaster- and subsequent master-project in the prototyping environment TrollLABS are presented: By building a desktop injection molding machine in-house, it was possible to test a large variety of mold materials produced on a variety of 3D printers and a CNC mill. In order to get a comparison to the real part from SBS and simulation results, the most successful attempts were tested in a three-point-bending test. Furthermore, a very complex mold was machined and successfully tested on an industrial injection molding machine.

1.1. Injection molding: Fundamentals

Injection molding works by melting a thermoplastic, and injecting it under high pressure into a cavity where the plastic is left to solidify again. The solid part can then be removed from the mold, while the latter is used over and over again. Designing a good mold is a difficult task, since one has to consider a variety of potential constraints and faults, such as draft angles, warping, and sink marks, to name a few. Machining one steel mold, as they are typically used for injection molding, can easily cost one million Norwegian Crowns (~120’000USD) and in case an error is discovered in the first tests, it has to be shipped back to the manufacturer, which is often in China. Despite all these challenges, injection molding is a fundamental production method for mass-manufactured plastic parts. While one mold is expensive, it can be used tens of thousands of times, subsequently reducing the price per part.

A commonly used plastic for injection molded parts is Polypropylene (PP). While it works great for the manufacturing method itself, it exhibits a problematic range of inconsistencies. It is not homogenous, and the flow during the injection will introduce some anisotropy in the material [4,5]. PP is highlighted since it can be recycled and therefore offers the possibility for a more sustainable product line. It was also the material used for injection molding the small test piece (see section 3).

A common, and great tool for predicting the outcome of an injection molding process is performing a Finite Element Analysis (FEA). The digital model of a part is first split up into volume elements (‘mesh’), and one then applies certain mathematical constraints, describing how they interact with respect to e.g. temperature, or stress. The software then calculates all these interactions based on the applied models and allows the designer to analyze the physical conditions, e.g. stress concentrations within the part under certain load conditions, or the flow of a material during the injection process. Simulating the process of injection molding is feasible and also the industry standard. However, while the models improve their accuracy and subsequent fidelity of an FEA simulation, they still do not *exactly* match the experimental data [6]. With respect to recycled PP, the non-linear behavior of the material makes it extremely complex to fully capture the behavior of a part under loading and unloading conditions [7], and including all of these material properties in a model is highly complex, and induces other challenges, e.g. convergence problems [8]. Simulations with simpler, linear elastic models, do make the problem easier to solve, but do not offer the same resolution as a ‘perfect’ model. Therefore, any design based on simplified models will be over-dimensioned, and subsequently using too much material.

In addition, the more accurate a simulation should be, or the bigger a part, the longer it takes to fully solve the simulation. It is important to point out that a change in the design of a part also requires a highly time consuming recalculation of the previous simulation efforts, thus hindering iterative, physical prototyping.

1.2. Motivation

Given the overview above, this time- and money-consuming approach is not ideal for quick testing of either the mechanical durability of a new part, or the physical feeling thereof. Being able to rapidly prototype an injection molded part therefore helps on multiple levels: Since design-build-test-cycles help to rapidly improve the design during the product development process [9,10], companies should not be waiting for months between two iterations. Furthermore, addressing the different *characteristics* of prototypes, as [11] describes it, means that they have to answer a variety of questions. While including the final materials is not essential at the very beginning of the design phase, it becomes highly important when one wants to test the haptic sensations or ergonomics of e.g. a chair, and how much the backrest should flex, which cannot be replicated by additively manufactured parts. This is not just a mechanical stability issue, but also a user interaction on multiple levels. Quantifying these interactions in detail is still not possible, and subject to research [12,13]. [14] states that *'[…] only pre-production or prototype molding techniques provide true to life information on product performance, moldability, and dimensional tolerances.'* Enabling an iterative test environment with such high-end parts means that the company can rapidly improve their designs based on user experience, in order to not just meet, but exceed their customer's needs.

Another important factor is the ability to dimension a part to the exact needs. For a company that is striving for light and robust designs from recycled PP it becomes crucial to know the exact required dimensions, and not have an over-dimensioned part. This is not only important from a financial standpoint of view, where 1% material savings are directly translated into saving costs, but also from an environmental standpoint of view since being able to exclusively use recycled PP and only the perfect amounts thereof allows for a more sustainable production, and company image.

