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THREE VIEWS ON ADDITIVE MANUFACTURING: BUSINESS, RESEARCH, AND EDUCATION

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ABSTRACT

In the past years, the field of Rapid Prototyping and Rapid Manufacturing has been turned upside down by new innovations - making the technology available for everyone. Additive Manufacturing (AM) has become an essential element for product designers and engineers. This tutorial will feature a team of researchers from the Delft University of Technology who are playing an active role in transforming this disruptive technology for Industrial Design Engineering. We discuss this topic from three perspectives:

1) Business: we will show how trends in Computer-Aided Design (CAD) and AM are similar to the rise of Desk Top Publishing (DTP) and digital printing three decades ago. From a non-existent solution to a professional and expensive tool to a paramount tool that emancipates end users. How can the European industry play a profitable role in impacting this?

2) Research: Designers need new tools and methods to reap the benefits of AM. Such tools, often called Design for Additive Manufacturing (DfAM) are being developed in a new way. We will show examples and an emerging theory to go beyond CAD solutions.

3) Education: how can we teach academic courses on this topic? Textbooks are clearly not sufficient, nor are simple projects. In Delft, we have developed a unique full-semester course that has been taught for 3 years, yielding 100 alumni. Both structure and results of this minor on Advanced Prototyping will be discussed and shown.

KEYWORDS

Additive manufacturing, rapid prototyping, design support, innovation, education

1. INTRODUCTION

Additive Manufacturing (AM) represents a collection of production technologies. AM machines, also known as 3D printers, use these new production technologies. These machines generate three-dimensional solid objects, submit to testing, or assemble into working mechanisms. Manufacturers around the world for low-volume production, prototyping, and mold mastering use them.

The basic principles are:

- Layer by layer production
- Layer generation by liquid-based systems (polymerisation of resin - stereolithography), solid-based systems (Fused Deposition Modelling) and powder-based systems (sintering or melting of powder - Selective Laser Sintering).

Thereare in total ca. 30 AM processes and 40 AM machine manufactures on the market [1]. These AM machines are maturing and getting widespread and this technology has been predicted as a game changer in New Product Development, e.g. by Fortune magazine. The challenge is the development of new services, design methods, and workflows (materials, digital product specifications, quality control and logistics) and education to enable future designers to benefit to the full extent of the great amount of freedom that comes with AM technologies.

This tutorial consists of 3 sections. First the business perspective of AM will be discussed, followed by an overview of the on-going research at the Delft University of Technology, and finally our approach for AM in education. The intended audience is fellow academic educators and peers in industry.

2. BUSINESS

How can companies organize their business, to fully and sustainably profit from on-demand AM?

Traditionally, products are based on one design that is produced in large series in a centralized manner. Every user gets an identical product with very little space for personal modifications, if any. This flow from designer to user is illustrated in Figure 2A. In the workflow proposed in Figure 2B, the designer develops a customizable design which allows the user to input data. This data can for example be in the form of user-selected functional features, scanned anthropometric data, or aesthetic features.

AM can increase the sustainability of products on environmental and economic level;

- Less material waste. Material is added, layer-by-layer, during production. This allows a more efficient production process with less waste compared to traditional methods, such as milling.
- Lightweight products. The possible shape complexity allows the building of optimal shapes, material can be placed only where necessary creating lightweight products, such as shown in Figure 1. Also more functions can be integrated in one part.
- On-demand manufacturing. Products can be produced in short time after the moment the user requests it, instead of in advance production. This leads to less overproduction and consequently to less destruction of unsold products.

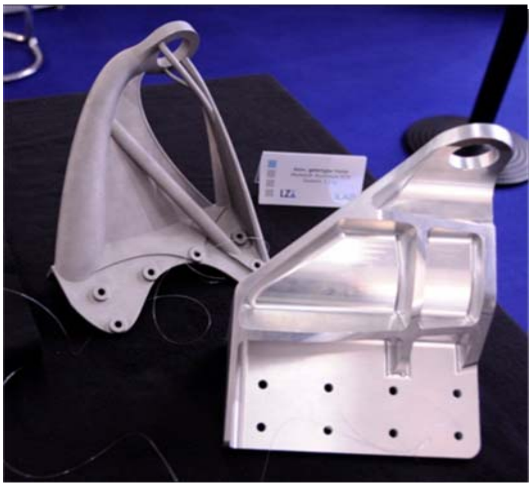


Figure 1 3D Printed Optimized Aircraft Part and Original Machined Part (Boeing and University of Technology Hamburg-Harburg)

Furthermore, social sustainability is also addressed; the main benefit for the user is that products can fit the user's wishes and requirements. Because there is no investment in a mold, every product can be unique; this way On-Demand AM enables Mass Customization. The user gains more direct influence in the final product, raising the question of what will remain the role of the designer. [1] [14, pp 41-59]

The common steps for all AM technologies are:

1. Conceptualization
2. Modelling and verification: digital CAD-model
3. Conversion: export to STL file
4. Pre-treatment: corrections of STL, orientating, generating supports and slicing
5. Machine set-up and fabrication: fully automated
6. Removal and clean-up: removing secondary supports and/or build material
7. Post-processing: abrasive finishing and coating

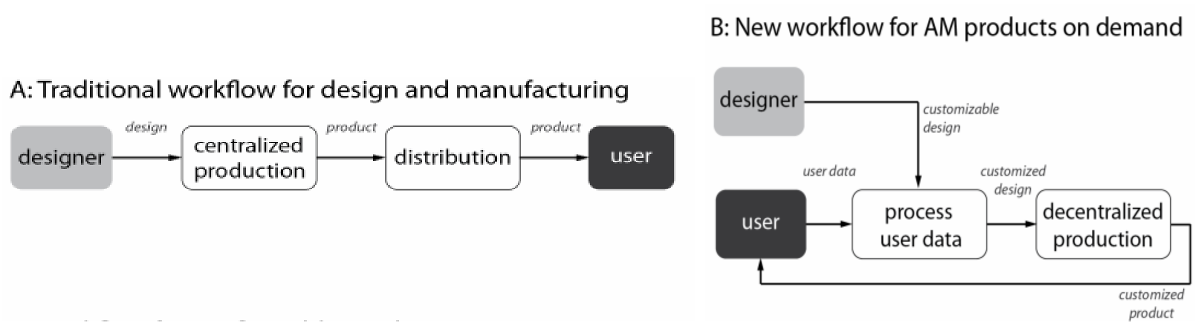


Figure 2 Traditional and new (on-demand) workflow for products.

