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# Designing a Power Tool to Show the Potentials of Additive Manufacturing - Effects of Additive Manufacturing on the Product Development Process

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## Abstract

Today Additive Manufacturing (AM) is mainly used for rapid prototyping and specialized parts for industrial and end-user applications. To communicate the design potentials of AM to a general audience it is useful to demonstrate it with a visionary product, similar to the concept cars of the automotive industry. We have redesigned a power tool to show the benefits of AM on an end-user product. This paper describes the Concept Tool, its different sub-systems and highlights the range of AM's applications. Furthermore we present our observations and findings during the product development process. Based on these findings a design supporting system is suggested to improve the development process for additive manufactured products.

## Introduction

Additive Manufacturing (AM) [1] processes are technologically mature for industrial production due to a sufficient process stability, productivity and resulting part quality. A rising competition between service providers [2] makes Additive Manufacturing economically feasible for a growing number of industrial and end-user applications [3]. Nevertheless, companies still face a number of challenges when implementing AM in their production of end-user parts. First the companies have to identify suitable parts for AM [4]. The second big challenge is to (re)-design the identified part, which was designed for conventional manufacturing, to allow an economical AM production.

AM is a new production process and allows new possibilities in design, but also restricts the design in different way than conventional manufacturing. The key to unlock the design potential of AM is to overcome the traditions and fixed mind-sets of experienced designers and of course the lack of knowledge on the new technology [5,6].

Design showcases are a useful aid to understand the potentials of AM for new products. Reflecting the showcases helps a designer to identify suitable parts with similar potentials on the product portfolio of their own company. There are various publications [3,6-8] presenting collections of individual parts to show different potentials of AM. To enable audience to understand the benefits of AM based on individual parts one has to explain its function, the surrounding context and application. One can save these tedious explanations by implementing the AM benefits into an easy to understand product. In the automotive industry they implement future technologies in only one showcase, commonly referred to as concept cars. Based on this procedure, the idea was born not to develop a new part but rather to develop a completely functional system to illustrate the different potentials of AM. Furthermore, observation of the development process of a complete system allows tenables identification of challenges and implications of AM on the overall product development process.

To avoid any bias of this observation from existing AM knowledge a team of AM novices was selected. The development project of the Concept Tool was started in the framework of a Focus Project at ETH Zurich. An interdisciplinary team with six mechanical engineering, two electrical engineering and two industrial design students had to develop a working system within nine months. The team selected a specific of handheld power tools and developed an additive manufactured tool to illustrate different potentials of AM.

To enable the team to select a suitable power tool they were introduced in the potential of AM and the four selection criteria, namely integrated designs, individualization, lightweight design, and efficient design [9]. With the selection criteria the team analyzed different power tools and decided on battery operated hammer drill. A list of requirements was specified for the hammer drill with an emphasis on demonstrating AM potentials. The mechanics and the working principles of a hammer drill had to be entirely understood to select the optimal functions or components for improvements and substitutions. Therefore, a structural functionality flowchart and a thorough system definition were made. In a next step a potential analysis was performed to determine which functions and sub-assemblies have the most potential to illustrate the benefits and capabilities of AM technologies. Six different models of drilling machines were disassembled and documented for this analysis. Some of the tools had additional gadgets, for example a dust extraction system. Each sub-assembly was assessed with respect for the four selection criteria.

Figure 1 plots the potential of each sub-assembly over the expected risk and effort of designing AM-solution challenge. The ideal part would have big potential and it would be a small challenge to realize. The best suited functions and sub-assemblies for the purpose of the Concept Tool were a gear box, a dust extraction system, the housing, the unit to generate the percussion energy and some electronic features like a horizontal positioning aid or borehole depth setting or . Other components like gear or electric motor where put out of scope for a re-design, because of their unfavorable ratio between challenge and potential benefits.