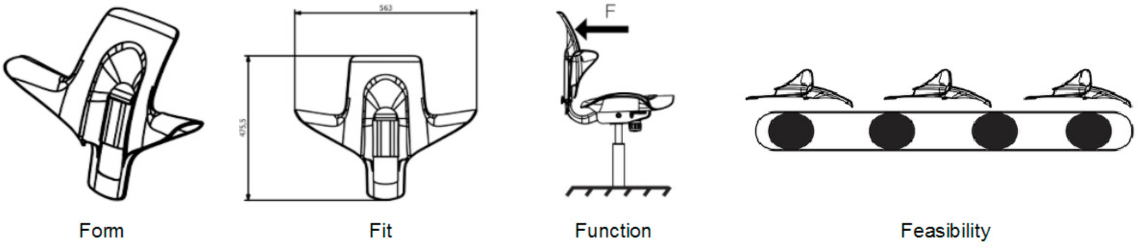
1.3. Method

Following the wayfaring model [15] the project had a focus on prototyping mass manufacturing and iteratively adapting to emerging requirements. A previous publication on this project described the relation between the wayfaring model and this project in detail [16]. We are aware that there is a wealth of ongoing work regarding 3D printing molds, or Direct Rapid Tooling, and some successful attempts have been reported [17,18,19]. However, our contribution is not to claim the best 3D printing or tooling method to produce 1000 parts. The focus lies on the experimental results, and on the low-cost approach that lead to 1-2 very successful prototypes that enable fast (<1 week) iterations regarding design changes. We believe that it is important to raise the awareness of the community that mass manufacturing can be prototyped in a relatively easy and cheap way.

2. Prototyping plastic components

Prototyping plastic components for furniture means prototyping on two levels: On the design side, one has to develop a form and a fit, or in other words a design, with specific dimensions. Prototyping of these two factors can easily be done digitally or analogue, by drawing the parts in a CAD program or simply creating them with soft prototyping materials, e.g. cardboard. More high-end models in the later stage of product development can be done by CNC milling and subsequently checking if the dimensions fit eventual neighboring parts.

On the material side, one has to develop and prototype the function and feasibility: For example, a backrest of a chair is not just a visually important object, the user of the chair is also actively interacting with it. It has to feel comfortable and absorb an eventual fall, which gives certain limitations when it comes to material choices. The feasibility comes from the design constraints given by the production method (see section 1.1), and cost efficiency. Fig. 1. visually describes the 'four Fs'.



Form

Fit

Function

Feasibility

Fig. 1. The 'four Fs' that a plastic prototype should address.

2.1. Desktop injection molding machine

Given the difficulties elaborated above, it was decided to find a solution for the challenges of prototyping plastic components. While there were injection molding machines standing around on campus, administrative obstacles made it impossible to get the easy access required in order to apply an iterative prototyping mind-set. Subsequently, we explored the possibility of building a desktop injection molding machine that yielded in the design that is shown in Fig. 2. The development process is described in [16].

2.2. Prototyping molds

While it is nowhere near the pressure and accuracy levels of an industrial machine, it quickly became obvious that the desktop injection molding machine opens the possibility for investigating how to rapidly prototype injection molded parts. Since the issue for SBS is the time and money used in machining the molds, and the unpredictability of the process, the focus was on exploring cheap and rapidly available manufacturing processes and comparing the quality of the outcome from using these molds on the desktop injection molding machine.

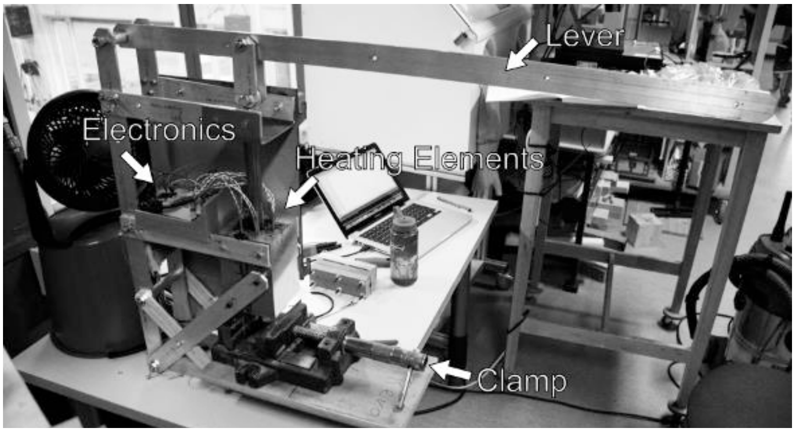


Fig. 2. The desktop injection molding machine in use: Clearly visible are the heating elements and the electronics, as well as the clamp for holding the molds. The long lever is for manually injecting the molten plastics.