2.1. Democratization of Production

Until approximately three years ago, AM techniques were reserved for design and engineering professionals. Recently, consumer-oriented service bureaus as Shapeways, Ponoko and Cubify have emerged and allowed everyone to upload a 3D file, select a material & AM process and the possibility sell designs. For example, Shapeways offers a collection of established and new AM methods and post processing options, with clear design rules concerning minimum wall thickness, tricks in post processing and so forth.

Another essential breakthrough are grassroots 3D printers, such as the RepRap and Makerbot. Heavily rooted in the FabLab community, these open-sourced designs have been evolving from rudimentary systems to accurate printers that can compete with commercial Fused Deposition Modeling (FDM) systems. Table 1 shows an overview of these inexpensive systems with their characteristics. This development accelerates innovations in the supporting software, to model, repair and pre-process the objects. Furthermore, it allowed the community to tinker with materials, build parameters and so forth. This stimulates democratization of this technology.

This open source development yielded a new industry in low-cost 3D printer kits and readymade systems. Some of these have been adopted by mainstream AM companies, such as the $1200 Cube printer by 3D systems, illustrated in Figure 3.

A final development in the democratization of AM is the emergence of the Cloud: new social networks allow online sharing of designs and new business with AM. For example, www.thingiverse.org is a public database where everyone can upload and share 3D models – allowing those who are not familiar with modeling to reproduce objects. The designs are shared under the Creative Commons Public Domain Dedication license, allowing non-commercial use. Furthermore, the aforementioned Shapeways allows everyone to open up an online store selling their 3D designs. Similar to the "App Store" principle, the manufacturing and distribution of the products is taken care of by Shapeways.

2.2. Desktop Publishing: Printing for All

Very little research has been performed on the methods to integrate this new manufacturing technology in industry. Furthermore, in practice almost all existing solutions are a sub optimization by replacing an existing production method. Placing the AM technology in this context of products on demand will also require benchmarking the technology for the discussed applications.

Table 1 Low-cost 3D Printers.

System Name	Approximate cost (Eur)	Build envelope (mm)
RepRap Mendel *(reprap.org)*	500	200 x 200 x 140
Printrbot *(printrbot.com)*	400	150 x 150 x 150
Fab@home *(fabathome.org)*	1200	200 x 200 x 200
UP! *(pp3dp.com)*	1200	140 x 140 x 135
Cube *(cubify.com)*	1000	140 x 140 x 140
3DTouch *(bitsfrombytes.com)*	2000	275 x 275 x 210
Makerbot *(makerbot.com)*	1300	225 x 145 x150
Glider 3D Printer *(botmill.com)*	1100	200 x 200 x 140
Ultimaker *(ultimaker.com)*	1200	210 x 210 x 220

To predict the business uptake we draw parallels and conclusions from the past by comparing the digitalization of 'writing & publishing' with "designing & manufacturing".

Around 1439, Gutenberg invented printing with movable type. For 500 years this craftsmanship of

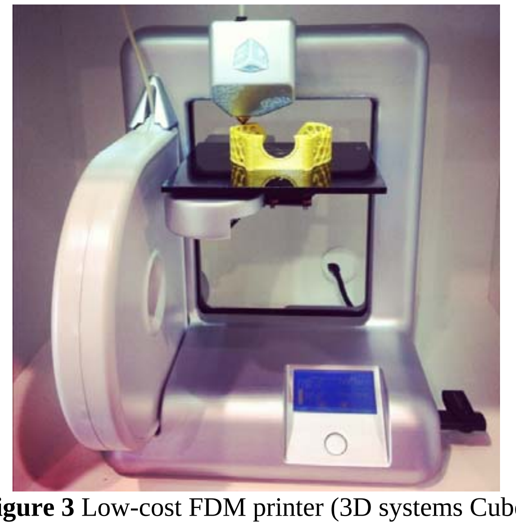


Figure 3 Low-cost FDM printer (3D systems Cube, $1200).

handset typesetting was used in the printing and publishing industry. During the industrial revolution Ottmar Mergenthaler invented machine typesetting (also called hot metal typesetting). He developed the linotype line-casting machine, so named because it set an entire line of type at a time.

In 1903 Ira Washington Rubel invented the offset press for printing on paper. In offset printing the inked image is transferred (or "offset") from an image carrier (the offset plate) to a rubber blanket, then to the printing surface. When used in combination with the lithographic process, which is based on the repulsion of oil and water, the offset technique employs a flat image carrier on which the image to be printed obtains ink from ink rollers, while the non-printing area attracts a water-based film, keeping the non-printing areas ink-free.

Nowadays the color image is created in a Desktop Publishing (DTP) application and the output is send as a digital (PDF) file directly to the Computer-to-Plate (CTP) process for writing the digital image on the metal or polyester offset plate [2]. In the CTP process the image from a digital file is recorded directly to the printing plate instead of creating a photographic film and making the plate as contact proof from the photographic film. Although CTP is a digital printing process the editor and printer's familiarity with the process, the equipment, the type of plates, the file format and preparation play a role in the success of the CPT process. Therefore the manual quality control by educated operator remains important.

This development made centralized mass-production of print possible. Books, magazines, papers, brochures, etc.

In 1978 Xerox and IBM introduced the digital black & white printer on the publishing market. In 1993 Indigo and Xeikon introduced the digital color printers. The color image is created in a DTP application and the output is send as a digital (PDF) file directly to a digital electrophotographical or inkjet printer. These processes are based on digital closed-loop (color) quality control for each step in the printing process.

Nowadays digital printer engines combine speed, quality, variable data capabilities and in line finishing. Printing on Demand (POD) is now the drive to decentralize production. Each single digital image (PDF file) can be printed and each page can contain a different image.