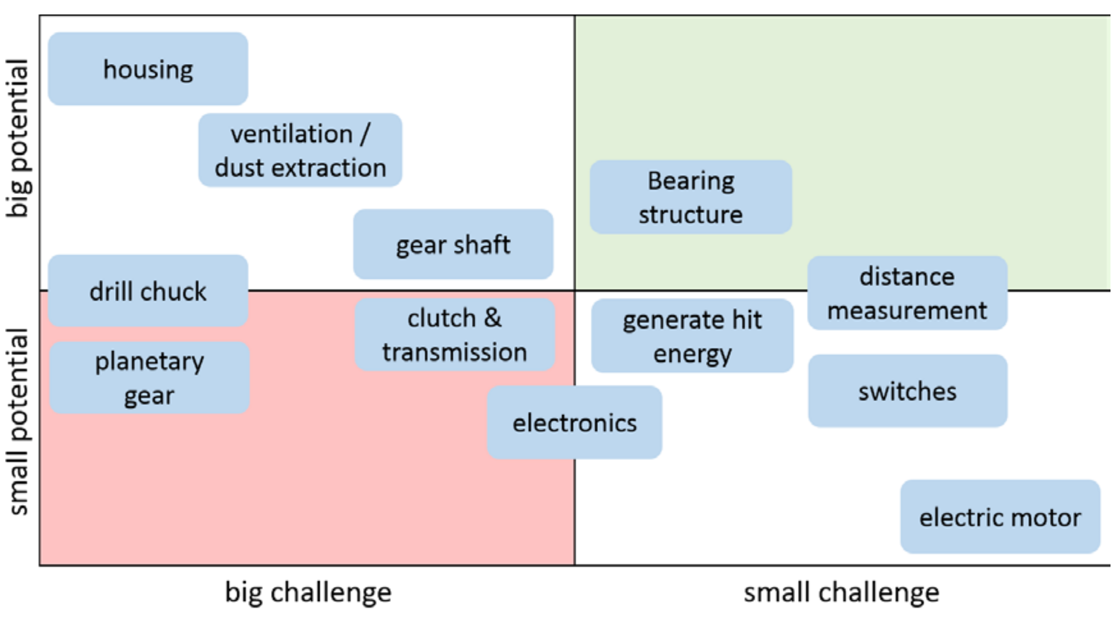

Figure 1: Evaluation of potential analysis

Based on the outcome of the function and potential analysis the team developed the following Concept Tool in an iterative process.

**Concept Tool**

The final design of the Concept Tool (see figure 2) offers all functions of a conventional hammer drill and some more like integrated dust extraction, digital controlling with display and novel internal device structure.


Figure 2: Final design of the Concept Tool

The Concept Tool is able to drill into wood and metal, hammer drill into concrete and stones or tighten screws. In the hammer drilling or drilling mode the desired bore hole depth can be set using a selection wheel placed in the front (see .figure 3). If the mode is set to screwing the torque can be adjusted using the same wheel. The machine stops automatically if the depth or torque limit is reached. An integrated display indicates the selected depth or torque. Furthermore, the direction of rotation and the mode are indicated using illuminated symbols. A main feature of the Concept Tool is the dust extraction system. The drill dust gets vacuumed in at the base of the tool and is transported to an integrated filtering system. The dust accumulates at the bottom of the handle, inside a dust collector. The collector can be removed, emptied and reattached to the tool. Before the cleaned air leaves the tool it is used to cool the electric motor, as well as to blow the drill dust into the extraction base. If the dust extraction system is not needed the base can be locked at the tool by pulling it all the way to the chuck and moving the slider on top of the base to the left.


Figure 3: Selection wheel and rotary switch (left), display (middle), dust extraction base with aperture (right)

The Concept Tool is powered by a Lithium Polymer (LiPo) battery. The battery is exchangeable and is locked to the tool using a newly developed magnetic locking mechanism. It snaps automatically to a locked position and mechanically fixes the battery to the tool. An SDS Quick mechanism from Bosch allows a fast and easy way of exchanging the drills.

Figure 4: Magnetic lock slider integrated in the housing of the exchangeable battery (left), pressure sensor covered with an flexible grid material (middle), horizontal positioning aid (right)

The Concept Tool is controlled in a unique way only with the index finger. All the main functions can be controlled by applying force on pressure sensors placed on both sides of the tool. It is therefore designed for left- and right-handed people. With a double tap on the pressure sensor the direction of rotation can be changed. Slight pressure with the index finger triggers a laser line projected to the wall. An electric version of a spirit level indicates with three Light-Emitting Diodes (LEDs) if the tool is held horizontal or not (see figure 4). This horizontal positioning aid allows drilling multiple holes at the same height. By firmly pressing the index finger on the pressure sensor starts the drilling process. The speed of rotation is controlled by the amount of force applied by the index finger. A sudden increase in pressure triggers the safe mode of the tool and drilling is impeded. This prevents unwanted initiations of the drilling process, for example when the tool falls to the ground.

With the exception of the bearings, shafts, gears and screws, all designed parts are produced with AM. The motor cooling unit and the bearing structure are produce by Selective Laser Melting (SLM) out of aluminum. The other parts of the Concept Tool are produced by Selective Laser Sintering (SLS). The centrifugal fan are made of Duraform HST, the grips are made of Duraform flex and all other designed parts are made of PA12.