3. Small scale test piece

The first test part that was reproduced is a lever from the HÅG Capisco Pulse chair (HÅG, Oslo, Norway), see Fig. 3. The goal was to compare the results from an FEA simulation to those of a three-point bending test, conducted with levers that were made with the desktop injection molding machine. The lever is a good example of both, a functional part, and an interaction point between the user and the chair. With its small size and relatively simple geometry, it offered a great starting point for exploring a variety of mold materials. The mold itself was modelled in Siemens NX9 (Siemens, Berlin, GER). The molds and materials that are highlighted below are the ones that lead to a testable result. The failed attempts and explored dead ends are left out due to limited space.

3.1. Production methods

For producing the molds, all the 3D printers and the benchtop CNC mill available in our research space, TrollLABS, as well as one externally sourced 3D printer were used. The machines as well as the materials that were used are listed in Table 1. The big challenge with cheap materials is that they are often soft, when compared to high quality metals. Since injection molding requires hard and smooth surfaces, the possibilities of coating the molds in order to improve the surface properties in respect to mechanical strength, as well keeping the molten thermoplastic from sticking to the mold, were explored. The successfully applied coatings were the epoxy West Systems 105, as well as the release agent Renlease QV 5110.

Table 1. Overview of the machines and according materials used for making the molds.

Type	Producer and Model	Materials
CNC Mill	Roland MDX-540 (Roland DGA, Irvine, CA, USA)	Wood (Red Oak) High Density Polyurethane (HDPU) Foam Aluminium (AA 6082-T6)
3D Printer (Sintering)	Blueprinter SHS (Blueprinter, Copenhagen, DK – Discontinued)	Nylon powder (Monochrome White)
3D Printer (Polymer Jetting)	Objet Eden 250 (Stratasys, Eden Prairie, MN, USA)	Photosensitive Polymer (VeroBlackPlus)
3D Printer (Fused Deposition Modelling)	Ultimaker 2 (Ultimaker, Geldermalsen, NED)	Polylactic Acid (PLA) Acrylonitrile Butadiene Styrene (ABS) Alloy 910 (Polymer Composite Filament)
3D Printer (Laminated Object)	MCOR Iris (Mcor Technologies, Co. Louth, IRL)	Paper (A4 office paper)
Epoxy	West Systems 105 (Gougeon Brothers, Inc, Bay City, MI, USA)	-
Release Agent	Renlease QV 5110 (Huntsman, The Woodlands, TX, USA)	-

3.2. Procedure

The individual molds were coated with the release agent and in some cases Epoxy. Upon drying, the mold was closed by eight bolts and, by the help of a mechanical clamp, pushed against the extrusion nozzle under the desktop injection molding machine. The PP granulate was heated to 230°C within the injection chamber and manually injected into the mold. The full set up in use can also be seen Fig. 2. Only the aluminum mold required pre-heating due to the very high heat conductivity and subsequent early solidification of the molten plastic. The final production step was to remove the cooled plastic parts from the mold. There was no post-treatment.

3.3. Three-point bending test

A common test to assess the strength of materials is the three-point bending test: A hydraulic press applies force to a part that is supported on two points. The resulting displacement is an indicator for the mechanical strength of the part. The test setup can be seen in Fig. 3. The max. displacement was 30mm at a rate of 3mm/s.

3.3.1. Simulation

In order to compare the test results to a reference value, a nonlinear simulation of the same test in ABAQUS (Dassault Systems, Vélizy-Villacoublay, FR) was conducted. The applied mesh was a tetrahedral mesh for the part, and a hexahedral mesh of size 0.9mm for the pin that was modelled with linear elastic isotropic steel properties (Young's modulus 210'000MPa, Poisson's ratio 0.3). The plastic lever was assigned linear elastic and nonlinear plastic isotropic properties, where the material data was based on tensile testing of polypropylene specimens (Young's modulus 1600MPa, Poisson's ratio 0.38) [20]. Without going into more detail regarding the simulation, it is important to highlight that the finite element model does not account for failure modes such as fracture, and therefore showed theoretical results throughout the entire enforced displacement.

3.3.2. Results

The plot in Fig. 3. shows the detailed results of the three-point bending test in comparison with the finite element simulation. Details about the mold materials are listed above in Table 1. All samples showed voids in the fracture surface and are made of PP. Due to different materials and a slightly different geometry (not completely filled, unlike the sample specimens), the original lever is not listed in the results.