2.3. Beyond Computer-Aided Design

Until the 80's the drawing board with ink pens and transparencies was used for drafting and designing a product. Making the product was based on the skills of the operator of the milling, cutting and drilling machines that were controlled manually via hand wheels or levers. Quality was related to craftsman ship. (Like offset before CTP).

By the introduction of the Numerical Controlled (NC) machine tools in the 1940s the first step to digital controlled production was set. The first NC machines built were based on existing tools modified with motors that moved the controls to follow points fed into the system on punched tape. The next steps were computer numerical control (CNC) machines.

The Hyatt brothers invented injection molding in 1872 as a manufacturing process for producing parts from polymers. The polymers are fed into a heated barrel, mixed, and mechanically forced into a mold where it cools and hardens to the configuration of the mold. In 1946, American inventor James Watson Hendry built the first screw injection machine, which allowed much more precise control over the speed of injection and the quality of articles produced. Since the 70's injection molding has been widely used for the manufacturing of a variety of plastic parts, from micro components to entire body panels of cars. The development of the mold made centralized mass-production of parts possible. All kinds of plastic, glass, metal, or ceramic are used for product (parts).

Molds are made by a mold/toolmaker from metal and precision-machined to form the features of the desired part. When filling the mold for the first time the toolmaker follows a special procedure to find the right process parameters for the desired quality. Once the equipment and the mold are tuned to successfully create the molded part, modern monitoring systems can be used to reproduce the part with the same quality.

When we compare the offset process to the injection molding process the mold is comparable to the offset plate. *When we consider the complete workflow from CAD to manufacturing this is the last hurdle to overcome in the digitalization of the manufacturing process.* The toolmaker cannot be digitalized and due to the costly mold the injection molding process is only usable for mass production.

Similar to DTP, Computer-aided design (CAD) was developed for the process of drafting and design. The great difference with DTP is that the CAD programs evolve relatively slowly. DTP applications like Word are user friendly and intuitive, CAD programs are still developed for the educated user.

CAD is mainly used for detailed engineering of 3D models and/or 2D drawings of physical components and was initially driven forward by the needs of the automotive and aircraft industry. CAD is used throughout the engineering process from conceptual design - sketch, drawing, physical model, scan data, or only an idea - and layout of products, through strength and dynamic analysis of assemblies to definition of manufacturing methods of components.

The end result is a 3D model that projects the main design intent the designer had in mind. This model can be printed, send digitally to other designers or saved for future editing. The 3D model can also be saved in STL format to send it to a AM machine to create the physical model. The growing market share of AM printers pushes more user-friendly CAD-applications.

2.4. Challenges of AM

In 1979 Ross Householder patented the application of Selective Laser Sintering, the first AM technology. Today there are more than 30 AM processes [1]. But it is clear that AM would not exist without 3D CAD. Virtually each CAD system has the ability to output to an AM machine. The reason is that the only data that the AM machine needs from a CAD system is the external geometric form. Today that is an .STL file. The quality of this file is comparable to the page description languages (PDL) of the 80's. A PDL describes the appearance of a printed page on a higher level than an actual output bitmap.

If you remember the dot-matrix printer hooked up to a personal computer in the 80's only low quality bitmap characters could be printed. Graphics could be done but the quality was only acceptable to the nerds. After 25 years of digital printing .PDF is the PDL that describes the appearance of a printed page in a higher level than an actual output bitmap. PDF documents printed with a color laser or inkjet printer approaches offset printing. *The PDF file is the digital (virtual) offset plate.*

The challenge for AM will be:

1. the optimisation/shake out of the mentioned 30 AM processes and
2. the development of the digital (virtual) mold language (like PDF)

Additive Manufacturing on Demand (AMOD) will be based on combination of speed, quality, variable data capabilities and in line post processing. By AMOD it will be possible to decentralize production. Each 3D CAD model (file) can be printed and each printed product can have a different design.

Revisiting the 7 steps of the AM process, mentioned at the start of this chapter, we have now discussed the challenge for step 1. to 5. The last two steps - Removal and clean-up and Post-processing – are comparable to the finishing machines behind an offset press or a digital printer. To enhance these process steps we have to develop dedicated robotics to automate these processes.

3. RESEARCH

3.1. Towards Design Methods for On-Demand Additive Manufacturing

In this section we discuss our efforts to reason what the development of AM mean for the discipline of Industrial Design Engineering, stating the question: "How should designers adapt or change their way of working to benefit from the possibilities of AM to the full extent?"

Although AM technologies have existed for over a decade, a significant increase in the applications of AM for the production of end-products has only started to take place over the course of the last years [1]. The capabilities of AM offer new possibilities in shape and function that go beyond currently existing design methods. Taking into account this trend towards the production of end-products using AM, we identify a need to address the gap between the possibilities of AM and available design methods and tools.

The objective of our research is twofold; we aim to develop new methodologies to support Design for Additive Manufacturing (DfAM), and in the process of this development, obtain a better understanding in how AM can enable New Product Development.

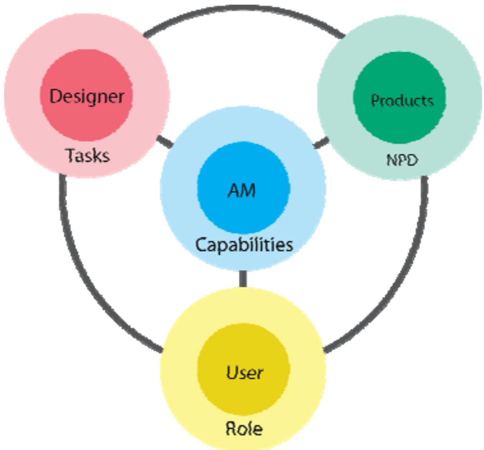


Figure 4 Research context of On-Demand Additive Manufacturing.

As addressed in the previous section, AM can have a big influence on how products are designed, produced and used. Furthermore it may yield completely new products and new product-service combinations. This research takes into account the playfield between AM, product, designer and user. This context is illustrated in Figure 4.

3.2. Design for Additive Manufacturing

Despite a growing body of knowledge concerning the technological challenges of AM, very little research has been performed on the methods that allow designers to deal with this game changer. Since traditional design methods are mainly focused on mold-based production methods, they do not allow designers to benefit from the opportunities AM has to offer. For example, industrial design students are still taught that decreasing the shape complexity and increasing the homogeneity of a product reduces the price of the product. While this is true for injection molding, the complexity of AM produced parts hardly influences the production costs.