## Subsystem bearing structure

The Concept Tool's innovative and AM specific solutions demonstrate the possibilities of AM. Three of the solutions are highlighted and present here. The gear and bearing in hammer drills are normally stored in an exoskeleton more precisely in the housing of the power tool. To show the potential of lightweight design in AM a bearing structure was designed based on the idea of creating a gear subassembly that absorbs all gear forces within the assembly. The goal was to optimize the structure with regard to predefined load cases and use as little material as possible. Such complex, weight optimized geometries are usually not manufacturable with conventional processes. In contrary to conventional manufacturing the complexity of the geometry does not affect the costs of additive manufactured parts. The bearing structure is therefore a very suitable part to show what AM is capable of in terms of lightweight design of load bearing parts.

The final design of the bearing structure is a scaffold with a half shell and four additional parts to fix the gear (see figure 5). This ensures an easy and fast way to assemble the gears and bearings, which are taken from a conventional power tool. The build direction of the structure was taken into account so it was possible to place the bearing seats in such a way that little to no postprocessing is necessary. Furthermore by applying the principle of early determination of the part orientation [10] it is possible to manufacture the bearing structure with a minimum of support material. The main part of the gear subassembly is built in the orientation shown in figure 5. The large, flat additive manufactured sheet at the bottom is necessary and acts as an interface between the structure and the cooling system. The other four additional parts of the subassembly are oriented differently to also allow manufacturing without any additional support material. At the end of the build process the few necessary supports can be removed easily. Besides heat treatment and sand blasting of all parts, only four threads are cut during postprocessing. The minimal weight achieved with an initial conceptual design based on the flux of the forces around the gears. Based on this ideal design a force optimized part was developed in several iterations of simulations and design changes. When hammer drilling with at a force of 100 N and a torque of 0.8 Nm the maximum stress in the final part is approximately 72 N/mm$^2$ and the maximum displacement 0.18 mm with a total weight of 60g.

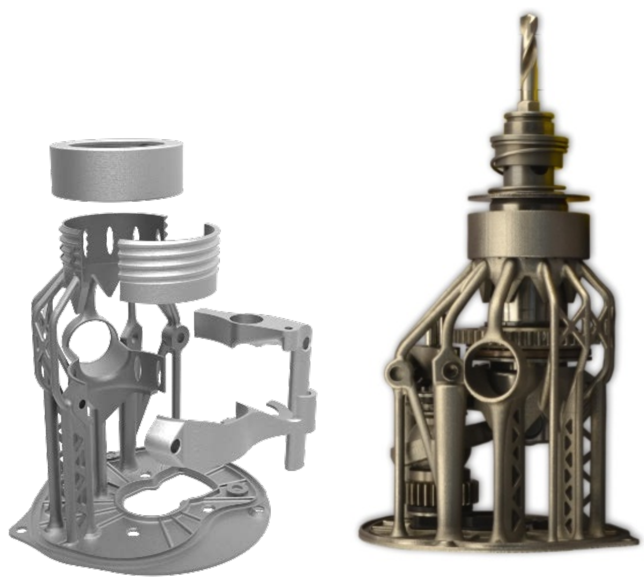

Figure 5: Design of the gears and bearing structure with the four additional parts (left), assembled part with gears and bearings (right)

**<u>Subsystem dust extraction and motor cooling</u>**

The goal of an integrated dust extraction system is to ensure a clean drilling process. The Concept Tool should be able to drill a hole with no visible dust left on the wall or below on the floor. The dust extraction system is integrated into the drilling machine such that it does not need any additional equipment like a vacuum cleaner. The system is able to filter the dust out of the air and the user of the tool can easily empty the filter system. To realize this feature a complex ventilation and extraction system was developed with a cyclonic separator, centrifugal fan and directly at the drilling hole an air outlet and the extractor inlet. The air flow is also used to cool the electric motor (see figure 6).

Figure 6: Overview of ventilation and dust extraction system (above), cyclonic separator (left), centrifugal fan with motor cooling (middle) and dust extraction base (right).

The heart of the dust extraction system is the centrifugal fan. It provides the necessary airflow and static pressure. The negative pressure at the inlet is used for dust extraction and transports the dust directly to the cyclonic separator. In the cyclonic separator the heavy dust particle are separated and fall down into the dust collector at the lower end of the handle. The collector is attached with a thread and easy to remove. When the cyclonic separator is turned upside down, a stopper in the dust collector prevents the dust from falling back into the separator. To protect the centrifugal fan and the motor cooling from remaining dust particles, a fine particle filter was added directly above the cyclonic separator. In this configuration, particles in the fine particle filter can fall down into the dust collector when the dust extraction system is turned off.