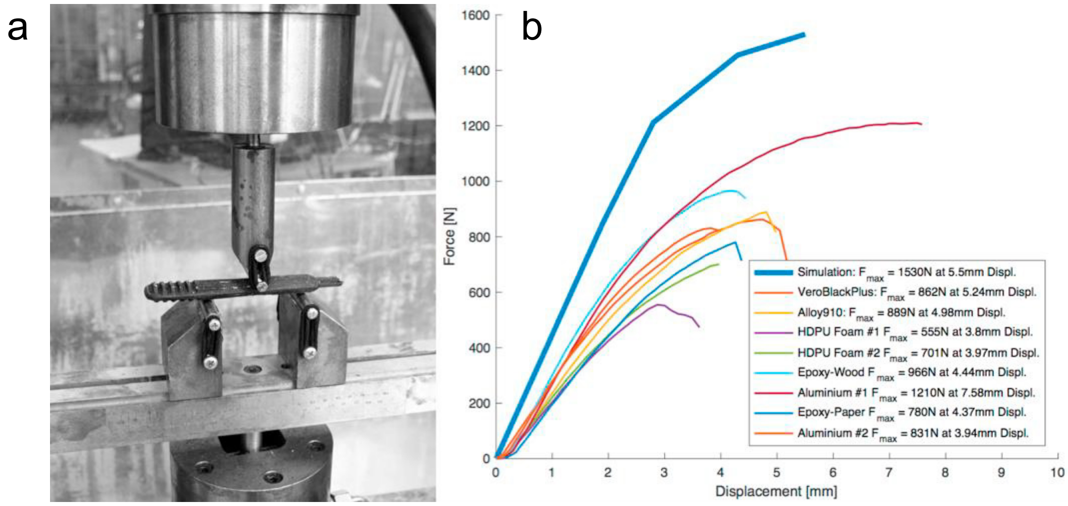


Fig. 3. (a) One of the levers in the three-point bending test setup; (b) Displacement vs. force plot of the three-point bending tests on the levers.

4. Full-scale test piece

While the hand injected parts showed some shortcomings, they were still of surprisingly good quality, given the crude desktop injection molding machine at hand. Based on the findings from the small samples, it was decided to select and test a big, complex part. The aim was to use one of the more successful direct rapid tooling approaches, and try the mold on a full-scale, industrial sized injection molding machine at OM BE Plasts (OM BE Plasts AS, Sellebakk, NO). While Aluminum showed the best test results, the earlier findings also showcased how simply a hard, smooth surface can deliver great results.

4.1. Test piece and test run

The part for the full-scale test was a quite complex and large (327x90x26mm) headrest from the Håg Sofi chair, as it can be seen in Fig. 4. Design features include ribs, bosses, radii, and holes. The large size of the part made it necessary to use the CNC mill and not an additive manufacturing method. The tool insert approach imposed several constraints and more sophisticated features, like holes for the ejector pins. While both, epoxy coated HDPU foam and epoxy coated wood showed good results as mold material, the anisotropy and high sensitivity to moisture of wood gave the upper hand to HDPU foam. Once the two halves of the mold were machined, they were coated with a very low viscosity epoxy, namely Hexion Epikote Resin MGS RIMR135 (Hexion, Columbus, OH, USA), and Hexion Epikote MGS RIMH137 curing agent. The mixing ratio was 100 weight units resin to 30 weight units hardener. The mixed solution was degassed and the coated mold halves were cured in an oven at 60°C for 8 hours. The total production time for the complete mold (excluding CAD modelling) was around three days. The final mold is depicted in Fig. 4. The full-scale trial molding consisted of two injection shots with low viscosity polypropylene of type 401-CB50: cylinder temperature 190°C; injection time 3.55s; post-filling time 5s; cooling time 30s (1st shot) / 120s (2nd shot); clamping force 800kN; injection pressure 100Bar.

4.2. Outcome

In the first attempt, too little resin was injected to completely fill the part. However, except for the very outer ends, all geometry features were well captured. Upon ejection, some of the thicker areas had not yet frozen, and subsequently the geometry of these areas was affected. Otherwise, the general surface finish was excellent when comparing to parts made in a steel mold. The mold was completely intact after the first attempt, and was reusable. For the second attempt, more resin was injected as an attempt to fill the entire part. Unfortunately, the increased volume put too much pressure on the mold, which caused some features to break off. Fig. 4. shows the results from both attempts.