To approach the knowledge gap we have formulated the following questions:

- How should designers adapt or change their way of working to a process where AM is the primary production method?
- Which methods must be developed to allow the design of AM products that outperform current products in terms of material use, weight, strength, stiffness etc.?

These research questions are supplementary to the Roadmap for Additive Manufacturing [3], where the authors recommend the development of such new methods. While Rosen [4] proposes a DfAM method, his method is limited to one approach for the application of lattice structures. Furthermore his method describes the process of applying this lattice structure to already made designs and is therefore not an integral part of the design process.

Before starting to develop such new methods, we need a better understanding of AM technologies, the technological benefits, the new functionalities they could enable and what implications this has on Industrial Design Engineering. The following sections describe our approach and findings in these fields.

3.3. Three-link chain model

In order to reason on the technology affordances that AM enables, we base our approach on Olson's Three Link Chain Model (3LCM), which originated from the material science domain [5]. This model, illustrated in **Error! Reference source not found.**, considers the linear relationships between the elements performance, properties, structure, and process.

The performance represents the behavior of the product to be designed. This behavior is typically included in a list of requirements by the designer. To achieve the desired behavior of the product, the designer can determine specific properties for the product's parts. These properties can be based on quantifiable desired behavior, such as maximum weight or strength, or less easy to quantify behavior, such as visual or tactile properties. The structure is the physical layout that directly controls the properties of the product. These structures can be on the scale of product features, such as handles, ribs, and cooling elements, or smaller, in the form of cell structures that build up bigger elements or, even smaller, on the material level, the density or structure of the material. Finally, processing represents a

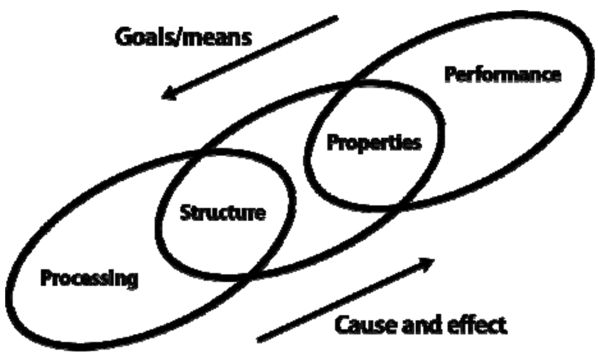


Figure 5 Three Link Chain Model.

specific manufacturing method.

In the original article, the 3LCM links material science to material engineering. Analysis of materials follows the deductive path, by investigating the material's structure that follows from its processing and deducing the properties and eventually the performance by cause and effect logic. Complementary, material engineering follows an inductive path by determining the desired performance and properties, the material structures that comply with this performance and processes that result in the desired structures. Usually, a design process does not follow any of these two directions through the framework linearly but an iterative process where both induction and deduction are applied.

In line with the DfAM framework proposed by Rosen [4], we adopt the 3LCM as a reasoning framework for design. The distinction between processing, structure and properties allows an expressive reasoning model to consider the benefits of AM, such as lightweight structures, material behavior in graded materials and the influence of the fabrication means on these properties.

When we use the model for DfAM instead of material science, the meaning of the model remains but the context changes. Traversing from performance to processing represents a design process where, starting with a desired performance, a choice is made for the manufacturing process. Following this inductive path, depending on the needed structure, an AM process can be selected which is suitable to create the needed structure. The deductive path can also be taken, which could be in the form of a simulation. Starting with an AM technology, a designer can deduce which structures a specific AM process can produce. These structures influence the product's properties and thus it can be reasoned whether the performance of the product will be satisfying.

Rosen's interpretation of the 3LCM is primarily focused on the design of cellular structures, which are only possible to create using AM. However, we increase the scope of the paradigm, as AM affords a larger variety of phenomena (e.g. graded materials, reflectance and electrical conductivity). A full discussion on this scope is found in [6].

3.4. Properties and Structures

In an attempt to map the structures which are covered in literature and the properties that are aimed for, we focus on the structure-properties link of the 3LCM. A literature survey was conducted covering journals on rapid prototyping, engineering design research and proceedings of engineering conferences such as ASME and conferences on computer graphics, such as SIGGRAPH.

The reviewed literature applies structures to achieve a wide variety of properties. We have identified six sets of properties that are frequently aimed for, namely stiffness, strength, compliance, thermal, dynamic and visual properties.

We categorized the structures that are described in the literature into three scale ranges: micro, meso and macro. Structures with feature sizes between 0.1 and 10 mm are considered meso scale. All structures with smaller features are counted among the micro-scale and all bigger-sized structures are considered macro scale.

To visually illustrate the reviewed literature, we have mapped the references in a matrix of properties and structures. This matrix is illustrated in Figure 7, also highlighting some of the structures discussed in this literature by images.

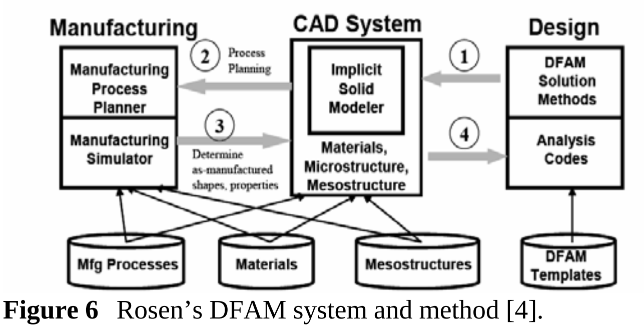


Figure 6 Rosen's DFAM system and method [4].