The cleaned air flows into an additive manufactured cooling structure for the motor. The cooling structure is optimized for an optimal flow and heat exchange and is not manufacturable in a conventional way. It is built in aluminum without any support material. The optimized airflow reduces the motor temperature of ten Kelvin. After the cooling system the majority of the air leaves the tool through an outlet. A small portion is redirected to the front into the base. This airflow is used to clean the drill and the drilling hole. The outlet is placed opposite of the inlet of the dust extraction channel. The channels to transport the clean and dusty air to and from the drilled hole are integrated in the beams holding the dust extraction base. The cooling system and the whole flow optimized dust extraction system are a good illustration of how AM can increase the performance with an optimal design.

The dust extraction system is further enhanced by another interesting feature in the dust extractor base. To ensure the vacuum cleaning of the drilling hole, it is important that the dust extraction system draws air and dust from the hole and not the ambient air. The backside of the base has to be closed around the rotating drill. To enable different drill diameters the closure on the backside has to be adjustable. Therefore the adjustable aperture in figure 7 was designed. The base contains four movable parts, three blades and a control ring, but was manufactured by selective laser sintering directly inside the base in one piece (see figure 7).

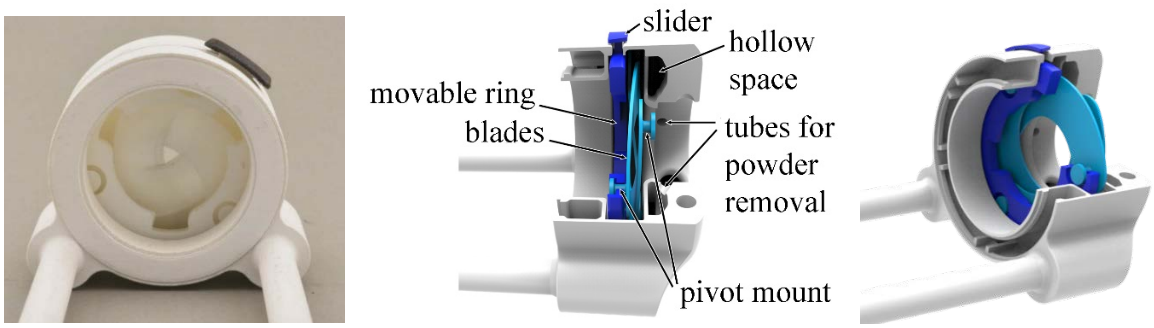


Figure 7: Aperture: manufactured in closed position (left), sectional view (middle/right)

Thes three blades are guided in the base at one end and in a movable ring at the other end. The ring can be moved with the slider to open and close the blades of the aperture. The integrated aperture with its printed movable part demonstrates functional integration in additive manufactured parts.

There are numerous other good ideas illustrating the different potentials of AM in a highly integrated holistic system. The general function of the hammer drill does not need an explanation for a general audience to be understood. It is a perfect visualization of AM's potentials and allows direct discussion of them in several subsystems and solution details.

## Reflection of the design process

The whole nine month of the product development process were highly influenced by the different capabilities of additive manufacturing in comparison to conventional processes. The short lead time of AM parts allowed more and faster design iterations.

The main technical functions were treated as individual subprojects following its own individual plan and pace, only bound to the overall project deadlines, like design freezes. Each subproject was realized by a sub-team consisting of up to three members. The engineering boundaries for each sub-project were the interfaces and predefined installation spaces.

This adaptive project organization was also needed because the various AM processes bring different production speeds and costs. While metal parts are relatively expensive and need to be scheduled with a production period of up to two weeks, some rapid prototyping plastic parts are available within a couple of hours and relatively cheap. Therefore, the realization process of each subproject was bound to the corresponding manufacturing method. Other subprojects such as the development of the electronic system followed their individual iteration steps. Nevertheless, all sub-projects, of mechanical or electronic nature, were similarly organized. The progress of the functions and their feasibility were evaluated in regular meetings. If needed, a non-realizable function was dismissed and replaced. For example no feasible solution was found in adequate time for a hammering mechanism. Therefore the components of an existing hammer drill were reused (see figure 8). This chosen project structure allowed to continuously test, evaluate, extend and improve single components and consequently the complete product.