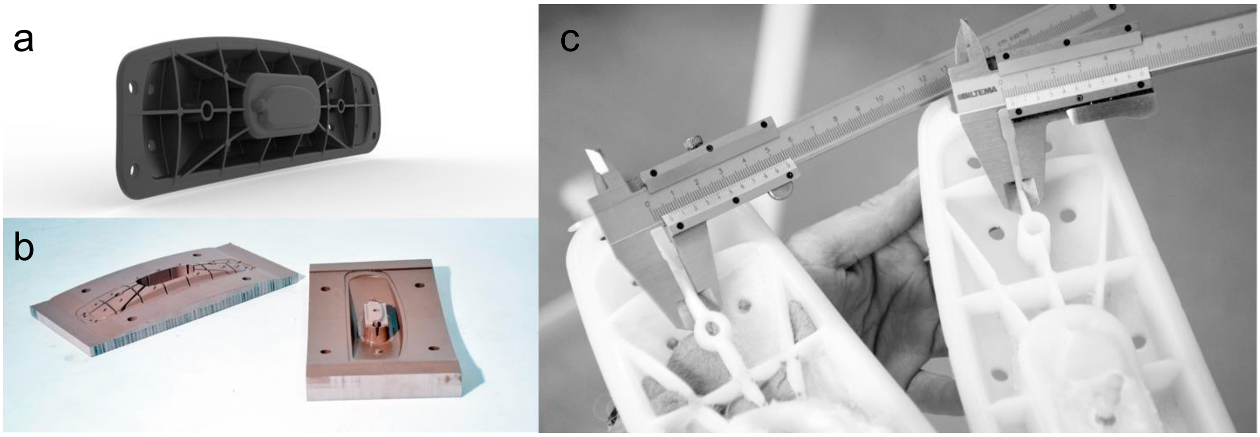


Fig. 4. (a) Rendering of the headrest; (b) the finished molds; (c) the results from the two attempts. The second shot (left) broke the mould due to excess material being injected, the first shot (right) showed very good features.

5. Discussion

The needs that are stated in the introduction are in respect to early stage prototyping and the fuzzy front end product development. While there is still a lot of work to be done in that direction, we contribute a case study that supports prototyping of plastic parts.

The eight small-scale tests are by far not of a statistically relevant sample size, especially since most of them were done in different mold materials. They do, however, give a good first indication of using a desktop injection molding machine. While the machine has some shortcomings with respect to controllability of the injection process per se, it provided sufficient pressure and power for making dozens of small levers (only the most successful attempts were listed in this article).

With respect to the three-point bending test, it was striking that all samples showed cavities of various sizes. This is probably connected to the limited injection pressure of the hand powered device. A more powerful, automatic injection machine would most likely provide much better results. The simulation gives a good indicator for the physical samples, although it did not take fractures into account. One can see that the maximum load of the best sample cracks at 79% of the maximum load in the simulation data (Aluminum #1 at 1210N, vs. 1530N in the simulation). Again, a more consistent and powerful machine could bring the curves even closer together.

While the full-scale part was based on the learnings from the explorative work on the small levers, it provided results of surprising qualities. Despite breaking after two shots, it gave valuable insights into the potential of this approach. Both, us, and the operators of the machine did not anticipate the large differences to a steel mold when it comes to thermodynamic behavior of the mold. Furthermore, the operator did not get enough tries in order to get the right amount of material per shot. Based on the statements of the operator, these shortcomings are possible to overcome if there is the possibility to do more test-runs on this part. Given the production time, it is reasonable to assume a potential of 1-2 full scale tests within one week, for a large, complex part.

5.1. Prototyping – not producing – on a desktop

As stated at the beginning, the aim of this experiment was to find a way to enable rapid, iterative prototyping of injection molded parts – not to find a way of mass producing on a desktop. Although the small levers did not deliver any data for statistical analysis, the full-scale test would not have been possible without the learnings from them. Furthermore, the full-scale test showed that it is possible to prototype injection molding: By making mold(s) from cheap materials, and using them on a regular injection molding machine, one can prototype, and test the plastic parts. Rapid and frequent design changes are no longer equal to high costs, but can be encouraged. This means that future products can not only make use of prototyping as a tool to improve the user experience, and overall outcome. It is also as a mean of exploring the limits of material savings and the implementation of materials that are extremely difficult to predict in simulations, such as recycled PP. If a company with a much broader experience and machine pool follows the same approach, prototyping – not mass production – of injection molding is possible in-house. While it eventually takes an initial investment for the machines, the prospect of 1-2 full scale tests within one week and subsequent material and design optimizations build a strong argument. Furthermore, it greatly reduces the risk of erroneous mold design, and therefore high costs and long production delays. Also, one should explore the possibilities of combining simulations with physical prototypes, as described in [8] in the case of a rotary spring. The work presented here was done by one master student within six months. Further work will hopefully reveal more mold materials and simple injection molding techniques.

Acknowledgments

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