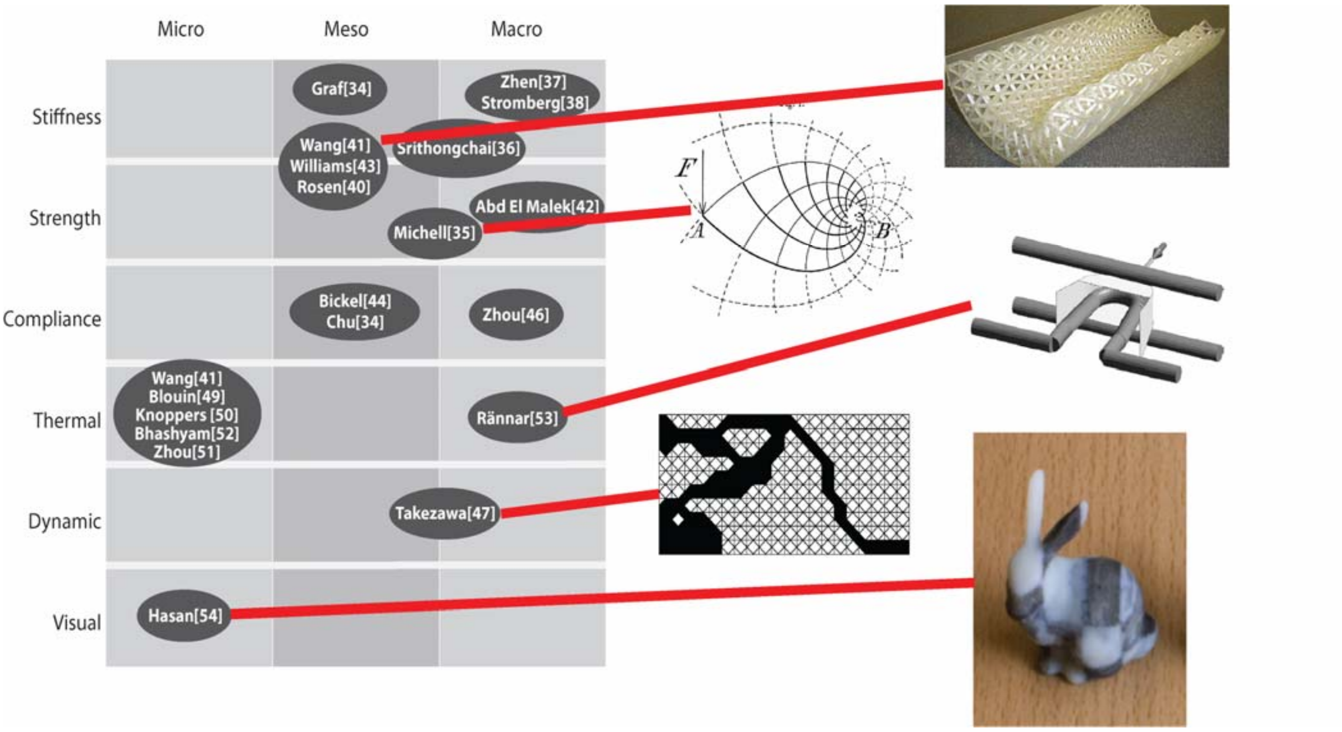


Figure 7 Overview of structures and properties covered in literature.

This matrix provides us with a new view on the literature. Some areas in the matrix are densely populated. For example, it can be observed that much literature covers the design or generation of structures for specific strength or stiffness properties. This can be explained by the fact that keeping the volume of used material to a minimum while complying with the desired stiffness or strength has permanently been one of the key elements in engineering. Other areas in the matrix remain empty or less populated, indicating that some properties are seldom aimed for using AM. This is the case for dynamic and visual properties, for example. The latter indicates that there are properties, relevant for Industrial Design Engineering, such as visual properties which have not yet been sufficiently covered in literature. It also has to be noted that the list of properties in the matrix is limited to the properties we have found in the reviewed literature. There are numerous other properties, such as tactile and acoustic, that Industrial Designers deal with during a design process and thus could be an interesting topic in AM research.

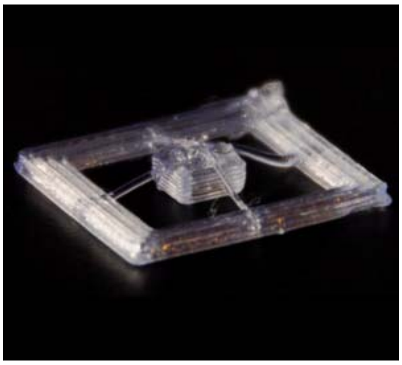
By focusing on 3 properties, namely compliant, visual, and acoustic, we have attempted to cover some of the significant properties enabled by AM which have remained unexplored in the literature, the blank areas in the overview matrix in Figure 7. We have done so by developing new workflows for modeling structures with these properties and producing them using AM. Table 2 describes our efforts and highlights some of the results.

3.5. Implications for Industrial Design Engineering

In the previous section the exploration of several of the new possibilities of AM has been discussed. In this section we describe our effort to develop a method to document the knowledge needed to use these possibilities. The development of the described objects, yields new knowledge in two domains. On one hand new capabilities of AM are explored, on the other hand knowledge is generated on how these new structures can be designed. The latter is a component of DfAM knowledge. To gain a better understanding of how the development of this knowledge could be supported, we have explored the use of wikis during the design and AM production of novel structures.

Students enrolled in the minor Advanced Prototyping, a full-semester course organized by the authors, were provided a wiki environment which was used during a project where objects with new visual functionalities were designed, modeled and produced by AM. This setup is described in more detail in Section 4.3. The use of a wiki environment for DfAM knowledge was evaluated by analyzing the students' reflection on their use of the wiki and by examining the resulted wiki on structure and content. The results show that the wiki has been a valuable tool to document the newly generated knowledge. Although the first groups reported not to have used the wiki for the acquisition of knowledge, as the amount of knowledge on the wiki accumulated over the weeks, the latter groups indicate an increase of this use.

Table 2 Overview of designed and manufactured structures resulting in three properties.