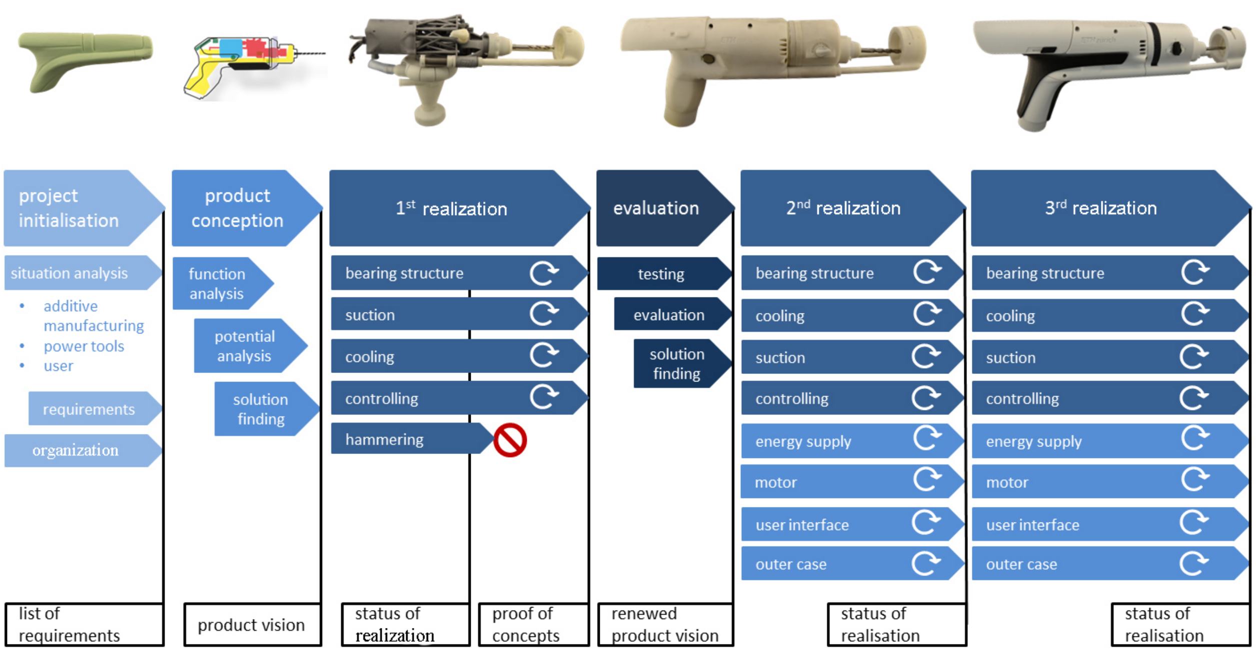


Figure 8: Development process

Additive manufacturing enabled the large number of iterations, but AM was also a cause for iteration. The team members were novices in the area of additive manufacturing. They were trained with the basic knowledge on AM and had access to common and available design guidelines. The team designed the first realization of the tool based on this knowledge. During the assembly of the parts and the following tests, valuable feedback was derived from the additive manufactured parts. The feedback was used to improve the design, especially to reduce postprocessing and to fix not working functions.

During course of the project it turn out there is an additional need for supporting different aspects of design process with an AM design guideline, particularly for AM novices, was determined. The inadequate designs of the first realization were primarily traced back to insufficient information given by design rules and design guidelines for specific design situations. The tow following situations are exemplary for these problems.

The first exemplary situation is the need to remove remaining powder from cavities is already know and described. Especially in Selective Laser Sintering the removal can be difficult. In several publications of design rules numerical values are given on the minimal gap between two walls. The given information is correct and important, but it corresponds to simple geometries and does not have to be valid for more complex ones. There is no additional information for complex geometry and how to design a part for an effective and efficient powder removal.

A second exemplary situation was the lack of guidelines for the overall design process. The team started with an idea and designed the part in CAD. After feedback for the AM service provider and postprocessing they had to redesign the part. In particular on metal parts produced by Selective Laser Melting (SLM) one can save support material and postprocessing effort and in the end to save cost, by an improved design process. Based on this learning we started to develop a guideline for the design process. For example, the part orientation should be determined before designing the part in CAD. This enables the incorporation of the orientation in the detailed design and reduces the need for support material, improves surface quality and reduces heat deformation. Due to the early determination the effort for postprocessing is reduced and design iterations can be avoided [10].

## Conclusion

For a better understanding and visualization of AM's possibilities a working system - the Concept Tool - is presented. The presented Concept Tool has a various features, which demonstrate the potential and design freedom of AM. Especially, features like the flow channels for dust extraction and aperture are only producible with AM. The findings of our team observations showed a lack in supporting systems for designer and emphasized the need for a supporting design guideline for the overall development process. The goal is to support designers in the design process of systems containing AM components and to unlock the full potential of AM.

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