Compliant properties	Visual properties	Acoustic properties
Compliance, opposed to stiffness, is applied when a desired amount of deformation is required. We have explored the AM production of compliant structures such as buttons and (robotic) grippers. A clicking button was produced on a sub-€1000 printer. The functionally compliant elements of this button consist of a single bead of extruded material. In literature, such desired deformation behavior is approached on the level of meso and macro structures, as shown in Figure 7. Examples include, deployable aircraft wings and shoe soles with desired deformation and damping.	Because with AM the structure and material can be manipulated locally throughout a volume, the way that light interacts with the object can be manipulated, yielding new degrees of freedom for industrial design. Light interactions of AM produced objects that we have studied include reflectance, subsurface scattering. The image below illustrates a phone cover with designed reflectance. Among the few researchers dealing with visual properties of AM, Hašan et al. developed a process to model and fabricate translucent objects of which they can control how light passes and interacts through the volume [7].	The structure and material influence the acoustic properties of components. This holds for deliberate sound production (e.g. speakers) and for product noise (e.g. from motors). We have focused on mouthpieces of woodwind instruments, illustrated in the image below. The internal geometry of this component strongly influences the sound quality and playability of the instrument. The hierarchic complexity enabled by AM, allows the manufacturing of structures that alter the acoustic properties. This can be done not only by altering the geometry but also by the composition of material (eigen frequency).
		
Clicking button with designed compliance	Surface with designed reflectance	Saxophone mouthpieces

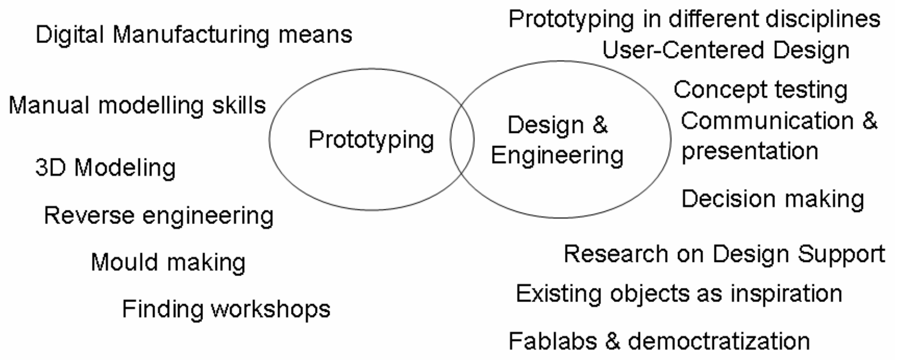


Figure 8 Topic map of the advanced prototyping curriculum.

4. EDUCATION

At current engineering and design schools, students are not challenged to develop prototyping skills: most curricula stress the importance of fuzzy-front end conceptualization and virtual modeling and simulation. For example, in the undergraduate curriculum of architecture, model making is typically seen as a low level skill that is hopefully used in design projects [8]. It depends on the mentor and coverage of projects whether students are challenged to really apply such skills later in their education.

Furthermore, educators are faced with reductions on budgets and contact hours, which yields a catch-22 in setting up curricula concerning physical model making. This can lead to extremes of graduating MSc/MA students who have never created something physical, and are unable to explore and present a design without digital support.

4.1. Prototyping as an academic ability

In our view, model making and prototyping skills are crucial for future design engineers. This is valid across disciplinary boundaries, ranging from industrial design and architecture to electronic and aerospace engineering. For all, prototyping can have four roles:

1. Exploration: to probe physical space by using physical components.
2. Verification: to assess a design against the specification – for example durability or ergonomics.
3. Communication: to create shared insight or to start a dialogue with other professionals. To enable decision-making.
4. Specification: to function as a reference model, as traditionally happens in the car industry.

Although never proven indefinitely, we have strong evidence that the inclusion of physical prototypes does benefit the design process. Successful prototyping requires awareness of suitable technologies, access to these technologies, available time, and sufficient personnel [9]. We claim that the shortage of any of these elements will effectively limit the opportunity to realize student designs physically within the curriculum. Furthermore, the act of prototyping can be seen as a way to enable front-loading in complex product realization processes: to address challenges before heavy investments are made [10]. We argue that this knowledge, competences and skills need to be addressed in an academic setting, yet at the same time require an action learning Approach: learning by doing and reflecting.

In the next section, we propose a multifaceted course program to face these challenges. It represents a unique approach, encompassing both high-tech and low-tech prototyping techniques, from theory to practice.

4.2. A full-semester minor programme

In the Netherlands, a secondary field or “minor” can be selected during the undergraduate academic study, which accumulates to a full-time semester work or 30 credits by the European Credit Transfer System (ECTS). At Delft University of Technology, these minor programs are always given in the winter semester.

The roots of the Advanced Prototyping minor are from both Industrial Design and Architectural Design. The programme is organized by the research sections on Computer-Aided Design and Aesthetics, in close collaboration with the workshops of both departments. Each provides approximately 50% of the curriculum, with strong interconnected course

Table 3 Constituents of the Minor on Advanced Prototyping.

Module	Lectures (hours)	Practice (hours)	Project
BK7500 Design of prototypes	Introduction (4) Design methodologies (8) Human-Centered Design & prototypes (8)	Workshop – manual skills: wood/plastic/metal (20)	LightStyle
IO3850 Advanced prototyping for design	Rapid prototyping Techniques (8) 3D modelling (8) Prototyping in industry (16) Prototyping in Research (4)	3D modelling- Rhino (60) Workshop – CNC skills & 3D printing (16)	Augmenting prototypes
BK7510 Objet trouvé	Reverse Engineering (2) Guest lectures (4)	Carrousel (48)	Objet Trouvé
IO3851 Personal prototyping project	prototyping experiences by alumni (4) Decision support through prototyping (4)	Carrousel (48)	Handwriting

components. The intention is to connect the theory with practice, and this requires guest lecturers and master classes – typically by alumni or professionals of these studies.

The main learning objective is to allow the students to attain competence in prototyping strategies: what can be prototyped and what is the most effective way to create/use physical models during design and engineering challenges. The topics of the minor curriculum are depicted in Figure 8: based upon prototyping techniques and design methods. For each, a theoretical backdrop is presented in a number of lectures, while practice sessions allow the attendants to get familiar with the basic and advanced

Figure 9 One of the LightStyle designs, made from Laser-cut PMMA..

skills in prototyping. The lectures, practice, and projects are specified in Table 3. This full-time curriculum is split in four modules, all last 10 weeks and deliver 7,5 ECTS. Effectively, the semester's first part is focused on basic skills and theoretical notions (IO3850 and BK7500). This is particularly necessary as attendees have a diverse background (not necessarily design or engineering). The second part of the semester is focused on employing prototyping in different ways, e.g. as inspiration, manufacturing means or organizational catalyst (IO3851 and BK7510).

The four projects are an essential part of the curriculum and all are directed to operationalize the skills and knowledge accumulated though the other components. During the LightStyle project, a lamp has to be designed, modeled and manufactured. This is an individual assignment that requires consideration of physical aspects of light/shadow and yields at least 3 intermediate prototypes. The second project is entitled Augmenting Prototypes and is a team effort to develop a new prototyping technique/method, and will be discussed in the next section. The third project, entitled Objet Trouvé focuses on getting inspiration of the external physical world/with existing found objects. The final project, entitled Handwriting is a jewelry design assignment that includes 3 types of 3D printing (Plaster, Plastic and Metal). This project stresses the importance of the designer/maker's personality and the choices in detailing/presentation.

4.3. Prototyping and Research

Two specific components were devised to challenge the undergraduate students to look beyond existing solutions. Both include a coach, an assignment and a reporting/reflection means yet in different instantiations.

Augmenting prototypes project

In five weeks time, students work in groups of 4 together with a scientist to develop and test a design support tool. The assignment should be close to the scientist' research topic, thus allowing an optimal transfer of knowledge and lab equipment. In the past years, the assignments included:

- Building a handheld haptic feedback tool based on a solenoid and Bluetooth;
- Reproducing 17th century glass by CT scanning, reverse engineering and porcelain molding;
- Developing 3D printed musical instruments;
- Optimizing 3D printed Badminton shuttlecocks – including FEM and wind tunnel experiments;
- Making a 3D printer from a LavaLamp – including thermofluid modeling;
- Building a portable projector-based Augmented Prototyping system;

The end result- typically a working model and a video or poster - is demonstrated in a public exhibit, entitled *Science Fair* as a reference to high-school exhibits in the United States with a similar intention. This exhibit is open to the public and allows the students to explain their challenges and skills to peers.

During the execution of the project the teams are required to keep a public web log (blog) to inform other students (and the public) about the progress and challenges they face. During intermediate project reviews, team presentations are held in which the students can only use this blog and physical prototypes.

Figure 10 Intermediate results of the 17th century glass reproduction (plaster mold and 3D print).

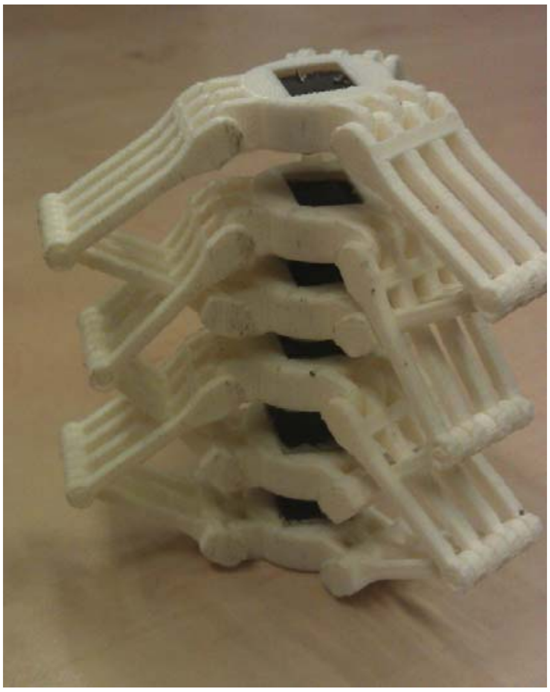


Figure 11 Design during the carrousel chain: foldable structure, printed by FDM.

Carrousel

Later in the program, a collection of advanced skills and innovations is selected which the students have to master and extend in just one week. After each topic, the team shifts to another, handing over their results to the next group, thus creating a carrousel. At the end of this carrousel the results are shown in short presentations.

The following topics have been hosted:

- 3D scanning & Reverse Engineering;
- Visual properties of AM;
- 3D printing of chains and cell structures;
- Building and programming a drawing robot (based on the boo-bot platform).

This weekly exposure to new assignments and contexts is devised to be in synch with the running design projects: feeding these with novel ideas and skills. As mentioned in section 3.5, the attendees were required to document their insights and results (pictures) in a wiki – allowing a networked knowledge base that can accumulate during and after the program.

4.4. Results of three years

At present, 105 students have attended this program from different backgrounds and locations. The pie chart in Figure 12 shows the differentiation between them, showing a large number of Industrial Design attendees – who express the lack of prototyping in their regular curriculum. A similar need is expressed by the architecture students, while others such as aerospace engineering typically select this minor program to extend their skills to design-related work. Each year, the enrolment was full within a week, which is fast compared to other minor programmes at Delft University. Furthermore, the motivation of the participants is high, as can be noticed by the attendance during presentations and the fact that almost all students receive a "satisfactory" or higher grade, for the last year 7.6 out of 10 for the design work and 8.0 out of 10 for the research project. Furthermore, the course also proves the ability of undergraduates to have impact on research: throughout the years, these projects have lead to approximately 5 conference papers and a number of patent filings.

One of the practical challenges of this course is the scheduling of the machine instructions: as there are only limited facilities to instruct students on lathe/milling skills. This raises challenges when large groups have to be catered for - the intention is to have a maximum timespan of 1 week for all attendees to get acquainted with one particular skill.

Another challenge is the selection of a good textbook on this topic. At present, we employ "Rapid Prototyping and Engineering Applications" [11], which provides a good background on the technologies, yet lacks topics on the role of prototyping and how model making is used in several disciplines.

4.5. Comparison with other prototyping programs

There are a number of smaller courses on prototyping, for example at Carnegie Mellon that encompasses electronics [12], and at Virginia Tech, shaped in graduate elective courses [9]. Most of these stem from engineering or computer science departments, allowing less time on the impact of prototyping on the design process.

Two curricula have a similar volume to the minor program described above, namely the "Computer-Aided Design Analysis and Prototyping" course at

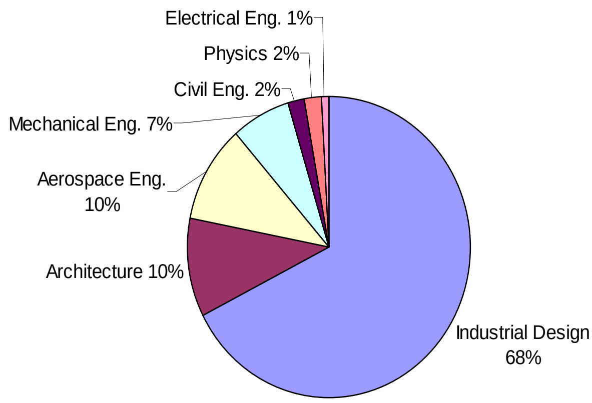


Figure 12 Alumni backgrounds (n=105).

the Department of General Engineering, University of Illinois at Urbana-Champaign, and the fablab academy.

The first is a 16 week course, described by [13]. Its main ingredients are lectures on CAD and CAE, as well as four large projects considering various virtual modeling aspects. However, the course is specifically focused on mechanical engineering and does not cover the function of modeling in design, nor how manual or automatic manufacturing works can be employed. Furthermore, only one physical model is created in the final week of the course.

The fablab academy[1] is a part-time virtual course, provided in the spring semester (5 months). Its roots are from the MSc course entitled "How to Make (almost) Anything" that is hosted by the MIT since 1998. It uses videoconferencing and local fablabs (currently 7) to host the lectures and instructions, while the attendees work on 1 project. The course starts with a "boot camp" of 10 days fulltime practices of to get acquainted with all the technologies available at the fablabs. The remaining topics overlap those of the previously mentioned course, also hosting lectures on intellectual property However, it does not little attention to design nor to manual craftmanship.

[1] http://fabacademy.org

5. CONCLUSIONS

In this article we explained three aspects of AM summarized below:

Business

- The development of the offset plate made centralized mass-production of print possible. Books, magazines, papers, brochures, etc.
- The development of the mold made centralized mass-production of products/parts in all kinds of materials -plastic, glass, metal, or ceramics - possible
- Printing on Demand (POD) is based on the combination of speed, quality, variable data capabilities and in line finishing. This makes it possible to decentralize production. Each image (PDF) can be printed and each page can be a different image.
- Additive Manufacturing on Demand (AMOD) will be based on combination of speed, quality, variable data capabilities and in line post processing. By (AMOD) it will be possible to decentralize production. Each 3D CAD file can be printed and each product can be a different design.

Research

- The Three-link chain model as the central paradigm of materials and science engineering is a good approach in linking structures to properties.
- There is insufficient knowledge on the technological affordances of AM. We have designed and produced novel AM constructions that exhibit unique compliant, visual, and acoustic properties.
- AM will have a big influence on product design but the development of DfAM approaches is required.
- A wiki was employed as an environment to support the building, documentation, and use of DfAM knowledge.

Education

- We developed a full-semester curriculum on physical and digital model making, a minor on Advanced Prototyping; AM is used throughout the courses, as well as more traditional manufacturing techniques.
- Based on action learning, this programme hosts several design and research projects. This includes building 3D printers and using wiki's and weblogs;
- More than 100 3rd year BSc students have attended this minor successfully; Outcomes result in publications, patents and new business ventures;

Overall, we may conclude that the impact of AM is considerable. As the enabling technologies are getting better and cheaper, new opportunities arise in all three fields described above – and the activities of one university are not isolated from the rest of the world. This requires attention in a larger context, in international partnerships and consortia – for example in the context of the European Union (FP7, INTERREG and so forth) or beyond.

REFERENCES

[1] T. Wohlers, *Wohlers Report 2010, Additive Manufacturing State of the Industry Annual Worldwide Progress Report*. Fort Collins, Colorado: Wohlers Associates, Inc, 2010.

[2] H. Kipphan, *Handbook of Print Media: Technologies and Production Methods*. Secaucus, NJ, USA: Springer-Verlag New York, Inc., 2006.

[3] D. L. Bourell, M. Leu, and D. W. Rosen, "Roadmap for Additive Manufacturing: Identifying the Future of Freeform Processing," The University of Texas, Austin, 2009.

[4] D. W. Rosen, "Computer-aided design for additive manufacturing of cellular Structures," *Computer-Aided Design & Applications*, vol. 4, no. 5, pp. 585–594, 2007.

[5] G. B. Olson, "Computational Design of Hierarchically Structured Materials," *Science*, vol. 277, no. 5330, pp. 1237-1242, Aug. 1997.

[6] E. L. Doubrovski, J. C. Verlinden, and J. M. P. Geraedts, "Optimal Design for Additive Manufacturing: Opportunities and Challenges," in *ASME IDETC Conference, DETC2011-48131*, 2011.

[7] M. Hašan, M. Fuchs, W. Matusik, H. Pfister, and S. Rusinkiewicz, "Physical reproduction

of materials with specified subsurface scattering," *ACM Transactions on Graphics*, vol. 29, no. 4, p. 1, Jul. 2010.

[8] T. Purcell and K. Sodersten, "Design Education, Reflective practice, and design research," in *Designing in context*. Delft: Delft University of Technology, pp. 395-410, 2001.

[9] J. H. Bøhn, "Integrating rapid prototyping into the engineering curriculum – a case study," *Rapid Prototyping Journal*, vol. 3, no. 1, pp. 32-37, 1997.

[10] S. Thomke and T. Fujimoto, "The Effect of 'Front-Loading' Problem-Solving on Product Development Performance," *Journal of Product Innovation Management*, vol. 17, pp. 128-142, 2000.

[11] F. W. Liou, *Rapid Prototyping and Engineering Applications: A Toolbox for Prototype Development*. CRC Press, 2007.

[12] A. Smailagic, D. Siewiorek, and U. Maurer, "A context-specific electronic design and prototyping course," in *Proceedings of the International Conference on Microelectronic Systems Education*, 2005, pp. 1-2.

[13] J. M. Leake, "Development of an advanced course in computer-aided design, analysis and prototyping," in *ASEE, Annual Conference Proceedings*, 2004.

[14] I. Gibson, D.W. Rosen, D.W., B. Stucker, Additive Manufacturing Technology, Springer, 2009.

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